-

Suplemento:

TECHNOHERITAGE 2019 - ***Fourth edition of the International Congress on Science and Technology for the Conservation of Cultural Heritage***

GRUPO ESPAÑOL de CONSERVACIÓN
International Institute for Conservation of historic and artistic works

Ge-conservación
Conservação | Conservation

TECHNOHERITAGE 2019

IV International Congress
Science and Technology for the Conservation of Cultural Heritage

Índice

Suplemento:

Presentation / Presentación

The Network of Science and Technology for the Conservation of Cultural Heritage promotes the collaboration between the agents and stakeholders of the science-technology-business system, sharing experiences, knowledge, and technology with the main goal of contributing to the conservation and safeguard of Cultural Heritage.

The fourth edition of the International Congress on Science and Technology for the Conservation of Cultural Heritage was held in Seville, Spain, 26-30 March 2019, was focused on the application of digital and new technologies for the sustainable management, knowledge and social innovation for the prevention, conservation and management of heritage. More than 150 abstracts were received. The Congress had the support of Spanish National Research Council, Andalusian Institute of Historical Heritage, University Pablo de Olavide and University of Seville. And partially funded by the Spanish research projects

•ART-RISK: Artificial intelligence applied to preventive conservation of heritage buildings - a RETOS project of Ministerio de Economía y Competitividad and Fondo Europeo de Desarrollo Regional (FEDER), (code: BIA2015-64878-R; MINECO/FEDER-UE)

•TUTSOSMOD: Sustainable management of cultural heritage through BIM and GIS models: contribution to knowledge and social innovation. A project funded by the Ministry of Science, Innovation and Universities (HAR2016-78113-R)

This special issue includes papers from Technoheritage participants in the congress, based on the use of digital and new technologies, physico-chemical techniques or vulnerability assessment, among others. In this context, Science and Technology for the Conservation of Cultural Heritage have a key-role in research, establishing new methodologies and protocols towards better knowing of our historical buildings, archeological sites and artworks.

La Red de Ciencia y Tecnología para la Conservación del Patrimonio Cultural promueve la colaboración entre los agentes y las partes interesadas del sistema ciencia-tecnología-empresa, compartiendo experiencias, conocimientos y tecnología con el objetivo principal de contribuir a la conservación y salvaguarda del Patrimonio Cultural.

La cuarta edición del Congreso Internacional de Ciencia y Tecnología para la Conservación del Patrimonio Cultural, celebrada en Sevilla, España, del 26 al 30 de marzo de 2019, se centró en la aplicación de nuevas tecnologías digitales para la gestión sostenible, el conocimiento y la innovación social para la prevención, conservación y gestión del patrimonio. Se recibieron más de 150 resúmenes. El Congreso contó con el apoyo del Consejo Superior de Investigaciones Científicas de España, el Instituto Andaluz de Patrimonio Histórico, la Universidad Pablo de Olavide y la Universidad de Sevilla. Y estuvo parcialmente financiado por los proyectos de investigación españoles:

•RIESGO DE ARTE: Inteligencia artificial aplicada a la conservación preventiva de edificios patrimoniales: un proyecto RETOS del Ministerio de Economía y Competitividad y Fondo Europeo de Desarrollo Regional (FEDER), (código: BIA2015-64878-R; MINECO / FEDER-UE)

•TUTSOSMOD: Gestión sostenible del patrimonio cultural a través de modelos BIM y SIG: contribución al conocimiento y la innovación social. Un proyecto financiado por el Ministerio de Ciencia, Innovación y Universidades (HAR2016-78113-R)

Este número especial incluye artículos de los participantes del congreso Technoheritage, sobre el uso de las nuevas tecnologías digitales, técnicas fisicoquímicas o la evaluación de la vulnerabilidad, entre otros. En este contexto, la Ciencia y la Tecnología para la Conservación del Patrimonio Cultural tienen un papel clave en la investigación, estableciendo nuevas metodologías y protocolos para conocer mejor nuestros edificios históricos, sitios arqueológicos y obras de arte.

During the Technoheritage conference, each presentation (oral or poster) was evaluated by two reviewers, and some authors were asked for publication in a special issue of Ge-Conservación. The final papers according the standard for authors of the journal, were also evaluated by double blind per review system.

We sincerely acknowledge the work of Technoheritage network, authors, Local Organizing Committee, Scientific Organizing Committee and the anonymous reviewers.

*Although all care is taken to ensure integrity and the quality of this publication and the information herein, no responsibility is assumed by the publishers, editors nor the authors for any damage to the property or persons as a result of operation or use of this publication and/or the information contained herein.

*The Editors declare that they have no conflicts of interest regarding the publication of this Special Issue.

Durante el congreso Technoheritage, cada presentación (oral o póster) fue evaluada por dos revisores, y se informó a algunos autores que la posibilidad de publicar en un número especial de Ge-Conservación. Los trabajos finales, según el estándar para autores de la revista, también fueron evaluados por un sistema doble ciego de revisión.

Quisiéramos agradecer sinceramente el trabajo de la red Technoheritage, los autores, el Comité Organizador Local, el Comité Organizador Científico y los revisores anónimos.

* Si bien se toman todas las precauciones para garantizar la integridad y la calidad de esta publicación y la información aquí contenida, los editores, editorial y autores no asumen ninguna responsabilidad por ningún daño a la propiedad o personas como resultado del funcionamiento o uso de esta publicación y/o la información aquí contenida.

* Los editores declaran que no tienen conflictos de intereses con respecto a la publicación de este número especial.

Editores invitados

Javier Becerra Luna

Universidad Pablo de Olavide, Sevilla, España

Pilar Ortiz Calderón

Universidad Pablo de Olavide, Sevilla, España

Francisco S. Pinto

Universidad de Sevilla, Sevilla, España

Ge-conservación
Conservação | Conservation

Electrochemical evaluation of the patina of the weathering steel sculpture *Once Módulo*

A. Crespo, B. Ramírez-Barat, I. Díaz, E. Cano

Abstract: Weathering steels (WS) have been widely used due to the protective rust formed on the surface of the bare metal exposed to the atmosphere. They have been studied attending to specifications and characteristics in engineering, but in cultural heritage the use of this material does not follow the same criteria and has different needs which must be addressed. Among them, the design and the location of the sculpture may have an impact on the rust formed and may not be as protective as it was supposed to be.

This work presents the study of the weathering steel sculpture *Once Módulo* which shows areas with different exposure to rainwater and different surface heterogeneities. The results obtained by Electrochemical Impedance Spectroscopy (EIS) have shown that the protective ability of the rust depends on the previous differences and that design and location of the artwork play an important role for its conservation.

Keywords: weathering Steel, sculpture, electrochemical impedance spectroscopy, atmospheric corrosion, conservation, contemporary art.

Evaluación electroquímica de la pátina de la escultura en acero patinable *Once Módulo*

Resumen: Los aceros patinables han sido ampliamente utilizados debido a la habilidad protectora de la herrumbre que se forma en la superficie del metal al exponerlo a la atmosfera. Su estudio se ha enfocado en las especificaciones y características desde un punto de vista ingenieril, sin embargo, en patrimonio cultural el uso de este material no sigue los mismos criterios y tiene distintas necesidades que han de atenderse. Entre ellas, el diseño y la localización de la escultura pueden tener un impacto en la herrumbre formada y esta puede no ser tan protectora como se supondría.

Este trabajo presenta el estudio de la escultura de acero patinable *Once Módulo* la cual muestra áreas con distinta exposición al agua de lluvia y distintas heterogeneidades superficiales. Los resultados del análisis con Espectroscopia de Impedancia Electroquímica (EIE) han mostrado que la habilidad protectora de la herrumbre depende de las diferencias anteriores y que el diseño y la localización de la obra juegan un importante papel en su conservación.

Palabras clave: acero patinable, escultura, espectroscopia de impedancia electroquímica, corrosión atmosférica, conservación, arte contemporáneo

Introduction

Weathering steels (WS), also known by the commercial name Cor-Ten, are carbon steels with alloying elements such as chromium, copper and nickel in quantities lower than 3-5% (Morcillo et al., 2013). WS are widely used in civil engineering due to their ability to naturally develop a protective patina at low aggressive atmospheres, which slows down the corrosion of the base metal and makes no need of painting the material (Díaz et al., 2012). Since the 1960s WS have also been used in contemporary art and architecture thanks to the rich colors of the patina and with the aim of placing outdoors sculptures which could remain even longer than bronze (Scott, 1991). However, there are some characteristics differences in the use of WS in cultural heritage compared to civil engineering that may modify and affect the protective ability of the rust.

The first difference is the use of acids and salts on the surface of the steel. As the appearance of the appealing patina needs long exposure times, sculptors and blacksmiths usually accelerate its formation with chemical treatments (Crespo, 2016). The second issue is the geometry of the sculpture, as one of the conditions for a patina to be

Figure 1.- Sculpture *Once Módulo* from different perspectives.

protective is the alternation of wetting and drying cycles (Stratmann et al., 1983), the design may have sheltered zones and water accumulation zones with different time of wetness (ToW: number of hours per year in which the relative humidity is higher than 80% and the temperature is beyond 0ºC, according to the ISO 9223). The last difference is the location of the artwork, if the artwork is constantly wet –as in parks with watering zones- or if is mainly dry – as under a porch or trees- the wetting and drying cycles may be altered and have consequences on the protective ability of the rust. A good understanding of these effects is important to foresee the long-term durability of the artwork and contribute to its preservation.

The sculpture *Once Módulo* was performed by Amador Rodríguez (Ceuta 1926, Madrid 2001), a Spanish sculptor and painter. He has worked with different materials depending on the message of his artwork; among them, steel was the first material he used. *Once Módulo* was performed in 1971 during his rationalist period, while he was studying different geometry forms (Gómez, 2016) which are expressed in this artwork [figure 1]. The sculpture is a cube with dimensions of 160 cm. each side made of WS with circular shapes inside. It was acquired by the Museo Nacional Centro de Arte Reina Sofía in 1971 and deposited at the Museo de Escultura al Aire Libre de Leganés (Madrid) in 2000-2001.

The aim of this work is to analyze the protective ability of the sculpture patina in areas with different time of wetness and different visual surface heterogeneities to study the effect that it may have on the development of the rust.

Methodology

—1. *Zones of analysis*

The sculpture *Once Módulo* is placed at the Museo de Escultura de Leganés (south of Madrid, Spain). The museum is outdoors and inside of a park. The environment could be classified as urban atmosphere of corrosivity category C2 for plain carbon steel, according to ISO 9223. The sculpture has a complex geometry with areas of different time of wetness. Two of these areas were chosen for analysis: a vertical one labeled as Normal zone and another area labeled as Sheltered zone with less exposure to rainwater. In the vertical area it is possible to distinguish differences in color and texture in the patina, so a third zone was chosen in this area and labeled as Irregular zone. The three zones of analysis are shown in [figure 2]. Although the number of measurements is low for statistical purposes, in this work only comparative study has been taken into account.

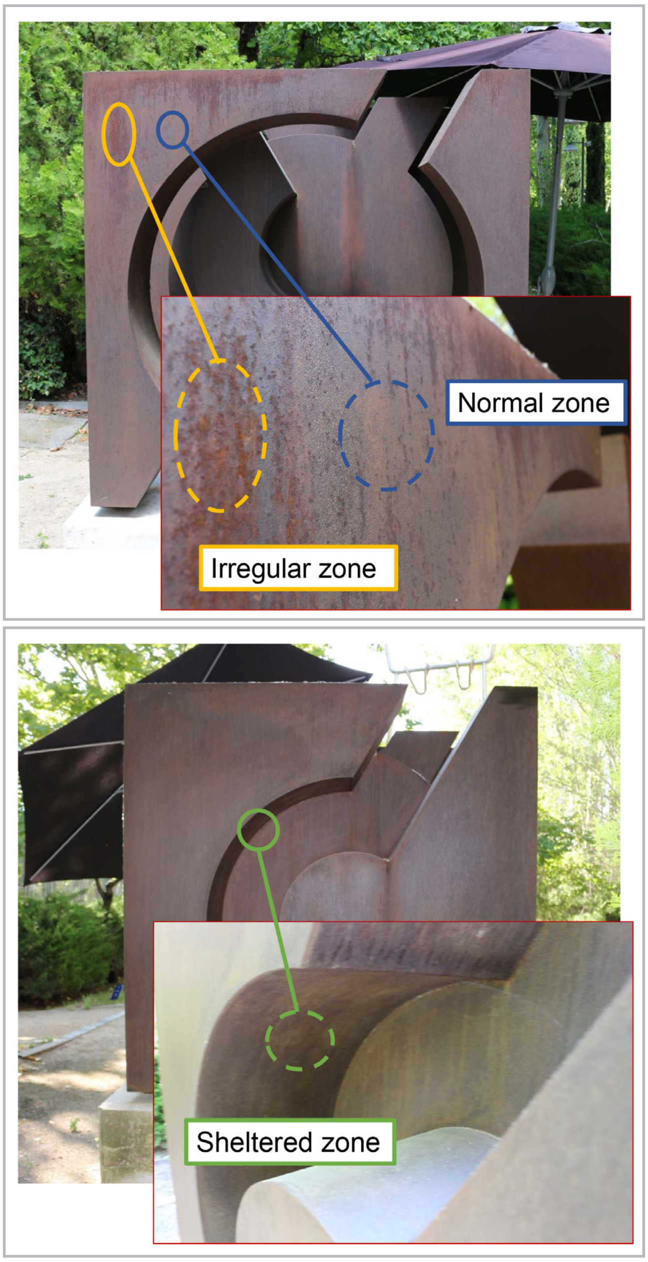


Figure 2.- Details of the three zones of analysis (solid circles) and magnifications (dashed circles). Normal zone (blue), Irregular zone (yellow) and Sheltered zone (green).

—2. *Techniques*

The protective ability of the rust in the different areas of the sculpture was measured by Electrochemical Impedance Spectroscopy (EIS). EIS is a very useful technique because it provides information about the corrosion process as well as the protective behavior of the patina, however its application for in situ analysis is complicated due to the difficulties of placing an electrochemical cell with a liquid electrolyte on the usually curved, rough and non-vertical surfaces of the sculptures (Ramírez Barat and Cano, 2018). To perform EIS analysis directly over the patina of the metallic sculpture, a portable electrochemical cell was designed (Cano et al., 2014, Ramírez Barat et al., 2018). In this study, the electrochemical cell consists of a stainless-steel mesh as counter electrode, a Ag/AgCl electrode as a reference and the electrolyte is an artificial rain prepared in the laboratory according to the pollutants of Madrid; the electrolyte was gelled with 3% agar. EIS analysis have been performed with a Gamry Reference 600 potentiostat, the sequence applied was 1800 seconds of Open Circuit Potential (OCP) and EIS from 100 kHz to 10 mHz with an amplitude of 10 mV. The fit of the results was made with Zview software.

EIS results have been analyzed with reference to the patina thickness, which has been measured with an Elcometer 456 gauge, using a probe for ferrous materials in the same areas tested for EIS.

Finally, as aesthetical properties are a matter of importance in cultural heritage, color has been measured in the same areas with a Konica Minolta spectrophotometer CM-700-d. Differences between two colors are a subjective matter, but a way to measure them is with the parameter ΔE calculated with the differences in the CIEL*a*b* sphere coordinates with the following formula.

$$\Delta E=\sqrt{(\Delta L^2+\Delta a^2+\Delta b^2)}$$

To evaluate the differences in color, the previous formula has been applied. Variation of the L* parameter (brightness) and a* and b* parameters (green- yellow and blue-red axes respectively) have been calculated for the three measured zones, therefore, it is possible to compare the color obtained in the three zones of analysis among each other.

Results and discussion

—1. *Electrochemical impedance spectroscopy*

To obtain information about the measured systems it is useful to fit the results to an equivalent circuit. The equivalent circuit provides information of each electrical component, which can be associated with the different parts of the measured system. Fitting is not an easy task, many equivalent circuits have been tested but the best results and physical meaning were obtained with the one proposed by Dhaiveegan et al. (2014) and shown in figure 3.

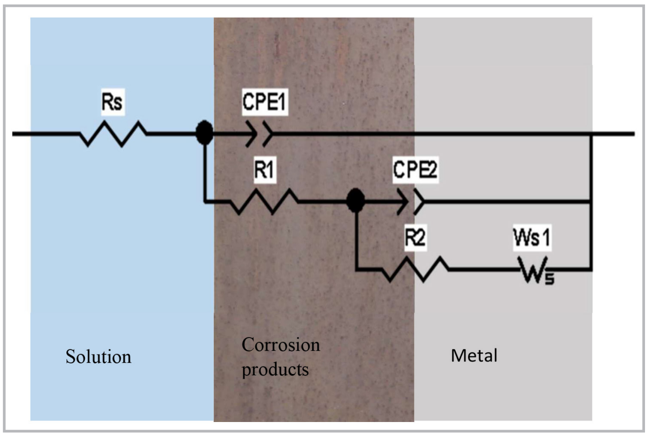


Figure 3.- Equivalent circuit proposed and its representation in the corrosion layer.

In the equivalent circuit, Rs represents the ohmic drop; CPE1 and R1 are the constant phase element and the resistance of the corrosion products respectively; CPE2 and R2 represent the constant phase element associated to the electrochemical double layer and the charge transfer resistance of the corrosion process; and Ws is the Warburg impedance associated with diffusion of the species through the diffusion layer. In this work we are going to focus on the resistance of the corrosion products (R1) and the charge transfer resistance (R2) in the three zones of analysis. Representative EIS results are shown in table 1 and experimental data together with the respective fittings are shown in figure 4.

The different fittings show a very good Chi square as well as a good fit in the graphs. The resistances of the corrosion products (R1) have low errors although the resistances of the charge transfer process (R2) have higher errors. All errors are acceptable, even for the R2 for the Sheltered zone, the higher error, it is lower than the differences between different zones.

According to the results of the resistance of the corrosion products (R1), the Normal zone has a resistance value that is approximately twice the other two zones (the

Table 1.- Resistances of the equivalent circuit obtained for the three analyzed areas of the sculpture *Once Módulo*

	R1 (Ohm)	R1 error (%)	R2 (Ohm)	R2 error (%)	Chi square
Normal zone	894.8	1.03	1637	24.29	4.39E-4
Irregular zone	417.3	0.43	1005	22.67	6.95E-5
Sheltered zone	428.3	10.02	240.9	61.22	1.35E-4

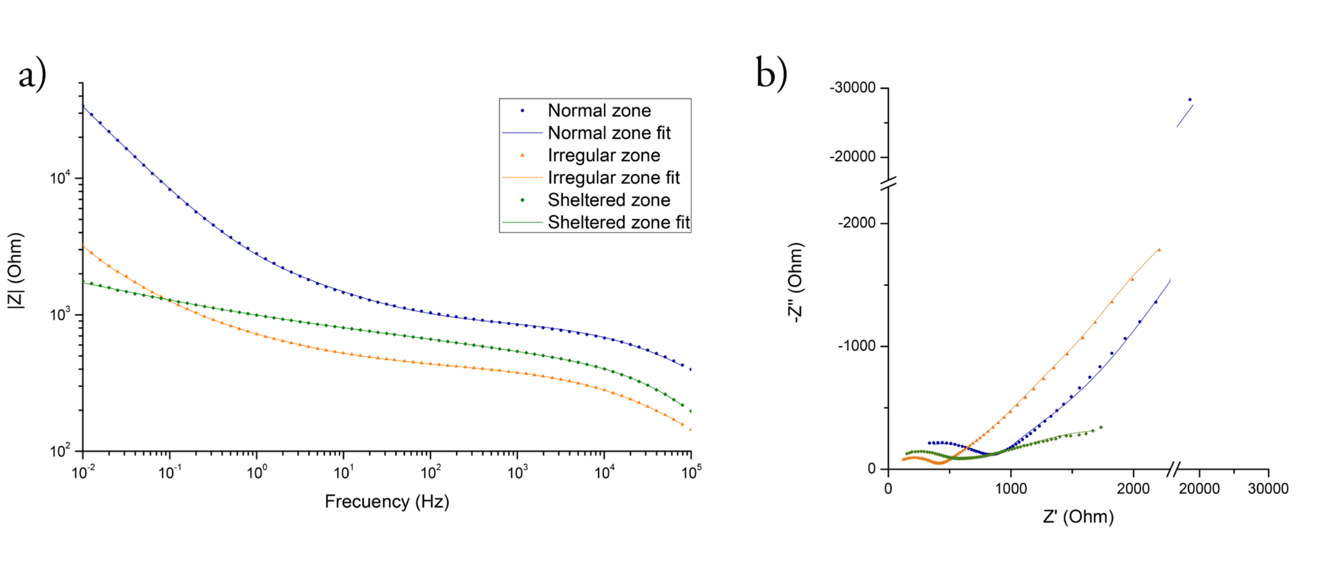


Figure 4.- Impedance module plot (a) and Nyquist plot (b) for the three zones of analysis of the sculpture *Once Módulo*.

Irregular and the Sheltered). This fact indicates that the corrosion products have a higher protective effect in this area.

The Irregular and Sheltered zones have very similar values of R1 so this two corrosion layers have similar protective properties. The charge transfer resistance (R2) is also higher in the Normal zone, with Sheltered zone being the least resistant. Results show a better protective ability in the Normal zone while the Sheltered zone is more susceptible to suffer corrosion processes.

Results do not necessary indicates that the sculpture *Once Módulo* is at risk but that there are areas within the sculpture that are more susceptible to atmospheric corrosion. The artwork is placed outdoors in a park of Leganés with probably little pollution, which suggests that the environment is optimal for this material (Morcillo et al., 2019).Therefore, at the time the analysis were made, there is no need to think that the sculpture is at any kind of risk that may compromise its conservation.

—2. *Thickness*

The thickness of the patina was measured in fifteen different points in each of the three analyzed areas. The average thickness and standard deviation are shown in table 2.

Table 2.- Results of patina thickness for the three analyzed areas in the sculpture *Once Módulo*.

Normal zone (µm)	Irregular zone (µm)	Sheltered zone (µm)
103.7 ± 21.88	56.7 ± 9.46	43.1 ± 7.21

The Normal zone has close to the double of the thickness than the other two areas, which is in accordance with the higher resistance shown by EIS results of the corrosion layer (R1). Although the Irregular zone had a rough aspect and was expected to be thicker, the thickness of its patina is more similar to the Sheltered zone than to the Normal zone. Authors have measured the thickness of their own hair following the experiment performed by (Diez, 2015), values between 50 and 60 µm were obtained. Although these patinas are very thin, there is not much difference from a patina developed for five years in a rural environment (Díaz et al., 2018). This indicates that the corrosivity of the environment of the park in the Museum is low.

The results of the resistance of the corrosion products are in agreement with the patina thickness and indicate that, although the Normal and the Irregular zone are very close in the sculpture and have same exposure to rainwater, they have notable differences in their behavior against atmospheric corrosion. The Sheltered zone, with less time of wetness, has the poorest protection against atmospheric corrosion but, as mentioned above, its risk to suffer severe atmospheric corrosion processes will depend on the environment.

—3. *Color*

Color has been analyzed in fifteen different points around the zone of analysis. Results are reported using the CIEL*a*b* sphere where L* parameter represents the luminosity (being the value 100 white and 0 black) and the a* and b* parameters represents the content in green (negative a*) and red (positive a*) and the content of blue (negative b*) and yellow (positive b*). Results are shown in table 3 and in figure 5.

Table 3.- L*a*b* results for the three zones of analysis.

	L*	a*	b*
Normal zone	32.4 ± 0.4	4.9 ± 0.7	5.3 ± 1.3
Irregular zone	27.0 ± 1.7	8.3 ± 0.8	7.0 ± 0.7
Sheltered zone	35.2 ± 0.7	5.4 ± 0.3	8.2 ± 0.4

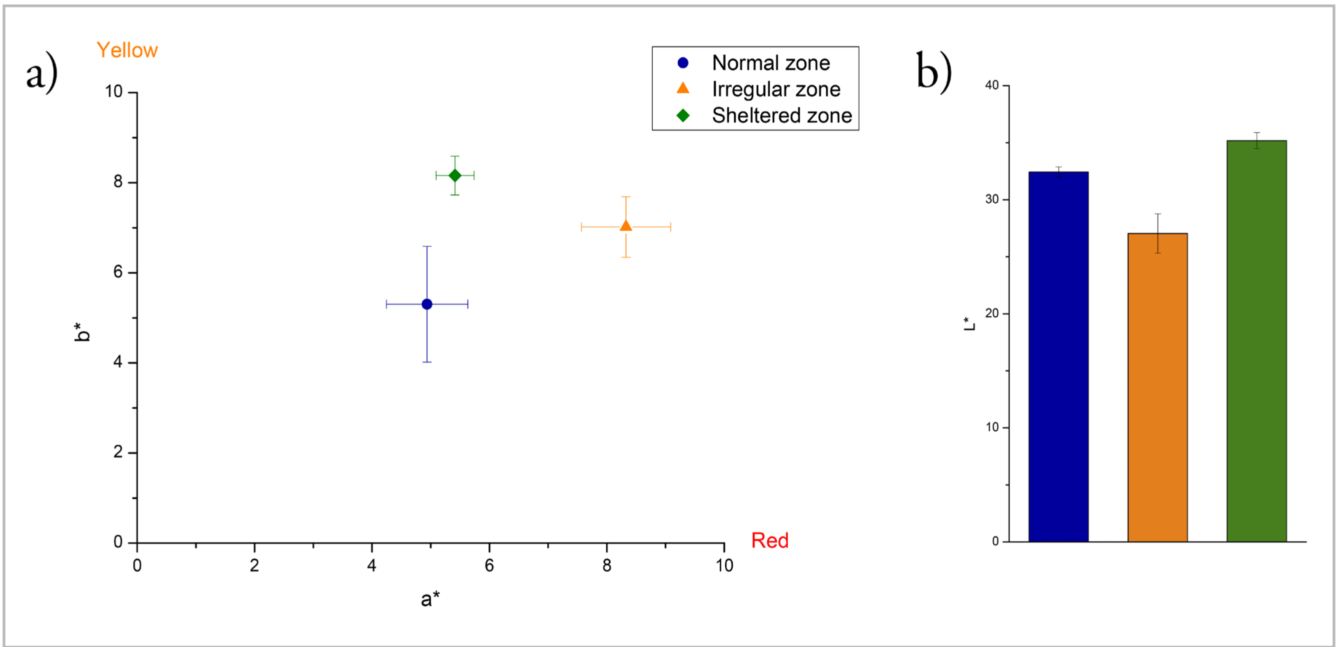


Figure 5.- Chromatic parameters a* and b* (a) and luminosity parameter L* (b) .

As a* and b* have positive values it means that the tone of the patina tends to orange, however the values are quite low, so the colors are dull. Also, the L* values are closer to the center of the sphere (50), so the colors are grayish and weak. Comparing the three zones of analysis, the Irregular zone has higher values in parameters a* and b* and a lower value of L*, it is the most vivid color with a darker tone. Data of color differences ΔE between the three zones of analysis are shown in table 4.

According to the bibliography, if ΔE is higher than 1 (Ghelardi et al., 2015) the color differences are perceptible for the human eye. In the case of study all the zones have differences much greater than 1, being the Irregular zone the most different one with a ΔE = 6.6 with the Normal zone and ΔE = 8.7 with the Sheltered zone. This is in accordance with initial observations as this area was analyzed due to the differences in a visual inspection. According to the EIS analysis, in this case, the visual differences are related to different protective abilities against corrosion.

Conclusions

The use of WS in cultural heritage has some peculiarities that have to take into account; among them, the design of the sculptures may yield differences in the protective ability of the patinas. It has been proved that Sheltered zones develop the less protective corrosion products although the risk to suffer damage will depend on the atmosphere to which it is exposed. In this case of study and at the time analysis were performed, there is no risk for the sculpture due to the low pollution of the atmosphere.

Table 4.- ΔE results of the three areas of analysis in the sculpture Once Módulo

ΔE	Normal zone	Irregular zone	Sheltered zone
Normal zone	-	6.60	3.99
Irregular zone	6.60	-	8.72
Sheltered zone	3.99	8.72	-

Under a visual analysis, some heterogeneities are evident in the surface and may be related to less protection against corrosion. Changes in color and thickness have reveal differences in the protective characteristics of the rust. A full documentation of the history of the artworks and a complete study of the sculptures are necessary in order to assure the preservation of WS.

Acknowledgments

Authors acknowledge Juan Carlos Roldán for his work in field measurements and his work with audiovisual material. Rosa María Izquierdo from the Museo de Escultura de Leganés and Pilar García from the Museo Nacional Centro de Arte Reina Sofia for their kind support and patience. And to the Agencia Estatal de Investigación for the grant BES-2015-071472 and to Comunidad de Madrid for the project TOP-HERITAGE CM (S2018/NMT_4372) for financial support.

References

CANO, E., CRESPO, A., LAFUENTE, D., RAMIREZ BARAT, B. (2014). "A novel gel polymer electrolyte cell for in-situ application of co-rrosion electrochemical techniques". *Electrochemistry Communi-cations*, 41:16-19. https://doi.org/10.1016/j.elecom.2014.01.016

CRESPO, A. RAMÍREZ-BARAT., B. CANO, E. (2016)."Artificial patinas in contemporary weathering steel sculpture". In *International Conference YOCOCU*. V International Conference of Youth in Conservation of Cultural heritage. Madrid.

DHAIVEEGAN, P., ELANGOVAN, N., NISHIMURA, T., RAJENDRAN, N. (2014). "Electrochemical Characterization of Carbon and Weathering Steels Corrosion Products to Determine the Protective Ability Using Carbon Paste Electrode (CPE)". *Electroanalysis*, 26, 2419-2428. https://doi.org/10.1002/elan.201400240

DÍAZ, I., CANO, H., CHICO, B., DE LA FUENTE, D., MORCILLO, M. (2012). "Some clarifications regarding literature on atmospheric corrosion of weathering steels". *International Journal of Corrosion*, 2012. https://doi.org/10.1155/2012/812192

DÍAZ, I., CANO, H., CRESPO, D., CHICO, B., DE LA FUENTE, D. MORCILLO, M. (2018). "Atmospheric corrosion of ASTM A-242 and ASTM A-588 weathering steels in different types of atmosphere". *Corrosion Engineering Science and Technology*, 53: 449-459. https://doi.org/10.1080/1478422X.2018.1500978

DIEZ, A. (2015). *Cómo medir el grosor de un pelo usando un láser casero* [Online]. https://www.elespanol.com/omicrono/tecnologia/20150425/medir-grosor-pelo-usando-laser-casero/28497157_0.html: El Español. [Accessed 07/03 2017].

GHELARDI, E., DEGANO, I., COLOMBINI, M. P., MAZUREK, J., SCHILLING, M., KHANJIAN, H., LEARNER, T. (2015). "A multi-analytical study on the photochemical degradation of synthetic organic pigments". *Dyes and Pigments*, 123: 396-403.

GÓMEZ, P. (2016). Amador Rodríguez Menéndez [Online]. http://www.esculturaurbana.com/paginas/ama.htm#p). [Accessed 21/10 2019].

MORCILLO, M., CHICO, B., DÍAZ, I., CANO, H., DE LA FUENTE, D. (2013). "Atmospheric corrosion data of weathering steels. A review". *Corrosion Science*, 77: 6-24. https://doi.org/10.1016/j.corsci.2013.08.021

MORCILLO, M., DÍAZ, I., CANO, H., CHICO, B., DE LA FUENTE, D. (2019). "Atmospheric corrosion of weathering steels. Overview for engineers. Part I: Basic concepts". *Construction and Building Materials*, 213: 723-737. https://doi.org/10.1016/j.conbuildmat.2019.03.334

RAMÍREZ BARAT, B., CANO, E. (2018). "In Situ Electrochemical Impedance Spectroscopy Measurements and their Interpretation for the Diagnostic of Metallic Cultural Heritage: A Review". *ChemElectroChem*, 5: 2698-2716.

RAMÍREZ BARAT, B., CANO, E., LETARDI, P. (2018). "Advances in the design of a gel-cell electrochemical sensor for corrosion measurements on metallic cultural heritage". *Sensors and Actuators, B: Chemical*, 261: 572-580.

SCOTT, J. (1991). "Conservation of weathering steel sculpture". In: *Saving the twentieth century: the degradation and conservation of modern materials*, Ottawa, Canada. Canadian Conservation Institue.

STRATMANN, M., BOHNENKAMP, K., ENGELL, H. J. (1983). "An electrochemical study of phase-transitions in rust layers". *Corrosion Science*, 23: 969-985. https://doi.org/10.1016/0010-938X(83)90024-0

Author/s

Ana Crespo Ibáñez
a.crespoibanez@cenim.csic.es
Centro Nacional de Investigaciones Metalúrgicas (CENIM) – Consejo Superior de Investigaciones Científicas (CSIC)

Ana Crespo obtained her bachelor degree in Chemistry with specialization in Chemistry of Materials in 2011 from the Complutense University of Madrid. During her bachelor she started the study of materials in cultural heritage with the project "Spectroscopic analysis of additives of concrete" at the Institute for the Structure of Matter. She continued her academic training with the master degree in Materials Science and Engineering in 2013 from Carlos III University of Madrid, where she obtained the award of basic science and engineering for the design of a portable electrochemical cell with gel-electrolyte, carried out at the CENIM. After working in the UK she returned to Spain to start her PhD at the CENIM with the project "Characterization and evaluation of artificial patinas in weathering steel sculpture". Her work is focused on the study of natural and artificial patinas in weathering steel sculpture with Raman spectroscopy and electrochemical techniques. During her PhD she made an internship at Commissariat à l'energie atomique de Saclay (France) studying Raman mapping and EDS analysis in rust; she has participated in 8 national and international projects, 1 of them as principal investigator at the synchrotron SOLEIL; 8 publications in congress, 7 of them international; she has collaborated in specialized training courses and postgraduate courses with Carlos III University of Madrid, Pablo de Olavide University of Seville, Menéndez Pelayo International University. She is currently writing her PhD thesis that hopefully will be finished at June 2020.

Blanca Ramírez Barat
blanca.ramirez@csic.es
Centro Nacional de Investigaciones Metalúrgicas (CENIM) – Consejo Superior de Investigaciones Científicas (CSIC)

Postdoctoral researcher in the group "Corrosion and Protection of Metals in Cultural Heritage and Construction (COPAC)" at the Nacional Centre for Metallurgical Research (CENIM-CSIC), Madrid, Spain. After receiving her BA in Fine Arts (conservation), she graduated in Chemistry at the Complutense University in Madrid and completed her PhD in Materials Science and Engineering at the Carlos III University in Madrid. Her research is focused in the application of electrochemical techniques for conservation assessment and diagnosis in metallic cultural heritage and her doctoral thesis has been dedicated to the development of an electrochemical cell for in situ measurements on cultural heritage. She is also involved in several projects, networks and activities related to Heritage Science such as the Spanish Network of Science and Technology for the Conservation of Cultural Heritage (TechnoHeritage), the National Plan for Research Conservation in Cultural Heritage (PNIC), CSIC´s Interdisciplinary Thematic Platform Patrimonio Abierto: Investigación y Sociedad, PTI-PAIS (Open Heritage: Research and Society) or the Spanish Node of the Research Infrastructure for Heritage Science (ERIHS.es).
https://orcid.org/0000-0001-5306-4057

Iván Díaz Ocaña
ivan.diaz@cenim.csic.es
Centro Nacional de Investigaciones Metalúrgicas (CENIM) – Consejo Superior de Investigaciones Científicas (CSIC)

He received his Bachelor's degree in materials chemistry and his PhD, with a distinction "cum laude", from the Complutense University in Madrid. His doctoral thesis was one of the first in-depth research conducted in Spain on atmospheric corrosion of weathering steels, incorporating nickel in its composition. During his PhD, he received several pre-doctorate research scholarships to complete his training in the characterization of rust at the Old Dominion University (USA) and University of Antioquia (Colombia). He has a solid background in electrochemical and accelerated corrosion tests and its research focus is on indoor and outdoor atmospheric corrosion of metals. As a result, he has published around 40 research papers in peer-reviewed journals in the field of atmospheric corrosion and has carried out scientific-technical assistance tasks for the industry. Currently, he is working as postdoctoral researcher in the group "Corrosion and Protection of Metals in Cultural Heritage and Construction (COPAC)" at the Nacional Centre for Metallurgical Research (CENIM-CSIC), Madrid, Spain.

Emilio Cano
ecano@cenim.csic.es
Centro Nacional de Investigaciones Metalúrgicas (CENIM) – Consejo Superior de Investigaciones Científicas (CSIC)

Emilio Cano is Tenured Scientist at the National Center for Metallurgical Research (CENIM) of the Spanish National Research Council (CSIC) in Madrid, leading the research group "*Corrosion and Protection of metals in cultural heritage and construction*" (COPAC). He graduated in Fine Arts Conservation in 1996 and obtained his PhD in 2001 from the Complutense University of Madrid, after an internship at the Canadian Conservation Institute (CCI), Ottawa. As heritage scientist, his work has focused in the study of corrosion and protective systems for the metallic Cultural Heritage, atmospheric corrosion in museums and exhibitions; and the application of electrochemical techniques and corrosion inhibitors for the conservation of the cultural heritage. He has published more than 125 scientific articles (88 in JCR/Scopus indexed journals), and presented at more than 100 scientific conferences. He has participated in 33 national and international research projects (6th and 7th Framework Programmes and Horizon 2020 from the EU), being PI in 14 of them in the last 10 years. These projects and several research contracts have been developed in collaboration with the most relevant institutions working on conservation of cultural heritage (Instituto del Patrimonio Cultural de España, Patrimonio Nacional, Museo del Prado, Museo Guggenheim Bilbao, Museo Arqueológico Nacional, Museo Nacional de Ciencia y Tecnología, etc.). Spanish Representative in the Executive Board of the Joint Programming Initiative "*Cultural Heritage and Global Change: a Challenge for Europe*" from 2011-2017. Assistant Coordinator of the International Council of Museums-Conservation Committee (ICOM-CC) Metal Working Group since 2012; Coordinator of the Spanish Network for Science and Technology for the Conservation of Cultural Heritage (Technoheritage) since 2015, Fellow of the International Institute of Conservation (IIC) and member of the Spanish group of the IIC (GE-IIC); coordinator of the Spanish Node of the European Research Infrastructure on Heritage Science (E-RIHS).
https://orcid.org/0000-0002-8716-3931
http://www.cenim.csic.es/index.php/presentacion-copac

https://doi.org/10.37558/gec.v17i1.761

Ge-conservación
Conservação | Conservation

Conservation to overcome oblivion. New methods for the survival of lost heritage memory

María José Merchán, Emiliano Pérez

Abstract: Unfortunately, it sometimes happens that heritage buildings and structures unearthed during the construction of new infrastructures cannot be adequately conserved once dug out. Before the eternal doubt, keeping or covering them, the economic aspect often takes precedence. Luckily, when the decision is to hide it again, technology offers the possibility of acquiring, modelling and storing the 3D data of the remains and allows their later visualization with a very realistic appearance. Therefore, the memory of these remains destined to be forgotten survives beyond the archives of the professionals who documented them. In this paper, the opportunities opened by Augmented and Virtual Reality applications for the preservation and dissemination of re-covered, or even lost, remains will be explained through the finding came about in the works performed for renovating an old road in Fuente del Maestre (Spain).

Keywords: conservation, cultural heritage, 3D modelling, augmented/virtual reality

Conservación para superar el olvido. Nuevos métodos para la supervivencia de la memoria del patrimonio perdido

Resumen: A veces sucede que, desafortunadamente, los edificios históricos desenterrados durante la construcción de nuevas infraestructuras no pueden conservarse adecuadamente una vez excavados. Ante la eterna duda, mantenerlos o cubrirlos, el aspecto económico muy a menudo tiene prioridad. Por suerte, cuando la decisión es ocultarlo nuevamente, la tecnología ofrece la posibilidad de adquirir, modelar y almacenar los datos 3D de los restos para su posterior visualización de forma muy realista. De esta manera, el recuerdo de estos restos destinados a ser olvidados sobrevive más allá de los archivos de los profesionales que los documentaron. En este documento, las oportunidades que se abren gracias a la Realidad Aumentada y la Realidad Virtual aplicadas a la preservación y difusión de aquellos restos que deben ser enterrados de nuevo y que, incluso, llegan a perderse, se explicarán a través del hallazgo que se produjo en los trabajos realizados para renovar una antigua carretera en Fuente del Maestre (España).

Palabras clave: conservación, patrimonio cultural, modelado 3D, realidad aumentada/realidad virtual

Introduction

Defining what conservation means is a very arduous task. It must be considered from a holistic viewpoint: from culture to society, from identity to management. Thus, giving a definition from one of its aspects implies, necessarily leaving apart the others. Conservation has to do with restoration so tightly that people sometimes mix up both terms. But conserving doesn't always imply restoring. In the same way, conservation is related to preservation in such a way that both are often perceived like synonymous. The ICOM, which assumes this quasi correspondence between the two terms, states: "To preserve means to protect a thing or a group of things from different hazards such as destruction, deterioration, separation or even theft; this protection is ensured by gathering the collection in one place, inventorying it, sheltering it, making it secure and repairing it" (Desvallées & Mairesse 2010: 65). Preserving to ensure the continuity of things implies the recognition that tomorrow's public is equally important than today's (Castriota 2019: 49).

But nowadays, conservation/preservation goes beyond prolonging the heritage assets' physical lives for the far future. Other values, not always tangible, must also be preserved for the coming generations: what they mean for the identity of the people in the surroundings, their relation with the natural environment, besides their historical, artistic, cultural, political, economic or social value (Hölling 2017: 87). In order to get to this end, it is essential to maintain the authenticity of the heritage property (ICOMOS 1994), always following the principles of restoration gathered in successive charters along the years (ICOMOS 2004).

Paradoxically, conservation seems even more necessary when the cultural assets are going to disappear. In these cases, "conservation" plays a very important role in preserving the memory of the heritage for future generations to know it. When the strategy of documenting the cultural property before its disappearance is complemented with well-focused dissemination activities, this type of conservation could mean economic and social improvements for the population of the area. This is the case tackled in this paper, conservation to overcome the oblivion that, sooner or later, goes irretrievably linked to the disappearance.

On this way towards the safeguarding of cultural heritage, technology has come to help and improve the labour of experts in conservation with new multidisciplinary methods (Cozzani 2017, Zhou 2012). Within the most used scientific techniques applied to the cultural heritage, those related to 3D digitizing and modelling (Tucci et al. 2017; Aicardi et al. 2018; Andreu & Serrano 2019), as well as the development of Virtual Reality and Augmented Reality applications have already established useful and recognized methodologies (Bekele et al. 2018) to become essential in all the research, documentation and dissemination stages of the conservation procedures nowadays (Ruiz Bazán & Vita 2017: 208).

Concerning the investigation, the advances produced by these new methods entail a deeper understanding of cultural goods and greater savings in working hours, as well as they also allow real-time monitoring, visualization and intervention without manipulation, since it is a non-invasive/non-destructive technology (Niquet & Mas-Barberà 2018: 6). When talking about documentation, the creation of digital repositories of artworks, monuments and sites ensure their survival along the years. Furthermost, linking this idea of "persistence" with the use of technology for dissemination, it must be said that 3D technology applied to cultural heritage is a very effective method for people to know and remember. It allows providing not only a "copy" of the very goods but also an understandable and enjoyable interpretation, far from the unintelligible fragments they can often see in reality. These two last possibilities, documentation and diffusion, are even more relevant whether the archaeological remains have to be covered again and cannot be seen anymore (Tait 2016). This way, in recent years, it has demonstrated to be very useful in cases of destruction associated with war conflicts and catastrophes since 3D digitization together with the digital fabrication (Merchán et al. 2019) are perfect tools for preserving and transmitting the heritage to future generations (Ruiz Torres 2017: 148). To perform the entire task, from documentation to dissemination, the existence of interdisciplinary work teams, composed of humanists and technologists, is necessary to achieve the equilibrium between what has to be shown (historical/artistic/social, etc. meaning) and the way it is (which has to do with the technological resources).

As mentioned, among the experiences based on 3D models used for the dissemination of cultural heritage, Virtual Reality (VR) and Augmented Reality (AR) are the most relevant. Regarding Virtual Reality experiences, two different type of them can be found in literature. On the one hand, some of them use 360º photos and video tours, with a high potential for disseminating the Heritage, since it is valid for a great range of devices (Argyriou et al. 2020; Mah et al. 2019; Njerekai 2019; Sánchez-Aparicio et al. 2019). On the other hand, other experiences make use of 3D environment that can be toured in real time but usually need more specific devices to visualize them. It is worth mentioning some initiatives carried out lately for enabling the visualization of pieces, monuments or sites which have unfortunately disappeared (Pérez et al. 2018) or whose bad state of conservation or some other reasons (distance, inaccessible location, etc.), prevent them to be seen/visited (Pérez et al. 2019). In these cases, VR has proven to be very helpful to bring back this "lost" cultural heritage to people. In spite of this, it is not the most utilized tool when it comes to its dissemination. Firstly, because the viewer's vision is replaced by a virtual world, which makes the real heritage remains happen in a second place. Secondly, the high economic cost of virtual reality equipment must be taken into account. This makes the use of this technology not affordable for many museums, interpretive centres and other cultural institutions.

Regarding Augmented Reality, the most accepted definition is that posed by Azuma (Azuma 1997). He defines an AR system as the one that fulfils all the following properties: (1) combines real and virtual content, (2) in an interactive environment in real-time and (3) is registered in 3D. Unlike VR, the fact that users can visualize added information (virtually created) without losing sight of the main elements of the real world makes the AR applications more suitable to be applied to cultural heritage on most occasions. It is also a more affordable and accessible resource since the most used AR devices are mobile phones or tablets. Hence, the problem of economic cost is overcome. In the last and more sophisticated experiences, the use of specific glasses which do not impede the vision of the "real world" starts to be habitual. They integrate a small screen in the lenses that project the virtual models that must be seen by users. In some of these AR glasses, there are two small screens, one per eye, to create a stereoscopic pair that allows 3D viewing. Likewise, they can also incorporate cameras that analyse the environment to locate the models in a realistic way or that interpret the users' gestures in the case they serve to interact with the AR application. Although the cost of these devices is becoming increasingly affordable as they become popular, they are still prohibitively expensive.

In the light of the possibilities offered by this 3D technology for the dissemination of "disappearing" heritage and, thus, for the preservation of its memory, an immersive VR experience and an Augmented Reality application are being developed. Both are designed to allow the users to visit and understand those archaeological sites that are hidden from sight, specifically the one known as "La Matilla" (Fuente del Maestre, Spain), which had to be re-covered by the EX-360 road after its excavation.

This paper presents the procedure followed to create these two applications, for which it was necessary to design a method that allowed merging the 3D data acquired by different devices so that to obtain a unique digital model of the site. The content is structured as follows. Firstly, the site of "La Matilla" and its historical context are described. Secondly, 3D data acquisition and modelling are explained. The next section is devoted to detail the procedure followed to design both applications. Afterwards, future work is outlined. Finally, some conclusions are drawn.

"La Matilla". A multicultural archaeological site

During the improvement works of the road EX-360, which links the towns of Fuente del Maestre and Villafranca de los Barros (Badajoz, Spain), some archaeological remains were unearthed at the height of the place known as "La Matilla".

Located at the foothills of the Sierra de San Jorge, these findings were not a surprise for experts as the existence of a large water storage pond from the Roman period was known to exist in the surroundings since a long time ago. The width and height of the still visible walls, as well as the dimensions of the pool, made experts think that some type of Roman settlement would exist in this zone. Besides, fragments of *sigillata* pottery from different epochs (from 1st to 3rd centuries AD) had been recovered on the surface of the area, reinforcing the idea of a Roman presence in this zone. The importance of the site continued, at least, until the Middle Ages as it is documented the existence of a church of Hispanic-Visigoth origin that survived until the nineteenth century as the hermitage of San Jorge (Pascual 1999: 21).

In spite of this knowledge about the past of this area, when archaeologist arrived there, they just found a diaphanous extension which did not betoken the richness it hid in its subsoil. Thus, employing archaeological methodology, they were able to read the history of the place, from the 20th century remains to those dated in the founding moments of *Augusta Emerita*. In this process, several historical stages were documented (Arabic, Visigoth and late Roman) to which the silos and burials found during the excavation would correspond.

As for the Roman strata, 9 different ceramic ovens and a badly preserved building were documented. Experts think that inside this building the administrative tasks that the management of this pottery industry entailed would have been carried out [figure 1]. The kilns had been excavated in the ground, made of limestone, which has allowed the conservation of much of these substructures. The construction was made of brick, the same material in which were built some semi-circular arches of perfect execution, which were still visible [figure 2]. In some of these ovens, the upper grate was also fairly well preserved. Archaeological analyses of both the structures and the fragments of pottery recovered in the area have confirmed the useful life of this production centre, which would have been in operation between the 1st and 2nd centuries AD (Sánchez González 2019:13-14).

Unfortunately, these remains appeared just under the course of the new road, so the problem of their conservation raised. After proposing several options, most of which meant a considerable increase in time and cost, the political decision was to cover the remains, trying to preserve their integrity as much as possible, according to the recommendation made by the heritage experts at the Junta de Extremadura. However, this meant demolishing the arches so magnificently preserved for centuries. To conserve the memory of the site, the group "3D CO-VIM", belonging to the University of Extremadura, proposed the digitization of the site and the creation of a 3D model that would allow both the researchers and the public to have a realistic digital copy of this missing heritage. This digital

Figure 1.- Aerial photograph of the excavations.

Figure 2.- A) Photo of the entrance to the bigger oven (H2) B) Photo of one semi-circular arch belonging to the H1 oven.

model would also allow the design and development of some basic AR/VR applications that make possible the visualization of the 3D model.

The procedure followed to reach this goal will be explained in the next sections.

Digitizing and modelling

Digitization process

Nowadays, different technologies are available to undertake a digitalization work: laser scanners, structured-light sensors, photogrammetry, etc. When it comes to choosing among them, it is important to consider several aspects: the basic specifications of the devices, the differences between the outcomes provided by each technology, the lighting conditions, the features of the object/building/space to be digitized and the subsequent use that the acquired data will receive. In this work, we applied the three different technologies we had at our disposal in the acquisition phase: a Faro LS880 Laser-Scanner, an Artec MHT 3D structured-light hand-held scanner and a Nikon D60 digital camera. Technical specifications of the two 3D scanner are summarized in Table 1. Regarding the digital camera, it has a resolution of 10.2 Mpix, a sensor size of 23.6mm x 15.8mm and a we used a lens of 3.06x zoom 18-55mm (27-83mm eq.).

By using these three options, our aim was not to repeat the digitization process three times but to apply each of them selectively. Based on topology, two different environments could be distinguished in the site: the vast exterior area in which the remains were located and the interior of the two better preserved kilns (H1 and H2). The differences in the preservation state, space and light conditions imposed the technology to use in each.

Before starting, we were aware that 3D models obtained through the resulting data generated with the laser scanner would be employed only to document the site, whereas the data obtained using the Artec scanner and the Nikon camera would be applied both for documentation and visualization applications. Given that we have used two technologies to digitize the outside zone, the Faro laser scanner and the Nikon camera, we obtained two different resolutions models of that area: the laser scanner generates a higher resolution model and the photogrammetry a medium-low resolution one, both of them textured but with a significant difference in the quality of the textures. The former model is more suitable for documentation because it provides a more precise reconstruction of the real environment, while the latter is more appropriate for visualization applications, which cannot manage very high-resolution models in real-time. Reducing the higher resolution model allows to obtain a medium-low resolution one, obviously at the cost of an elevated time consumption. Moreover, the quality of textures produced by the Faro laser scanner is poorer than

Table 1.- Technical specifications of the 3D scanners employed in the site.

	FARO LS880	**ARTEC MHT 3D**
		
ACCURACY	+/- 3 mm	0.1 mm
RANGE	Up to 80 m	0.4 to 1 m
DATA ACQUISTION SPEED	120.000 points/s 4 minutes for a full 360° 3D view consisting of 28 million points	500.000 points/s
FIELD OF VIEW	360° Horizontal 320° Vertical	closest range 214 mm x 148 mm furthest range 536 mm x 371 mm

the photos taken by the Nikon camera so that, consequently, the final visualization will be poorer.

Reconstruction process

As mentioned before, this step was carried out applying three different technologies, with a specific strategy for each of them. Regarding the laser scanner, after the analysis of the area to be digitized and considering the range of 80 m that the Faro laser scanner offers, the scanning procedure designed consisted of positioning the scanner station in three different points that could cover the whole area. These selected positions can be observed in Figure 3.

With respect to photogrammetry, it is generally recommended to optimize the number of photos, considering an 50% overlapping between images, in order to avoid the collapse of the workstation in charge of computing the photogrammetry, and to do it using a reasonable time. In that case, since it was known that the whole site was going to be covered by the future road, the followed strategy in this stage was to generate a bank of images with a great redundancy. The idea was to postpone the manual choice of the optimized bank of images until the 'laboratory' computing stage. Specifically, over 2500 photos were taken along the site. The technician took photos from different tripod positions and, in each position, she rotated the orientation of the camera until completing a circle and applying an approximate. Logically, the density of the tripod positions was higher in that zones where there were more archaeological rests. The Figure 4 can give an idea of the photos' distribution within a portion of the site.

Finally, the interior of the ovens digitization was carried out by iteratively scan and check the remaining parts, until they were completely acquired. At the end, we found that only a few portions in the ceiling were inaccessible to the handy scanner. Moreover, in this part of the site, a bank of images was also taken, in order to have an additional support 3D model to offer the missing information in those inaccessible portions.

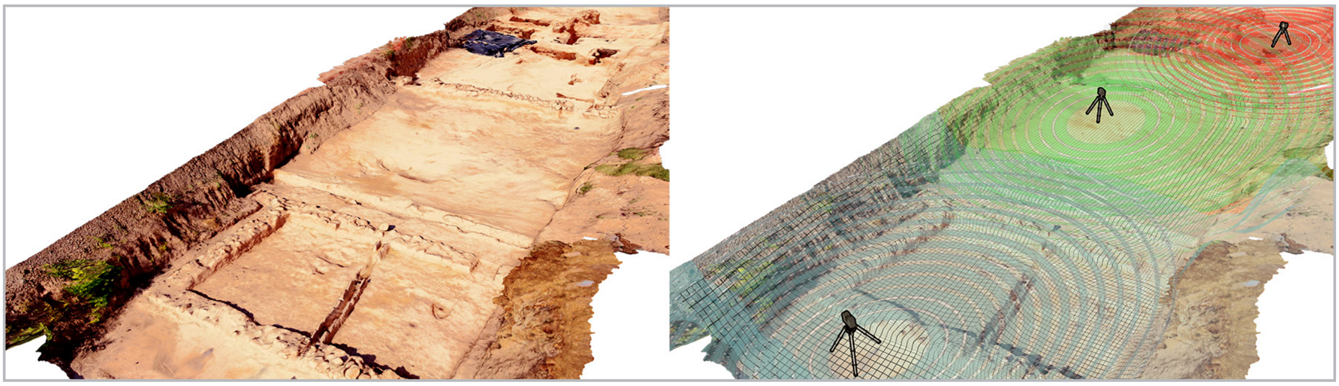


Figure 3.- Representation of the distribution of laser scanner locations to cover the whole area: on the right, the archaeological site; on the right, the three different locations that were selected

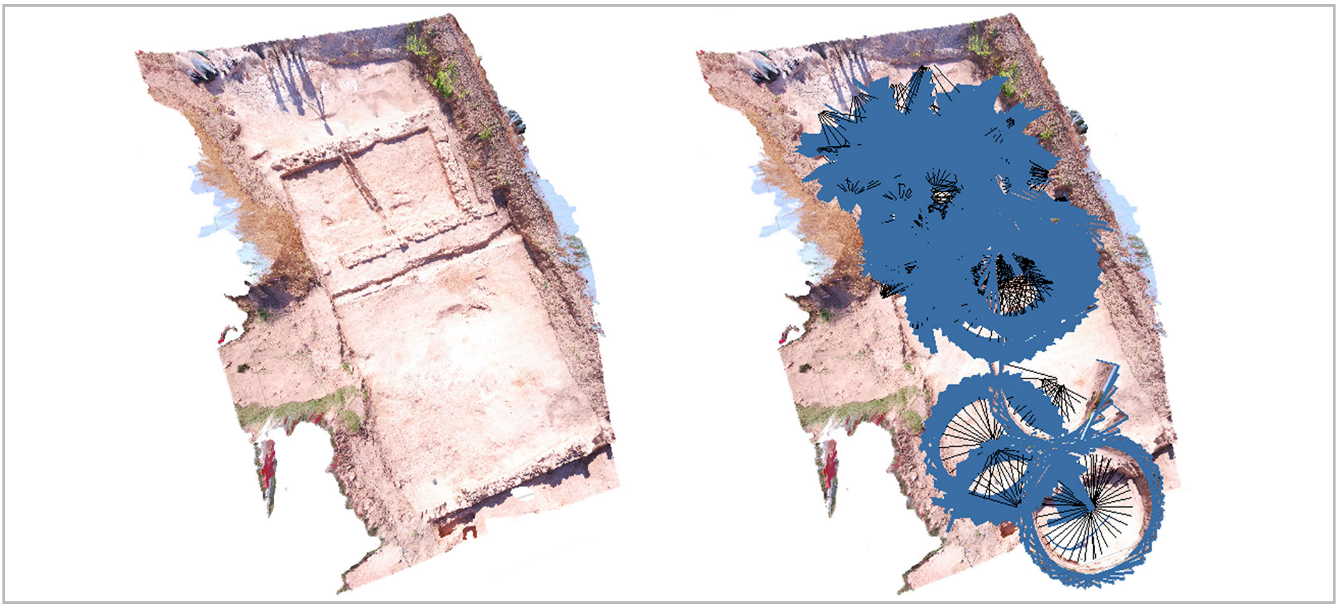


Figure 4.- Distribution of the taken photos along a portion of the site, with more density of camera positions in the areas with more rests.

After the digitization process, three packages of 3D data obtained from the three different acquisition technologies were available, as mentioned. Such data were processed independently by means of three different specific software to generate the resulting 3D models. Figure 5 depicts the work scheme that we followed to produce the final textured 3D models starting from the acquisition stage.

Regarding the data acquired with the laser scanner, a coloured 3D point cloud with a linear accuracy of ± 3mm at 25 m, the required steps to obtain the 3D model are: registering of the point clouds; filtering noise and outliers; fusion, which produces a unique point of cloud; compute the mesh that fits such cloud, by triangulating the points; and calculation the texture of that mesh. Except for the triangulation and texture computation, which were carried out using Meshlab, the main software used was Faro Scene.

The structured-light scanner produces a set of textured partial meshes which are portions of the element scanned. The resolution of these acquired data is up to 0.5 mm. These data require some consecutive standard steps: registering in the same reference system; filtering to remove errors and noise; fusion to generate a single mesh, and filling holes. Sometimes it is also necessary to retouch the final surface to equalize and make it up. Finally, it is mandatory to carry out an analysis of the final mesh and repair it to obtain a consistent surface with no errors. In our case, the first three steps were implemented with the Artec Studio software. The filling-holes process was made by applying the algorithm explained in (Pérez et al. 2008), in Matlab. The open software Meshlab was employed to analyse and repair the mesh. And, finally, the occasional surface retouching was done in the Blender software. Also, equalization was applied to the texture in some specific cases by using the GIMP software.

The last device employed was the Nikon camera, with which a vast set of photos were generated. Since it has a 10 megapixels sensor, the resolution of these images is 3872 x 2592. In this case, the steps that have to be followed to generate de 3D models through photogrammetry were: aligning and pairing each subset of photos; generating the dense point clouds to produce a set of meshes; registering of all the meshes; fusion to obtain a unique surface and generation of the whole texture. Here, it is worth mentioning that photogrammetry does not produce a model as accurate as of the one obtained with the previous technologies in terms of scale. Therefore, the final model must be scaled. The scale factor is obtained by manually measuring some meaningful distances in the previous models, generated using the scanners, that is, in real scale, and applying them to the photogrammetric model. No targets were used during the scanning process, so this entails the search of common accessible points, located in sharp areas, in both models the one generated with scanner and the one generated with photogrammetry. All these steps are done, in a first approach, with the software Agisoft Metashape. Then, to get a fine adjustment, the Artec Studio software offer an interesting tool to be applied. It can compute a non-homogeneous registering process, that is, it can reorient and slightly deform a mesh with the aim of accurately fit the photogrammetry mesh to the reference one: the one generated with scanner.

In the end, a high-resolution textured model of the outdoor area is obtained from the laser scanner data. Also, a medium-low resolution textured model of the same

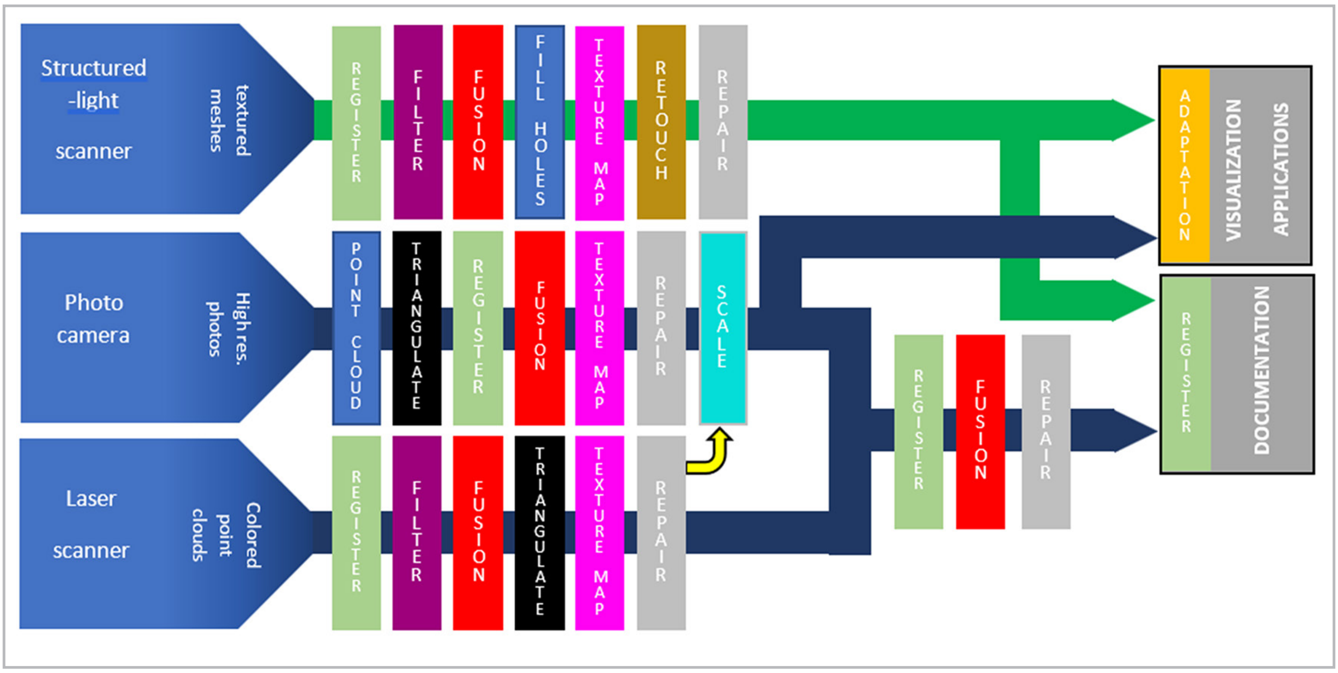


Figure 5.- Scheme of the procedure to obtain the final textured 3D models.

Figure 6.- Reconstructed 3D mesh (left) and 3D textured model (right) of the H2 oven, both of them obtained using photogrammetry techniques.

area was generated from photogrammetry techniques. The differences between these two models are the resolution of the final mesh, better in the former one, and the quality of the final texture, better in the latter model. Since the high-resolution model is going to be used for documenting the archaeological site and keep its memory, we decided to improve its texture and complete the parts that were not correctly acquired with the laser scanner using the photogrammetric model. Therefore, both models had to be registered in a common reference system, a fusion process was applied, a repairing step was also carried out and, finally, the improving of the original texture was done with Blender software, by projecting some of the Nikon camera photos onto the geometric model.

The other resulting models of the reconstruction process were those of the interiors of the kilns. These are high-medium resolution textured meshes, generated thanks to the Artec scanner, as well as to the photogrammetry techniques respectively, can be used for both documentation and visualization applications [figure 6].

At this point, there was not a complete model of the entire site available yet since we had created each part separately. For this reason, the integration of all the separated meshes to obtain a unique single mesh of the site became necessary. This integration was done by registering all the models, which entailed the positioning of the kilns in the corresponding location within the exterior model. Although both meshes had overlapping zones, a user-assisted registration was utilized.

Visualization applications

As said, two different visualization applications were designed: an immersive VR experience and a AR application.

Technically, the visualization of 3D objects in real-time has a strong dependence on both the hardware used and the number and quality (resolution of meshes and textures) of the objects to be visualized. After the digitization process, explained in previous sections, the quality of the 3D model is high. Therefore, to use the digitized models in real-time visualization it is mandatory reducing their quality, mainly in terms of the resolution of the meshes, to a specific level that can be managed by the hardware. In addition to that, the software used to design and program the visualization applications also imposes some requirements that have to be taken into consideration inescapably.

In the following subsections, the two main steps necessary to develop the visualization applications are summarized: quality reduction and data adaptation, and applications design.

Quality reduction and data adaptation

Before analysing how to carry out the reduction and adaptation, it is useful to categorize the data to be used in the applications. Thus, the following division was established: category A (laser scanner data); category B (Artec scanner data); category C (photogrammetry data); and, category D (3D modelled synthetic data). We have explained above how the models belonging to these categories were created, except for the ones of category D. We include in that category the 3D elements modelled using Blender software that will be introduced in the visualization as decoration or as support to improve the final result.

As mentioned above, the 3D models belonging to categories A and B are generated in high resolution for the ones and in medium-low resolution the ones of category C. We modelled the 3D objects of category D in medium-low resolution, keeping in mind the requirement of real-time visualization. Moreover, the elements of categories A and C represent the same area of the site, although in different resolutions. Since a high resolution is not needed in the visualization applications, we discard at this point the elements included in the category A. On the contrary, the interior of kilns was just stored in high-resolution (category B elements) and no other lower-resolution data are available. Therefore, before designing the applications, it is necessary to modify the models of categories B and C, regarding the type of data and their quality (resolution of mesh and resolution and size of texture). This classification and the modifications undertaken are summarized in the table shown in figure 7.

In it, by "type of 3D data" we mean how 3D and colour information is stored, i.e., whether it is a point cloud or 3D mesh and whether there is a texture image that stores colour information (needed for the visualization application) or not. In this case, as the elements of category A were discarded (X sign), the rest of the categories are composed of objects defined by 3D meshes, so it is not necessary to modify the type of data (hence = sign). Concerning the colour, the elements of categories B and C have their own images of textures. Therefore, no modification in this sense is necessary either.

As far as quality is concerned, it is mandatory reducing it for the category B elements. However, in the case of the elements of category C, stored in medium-low resolution, it will depend on the hardware used. As will be explained below, two applications have been developed: a virtual reality application and an augmented reality application. The first one usually runs on desktop PCs, whereas the latter runs on mobile devices. So, the different specifications of both platforms are evident, being less powerful the mobile devices in terms of 3D representation in real-time. In this respect, since all 3D models are used in both types of applications, a quality reduction must also be applied to the elements of category C.

This quality reduction is implemented in two steps: one first reduction aimed to designing the VR application and a consecutive further reduction to prepare the elements for the AR applications, i.e. to be visualized in much less powerful devices. Every step of that quality reduction consists of reducing the number of triangles composing the 3D meshes, reducing the quality of texture images and group them into bigger images, more optimal for the real-time (Pérez et al. 2018).

Applications design

For both the AR and the VR application we have designed proofs of concepts to visualize all the acquired data. The software employed was Unity with added libraries for the use of specific head-mounted displays (Windows Mixed Reality Lenovo Explorer) and the generation of AR mobile applications (ARCore libraries for Android).

Regarding the VR application, it allows the user to explore the entire archaeological site. It is possible to tour all the exterior area and, also, the interior of ovens. Moreover,

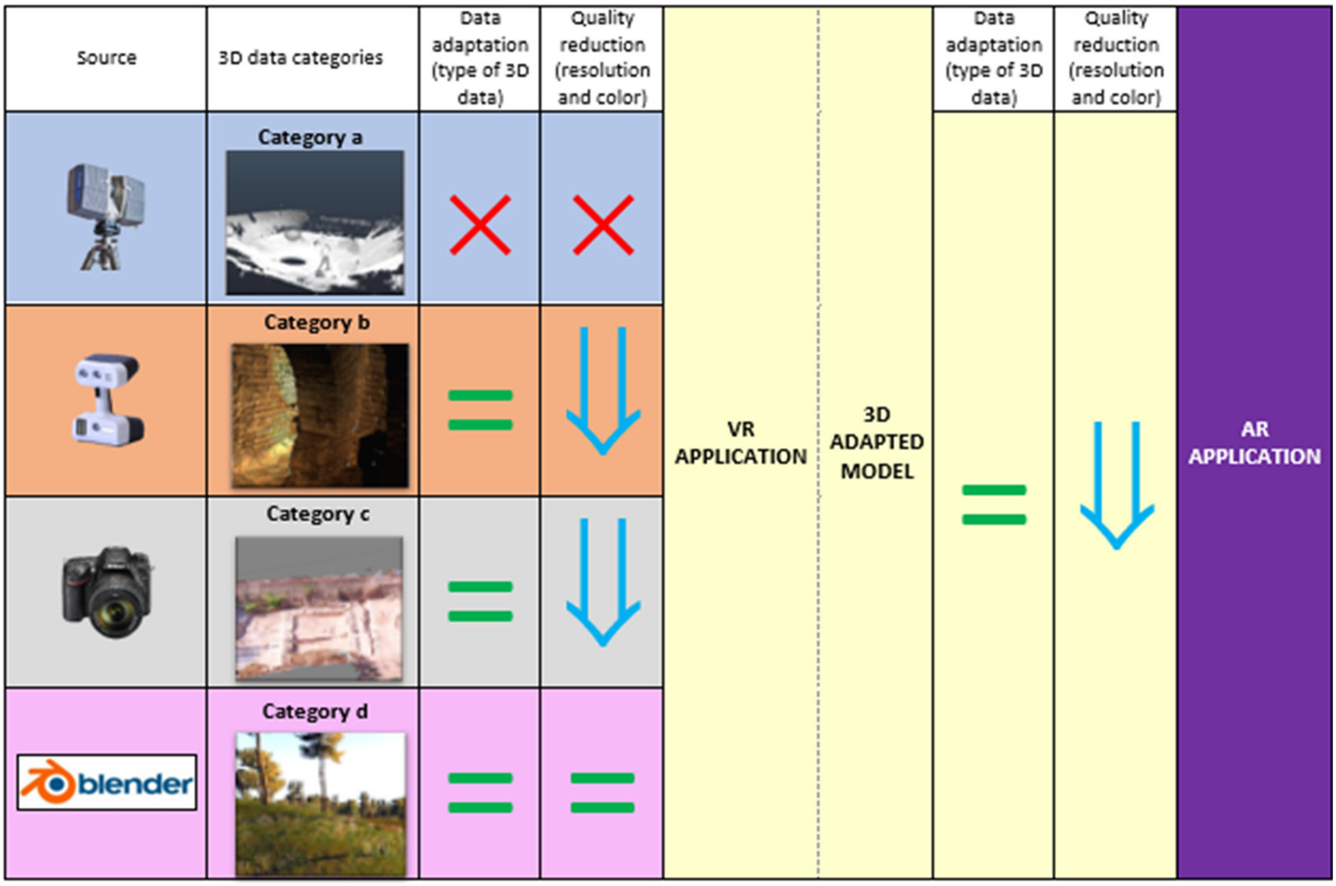


Figure 7.- Modifications undertaken regarding the type of data and the quality: "X" Ξ not used; "=" Ξ no adaptation required; "⇓" Ξ decrease.

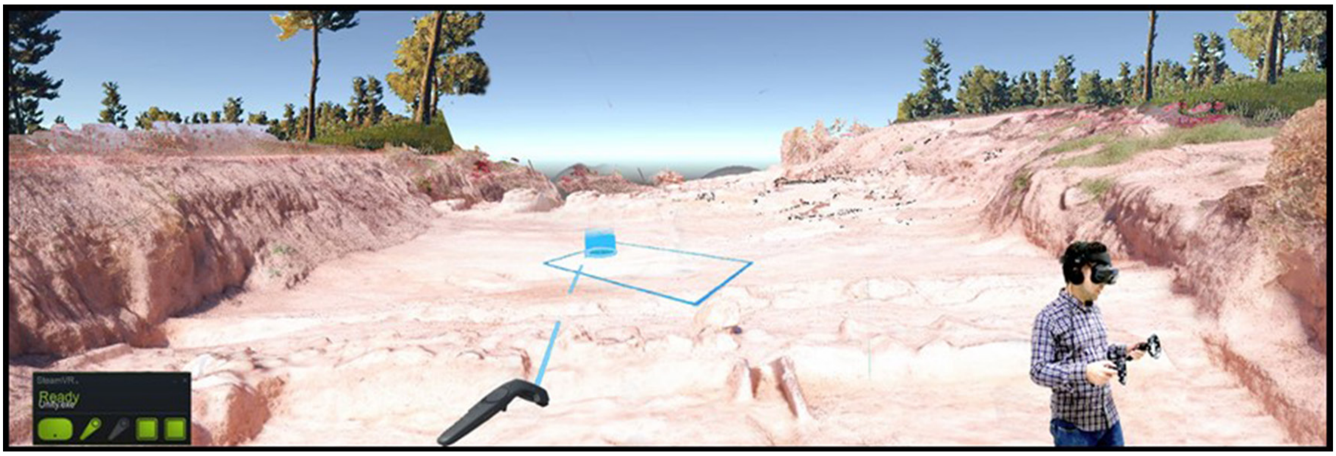


Figure 8.- Appearance of the VR experience.

some decoration elements were added to complete the environment where the site is located (vegetation, trees, sky, background) [figure 8].

In concern to the AR application, it also represents the site in real-time, although over the visualization of the mobile device's camera. This permits the instant change of point of view as the user walks. The current application does not need the use of external markers, so it is always possible to visualize the remains independently of the user's location. Additionally, to develop this application, we employed a medium-high specification mobile capable of managing an elevated number of triangles. However, it is not powerful enough to load the whole archaeological site with enough resolution of the interior of the kilns. This is why we had to split the model into portions to offer the user the possibility to load each portion separately. Specifically, we have 3 portions of the exterior area and 2 portions corresponding to the inside of the kilns [figure 9].

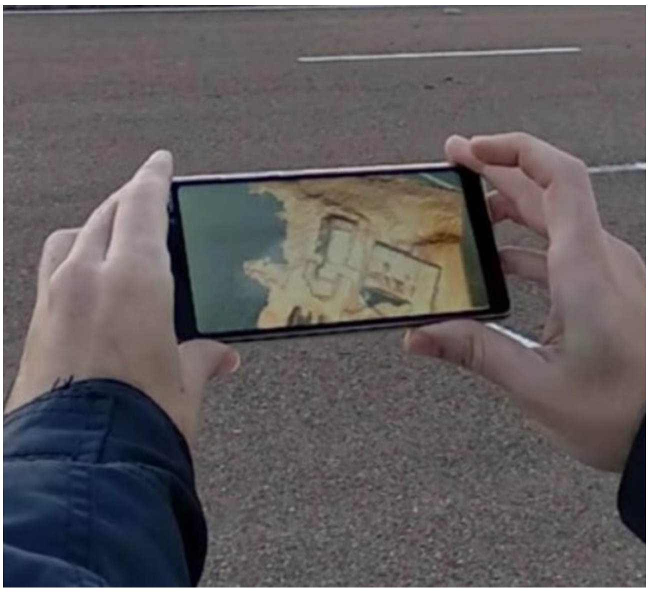


Figure 9.- AR application used *in situ.*

Discussion

As said above, the two applications developed are in their initial stages. Although while designing them, we carried out several tests to check some features: look, usability, delay, etc., it is obvious that an experimental study would be necessary. This study must involve different types of users, from experts in heritage to common visitors, from tourism managers to politicians.

The idea is to meet decision-makers to plan a strategy that includes the development and improvement of the applications, the testing with the public and the purchase of the necessary devices. This way, it would be possible to provide the inhabitants of Fuente del Maestre and the surroundings with some tools that allow them to know, enjoy and remember a part of its history that otherwise could fall into the oblivion. Having this type of dissemination tools would also enhance the attraction of tourism to a population that, although it was declared Historic-Artistic Site in 1998, is a little far from the usual touristic routes.

Conclusions

Sometimes it is impossible to conserve heritage for eternity. Not only because of decisions beyond the experts' criteria, but also with their consent, when the proper preservation of the remains cannot be assured. In these cases, before an announced lost, technology become a perfect ally to overcome the oblivion that the disappearance entails. The better way to preserve the cultural heritage for future generations is, in these cases, keep its memory for the people.

Throughout these pages, we have approached the application of 3D modelling to the documentation, research and dissemination of cultural heritage. Focused on the specific case of the re-covered, and so, lost Roman remains found in the nearby of Fuente del Maestre, the process to acquire 3D data of the whole site with different technologies was described. As said, choosing a specific technology depends on the features of the structures and the subsequent use that these 3D model generated will receive.

The procedure to merge the different meshes has been also explained, as well as the transformation of those meshes to be utilized to design Virtual and Augmented Reality applications. Afterwards, we make a small digression on how these developed VR/AR experiences are and how they can be visualized. Finally, it describes and shows both the 3D model of the site and the tentative AR application designed and explains the future work to improve the virtual experiences and make them reach the people of nearby towns so that they can know this Roman site and prevent it falls into oblivion.

Acknowledgements

This work has been supported by the project IB16162 from Junta de Extremadura and European Regional Development Fund (ERDF) "A way to make Europe". The authors would like to thank the members of the Consejería de Movilidad, Transporte e Infraestructuras (Junta de Extremadura) for their willingness and support.

References

AICARDI, I., CHIABRANDO, F., LINGUA, A.M., NOARDO, F. (2018). Recent trends in cultural heritage 3D survey: The photogrammetric computer vision approach, Journal of Cultural Heritage, 32(1): 257–266. https://doi.org/10.1016/j.culher.2017.11.006

ANDREU, J., SERRANO, P. (2019). "Contributions of the digital photogrammetry and 3D modelling of Roman inscriptions to the reading of damaged tituli: An example from the Hispania Tarraconensis (Castiliscar, Saragossa)", Digital Applications in Archaeology and Cultural Heritage, 12. https://doi.org/10.1016/j.daach.2019.e00091

ARGYRIOU, L., ECONOMOU, D., BOUKI, V. (2020). "Design methodology for 360 degrees immersive video applications: the case study of a cultural heritage virtual tour", Personal and Ubiquitous Computing. https://doi.org/10.1007/s00779-020-01373-8

AZUMA, R.T. (1997). "A Survey of Augmented Reality", Presence: Teleoperators and Virtual Environments, 6 (4): 355–385.

BEKELE, M. K., PIERDICCA, R., FRONTONI, E., MALINVERNI, E. S., GAIN, J. (2018). "A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage", Journal on Computing and Cultural Heritage, 11 (2): 1–36. https://doi.org/10.1145/3145534

CASTRIOTA, B. (2019). "Authenticity, Identity, and Essentialism: Reframing Conservation Practice". In: What is the essence of conservation? Materials for a discussion. F. Mairesse & R. F. Peters (Eds.). ICOFOM: París: 39-48.

COZZANI, G., POZZI, F., DAGNINO, F.M., KATOS, A.V., KATSOULI, E.F. (2017). "Innovative technologies for intangible cultural heritage education and preservation: the case of i-Treasures", Personal and Ubiquitous Computing 21(2): 253-265. https://doi.org/10.1007/s00779-016-0991-z

DESVALLÉES, A., MAIRESSE, F. (Eds.) (2010). Key concepts of museology. Armand Colin: París.

HÖLLING, H. (2017). "The technique of conservation: on realms of theory and cultures of practice, Journal of the Institute of Conservation, 40 (2): 87-96.

ICOMOS (1994). The Nara document on authenticity.

ICOMOS (2004). International Charters for Conservation and Restoration. Monuments and sites I. ICOMOS: München.

MAH, O. B. P., YAN, Y., TAN, J. S. Y., TAN, Y-X., TAY, G. Q. Y., CHIAM, D. J., WANG, Y-C., DEAN, K., FENG, C.-C. (2019). "Generating a virtual tour for the preservation of the (in)tangible cultural heritage of Tampines Chinese Temple in Singapore", Journal of Cultural Heritage, 39: 202-211. https://doi.org/10.1016/j.culher.2019.04.004

MERCHÁN, M.J.; MERCHÁN, P.; SALAMANCA, S.; PÉREZ, E.; NOGALES, T. (2019). "Digital fabrication of cultural heritage artwork replicas. In the search for resilience and socio-cultural commitment", Digital Applications in Archaeology and Cultural Heritage, 15: e00125. https://doi.org/10.1016/j.daach.2019.e00125

NIQUET, N.D., MAS-BARBERÀ, X. (2018). "El registro 3D como medio para el análisis y difusión del patrimonio escultórico. El caso de la escultura en cera del Écorché", Ge-conservación, 13: 5-16. https://doi.org/10.37558/gec.v13i0.551

NJEREKAI, C. (2019). "An application of the virtual reality 360 degrees concept to the Great Zimbabwe monument", Journal of Heritage Tourism. https://doi.org/10.1080/1743873X.2019.1696808

PASCUAL, J. (1999). "Fuente del Maestre: Dos mil años de historia". En: Fuente del Maestre. 100 años de ciudad, 2000 años de historia. Pascual, J. (coord.). Excmo. Ayto. Fuente del Maestre: 13-53.

PÉREZ, E., SALAMANCA, S., MERCHÁN, P., ADÁN, A., CERRADA, C., CAMBERO, I. (2008). "A Robust Method for Filling Holes in 3D Meshes Based on Image Restoration". In: Advanced Concepts for Intelligent Vision Systems, 10th International Conference, ACIVS 2008, Bourennane, S. et al. (Eds.). Springer: 742-751. https://doi.org/10.1007/978-3-540-88458-3_67

PÉREZ, E., MERCHÁN, M.J., MORENO-RABEL, M.D., MERCHÁN, P., SALAMANCA, S. (2018). "Touring the Forum Adiectum of Augusta Emerita in a virtual reality experience". In: Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection, Ioannides, M. et al. (Eds.). Springer: 548-559.

PEREZ, E, MERCHÁN, M.J., SALAMANCA, S. AND MERCHÁN, P. (2019). "Virtual reality to allow wheelchair users touring complex archaeological sites in a realistic manner. Towards their actual social integration", International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W9: 597-604. https://doi.org/10.5194/isprs-archives-XLII-2-W9-597-2019

RUIZ BAZÁN, I., VITA, G.E.E. (2017). "The utility of the application of new three-dimensional technologies for the study and dissemination of heritage from a historical technical perspective: case studies", Ge-conservación, 11: 208-203. https://doi.org/10.37558/gec.v11i0.480

RUIZ TORRES, D. (2017). El uso de tecnologías digitales en la conservación, análisis y difusión del patrimonio cultural. Acción Cultural Española (AC/E).

SÁNCHEZ-APARICIO, L. J., MORENO-BLANCO, R., MARTÍN-JIMÉNEZ, J. A., RODRÍGUEZ-GONZÁLVEZ, P., MUÑOZ-NIETO, A. L., AND GONZÁLEZ-AGUILERA, D. (2019). "Smartwall: A new web-based platform for the valorization of the medieval wall of Ávila", Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W15: 1055–1062. https://doi.org/10.5194/isprs-archives-XLII-2-W15-1055-2019

SÁNCHEZ GONZÁLEZ, L.M. (2019). "A high-roman-empire alpharera industry between Villafranca de los Barros and la Fuente del Maestre", El Hinojal, Revista de Estudios del Muvi, 12: 8-21.

TAIT, E., LAING, R., GRINNALL, A., BURNETT, S., ISAACS, J. (2016). "(Re)presenting heritage: laser scanning and 3D visualisations for cultural resilience and community engagement", Journal of Information Science, 42(3): 420–433. https://doi.org/10.1177/0165551516636306

TUCCI, G, BONORA, V, CONTI, A, FIORINI, L. (2017). "High-quality 3D models and their use in a cultural heritage conservation project", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W5: 687-693. https://doi.org/10.5194/isprs-archives-XLII-2-W5-687-2017

ZHOU, M., GENG, G., WU, Z. (2012). Digital Preservation Technology for Cultural Heritage. Springer.

Author/s

María José Merchán
mjmerchan@unex.es
School of Industrial Engineering of the University de Extremadura, Badajoz, Spain

Works as a researcher at the School of Industrial Engineering of the University de Extremadura, Badajoz, Spain. She works on the application of technologies for problem-solving in the field of Cultural Heritage. She collaborates with the National Museum of Roman Art and has taken part in several national and international R & D projects. She has generated more than 20 technical contributions on prestigious journals and conferences.

Emiliano Pérez
emilianoph@unex.es
School of Industrial Engineering of the University de Extremadura, Badajoz, Spain

Is an Associate Lecturer at the School of Industrial Engineering of the University de Extremadura, Badajoz, Spain. He has worked as researcher in 5 R&D projects and has made more than 20 contributions in conferences and journals. He focuses his research on 3D Computer Vision and Virtual Reality: pattern recognition, modelling, representation and reconstruction of 3D objects, 3D sensors applied on cultural heritage, virtual simulation.

https://doi.org/10.37558/gec.v17i1.753

Ge-conservación
Conservação | Conservation

Analysis of urban vulnerability as a tool for cultural heritage preservation. The cases of the medium-sized historical ensembles in Andalusia

Daniel Navas-Carrillo, Blanca del Espino Hidalgo, Juan-Andrés Rodríguez-Lora, Teresa Pérez-Cano

Abstract: This paper presents the urban vulnerability assessment as a complementary resource in heritage preservation policies, through the analysis of the thirty-nine medium-sized cities that have been listed as Historical Ensemble in Andalusia (Spain). The research seeks to make a sequential approach that addresses, from the general –the conceptual framework on urban vulnerability and the characterization of the analysis sample– to the particular –the analysis of the socio-economic, socio-demographic or residential vulnerability applied to the intermediate scale which has not been in-deep studied yet–. For this, it proposes to adopt the methodology implemented by the Spanish Ministry of Development in the Atlas of Urban Vulnerability, providing a territorial lecture of the results. The study concludes that medium-sized cities do not present a level of vulnerability lower to the largest ones but detecting specific urban weaknesses that should be addressed to improve the response of these cities to heritage preservation.

Keywords: Baetica, cultural heritage, heritage conservation, intermediate cities, urban heritage, urban planning, vulnerability indicators

Análisis de la vulnerabilidad urbana como herramienta de protección del Patrimonio Cultural. El caso de los Conjuntos Históricos en ciudades medias de Andalucía

Resumen: Este artículo proponer evaluar la vulnerabilidad urbana como herramienta complementaria en las políticas de protección patrimonial mediante el análisis de las treinta y nueve ciudades medias declaradas Conjunto Histórico en Andalucía (España). La investigación intenta realizar una aproximación secuencial que aborda desde lo general, el marco conceptual sobre vulnerabilidad urbana y la caracterización de la muestra analizada, hasta lo concreto, el análisis de la vulnerabilidad socioeconómica, sociodemográfica y residencial en la escala intermedia, aún no estudiada en profundidad. Para ello, se propone adoptar la metodología implementada por el Ministerio de Fomento de España en el Atlas de Vulnerabilidad Urbana, proporcionando una lectura territorial de los resultados. El estudio concluye que las ciudades medias presentan un nivel de vulnerabilidad que no es inferior al de las de mayor tamaño, sin embargo, se identifican ciertas debilidades que deberán ser abordadas para mejorar la respuesta de estas ciudades a la conservación de su patrimonio.

Palabras clave: Baetica, ciudades intermedias, conservación patrimonial, indicadores de vulnerabilidad, patrimonio histórico, patrimonio urbano, planificación urbana

Introduction

—Research definition

This research proposes the inclusion of urban vulnerability assessment as an additional tool to be considered in the cultural heritage preservation policies. This hypothesis is based on the fact that, just as other external aggressors are taken into account in preventive conservation, the urban weaknesses should also be considered. The social, economic and residential weaknesses could reduce the capacity as a collective that cities have for preserving their heritage. This vision utterly implies an urban approach to the heritage of these cities, beyond the individual assessment of their cultural assets. This vision is also aligned with the change produced on the concept of heritage in recent decades. Attention has shifted from primarily objective considerations to the subject which demands it (Ruiz Castillo 2004: 18).

For this purpose, this work has adapted the methodology provided by the Spanish Ministry of Development in the Atlas of Urban Vulnerability. This methodology has been validated through its application in different urban contexts of the Spanish geography (Temes, 2014; Antón-Alonso & Porcel, 2017; Rodríguez Peña, 2017; De Santiago Rodríguez, 2018). However, it has had a more significant impact on the analysis of the largest cities (Hernández Aja, Rodríguez Alonso, Rodríguez Suárez, 2018), finding a gap in the urban vulnerability analysis of the so-called medium-sized cities. In this sense, the research tries to identify the specific vulnerability issues of these intermediate urban scale, which differ from those of large cities.

Accurately, the weight of the system of medium-sized cities in the functional organisation is a fundamental characteristic that defines Andalusia; geographical framework analysed in this research. Andalusia is the most populous and the second-largest region in Spain, and approximately 60% of the autonomous territory is under the influence of a medium-sized city representing in population terms close to 15% of the inhabitants in the whole region. Besides, the historical relevance of the Andalusian medium-sized cities has been evidenced in national and international references (Madoz 1846-1850; Braun and Hogenberg 1572-1618). These circumstances have led to propose an analysis taking territorial organisation factors into account, according to the particular geographical characteristics, the historical evolution, the spatial planning or the specific legislation of each territory. In this sense, it seeks to provide a comparative study among different urban scales, which has not been developed yet.

On this regard, it is also important to mention that current territorial planning international strategies defend a polycentric model based on medium-sized cities. These cities not only favour a lower consumption of resources but also generate a more immediate relationship with the nearby rural environment. They contribute to avoid depopulation and acquire a key position in mitigating and adapting to climate change. Endowed with practically the same essential urban services as the large cities, they lack environmental problems, which ultimately means the increase of the population's quality of life (Del Espino Hidalgo & Navas Carrillo, 2018:146).

—Urban vulnerability and its repercussion on heritage preservation

The term vulnerability applied to urban dimension arises during the cold war linked to the need for intervention in many eastern cities (Bankoff, 2019). In general terms, we can define it as a state of high exposure to certain risks and uncertainties, in combination with a reduced ability to protect or defend oneself against those risks and uncertainties and cope with their negative consequences (United Nations, 2003). Consequently, the term vulnerability has been widely accepted as the socio-economic risks that could affect society (Bankoff et al., 2004). Since this point of view, it has entered into a variety of disciplines such as disaster risk analysis (Wisner et al., 2004), natural hazard geographical research (Weichselgarnter, 2001; Cannon, 2008; Ran et al., 2020), climate change impacts (Fussel, 2007; Lankao & Qin, 2011; Singh, 2017) or social-environmental approaches (Krellenberg et al., 2016). Thus, the vulnerability is currently related to resilience, a concept particularly extended in urban and regional planning in recent years (Cardoso, 2018; Faulkner, 2020). Terms that are in opposite sides (Godschalk, 2003), but should not be characterized as antonyms (Patel et al., 2020).

The vulnerability has also been applied to topics regarding social inclusion (Levron, 2010), such us, poverty, gender, class, caste, ethnicity, disability or elderly (Twigg, 2015). This perspective can be extended to urban studies. When done, it is inexorably linked to the application of preventive actions towards the inclusion of inhabitants (Ministerio de Fomento, 2012). It should be noted that their study has increased since 2008 due to the consequences of the economic crisis (Matesanz Parellada, 2017:29). Thus, the urban vulnerability can be understood as that process of unrest in cities produced by the combination of multiple dimensions of disadvantage, in which any hope of upward social mobility (to overcome their social condition of exclusion) is seen as extremely difficult to achieve. On the contrary, it carries a perception of insecurity and fear of the possibility of downward social mobility, of worsening of their current living conditions (Aguacil, 2006:161). However, it can be affirmed that the concept of urban vulnerability refers both to the increase of threats and risks that affect society and to the weakening of mechanisms to deal with such problems (Aguacil et al., 2014:18). In that sense, we can relate vulnerability to concepts largely addressed as the right to the city proposed by Henri Lefebvre (1968). Lately, it has been developed and reclaimed by social movements to fight against contemporary urban issues such as commodification and capitalism of the city, the decrease of social interaction and the rise of spatial inequalities and exclusion (Harvey, 2003).

As can be seen, urban vulnerability is, in short, directly related to the traditional dimensions of sustainability: economic balance, social equity and environmental resilience. However, a fourth dimension has been proposed as the centre or conceptual framework for the previous triangle: culture (Hawkes 2001). It is understood as to how our ancestors have adapted to the constant changes in environmental conditions throughout the cycles and have thus left a legacy to our times: cultural heritage, which must be understood as a source of inspiration, innovation and creativity to face current challenges. This approach evidences the need of including cultural heritage in sustainable development frameworks (UNESCO 2018), what necessarily must be connected to urban vulnerability assessment of the built cultural heritage, that is, the historical centres of the cities. Consequently, this work aims to evaluate urban vulnerability over a selection of urban areas – the historical centres and, particularly, the protected ones – of an urban category pointed out as an example of sustainability and equilibrium – medium-sized cities.

The system of medium-sized cities of Andalusia as a case study

— Definition of a medium-sized city

Medium-sized cities have been considered from the European directives as to the urban category with the best qualities for urban-territorial sustainability (European Union 2011: VII), what has encouraged the increase of their protagonism in territorial planning and development strategies, as well as to in framework policies. In the second half of the 20th century, many countries of the European Union focused part of their development policies on the dynamization of medium-sized cities. The first attempts derive from the theory of the central places of Walter Christaller (1933), extended by Auguste Lösch (1940) and from the concept of the pole of development in the regional scope used by Perroux (1955). Hirschman (1958) would formulate a theoretical body to be used in territorial planning for the promotion of the later called intermediate cities.

Currently, their defence is based on the sustainability of a polycentric territorial model against metropolization processes (Vilagrasa 2000). In this sense, in recent years, this urban category has aroused particular interest in the quality of life it presents, as it lacks many of the environmental problems of large cities, as well as in the very scale of the city that makes it more humane and accessible. On the other hand, medium-sized cities favour a more rational use of resources, guaranteeing access to specialised goods and services in conditions like those carried out in large urban areas (Llop Torné and Hoeflich de Duque 2007: 10). As for their definition, it should not be done exclusively in demographic terms, but understood by their strategic position within the functional organisation of a nearby region or regional scope, and far from the synergies of the principal regional centres, as stated in the Unesco Report on Intermediate Cities (Bellet Sanfeliu and Llop Torné 1999). According to it, the concept of the medium-sized city goes beyond the mere intermediate position between the large metropolitan areas and the rural sphere. It is necessary to consider the socio-economic and cultural conditions of each territory, which will determine the different municipal roles, regardless of the number of inhabitants. For Bellet and Beltrão, (2009: 43), "medium-sized cities articulate the territory and function as reference centres for a more or less immediate territory".

In the case of Andalusia, they are officially recognised by the Regional Spatial Plan (approved by Decree 206/2006, of 28 November), which proposes a hierarchical territorial structure – the System of Cities – distinguishing three categories: Regional Centres, Medium-sized Cities and Rural Areas. This classification has been made based on demographic size, diversity and dynamics of its economic base and functional weight. Although the size of a medium-sized city should not be measured in absolute terms, in Andalusian, it would correspond to populations between 100,000 and 15,000 inhabitants, coinciding with the hypothesis of Merinero and Lara (2010: 2).

— Cultural heritage characterization of the Medium-sized cities of Andalusia

This study follows the Andalusian Regional Spatial Plan, in Spanish *Plan de Ordenación Territorial de Andalucía* (Junta de Andalucía, 2006). This document includes a total of sixty-one medium-sized cities in the Andalusian geography [figure 1]. The research has selected those that have been or are in the process of being listed as Historical Ensemble. This classification means public recognition and legal protection of their heritage values as a whole. In the past, this responsibility exclusively corresponded to the Government of Spain. Currently, the Regional Government is also in charge to classify a city as Historical Ensemble.

The selected cities have been analysed according to their position in the territory. It has been necessary to distinguish between interior and coastal geographic domain due to the different evolution they have experienced during the 20th century. Special mention requires coastal cities since their development has been mainly boosted by mass tourism since the 60s. Out of the forty medium-sized cities in inner Andalusia (Del Espino Hidalgo 2015: 62), twenty-six (65%) have been listed as Historical Ensembles or are in process [table 1]. Besides, out of the twenty-one medium-sized cities located on the Andalusian coast (Navas-Carrillo et al., 2019: 250-251), thirteen (61.9%) have been listed or are under study. In addition to the individual built heritage assets, this classification assesses the urban, spatial and landscape configuration of these thirty-nine cities analysed as a whole. International agencies as UNESCO also has recognised the heritage value of several of these medium-sized cities. For instance, Úbeda and Baeza (Jaen) are listed on the World Heritage List as "Renaissance Monumental Ensembles of Úbeda and Baeza" (UNESCO 2003: 121), or the "Antequera Dolmens Site" (UNESCO 2016: 223), located in the Province of *Málaga*.

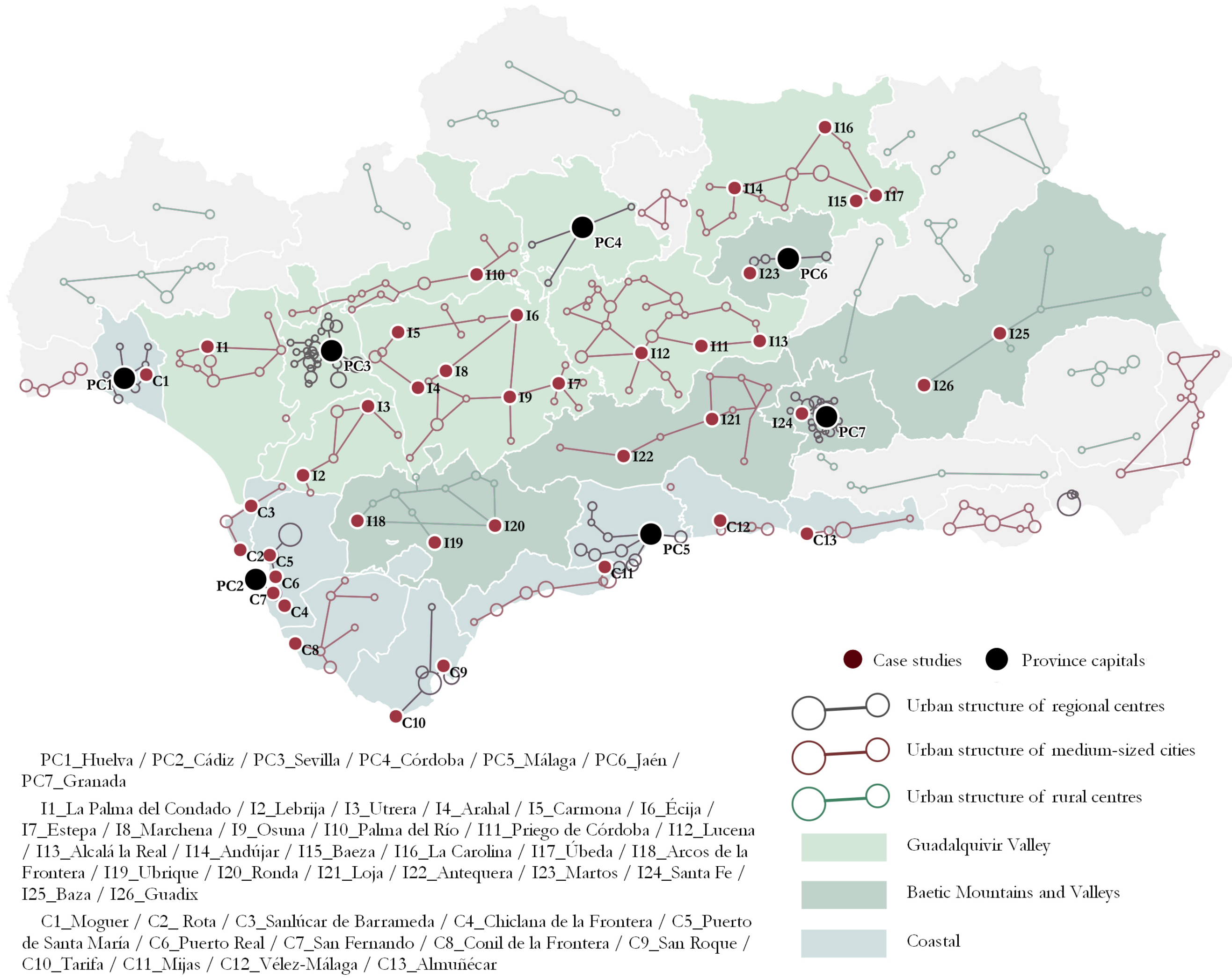


Figure 1.- Andalusian Urban System. Source: Compiled by the authors based on the Spatial Plan of Andalusia (Junta de Andalucía, 2006).

Table 1.- Geographic Domain, Territorial Unit and Medium-sized Cities listed as Historical Ensemble in Andalusia. Source: Compiled by authors based on data from the Spatial Plan of Andalusia (Junta de Andalucía, 2006) and the Institute of Statistics and Cartography of Andalusia (IECA, 2019).

Geographic Domain		Territorial Unit	Medium-sized cities according to the Spatial Plan of Andalusia
Inner	Guadalquivir Valley	Aljarafe-Condado-Marismas	La Palma del Condado (10,761 inhabitants)
		Bajo Guadalquivir	Lebrija (27,524 inhabitants) Utrera (50,728 inhabitants)
		Campiña y Sierra Sur de Sevilla	Arahal (19,526 inhabitants) Carmona (28,531 inhabitants) Écija (39,873 inhabitants) Estepa (12,505 inhabitants) Marchena (19,457 inhabitants) Osuna (17,560 inhabitants)
		Guadalquivir Valley	Palma del Río (21,064 inhabitants)
		Campiña y Subbético de Córdoba y Jaén	Lucena (42,605 inihabitants) Priego de Córdoba (22,408 inhabitants) Alcalá la Real (21,605 inhabitants)
		Centro Norte de Jaén	Andújar (36,793inhabitants) Baeza (15,841 inhabitants) La Carolina (15,261 inhabitants) Úbeda (34,345 inhabitants)

Table 1.- (continuation)

Geographic Domain		Territorial Unit	Medium-sized cities according to the Spatial Plan of Andalusia
Inner	Baetic Mountains and Valleys	Serranías de Cádiz y Ronda	Arcos de la Frontera (30,700 inhabitants) Ubrique (16,597 inhabitants) Ronda (33,877 inhabitants)
		Depresiones de Antequera y Granada	Loja (20,342 inhabitants) Antequera (41,239 inhabitants)
		Regional Centre of Jaén	Martos (24,215 inhabitants)
		Regional Centre of Granada	Santa Fe (15,157 inhabitants)
		Altiplanicies Orientales	Baza (20,412 inhabitants) Guadix (18,422 inhabitants)
Coastal		Regional Centre of Huelva	Moguer (22,088 inhabitants)
		Costa Noroeste de Cádiz	Rota (29,109 inhabitants) Sanlúcar de Barrameda (68,684 inhabitants)
		Regional Centre of Bahía de Cádiz-Jérez	Chiclana de la Frontera (84,489 inhabitants) Puerto de Santa María (88,405 inhabitants) Puerto Real (41,627 inhabitants) San Fernando (95,979 inhabitants)
		La Janda	Conil de la Frontera (22,529 inhabitants)
		Regional Centre of Bahía de Algeciras	San Roque (31,218 inhabitants) Tarifa (18,162 inhabitants)
		Costa del Sol	Mijas (82,742 inhabitants)
		Vélez-Málaga y Axarquía	Vélez-Málaga (81,643 inhabitants)
		Costa Tropical	Almuñécar (26,514 inhabitants)

Methodology

— Criteria for its application to the study sample

To meet the defined objectives, a system of medium-sized cities of heritage character has been chosen as a case study: those officially recognised in Andalusia purposing their preservation. That is, listed as Historical Ensembles according to what is indicated by Law 14/2007 on the Historical Heritage of Andalusia (Junta de Andalucía 2007). For this purpose, it has been necessary to determinate the criteria based on what urban vulnerability needs to be addressed.

In the case of the Spanish official framework, the Ministry of Development has developed a methodology to try to objectively analyse Urban Vulnerability through twenty urban indicators and from four perspectives (socio-demographic, socio-economic, residential and subjective). The resulting product can be checked on a web application, namely Atlas of Urban Vulnerability, firstly published in 2011. The methodology was reviewed to become part of the Urban Vulnerability Observatory in 2015, thanks to the approval of the Land and Urban Rehabilitation Law (Ministerio de Fomento 2015). This digital tool is playing a key role in the development of urban regeneration policies, including the Integrated Sustainable Urban Development Strategies (SUDS) as the result of implementing the Europe 2020 strategy to the field of urban development (Matesanz Parellada, 2018: 92).

This work adopts the methodology provided by the aforementioned Atlas using the data supplied by the Spanish National Statistics Institute in the most recent Population and Housing Census (2011). Although it is a statistical study based on 9% of regular residents, it is the last unified analysis for the set of Spanish municipalities and, therefore, with the same criteria for sampling, data collection and result interpretation. The next update is scheduled for release in 2021. Meanwhile, the National Statistics Institute elaborates the Continuous Household Survey annually since 2013. However, its data are grouped by provinces, and, consequently, it is not possible to use them in this research. Besides, the latest version of the Spanish Census does not provide the information needed for Subjective indicators; whose analysis would require a qualitative approach based on social perception (Ruiz, 2019:34). For this reason, the research has focused on the socio-demographic, socio-economic and residential dimensions. Specifically, the following fifteen indicators have been analysed:

- Socio-demographic vulnerability: Percentage of seniors aged 75 or more (I1), Percentage of families with only a person aged 64 or more (I2), Percentage of families with only an adult and a child (I3), Percentage of foreign population (I4), Percentage of foreign children (I5).
- Socio-economic vulnerability: Percentage of unemployed population (I6), Percentage of unemployed young population (I7), Percentage of contingent workers (I8), Percentage of workers without qualification (I9), Percentage of people without primary education (I10).
- Residential vulnerability: Percentage of dwellings with less than 30 m² (I11), Average adequate living area by inhabitant (I12), Percentage of population in dwellings without a toilet or WC (I13), Percentage of dwellings in ruined or deficient buildings (I14), Percentage of dwellings in buildings built before 1940 (I15).

Based on these considerations, the fifteen indicators mentioned above have been applied to the twenty-six medium-sized interior cities and thirteen coastal ones that have been listed as Heritage Ensembles. The numerical and percentage indicator values have been provided for the whole sample using the data supplied by the Population and Housing Census. This study includes a comparative analysis with the eight provincial capitals, which have the role of regional centres within the territorial organization of Andalusia. In order to properly analyse the results, two different general territorial domains should be identified within the set of Andalusian medium-sized cities. The geographical position, the substantial economic and demographic development or the particular dynamics of urban growth makes the coastal territorial structure differs significantly from the inner one, mostly traditionally characterised as agrocities. Besides, the territorial structure of inner Andalusia is marked by the presence of two structuring elements of the Andalusian territory: the Guadalquivir River and the Baetic System.

In the first phase, the complete information has been represented using a sequential colour scheme (the lowest levels in green and the highest ones in red), as shown in Tables 2 and 3. Subsequently, transforming the absolute values into quintiles, the general urban vulnerability index has been calculated, as well as the one corresponding to each of the three dimensions analysed: Socio-demographic, Socio-economic and Residential. The territorial distribution of these values has been represented through Geographic Information Systems, which has allowed to provide a territorial lecture of the urban vulnerability in Andalusia [figure 2].

3. Results

— Urban heritage protection. Urban planning as a preservation tool

Before evaluating the degree of heritage preservation that characterizes the analysed cities, it is necessary to expose the legal framework that currently regulates it. In Spain, the heritage preservation is carried out by different public administrations in various development levels: Central, Regional and Local Governments. The Government of Spain, through the Heritage Law, in force since 1985, can list heritage elements as *Bien de Interés Cultural* –hereafter BIC- (Cultural Interest Asset), the highest level of protection in the country. These elements can be listed as Monuments, Historical Gardens, Historical Ensembles, Historical Sites or Archaeological Areas.

Furthermore, heritage preservation can also be articulated since the regional level. Thus, in the case of Andalusia and after the transfer of competences in heritage matters in 1984, the first Andalusian Heritage Law was approved in 1991 (Junta de Andalucía 1991), updated in 2007 (Junta de Andalucía 2007). According to this law, the Cultural Interest Assets also be listed as Places of Ethnological Interest, Places of Industrial Interest, or Heritage Areas. Besides, it introduces a second level of heritage protection called *Bien de Catalogación General* –hereafter BCG- (General Cataloguing Asset). Both of them, and those Andalusian movable assets listed in the I*nventario General de Bienes Muebles del Patrimonio Histórico Español* (General Inventory of Movable Property of the Spanish Historical Heritage), are included in the *Catálogo General del Patrimonio Histórico Andaluz* –hereafter CGPHA- (General Catalogue of the Andalusian Historical Heritage).

Nonetheless, Local Governments has also a significant role in the safeguarding of heritage due to their proximity to the asset to be preserved. According to the *Ley de Ordenación Urbanística de Andalucía* –hereafter LOUA- (Andalusian Urban Planning Law), each municipality is obliged to include heritage preservation measures in the different urban planning instruments approved. In this sense, it is relevant to clarify that the Spanish legislation considers several urban development levels, whose impact on heritage preservation -given the scope of the measures- is consequently uneven. The first instrument to be considered is the *Plan General de Ordenación Urbana* -hereafter PGOU- (General Urban Development Plan). In some cases, general urban planning is regulated by the so-called *Normas Subsidiarias* -hereafter NNSS- (Urban Subsidiary Rules). They are repealed instruments, but which are still used in small towns after being updated according to the LOUA's requirements.

On a second level, the *Planes Especial de Protección* –hereafter PEP- (Preservation Urban Plans) should be mentioned. According to Article 14 of the LOUA, these plans have, among other purposes, to conserve, protect and improve the urban environment and, primarily, the bearer or expressive heritage of urban, architectural, historical or cultural values. In both instruments, the heritage preservation is mainly articulated through the so-called Protection Catalogues, which contain the detailed list and the precise identification of the assets and spaces that, due to their value, must be subject to particular conservation. Its formulation and approval can also be carried out independently.

According to the aforementioned urban and heritage preservation policies, the set of case studies have been analysed distinguishing again between interior and coastal geographic domain. As table 2 shows, 9 out of 26 (34.62%) cities studied in inner Andalusia are still regulated with NNSS, 5 of them have initiated the drafting of their PGOU, but they have not been approved definitely. 15 out of 26 (57.69%) of the General Plans had been approved before the LOUA's enactment, but all of them have been adapted to its articulate. Consequently, all the PGOU and NNSS include heritage preservation measures, although only 21 of them include a protection catalogue. In parallel, 10 out of 26 (38.46%) cities have approved a Preservation Plan for their Historical Ensembles.

In the cities analysed in the coast, as table 3 shows, only 1 out of 13 (7.69%) is still regulated by NNSS which were adapted to the current legal framework in 2010. 8 out of 13 (61.54%) General Plans had been approved before the LOUA's enactment, but all of them have been already updated. Consequently, all the PGOU and NNSS include heritage preservation measures, although only 11 of them include a protection catalogue. One of them, the Puerto de Santa María, has approved an additional heritage register. About Preservation Planning for their Historical Ensembles, 10 out of 13 (76.92%) cities have initiated its formulation; nevertheless, only 6 of them (46.15%) have definitely approved it.

Table 2.- Heritage protection by urban planning in medium-sized interior cities. Source: Compiled by authors based on the Regional Government's Planning Database (Junta de Andalucía, 2019).

MEDIUM-SIZED INTERIOR CITY	CURRENT URBAN PLAN	PROTECTION CATALOGUE	ADAPTATION TO LOUA	PROTECTION URBAN PLAN	ADDITIONAL REGISTER
Arcos de la Frontera (Cádiz)	PGOU 1994 PGOU 2014(1)	Yes	2010	2007	-
Ubrique (Cádiz)	NNSS 1987 PGOU 2015(1)	Yes	2010	No	-
Lucena (Córdoba)	PGOU 1999	Yes	2008	No	-
Palma del Río (Córdoba)	PGOU 2005	Yes	-	No	-
Priego de Córdoba (Córdoba)	PGOU 2015	Yes	-	No	-
Baza (Granada)	PGOU 2010	Yes	-	No	-
Guadix (Granada)	PGOU 2002	Yes	2010	No	-
Loja (Granada)	NNSS 1993	Yes	2009	No	-
Santa Fe (Granada)	NNSS 1998	Yes(2)	2009	No	-
La Palma del Condado (Huelva)	PGOU 2005	Yes	-	No	-
Alcalá la Real (Jaén)	PGOU 2005	Yes	-	No	-
Andújar (Jaén)	PGOU 2010	Yes	-	No	-
Baeza (Jaén)	PGOU 2011	Yes	-	1990	-
La Carolina (Jaén)	NNSS 1993	Yes	2011	No	-
Martos (Jaén)	PGOU 2013	Yes	-	No	-
Úbeda (Jaén)	PGOU 1996	Yes(2)	2009	1989(3)	-
Antequera (Málaga)	PGOU 2010	Yes(2)	-	1993	-
Ronda (Málaga)	PGOU 1991	Yes(2)	2010	-	-
Arahal (Sevilla)	NNSS 1994 PGOU 2019(1)	Yes	2009	2014	-
Carmona (Sevilla)	NNSS 1983 PGOU 2012(1)	Yes	2009	2009	-
Écija (Sevilla)	PGOU 2009	Yes	-	2002	-
Estepa (Sevilla)	NNSS 1988	Yes	2011	-	-
Lebrija (Sevilla)	PGOU 2016	Yes	-	2018	-
Marchena (Sevilla)	NNSS 1995 PGOU 2007(1)	Yes	2009	1994	-
Osuna (Sevilla)	NNSS 1985 PGOU 2017(1)	Yes(2)	2009	-	-
Utrera (Sevilla)	PGOU 2001 PGOU 2015(1)	Yes	2008	2009(4)	-

NNSS = Urban Subsidiary Rules | PGOU = General Urban Development Plan | LOUA = Andalusian Urban Planning Law (2002)
(1) provisional approval | (2) incomplete | (3) updated in 2000 | (4) updated in 2018

Table 3.- Heritage protection by urban planning in medium-sized interior cities. Source: Compiled by authors based on the Regional Government's Planning Database (Junta de Andalucía, 2019).

MEDIUM-SIZED COASTAL CITY	CURRENT URBAN PLAN	PROTECTION CATALOGUE	ADAPTATION TO LOUA	PROTECTION URBAN PLAN	ADDITIONAL REGISTER
Chiclana de la Frontera (Cádiz)	PGOU 2016	Yes	-	-	-
Conil de la Frontera (Cádiz)	PGOU 2005	No	2013	2003(1)	-
El Puerto de Santa María (Cádiz)	PGOU 2012	Yes		2009(1)	2015
Puerto Real (Cádiz)	PGOU 2009	Yes	-	1997	-
Rota (Cádiz)	PGOU 1994	Yes	2009	2019(1)	-
San Fernando (Cádiz)	PGOU 2011	Yes	-	2008	-
San Roque (Cádiz)	PGOU 2000	Yes	2009	2009	-
Sanlúcar de Barrameda (Cádiz)	PGOU 1996	Yes	2011	-	-
Tarifa (Cádiz)	PGOU 1989	Yes	2010	2012	-
Almuñécar (Granada)	PGOU 1987	Yes(2)	2009	2013	-
Moguer (Huelva)	NNSS 1992	Yes	2010	-	-
Mijas (Málaga)	PGOU 1999	Yes(2)	2010	2019(1)	-
Vélez-Málaga (Málaga)	PGOU 1996	No	2009	2008(3)	-

NNSS = Urban Subsidiary Rules | PGOU = General Urban Development Plan | LOUA = Andalusian Urban Planning Law (2002)
(1) provisional approval | (2) incomplete | (3) updated in 2014

The medium-sized coastal cities present average levels of vulnerability in the three dimensions that have been analysed. All the indicators are comprised between the second and fourth quintile. It should be noted that their socio-demographic vulnerability is lower to the regional centres. This fact is especially significative in the percentage of the elderly population (I1-I2) and the percentage of single-parent families (I3). By the contrary, their socio-economic vulnerability is slightly higher (I6-I10). Although they are characterised for certain uniformity, some general conclusions can be drawn. In average, they also present medium levels of vulnerability in the three dimensions. The results are similar to the coastal cities; being the indicators comprised between the second and fourth quintile. The socio-demographic vulnerability (I1-I5) is lower to the regional centres and the socio-economic vulnerability slightly higher (I6-I10). The residential vulnerability can be considered equivalent in both cases since half of the indicators are slightly higher in medium-sized cities and the other half in the regional centres [figure 2].

In inner Andalusia [table 3], two particular situations can be recognised based on the intensity and level of consolidation of these territories: Guadalquivir Valley (high intensity) and Baetic Mountains and Valleys (moderate intensity). In the first case, the territorial unities of the Campiña de Sevilla and the Bajo Guadalquivir should be highlighted. As table 3 shows, cities such as Arahal, Carmona, Écija, Lebrija, Marchena, Osuna or Utrera stand out for higher values in socio-economic vulnerability (I6-I10) compared to the rest of the dimensions except for Estepa. This city also has high levels of socio-economic vulnerability, but exclusively in

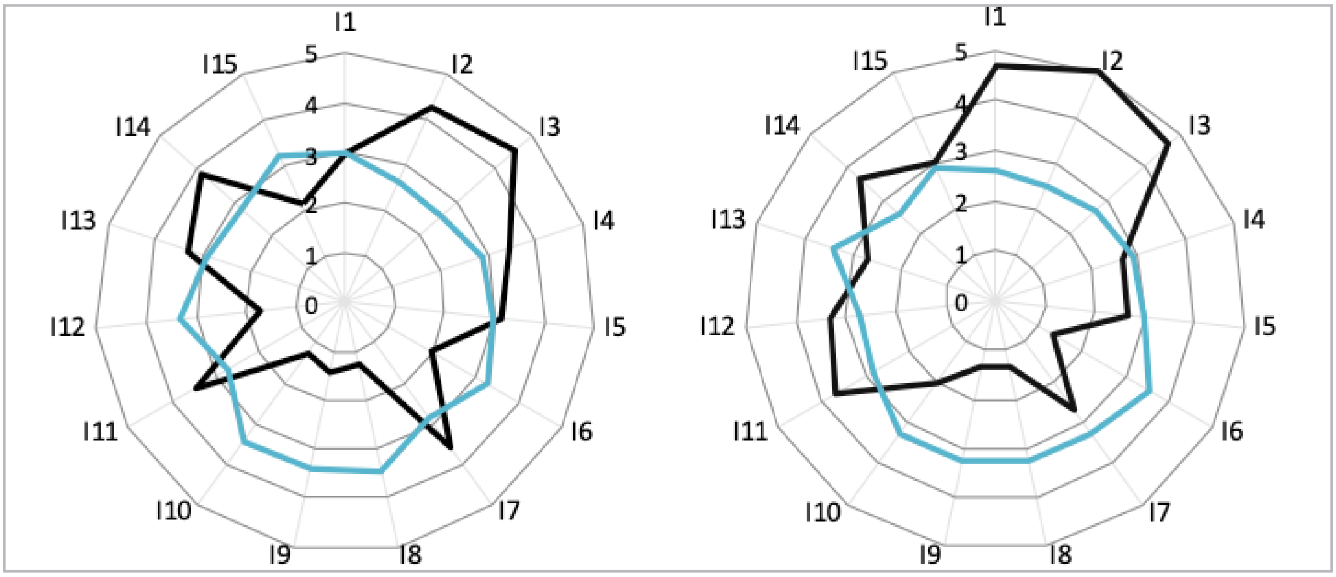


Figure 2.- Average levels of urban vulnerability in medium-sized cities (blue) and regional centres (black) in inner and coastal Andalusia. Source: Compiled by the authors based on data from Spanish Statistical Office (INE, 2011).

indicators I7 to I8. These data do not mean that the other values are in minimum positions. Thus, cities as Estepa, Lebrija, Marchena or Osuna show high levels of residential vulnerability, specially I15.

Besides, for the cases of Estepa and Lebrija, high levels are observed in indicators I12, I13 and I14. In the North-Centre of Jaén, the principal characteristic is the vulnerability levels of La Carolina. In this case, most of the indicators are at low levels. 9 out of 18 (50%) are under the first percentile except for indicators I6 and I13 which levels are close to the maximum. Furthermore, Priego de Córdoba stands out among the group of cities that constitute the Campiña and Subbética de Córdoba-Jaén. This medium-sized city has almost non-existent levels of residential vulnerability, on the contrary, has maximum levels in I4, I5, I8, I9 and I10 indicators. La Palma del Condado and Palma del Río, the only example analysed in their related territorial unit, are characterized by having most of their values at minimum levels.

In the Baetic Mountains and Valleys, five territorial units have been analysed. Among the case studies, Baza highlights as the city that presents the highest number of indicators at maximum levels at the axis drawn by the cities inserted in the Altiplanicies Orientales and the Depresiones de Antequera y Granada. Mainly those related to residential issues, although some indicators of socio-economic and socio-demographic vulnerabilities also have maximum values. Antequera presents the lowest

Table 3.- Urban vulnerability in medium-sized cities (blue) and regional centres (black) in inner Andalusia (percentage figures). Data has been represented using a sequential colour scheme (the lowest levels in green and the highest ones in red). Observations: (1) no foreign children registered; (2) no dwellings with less than 30 m^2 registered; (3) no dwellings without a toilet or WC registered. Source: Compiled by the authors based on data from Spanish Statistical Office (INE, 2011)

Cities	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15
Cádiz	9,08	4,18	5,71	1,74	0,11	19,03	59,71	34,40	20,12	9,74	0,73	31,51	1,38	15,08	22,78
Arcos de la Frontera	6,34	2,34	3,81	2,20	0,59	28,47	61,56	55,87	55,83	17,01	0,60	30,74	1,62	4,57	11,55
Ubrique	7,62	3,05	4,44	0,86	0,24	18,28	46,11	47,74	12,38	20,12	0,47	34,35	1,18	5,83	9,38
Córdoba	8,32	3,61	5,71	2,68	0,37	17,75	51,22	31,05	17,41	9,91	0,14	33,24	0,62	6,76	6,14
Lucena	7,05	2,69	4,18	5,38	0,61	21,36	47,10	38,57	27,55	14,63	0,17	34,68	2,26	4,62	2,46
Palma del Río	7,69	3,24	4,01	5,59	1,40	19,72	46,61	48,47	45,72	17,83	0,00(2)	33,79	0,52	1,10	2,72
Priego de Córdoba	10,97	3,74	6,02	2,63	0,92	19,61	43,80	44,48	39,85	18,65	0,00(2)	40,28	0,72	3,36	8,05
Granada	9,72	4,79	6,67	7,01	1,24	15,93	53,49	29,60	14,27	7,73	0,33	38,43	0,46	5,49	5,61
Baza	9,31	3,62	4,37	9,59	2,51	17,44	49,47	35,92	22,59	13,32	0,00(2)	43,78	0,52	5,50	7,25
Guadix	9,86	3,64	3,61	3,67	0,82	17,43	51,23	37,46	25,06	11,61	1,35	36,96	0,28	14,84	22,02
Loja	8,87	4,46	4,01	5,67	1,70	19,76	37,33	43,99	40,84	19,34	0,50	39,74	0,44	8,71	7,77
Santa Fe	7,74	2,09	8,70	4,35	0,00(1)	18,59	53,33	38,14	23,36	9,65	1,50	38,27	0,44	1,86	6,02
Huelva	7,26	3,18	5,95	4,90	0,82	18,87	56,12	36,76	23,73	8,11	0,09	31,70	0,62	11,81	4,52
La Palma	7,77	2,55	4,30	3,45	0,57	16,87	39,63	40,86	31,47	8,32	0,00(2)	37,15	0,28	4,55	12,69
Jaén	8,00	3,98	6,50	2,93	0,43	15,38	61,05	30,49	17,41	8,75	0,00(2)	35,16	0,53	3,66	4,15
Alcalá la Real	11,98	5,08	3,41	4,89	0,99	15,84	46,46	41,65	33,83	21,45	0,23	42,09	1,09	4,15	4,67
Andújar	8,76	3,70	4,81	2,68	0,44	21,29	58,99	38,54	29,98	17,42	0,00(2)	35,67	0,31	8,32	4,12
Baeza	9,15	4,26	3,98	4,47	0,18	17,00	40,32	38,81	19,63	13,56	0,00(2)	40,33	0,00(3)	1,05	7,37
La Carolina	7,25	2,61	4,47	2,42	0,00(1)	19,99	43,78	32,67	23,90	13,16	0,00(2)	36,25	0,18	0,98	6,39
Martos	10,21	3,82	4,33	4,56	1,37	17,32	42,16	39,16	33,72	16,99	0,00(2)	38,97	0,50	5,91	13,15
Úbeda	8,79	3,26	5,31	2,98	0,36	18,16	49,61	33,09	15,25	11,03	0,12	39,68	0,19	3,86	10,49
Málaga	7,21	3,52	6,18	7,84	1,39	18,73	51,99	31,83	21,33	9,40	0,30	33,15	0,70	4,42	3,90
Antequera	8,17	3,37	4,98	4,56	0,93	3,65	52,82	33,05	28,07	14,76	0,00(2)	34,65	1,65	6,42	5,41
Ronda	8,48	3,50	5,76	4,15	0,63	20,93	51,95	37,32	21,32	12,82	0,44	35,56	0,88	3,53	8,02
Sevilla	8,28	3,95	5,51	5,12	0,94	16,54	50,20	29,21	16,79	7,85	0,22	32,97	0,54	4,81	4,55
Arahal	7,28	1,77	2,64	1,39	0,21	24,32	60,04	49,05	52,23	16,93	0,18	34,29	0,00(3)	5,00	4,33
Carmona	7,54	2,22	4,79	2,98	0,83	24,31	57,00	44,61	47,50	14,57	0,00(2)	36,33	1,18	1,69	7,30
Écija	7,14	3,14	7,05	2,97	1,05	23,32	57,25	44,97	35,63	15,41	0,03	33,93	1,12	2,86	4,58
Estepa	7,30	0,35	3,90	3,78	0,00(1)	15,06	57,88	47,30	27,25	14,62	0,17	42,35	1,50	1,50	11,95
Lebrija	6,20	2,42	4,29	2,44	0,20	23,05	55,36	44,15	30,52	15,99	0,17	33,71	1,01	4,27	7,12
Marchena	7,67	2,98	5,04	3,86	0,10	21,26	59,19	46,50	42,83	17,55	0,00(2)	36,14	0,00(3)	2,27	7,37
Osuna	8,48	2,34	3,79	1,70	0,17	20,10	57,28	47,38	51,91	16,26	0,12	38,77	0,00(3)	6,34	11,58
Utrera	6,24	2,22	4,94	2,47	0,50	25,15	62,16	41,23	32,47	13,84	0,35	35,56	0,38	2,61	5,07
Regional centres	8,26	3,93	6,09	4,92	0,82	17,42	55,43	32,05	18,94	8,60	0,28	33,82	0,71	7,54	7,59
Medium-sized cities	8,23	3,02	4,65	3,68	0,67	19,55	51,09	41,96	32,72	15,26	0,25	37,08	0,70	4,45	8,03

levels of this region. However, it has two maximums in indicators concerning building matters (I13 and I14). Among the medium-sized cities of the Serranía de Cádiz and Ronda, Arcos de la Frontera has the highest values, mainly in the socio-economic dimension. In this sense, the similarity that exists between this city and Conil de la Frontera and Sanlúcar de Barrameda should be pointed out. These two coastal cities of the province of Cádiz also have maximum values in these indicators. Nevertheless, Ubrique is characterised by a higher level of vulnerability in residential areas. Finally, Santa Fe and Martos are located under the influence of a regional centre (Granada and Jaen, respectively). This fact makes them have similar patterns of behaviour as them. Just in the case of Martos, the indicators concerning population age (I1) and building age (I14-I15) are exceptionally higher than in Jaen.

On the other side, in the territorial domain of the Andalusian coast [table 4], the regional plan recognises eight territorial units mainly constituted by medium-sized cities. Two of these units are characterised by economic and productive factors: Costa del Sol and Poniente Almeriense (Navas-Carrillo et al., 2017:300). They appear as strongly anthropized units that have a monofunctional model (tourism or greenhouse agriculture). Within these two territorial units, the study sample only includes the city of Mijas. Highly polarised levels of vulnerability characterise this city. The vulnerability level in most of the indicators is minimum, even non-existent. However, the socio-demographic indicators (I2-I5) and the ones related to the housing surface (I11-I12) reach maximum values.

Meanwhile, the rest of the cases are less populated territorial units. Their functional model relates the two previous economic pillars – tourism and agriculture – with other development factors of urban, industrial and commercial economies. We highlight the case of Sanlúcar de Barrameda (Northwest Coast of Cadiz), Conil de la Frontera (La Janda), Vélez-Málaga (Axarquía) and Almuñecar (Costa Tropical), since they are the primary functional centres of their respective territories. The first two cities present high vulnerability in indicators 6 to 10, relating to economic aspects. This weakness is seen as a risk factor for heritage preservation. The situation in Vélez-Málaga and Almuñecar is not favourable either. Both stands out for high levels of vulnerability, except for indicators linked to the employment (I8) and the state of dwellings (I14) in Vélez-Malaga, and the young unemployment (I7) and the number of single-parent families (I3) in the case of Almuñecar. In any case, analysed as a whole, high vulnerability implies a generalized risk in both cases.

Other coastal cities as Chiclana de la Frontera, Puerto Real, San Fernando, San Roque, Tarifa, Puerto de Santa María or Moguer have also been included in the sample. It should be explained that they can be classified as medium-sized cities considering population criteria exclusively. However, these cities are under the strong influence of a nearby regional centre. This fact encourages their response to urban vulnerability differs from the previous ones. The case of San Fernando should be highlighted. As table 4 shows, it has the same pattern of behaviour as Cádiz, but having vulnerability indexes lightly inferior.

Table 4.- Urban vulnerability in medium-sized cities (blue) and regional centres (black) in coastal Andalusia (percentage figures). Data has been represented using a sequential colour scheme (the lowest levels in green and the highest ones in red). Observations: (1) no dwellings with less than 30 m^2 registered. Source: Compiled by the authors based on data from Spanish Statistical Office (INE, 2011)

Cities	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15
Cádiz	9,08	4,18	5,71	1,74	0,11	19,03	59,71	34,40	20,12	9,74	0,73	31,51	1,38	10,81	22,78
Chiclana de la Fr	4,33	1,22	5,66	4,51	1,13	24,25	62,31	38,89	24,06	9,47	0,05	34,47	1,74	4,36	2,77
Conil de la Fr.	5,45	1,06	3,79	6,41	0,69	25,63	63,41	41,80	37,07	15,31	1,28	30,22	1,14	1,75	4,85
Puerto de Sta. María	5,00	2,81	5,70	4,33	0,73	20,45	53,08	32,81	21,21	7,55	0,22	33,66	0,96	15,36	7,15
Puerto Real	4,61	1,87	5,30	2,34	0,86	20,58	55,07	39,19	20,72	9,15	0,53	31,55	0,80	3,18	4,64
Rota	5,15	2,62	3,50	4,18	0,29	19,30	54,62	36,70	26,70	11,24	0,14	30,73	1,42	3,03	7,75
San Fernando	5,96	2,40	6,02	1,51	0,39	18,94	56,63	34,53	17,53	7,33	0,21	30,12	0,97	5,54	6,77
San Roque	5,52	1,39	5,34	15,24	2,21	21,66	59,69	37,02	27,75	10,15	0,23	39,45	0,98	14,82	4,46
Sanlúcar de Bda.	5,66	2,00	6,15	1,36	0,04	26,12	63,45	47,29	35,22	14,92	0,73	29,31	1,31	5,79	5,79
Tarifa	6,72	0,94	5,44	8,73	1,30	21,92	53,42	42,89	21,33	14,15	0,53	30,88	1,14	3,04	14,82
Granada	9,72	4,79	6,67	7,01	1,24	15,93	53,49	29,60	14,27	7,73	0,33	38,43	0,46	5,49	5,61
Almuñécar	8,99	3,80	4,75	18,02	1,86	24,63	58,95	40,33	36,02	11,19	0,49	34,19	5,04	4,69	7,46
Huelva	7,26	3,18	5,95	4,90	0,82	18,87	56,12	36,76	23,73	8,11	0,09	31,70	0,62	11,81	4,52
Moguer	3,88	1,79	5,02	23,62	3,98	20,88	60,00	57,07	50,38	11,47	0,84	35,93	0,32	6,37	11,33
Málaga	7,21	3,52	6,18	7,84	1,39	18,73	51,99	31,83	21,33	9,40	0,30	33,15	0,70	4,42	3,90
Mijas	5,43	2,76	6,23	35,38	4,37	19,18	43,29	30,21	14,20	6,37	0,51	35,93	0,63	0,75	0,63
Vélez-Málaga	6,27	2,72	5,23	11,11	1,75	22,00	57,13	36,35	27,81	12,09	0,00(1)	34,80	1,15	3,06	5,98
Regional centres	8,67	4,16	6,19	5,53	0,92	17,90	55,06	31,94	18,57	8,95	0,46	34,36	0,85	6,90	10,76
Medium-sized cities	5,76	2,13	5,26	9,43	1,30	22,05	56,75	38,17	25,80	10,74	0,41	32,94	1,44	5,45	6,09

Discussions and conclusions

After analysing the results obtained, clear divergences can be observed between the vulnerability indexes that characterise each city of the sample. However, there is evidence of common trends or behaviour patterns in the set of cities under research, many of them since a territorial lecture. Most of the medium-sized cities highlight for their vulnerability in indicators I6 to I10 associated with socio-economic aspects, in contrast to regional centres or those intermediate cities close to them. The level of indicators I7, related to youth unemployment, is especially significant in the provinces of Cádiz and Jaén, and lower in the provinces of Granada and Jaén. In fact, as figure 3 shows, the territorial units of western Andalusia present a higher average level of socio-economic vulnerability. Mainly, the medium-sized cities studied in the Campiña y Sierra Sur de Sevilla, in the Bajo Guadalquivir, Costa Noroeste de Cádiz, and the regional centre of Bahía de Cádiz. By contrast, the case studies in the provinces of Granada, Málaga, Córdoba and Jaén have higher average levels of socio-demographic vulnerability (I1-I5). The regional centres also show high vulnerability indexes, highlighting the case of Granada.

In the case of residential vulnerability (I11-I15), there is a more uniform territorial distribution of values [figure 3]. However, slightly lower values are identified in many of the cities that have been analysed in the Guadalquivir valley. This fact reflects that settlements with a more significant relationship with the natural environment contribute to social equity to a greater extent than in province capitals, being something that affects the state of the houses. In this sense, the data obtained are considered positive since they involve greater social cohesion and a sense of belonging to a site. There intangible factors are of vital interest to the effective heritage safeguard. However, figure 3 also shows that in the vast majority of case studies, the values obtained in the three dimensions are compensated. As a result, the average vulnerability reaches medium levels, both in intermediate cities and regional centres.

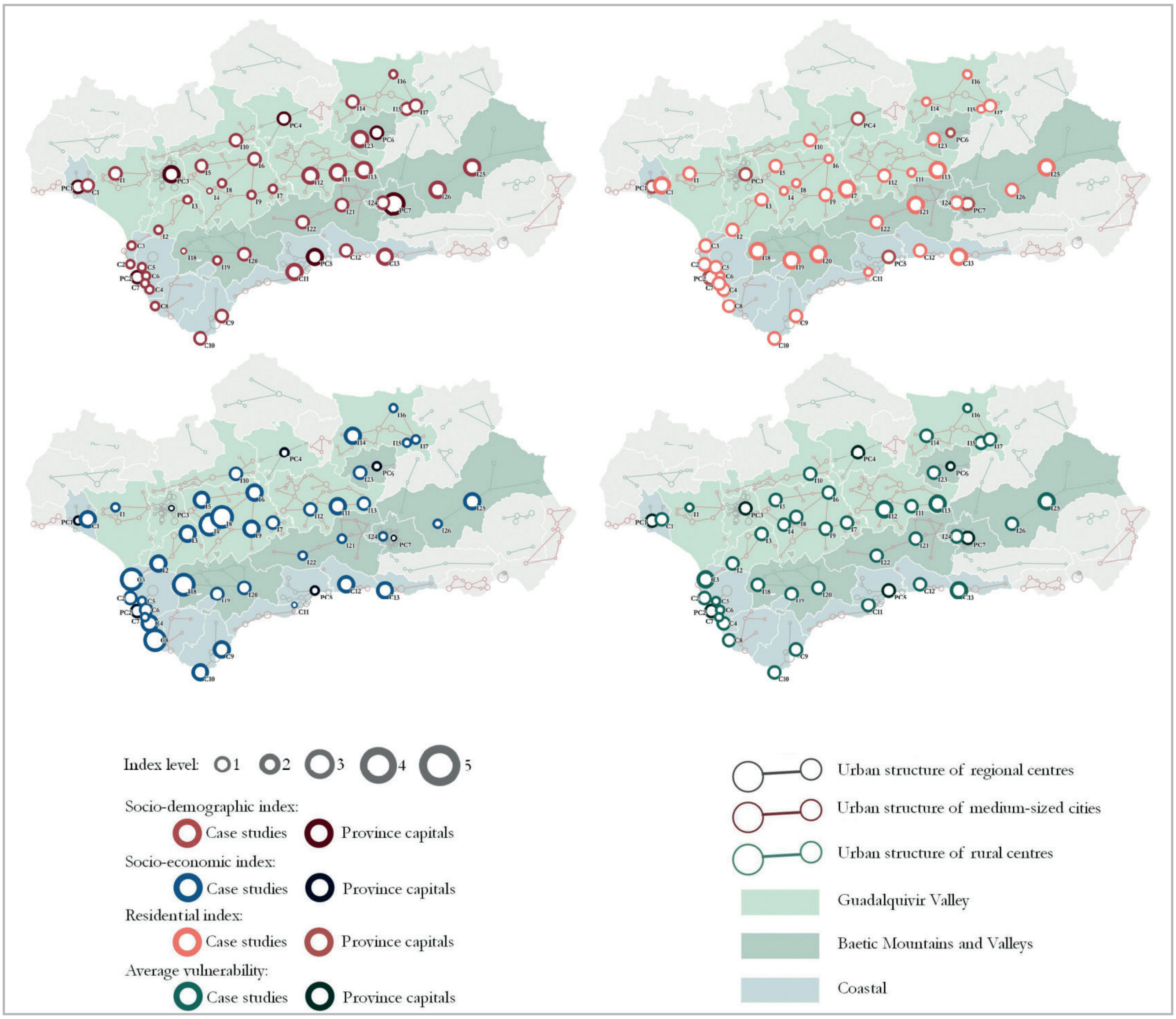


Figure 3.- Socio-demographic (red), socio-economic (blue), residential (green) and average (green) vulnerability in medium-sized cities (light colour) and regional centres (dark colour) in Andalusia. Source: Compiled by the authors based on data from Spanish Statistical Office (INE, 2011)

The data also allow extracting significant differences between the cities analysed in inland and coastal Andalusia. The majority of medium-sized interior cities have high levels of uneducated population, probably due to their configuration in the past as agricultural cities. This lower level of education could lead to a lower knowledge in heritage matters, so it would be desirable to promote the training and information of society to bring it to know, value and respect its historical legacy.

Coastal cities stand out for having the highest levels of economic vulnerability (I6-I10) and levels of foreigners (I4). The economic weakness can be perceived as a risk factor for heritage preservation; however, the influence of the foreign population would require more in-depth analysis. Among other issues, it will depend on the greater or lesser contribution of them to the socio-economic level of the city, for example, if the number of foreigners is compared between the Costa del Sol and the Costa Tropical in Granada. Consequently, the positive and negative effects of tourism must also be considered. The development of coastal cities has been characterised by sun-and-beach tourism. However, cultural tourism has recently been promoted as an alternative, beginning to play an essential role in preserving the heritage and promoting urban regeneration also in coastal cities. Nevertheless, cultural tourism can also carry certain risks for heritage conservation when it becomes the predominant activity in high-value areas such as the Historical Ensembles hindering their normal performance.

To conclude, the results obtained generally show that the medium-sized cities of Andalusia do not present a level of vulnerability lower to the regional centres. Consequently, both would have a similar heritage management capacity. However, several urban weaknesses have been identified, which would demand complementary analysis, for instance, expanding the study to the whole Andalusian territory or updating it with future census data. Likewise, it could also imply a comparative analysis with other national and international contexts Future lines of research that would contribute to a better understanding of urban vulnerability and improve the efficiency of the tools currently used for cultural heritage preservation.

Acknowledgements

This paper has been developed under the R&D project entitled Urban Heritage Characterisation and Cultural Tourism Model in Medium-Sized Cities. Potentialities and Challenges for its Internationalisation: Inner Baetica, funded by the competitive call of the State Plan 2013- 2016 Excellence – R&D Projects of the Ministry of Economy and Competitiveness of the Government of Spain (HAR2016-79788-P).

References

ALGUACIL GÓMEZ, J. (2006): “Barrios desfavorecidos: un diagnóstico de la situación española”. En: *V Informe FUHEM de políticas sociales: La exclusión social y Estado de Bienestar en España:* 155-168. Madrid: FUHEM-Icaria.

ALGUACIL GÓMEZ, J.; CAMACHO GUTIÉRREZ, J., HERNÁNDEZ AJA, A. (2014). “La vulnerabilidad urbana en España. Identificación y evolución de los barrios vulnerables”. *EMPIRIA. Revista de Metodología de Ciencias Sociales*, 27: 73-94. https://doi.org/10.5944/empiria.27.2014.10863

ANTÓN-ALONSO, F., PORCEL, S. (2017). “Transformación de barrios y densidad institucional: un análisis de la vulnerabilidad urbana en el Área Metropolitana de Barcelona”. *Seminario Internacional Las grandes ciudades en transformación. Dinámicas residenciales, segregación y vulnerabilidad*. Barcelona: Universitat de Barcelona.

BANKOFF G., FRERK G., HILHORST, D. (2004). *Mapping Vulnerability: Disasters, Development & People*. London: Earthscan

BANKOFF, G. (2019) Remaking the world in our own image: vulnerability, resilience and adaptation as historical discourses. *Disasters*. 43 (2): 221– 239. https://doi.org/10.1111/disa.12312

BELLET SANFELIU, C., BELTRÃO SPOSITO, M. E. (2009). L*as ciudades medias o intermedias en un mundo globalizado*. Lleida: Universitat de Lleida.

BELLET SANFELIU, C.; LLOP TORNÉ, J. M. (1999). *Ciudades Intermedias y Urbanización Mundia*l. Lleida: UNESCO, Ayuntament de Lleida, UIA, Ministerio de Asuntos Exteriores.

BRAUN, G., HOGENBERG, F. (1572-1618). *Civitates Orbis Terrarum*. Colonia.

CANNON, T. (2008). *Reducing People's Vulnerability to Natural Hazards: Communities and Resilience*. Bonn: United Nations University – World Institute for Development Economics Research

CARDOSO, M. M. (2018). “Estudio de la vulnerabilidad y la resiliencia en la ciudad de Santa Fe, Argentina: El rol de los servicios urbanos en general y del transporte de pasajeros en particular”. *Revista de geografía Norte Grande*, 73: 133-159. https://doi.org/10.4067/S0718-34022019000200133

CHRISTALLER, W. (1993). *Die zentralen Orte in Süddeutschland* (Central Places in Southern Germany). Translated by J. Fischer. New Jersey: Prentice-Hall.

DE SANTIAGO RODRÍGUEZ, E. (2018). “Herramientas de diagnóstico para las intervenciones de regeneración urbana integrada en la ciudad consolidada: ejemplos de España”. *Limaq. Revista de Arquitectura de la Universidad de Lima*, 4: 219-246. https://doi.org/10.26439/limaq2018.n004.2658

DEL ESPINO HIDALGO, B. (2018). *Las ciudades medias del centro de Andalucía. Análisis territorial y evaluación de su sostenibilidad*. Sevilla: Editorial de la Universidad de Sevilla.

DEL ESPINO HIDALGO, B., NAVAS-CARRILLO, D. (2018). "Planeamiento estratégico local y evaluación del Desarrollo Urbano Sostenible Integrado en ciudades medias". *Gestión y Análisis de Políticas Públicas*, 20: 143-163. https://doi.org/10.24965/gapp.v0i20.10481

HERNÁNDEZ AJA, A., RODRÍGUEZ ALONSO, R., RODRÍGUEZ SUÁREZ, I. (Dir.) (2018). *Barrios vulnerables de las grandes ciudades españolas*. 1991/2001/2011. Madrid: Instituto Juan de Herrera (IJH).

EUROPEAN UNION (2001). *Cities of tomorrow: Challenges, visions, ways forward*. Online: http://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/citiesoftomorrow/citiesoftomorrow_final.pdf (accessed 19th October 2019)

FAULKNER, J.; MURPHY, E. & SCOTT, M. (2020). *Developing a holistic 'vulnerability-resilience' model for local and regional development*. European Planning Studies. First published Online. https://doi.org/10.1080/09654313.2020.1720612

FÜSSEL, H. M. (2007). "Vulnerability: A generally applicable conceptual framework for climate change research". *Global Environmental Change* 17: 155–167. https://doi.org/10.1016/j.gloenvcha.2006.05.002

GODSCHALK, D. R. (2003). "Urban hazard mitigation: creating resilient cities". *Natural hazards review*, 4(3): 136-143. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136)

HARVEY, D. (2003). "The right to the city". *International journal of urban and regional research*, 27(4): 939-941. https://doi.org/10.1111/j.0309-1317.2003.00492.x

HAWKES, J. (2001). *The fourth pillar of sustainability. Culture's Essential Role in Public Planning*. Melbourne, Australia.

HIRSCHMAN, A. O. (1958). *The strategy of economic development*. New Haven: Yale University Press.

JEFATURA DEL ESTADO. (1985). "Ley 16/1985, de 25 de junio, del Patrimonio Histórico Español". In: *BOE núm. 155, de 29 de junio de 1985*. Reference: BOE-A-1985-12534. Madrid.

JUNTA DE ANDALUCÍA (2002). "Ley 7/2002, de 17 de diciembre, de Ordenación Urbanística de Andalucía". Pag. 25.084-25.145. In: *BOJA, núm. 154, de 31 de diciembre de 2002*. Sevilla: Junta de Andalucía.

JUNTA DE ANDALUCÍA (2006). *Plan de Ordenación del Territorio de Andalucía*. Sevilla: Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía.

JUNTA DE ANDALUCÍA (2007). "Ley 14/2007, de 26 de noviembre, del Patrimonio Histórico de Andalucía". Pag. 6-28. In: B*OJA, núm. 248, de 19 de diciembre de 2007*. Sevilla: Junta de Andalucía.

JUNTA DE ANDALUCÍA. (1991). "Ley 1/1991, de 3 de julio, de Patrimonio Histórico de Andalucía". Pag. 5573-5586. In: *BOJA, núm. 59, de 13 de julio de 1991*. Sevilla: Junta de Andalucía.

JUNTA DE ANDALUCÍA. (2019). "Consulta de planes urbanísticos y territoriales de Andalucía", en SITU@ Difusión de la Consejería de Medio Ambiente y Ordenación del Territorio de Andalucía. Online: http://ws041.juntadeandalucia.es/medioambiente/situadifusion/pages/search.jsf [consult: 19th October 2019]

KRELLENBERG, K., WELZ, J., LINK, F., BARTH, K. (2017). "Urban vulnerability and the contribution of socio-environmental fragmentation: Theoretical and methodological pathways". *Progress in Human Geography*, 41(4): 408–431. https://doi.org/10.1177/0309132516645959

LANKAO, P. R., QIN, H. (2011). "Conceptualizing urban vulnerability to global climate and environmental change". *Current opinion in environmental sustainability*, 3(3): 142-149. https://doi.org/10.1016/j.cosust.2010.12.016

LEFEBVRE, H. (1968). *Le droit à la ville* (Vol. 3). Anthropos: Paris.

LEVRON, E. (2010). I*dentification of Vulnerable People in Urban Environments: Assessment of Sustainable Livelihoods and Urban Vulnerabilities*. Palaiseau: Action Contre la Faim International.

LLOP TORNÉ, J. M., HOEFLICH DE DUQUE, S. (2010). *Ciudades intermedias*. Barcelona: Secretariado de la Red Mundial de Ciudades y Gobiernos Locales Unidos.

LÖSCH, A. (1940). T*he Spatial Organization of the Economy.* London: Encyclopædia Britannica

MADOZ, P. (1846-1850). *Diccionario Geográfico Estadístico Histórico de España y sus posesiones de Ultramar.* Madrid.

MATESANZ PARELLADA, Á. (2017). *Políticas urbanas y vulnerabilidad*. Tesis Doctoral. Universidad Politécnica de Madrid.

MATESANZ PARELLADA, Á. (2018). "Evolución de los parámetros del enfoque integrado en las políticas de regeneración urbana en los barrios vulnerables en España". *Gestión y Análisis de Políticas Públicas*, 20: 82-99. https://doi.org/10.24965/gapp.v0i20.10488

MERINERO RODRÍGUEZ, R., LARA DE VICENTE, F. (2010). *Las Ciudades Medias del interior de Andalucía. Caracterización y retos para el desarrollo turístico en un nuevo entorno*. Córdoba: Aecit.

MINISTERIO DE FOMENTO. (2012). *Análisis urbanístico de Barrios Vulnerables en España Sobre la Vulnerabilidad Urbana*. Madrid: Ministerio de Fomento. Gobierno de España.

MINISTERIO DE FOMENTO. (2015). *Atlas de la Vulnerabilidad Urbana en España 2001 y 2011. Metodología, contenidos y créditos*. Madrid: Ministerio de Fomento. Gobierno de España.

NAVAS-CARRILLO, D., PÉREZ CANO, M. T., DEL ESPINO HIDALGO, B., ROYO NARANJO, L. (2019). "Dualidad Turística Residencial de las ciudades medias del litoral andaluz". In: *TOURISCAPE, Turismo y Paisaje*, pp. 247- 260. Madrid: Tirant Lo Blanch.

NAVAS-CARRILLO, D.; ROSA-JIMÉNEZ, C., PÉREZ CANO, M. T. (2016). *Between Historic Sites and New Tourist Destinations: The Development of the First Periphery in Medium-Sized Andalusian Coastal Cities.* https://doi.org/10.30958/ajt.3.4.3.

PATEL, R., SANDERSON, D., SITKO, P., DE BOER, J. (2020). "Investigating urban vulnerability and resilience: a call for applied integrated research to reshape the political economy of decision-making". *Environment and Urbanization*. First published Online. https://doi.org/10.1177/0956247820909275

PERROUX, F. (1955). "Note sur la notion de poles croissance". *Économic Appliquée*, 8: 307-320.

RAN, J., MACGILLIVRAY, B. H., GONG, Y., HALES, T. C. (2020). "The application of frameworks for measuring social vulnerability and resilience to geophysical hazards within developing countries: A systematic review and narrative synthesis". *Science of The Total Environment*, 711 (134486): 1:16. https://doi.org/10.1016/j.scitotenv.2019.134486

RODRÍGUEZ PEÑA, V. (2017). *Análisis de la vulnerabilidad social-urbana en Valladolid: Una aproximación Geográfica*. Universidad de Valladolid.

RUIZ, A. (2019). "El potencial de la percepción social aplicada al análisis de la vulnerabilidad en planificación urbana". *EURE. Revista De Estudios Urbano Regionales*, 45(136): 31-50. http://dx.doi.org/10.4067/S0250-71612019000300031

RUIZ CASTILLO, J. (2004). "Los fundamentos de la protección: el efecto desintegrador producido por la consideración del Patrimonio Histórico como factor de desarrollo". *Patrimonio cultural y derecho*, 8: 11-36.

SINGH, C., DESHPANDE T., BASU, R. (2017). "How do we assess vulnerability to climate change in India? A systematic review of literature". *Regional Environmental Change*, 17: 527-538. https://doi.org/10.1007/s10113-016-1043-y

TEMES, R. (2014). "Valoración de la vulnerabilidad integral en las áreas residenciales de Madrid". *EURE. Revista De Estudios Urbano Regionales,* 40(119): 119-149. http://dx.doi.org/10.4067/S0250-71612014000100006

TWIGG, J. (2015). *Disaster Risk Reduction*. London: Overseas Development Institute

UNESCO. (2003). "Renaissance Monumental Ensembles of Úbeda and Baeza". In: *Decisions adopted by the 27th sesión of the World Heritage Committee*. Paris: UNESCO.

UNESCO. (2016). "Antequera Dolmens Site". In: *Report of the decisions adopted during the 40th session of the World Heritage Committee*. Istanbul: UNESCO.

UNESCO. (2018). *Re|shaping cultural policies: advancing creativity for development*. Online: https://unesdoc.unesco.org/ark:/48223/pf0000260678 [consult: 19th October 2019]

UNITED NATIONS. (2013). *Report on the world social situation, 2003. Social Vulnerability: Sources and Challenges.* New York: United Nations Reproduction Section.

VILAGRASA, J. (2000). C*iudades medias y ciudades intermedias: posicionamiento en la red urbana y procesos urbanos recientes. Online*: http://www etsav.upc.es/personals/monclus/cursos/ibarz.htm [consult: 19th October 2019]

WEICHSELGARNTER, J. (2001) "Disaster mitigation: The concept of vulnerability revisited". *Disaster Prevention and Management: An International Journal* 10: 85–95.

WISNER, B., BLAIKIE P., CANNON, T., DAVIS, I, (2004). *At Risk: Natural Hazards, People's Vulnerability and Disasters*. London: Routledge.

Author/s

Daniel Navas-Carrillo
dnavas@us.es
University of Seville (Spain

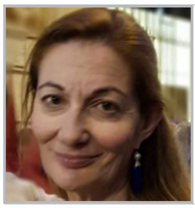
Is a PhD Researcher at the Urban and Regional Planning Department of the University of Seville (Spain). He holds a PhD in Architecture (2020), a MSC in Heritage and Architecture (2017) and a MSc in Innovation in Architecture (2016). His research aims to analyse the urban growth experienced in the third quarter of the 20th century in medium-sized cities from a heritage perspective. He has received several prizes such as the Urbanism and Architecture Biennale Research Award (2016) and the Young Researcher TechnoHeritage Award (2019).

Blanca del Espino Hidalgo
blanca.espino@juntadeandalucia.es
Andalusian Institute of Historical Heritage

Is a full-time PhD Researcher at the Andalusian Institute of Historical Heritage, Centre of Built Heritage, Department of Projects. She holds a PhD in Architecture (2015), a MSC in Heritage and Architecture (2011) and a MSC in Sustainable Cities and Architecture (2013). She has been a pre-doctoral and post-doctoral researcher and assistant professor at the University of Seville (Spain). Her research is focused on cultural heritage sustainability, mainly on urban and territorial dimensions, including landscape and social components.

Juan-Andrés Rodríguez-Lora
jrodriguez91@us.es
University of Seville (Spain)

Predoctoral Researcher at the Urban and Regional Planning Department of the University of Seville (Spain). He holds a Degree in Architecture (2016), a MSc in Heritage and Architecture (2018) and is currently studying a MSc in Urbanism, Urban Planning and Urban Design (2020). His research focuses on contemporary heritage preservation from an urban perspective. He has received several awards, such as the Extraordinary Degree Award (2016).



Teresa Pérez-Cano
tpcano@us.es
University of Seville (Spain)

Is a full-time Professor at the Urban and Regional Planning Department of the University of Seville (Spain) since 1995. Permanently collaborating with several Master and Doctorate programmes, she has been the director of more than 29 doctoral theses. Co-founder and director of the research group HUM-700 Heritage and Urban and Territorial Development in Andalusia. Focused on urban planning preservation, the group has conducted several types of research, urban plans, and professional advisory on classed buildings, monuments, historic centres, and landscapes. She has leaded several R&D projects on medium-sized cities in Andalusia

https://doi.org/10.37558/gec.v17i1.754

Ge-conservación
Conservação | Conservation

Heritage monitoring and surveillance using Sentinel satellite data in the Lower Alentejo (Portugal)

Steffan Davies, Martino Correia, Ricardo Cabral

Abstract: In this article, the potential of Satellite Remote Sensing (SRS) for large-scale monitoring of archaeological sites is analysed. This analysis focuses on the Portuguese Lower Alentejo region, where multiple sites have been destroyed over the last years, mainly due to intensive agriculture. The development of a surveillance system based on data from the Sentinel 1 and Sentinel 2 satellite constellations, named SENSEOS, had its pilot application in this region during the first half of 2019. In a vast region where authorities lacked the proper resources to timely detect events endangering the integrity of heritage sites, this system tried to overcome these issues. By using Synthetic Aperture Radar (SAR) and optical data, it was possible to detect such events through a technique labelled Normalized Difference Amplitude Index (NDAI). The identification of these changes on the surface, associated with potentially destructive events, contributed to minimize the damage and destruction of archaeological sites..

Keywords: sentinel, satellite remote sensing, heritage monitoring, archaeological site preservation, NDAI, amplitude index change detection, archaeology

Monitorización y vigilancia del patrimonio utilizando datos de satélite Sentinel en el Bajo Alentejo (Portugal)

Resumen: Se analiza el potencial de la teledetección satelital para monitoreo a gran escala de sitios arqueológicos. Este análisis se centra en la región portuguesa del Bajo Alentejo, donde se han destruido múltiples sitios en los últimos años debido a la agricultura intensiva. El desarrollo de un sistema de vigilancia basado en datos de las constelaciones de satélites Sentinel 1 y Sentinel 2, SENSEOS, tuvo su aplicación piloto en esta región durante el primer semestre de 2019. En una región donde las autoridades carecían de los recursos adecuados para detectar eventos a tiempo, poniendo en peligro la integridad de los sitios, este sistema intentó superar estos problemas. El uso de radar de apertura sintética (SAR) y datos ópticos permitió detectar eventos a través de una técnica denominada Índice de Diferencia Normalizada de Amplitud (NDAI), identificando cambios en la superficie asociados con eventos destructivos y minimizando la destrucción de los sitios arqueológicos.

Palabras clave: sentinel, teledetección por satélite, monitorización del património, preservación de sitios arqueológicos, NDAI, detección de cambio de índice de amplitud, arqueología

---

Introduction

This study was developed in the scope of a partnership between the Research Centre for Archaeology, Arts and Heritage Sciences of the University of Coimbra (CEAACP) and THEIA, a university spin-off company. The European Space Agency provided funding for this project through the Business Incubation Centre (ESA-BIC), with an incubation period at ESA-BIC Portugal between September 2017 and August 2019. The project resulted in the creation of a satellite monitoring and early warning system for archaeological heritage, called SENSEOS. The team has been developing the SENSEOS project as a pilot programme with two Portuguese public authorities, the Regional Department of Culture of Alentejo (DRCAlentejo), and the Regional Department of Culture of Algarve (DRCAlgarve), in order to assess the benefit of implementing an early warning system based on satellite remote sensing. The project has been monitoring 1396 archaeological sites in the Alentejo region, and 5 in Algarve. Every 6 days, all parties receive a report and, in the event of potential hazard, a risk map with observations or further interpretation is provided, if necessary. In order to share the results our data processing, SENSEOS project includes a WebGIS platform containing all the information, including archaeological site locations and their associated risk level.

The use of satellite remote sensing and Synthetic Aperture Radar (SAR) in the field of archaeology is not a recent phenomenon. While the technology is related to the popular Ground-penetrating Radar used widely in archaeology for non-invasive prospection (Conyers 2006), it differs in the fact that it offers a much larger field of view in exchange for image definition and visible features, while offering a much lower cost and completely remote approach. The first SRS studies applied to archaeology were published in the second half of the 1970s, and the first archaeological studies using SRS were published in the beginning of the 1980s, but the low resolution of the Landsat 1 satellite restricted their potential to the identification and study of paleolandscapes (Parcak 2009: 22). The same time period applies to the use of SAR systems in archaeological research, which were installed on aircraft and used for the study of anthropic landscapes where aerial photography proved to be unreliable (Adams, Brown, Culbert 1981). It was later during the 21st century that news applications of SRS applied to archaeology started to take form, in large part due to the increase in resolution of optical sensors such as Quickbird II, which allowed for an approach of SRS as a tool for archaeological prospection (Lasaponara & Masini 2005) as the resolution slowly approached that of aerial photography. SRS as a tool for heritage conservation and protection is the most recent of SRS developments in archaeology, enabled by the use of very high-resolution SAR sensors. One example of such an approach was applied in the city of Homs in Syria, which analysed the damage to public infrastructure and heritage caused by the armed conflict in the area (Tapete *et. al.* 2015). The study presented in this article represents a continuation of this last approach of using SRS as a method of identifying and preventing damage to heritage sites.

The main area of interest for this study is the Alentejo region in the South of Portugal, focusing on the Lower Alentejo area. Alentejo has a geographical extension of 31,551.2 $km^{2,}$ corresponding to approximately one third of the country's landmass. It is also home to thousands of archaeological sites and features, with 1064 documented sites in the municipality of Beja alone. The landscape of the Alentejo region, of a rural and agricultural nature, has been changing at a rapid pace, due to the substitution of cereal based crops and dryland farming with intensive plantations of, mainly, olive and almond groves. New sources of water, supplied through the construction of dams and the Alqueva irrigation system, have enabled this process to take place (Morgado 2019). Despite the economic and agricultural benefits of this development, great concern has been placed on the possible consequences it might have on public health and the environment (Lusa 2019). The new availability of water for the purpose of irrigation has led to the introduction of more profitable crop species that require the intervention of highly mechanized procedures. The conversion of dryland fields into intensive olive and almond groves relies on the use of these types of mechanized invasive methods for soil revolution, involving practices such as deep ploughing. Traditional farming practices, which rely on the use of animals or light mechanized procedures, rarely disturb deep soil layers located at a depth of more than half a metre (Dunker et. al. 1994: 38). This means that most archaeological sites have remained relatively unharmed despite being located within agricultural fields and plantations. Now, with intense mechanization of agricultural practices, the continued existence of intact archaeological sites, many of which remain unexcavated, is under a serious threat. The large extension of numerous agricultural fields, combined with the lack of labour to supervise landscape transformation adequately in critical areas containing archaeological features, presents a serious problem. In order to give an appropriate response to this situation, it is necessary to develop a system capable of quickly identifying events that threaten cultural heritage. The synoptic view of satellite images, combined with short revisit times of the Sentinel satellite constellation, could provide a solution to this problem, and have great potential as tools for continuous monitoring of large areas of interest.

Methodology

This study employed Sentinel-1 Synthetic Aperture Radar and Sentinel-2 Multispectral Data. The main advantage of radar systems like Sentinel-1 is the fact that they are capable of observing the Earth's surface in any type of weather conditions (Patel et. al., 2010, p. 244). Passive optical systems like Sentinel-2 provide information from multiple wavelengths but are highly vulnerable to clouds, which can make it impossible to view the surface under certain weather conditions. Sentinel-1's Synthetic Aperture Radar is an active sensor that provides its own source of illumination. This allows the satellite to produce an image based on its own light that returns to the sensor after being reflected from a target, in a process that is called backscatter. A number of different factors, such as surface morphology, surface characteristics, vegetation and soil humidity (Chen et. al., 2018, pp. 71-72), influence the intensity of the *backscatter*. Because agricultural practice affects all of these factors, it was hypothesized that radar data could serve as an indicator of agricultural activity in the proximity of archaeological sites. It would then be possible to use optical information as supporting data to extract further details whenever possible. The frequency of new satellite images, called revisit time, is 6 days for radar and approximately 5 days for optical data. All radar and optical data are derived from twin sister satellites (Sentinel-1A & Sentinel-1B for radar, Sentinel-2A & Sentinel-2B for optical), which have identical equipment, ensuring compatibility of image products and avoiding secondary effects and bias seen when using different systems with different resolutions when calculating indexes (Obata et al. 2012a; Obata et al. 2012b).

For this approach, we used a method we have referred to as NDAI, or Normalized Difference Amplitude Index. The way it functions is similar to the commonly used NDVI, or Normalized Difference Vegetation Index, widely employed in optical images since the 1990s (X. Zhang et al. 2006). The main difference is that instead of comparing the index between Red and Infrared pixel values (Carlson & Ripley 1997: p. 241), we compare the intensity values of radar pixels between two different acquisition dates. For this approach, we relied on the open source software environments SNAP (Sentinel Application Platform) and QGIS (Quantum Geographic Information System). Using GRD (Ground Range Detected) Sentinel-1 products, the first step is to import the dataset into the SNAP environment and apply a pre-processing workflow to calibrate and correct the data. For this process we used a similar workflow to the one presented by F. Filiponi (2019), without the need to convert the product to dB (decibel) at the end of operations, and using the stack tool instead of DEM (Digital Elevation Model) assisted co-registration (spatial alignment) of image pixels. Through SNAP, we apply Precise Orbits to allow for high precision co-registration, remove Thermal Noise and Border Noise to eliminate artifacts and noise in the backscatter signal, Calibrate to Sigma Nought to correct for incidence angle variations in backscatter and standardize images across the stack, apply noise filtering using the Lee Sigma algorithm with the default parameters to reduce speckle, correct the product geometry using the Range-Doppler Terrain Correction to remove SAR geometric distortion, and stack the results using the Create Stack tool with the Initial Offset Method option set to Product Geolocation. Using the resulting stack of images, we apply the Band Math tool to produce the NDAI products (one for each polarisation) based on the following algorithm, where ImageB and ImageA refer to the oldest and most recent image, respectively:

$$\left(\frac{\text{(ImageA-ImageB)}}{\text{(ImageA+ImageB)}}\right)$$

Optionally, and to reduce processing time in the GIS environment during the vectorisation procedure, it is advisable to filter out unwanted data through the Band Math Operator, using the following algorithm. Where $NDAI_{layer}$ is the input NDAI product and x and y are the maximum and minimum desired values (such as -0.5 and 0.5), respectively:

$$(\textit{if } NDAI_{layer} \leq x V\ NDAI_{layer} \geq y \textit{ then } NDAI_{layer} \textit{else NaN})$$

This algorithm can be understood as: "if the input NDAI layer pixel is less or equal to x or greater or equal to y, then preserve its value, otherwise reclassify as *null*". The result will filter out values regarded by the user as noise or unwanted data, which will be ignored by the vectorisation tool. The above formula reclassifies the NDAI input by maintaining pixel values that are below or equal to x or above or equal to y, and all the others in between are given a null value.

Using the Band Select tool, the NDAI products are separated from the stack and exported as GeoTIFF / BigTIFF format.

The NDAI GeoTIFF products can now be imported into QGIS. For manual inspection, the rasters are given a single band pseudocolor style based on discrete values (increments or decrements of 0.1 in a -1 to 1 range). For automated inspection, the NDAI rasters need to be reclassified based on a rules table (Table. 1) and vectorized to convert them into vector format. For reclassification, it was necessary to multiply NDAI values by 100 using the SNAP Band Math tool before exporting in order to transform the normalized values from float to integer format with two decimal places of precision (in QGIS 3.4, the GRASS 7 r.reclassify tool only worked properly with integer values). A rules table (table 1) was used to reclassify the image pixels to integer values ranging from 1 to 10.

After this process, the image is simplified and it is possible to cross the areas of interest that are defined by some type of geometry (such as buffers) with the vectorized pixels of the NDAI processing using the Select by Location tool. The output will be based on the geometric predicate (Boolean criteria) the user defines in the selection process, which in this case would be the intersect predicate (returns TRUE if the intersection between vector features does not result in an empty set).

Table 1.- Example of a rules table used for reclassifying NDAI rasters into discrete values.

-100	thru	-90	=	1	Very High Loss
-90	thru	-80	=	2	High Loss
-80	thru	-70	=	3	Medium Loss
-70	thru	-60	=	4	Low Loss
-60	thru	-50	=	5	Very Low Loss
-50	thru	50	=	6	Noise
50	thru	60	=	7	Very Low Gain
60	thru	70	=	8	Low Gain
70	thru	80	=	9	Medium Gain
80	thru	90	=	10	High Gain
90	thru	100	=	11	Very High Gain

We normalized the data in order to allow us to work within the same ranges between different periods of observation, even if the degree of changes is different between image pairs. We filtered out a portion of the resulting data close to the value of zero (in an interval such as -0.5 and 0.5) in order to remove variations caused by noise or not very significant changes on the surface. This normalized data is subsequently categorized according to the severity of changes between image pairs, in order to allow the detection of different levels of changes in the landscape that could correspond to different kind of agricultural or physical events on the surface. Ploughing, for example, could produce a different pixel value compared to events such as irrigation or germination. In order to assess if surface change may have affected the archaeological sites, the information derived from the change detection processing is crossed with geographical information of archaeological sites in the area. A buffer is created around these sites in order to define a "sensitive area", and if the buffer crosses an area with identified changes, it is added to a selection along with all the other affected elements. These can then be extracted onto a layer and exported to be displayed on Google Earth or Google Maps.

Results

—*Pisões*

The archaeological site of Pisões is a partially excavated roman *villa*, containing a complex arrangement of structures of a domestic, agricultural a funerary nature, including four mausoleums (Pereira, Soares & Soares 2013). The *villa* incorporates an advanced water supply, storage and distribution system which would have been necessary for the bathing and pool facilities, as well as the requirements for agricultural production (Serra 2008: 505). The site has suffered from a lack of maintenance that has led to its degradation over the years, despite its cultural importance (Dias 2017). Agricultural activity destroyed the unexcavated portion of the site, containing important features such as an aqueduct located underneath a water reservoir in a field to the Northeast, at an unknown date (Lemos 2018). To test our approach and to try to determine a time interval for these destructive events, a historical analysis was performed using archive imagery.

Observation of Sentinel 2 time series from 2017 shows that most of the surface transformations occurred during the second trimester of the year. Evidence that supports this observation includes the disappearance of the water reservoir in the Northeast of the excavated site, between the 5th and 15th of April 2017. This water reservoir was located in very close proximity to the roman aqueduct identified at the site. Clear images are not available from Sentinel-2 until the 15th of May 2017. At this point, there seems to have been a unification of this field plot with another one adjacent to it in East-Northeast direction that had contained a small grove. These changes are indicators of possible preparation of land for future plantation.

For radar analysis, we applied NDAI processing to Sentinel-1 satellite data. Pairs of images with a temporal baseline of approximately one month, beginning in 2014, were analysed. Of the changes verified in these images, the most intense correspond to an event of relatively high values between the 5th of October and the 4th of November 2017. Thereafter we processed the products chronologically situated between these two dates, with a temporal baseline of 6 days. Results show that the event occurred between the dates of 11th and the 17th of October 2017. Histograms of the output of NDAI processing corresponding to these dates [figure 1] show that values peak at or close to 0, indicating good quality of inputs. The area corresponding to higher value NDAI pixels fits within the boundaries of the plot and shares the same shape [figure 2]. It is not known what happened during this time, but changes in other fields could indicate agricultural activity.

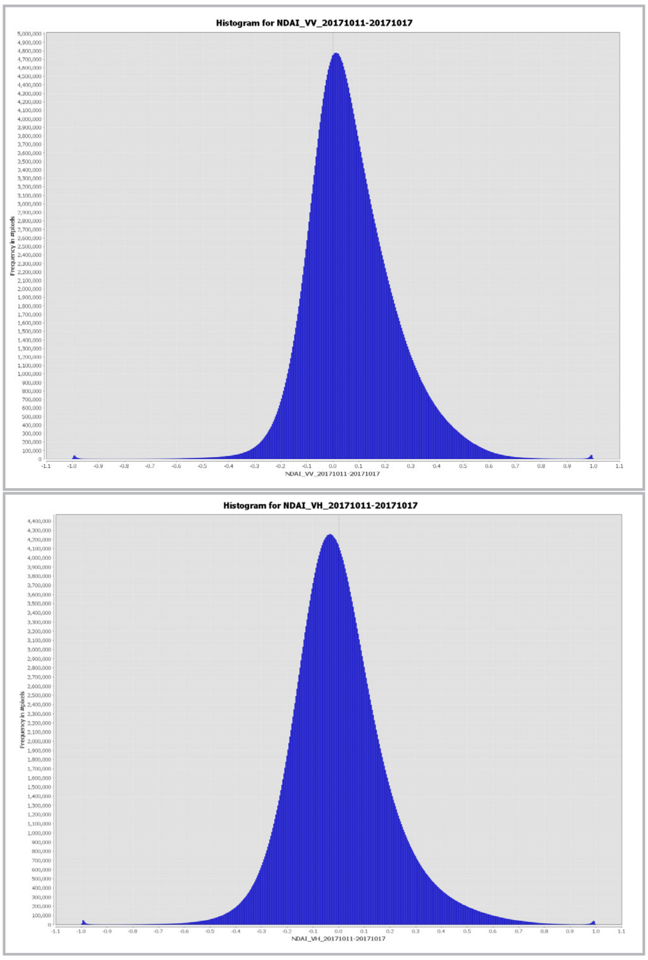


Figure 1.- NDAI Histogram for both polarizations (VV & VH) representing pixel values and pixel frequency corresponding to the dates of 11 to 17 October 2019. They peak close to the value of 0 (no change in amplitude)..

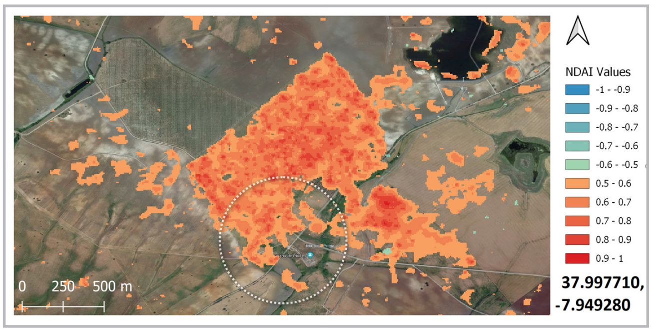


Figure 2.- Results of radar signal processing for *Pisões*, using NDAI change detection. Amplitude gain is shown as red, amplitude loss as blue. Archaeological context is within the circle.

Quinta do Estácio 10

The site called *Quinta do Estácio 10* is an archaeological context from the Roman period, located in Salvada e Quintos (Beja, Portugal). Archaeological trial trenching revealed a series of archaeological structures related to the transportation of water, as well as a concentration of archaeological materials, mostly ceramic building materials and pottery shards (Omniknos Arqueologia n.d).

Two Sentinel-1 images corresponding to the dates of the 15th and 21st of July 2019 were processed using the NDAI workflow. Histograms of NDAI results [figure 3] show that most values are equal or close to 0, indicating good quality of both input images for each polarization. The results show evident patches in the field that encloses the archaeological site and also in the field immediately to the South [figure 4]. There is the possibility that some of these spots are present due to the buildings that exist adjacent to the paths. A person was dispatched to the location in order to confirm if these results represented changes on the surface of the field where the archaeological site was located. Inspection of the site revealed intense soil mobilization including the opening of deep trenches in both perpendicular and parallel orientation in relation to the nearby river [figure 5]. Harrowing had also occurred on the site but its effects were superficial. The surplus soil that resulted from these activities was deposited in the field. Assessment of the location revealed damage to at least one of the foundations of the roman aqueduct.

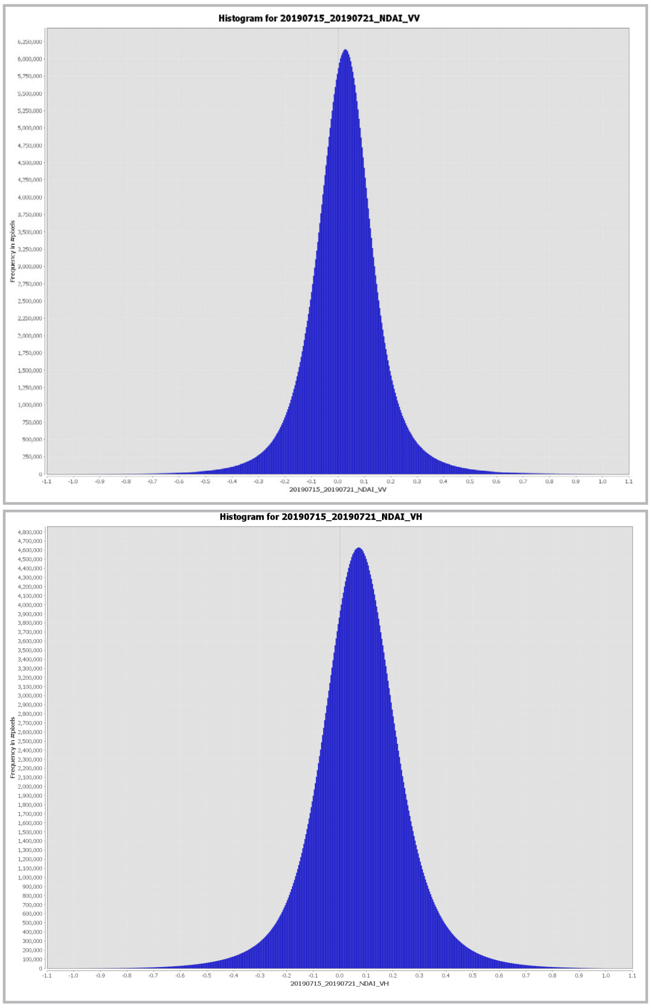


Figure 3.- NDAI Histogram for both polarizations (VV & VH) representing frequency of pixel values corresponding to the date of 15 to 21 July 2019. They peak close to the value of 0 (no change in amplitude).

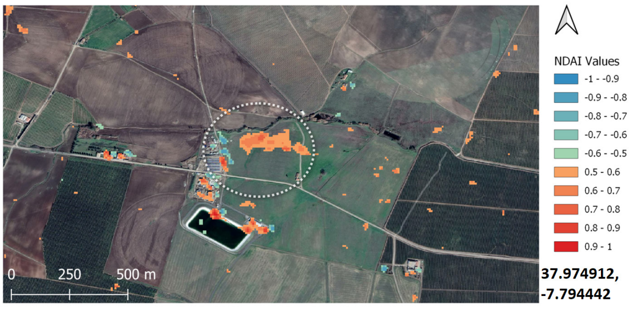


Figure 4.- Results of radar signal processing for *Quinta do Estácio 10*, using NDAI change detection. Amplitude gain is shown as red, amplitude loss as blue. Archaeological context is within the circle.

Figure 5.- Ground observation of the site of *Quinta do Estácio 10*. Photo A: Damage to archaeological features. Photo B, C, D: Different perspectives of the damage to the site

Conclusión

This work highlights one of the main advantages of satellite data applied to Archaeology, which is the ability to perform large-scale territorial analysis and monitor destructive events on thousands of sites on a weekly basis, with a potentially global application. The results of these tests have validated the possibility of using satellite remote sensing data as a tool for monitoring archaeological sites. We believe, however, that it is necessary to use this approach in conjunction with local authorities for inspection and validation of results, in order to eliminate false positives and respond swiftly to destructive events before they affect heritage sites or before further damage is done. As such we recognize this approach as a tool to be used in articulation with additional means, in a wider comprehensive strategy for heritage protection. The main advantage of this methodology is the low cost for this type of service due to the free availability of Sentinel data, low operational costs associated with remote sensing processing, and the ability to use completely open source software for data processing. This is in contrast to traditional means of surveillance, with high logistical costs, derived from the extensive use of technicians on the ground when covering very large areas. The implementation of this technique will require cooperation with the entities responsible for archaeological conservation at a national or regional level, in order to have access to the databases containing the geographical positions of identified heritage sites and to ensure a swift and appropriate response to the identified occurrences. Future developments can include the incorporation of machine learning and automated cross-correlation of information from Sentinel-1 such as phase coherence, and Sentinel-2 such as NDVI (Normalized Difference Vegetation Index) or NDWI (Normalized Difference Water Index) in order to discard false positives and identify the nature of the changes that are visible with this type of approach.

References

ADAMS, R. E. W., BROWN, W. E., CULBERT, T. P. (1981). "Radar mapping, archaeology, and ancient Maya land use.", *Science*, 213(4515): 1457-1468.

CARLSON, T. N., RIPLEY, D. A. (1997). "On the relation between NDVI, fractional vegetation cover, and leaf area index", *Remote sensing of Environment*, 62(3): 241-252.

CHEN, F., YOU, J., TANG, P., ZHOU, W., MASINI, N., LASAPONARA, R. (2018). "Unique performance of spaceborne SAR remote sensing in cultural heritage applications: Overviews and perspectives", *Archaeological Prospection*, 25(1): 71–79. https://doi.org/10.1002/arp.1591

CONYERS, L. B. (2006). "Ground-penetrating Radar for Archaeological Mapping", In: Wiseman J., El-Baz F. (eds) Remote Sensing in *Archaeology. Interdisciplinary Contributions to Archaeology*. Springer, New York, NY

DIAS, C. (2017). "Villa romana de Pisões é agora a luxuosa casa das ervas daninhas", *Público*, 17 July. https://www.publico.pt/2017/07/17/local/noticia/villa-romana-de-pisoes-foi-descoberta-ha-50-anos-e-esta-coberta-de-ervas-daninhas-1779095. [accessed: 25/10/2019].

DUNKER, R., VANCE, S., HOOKS, C., DARMODY, R. (1994). "Use of Cone Penetrometer Data to Evaluate Prime Farmland Rooting Media", *Reclamation and Revegetation*, 3: 38-47. http://doi.org/10.21000/JASMR94030038

FILIPPONI, F. (2019). "Sentinel-1 GRD Preprocessing Workflow", *Proceedings*, 18(1): 11. https://doi.org/10.3390/ECRS-3-06201

LASAPONARA, R., MASINI, N. (2005). "QuickBird-based analysis for the spatial characterization of archaeological sites: Case study of the Monte Serico medieval village", *Geophysical Research Letters*, 32(12).

LEMOS, N. (2018). "Zona envolvente à villa romana de Pisões terá sido fortemente afetada pela plantação de um olival intensivo", *Diário do Alentejo*, 29 January.

LUSA (2019). "Culturas intensivas no Alqueva geram receios que agricultores dizem infundados", *RTPNotícias,* 13 July. https://www.rtp.pt/noticias/economia/culturas-intensivas-no-alqueva-geram-receios-que-agricultores-dizem-infundados_n1160161. [accessed: 25/10/2019].

MORGADO, M. (2019). "Olival no Alentejo: a revolução agrária 4.0 à volta do Alqueva", *Sapo, 24* February. https://24.sapo.pt/economia/artigos/olival-no-alentejo-a-reforma-agraria-4-0-a-volta-do-alqueva. [accessed: 25/10/2019].

OBATA, K., MIURA, T., YOSHIOKA, H. (2012). "Comparison of scaling effects in fraction of vegetation cover between algorithms based on linear mixture model using VI", *2012 IEEE International Geoscience and Remote Sensing Symposium*: 1002-1005. https://doi.org/10.1109/IGARSS.2012.6350821

OBATA, K., MIURA, T., YOSHIOKA, H. (2012). "Analysis of the Scaling Effects in the Area-Averaged Fraction of Vegetation Cover Retrieved Using an NDVI-Isoline-Based Linear Mixture Model", *Remote Sens*, 4: 2156-2180. https://doi.org/10.3390/rs4072156

OMNIKNOS ARQUEOLOGIA (n.d.). "Execução do Circuito Hidráulico Baleizão - Quintos e respetivos Blocos de Rega - Quinta do Estácio 10", Field Report. https://biblioteca.edia.pt/BiblioNET/Upload/PDFS/M03406.pdf [accessed: 25/10/2019]

PARCAK, S. H. (2009). *Satellite remote sensing for archaeology*. London & New York: Routledge.

PATEL, V. M., EASLEY, G. R., HEALY JR, D. M., CHELLAPPA, R. (2010). "Compressed synthetic aperture radar", *IEEE Journal of selected topics in signal processing*, 4(2): 244-254. https://doi.org/10.1109/JSTSP.2009.2039181

GRUPO ESPAÑOL de CONSERVACIÓN
International Institute for Conservation of historic and artistic works

PEREIRA, C., SOARES, A.M.M., SOARES, R.M. (2013). "Os mausoléus da villa romana de Pisões: a morte no mundo rural romano", *Revista Portuguesa de Arqueologia*, 16: 303-321.

SERRA, M. (2008). "Novos dados para o conhecimento da Villa romana de Pisões (Beja)", *Vipasca*, 2: 503-507.

TAPETE, D., CIGNA, F., DONOGHUE, D.N. AND PHILIP, G. (2015). "Mapping changes and damages in areas of conflict: from archive C-band SAR data to new HR X-band imagery, towards the Sentinels", En *Proceedings of FRINGE'15: Advances in the Science and Applications of SAR Interferometry and Sentinel-1 InSAR Workshop*, Frascati, Italy, 23-27 March 2015, Ouwehand L., Ed., ESA Publication SP-731. https://doi.org/10.5270/Fringe2015.pp149

ZHANG, X., G. YAN, Q. LI, Z-L. LI, H. WAN, AND Z. GUO (2006). "Evaluating the fraction of vegetation cover based on NDVI spatial scale correction model.", *International Journal of Remote Sensing*, 27(24): 5359-5372. https://doi.org/10.1080/01431160600658107

Author/s

Steffan Clent Ap Davies
steffan@theia.pt
THEIA; CEAACP Coimbra, Portugal

Steffan Davies holds a Licentiate degree in Archaeology and a Master's degree in Archaeology and Territory, with a specialization in Archaeogeography, both by the University of Coimbra (Portugal). He is a researcher in the Centre of Studies in Archaeology, Arts and Heritage Sciences of the University of Coimbra (CEAACP), and is currently working at the Portuguese company THEIA in Research and Development, in fields such as Satellite Remote Sensing, Computer Programming., Virtual Reality and Digital Heritage.

Martino Correia
martino@theia.pt
THEIA; CEAACP Coimbra, Portugal

Martino Correia has graduate in "Archaeology and History" by the University of Coimbra (Portugal), with a Master's degree in "Archaeology and Territory" by the same University and a post-graduation in "European Heritage, Digital Media and the Information Society" carried out at the Universities of Coimbra and Salento (Lecce, Italy). He is a researcher in the Centre of Studies in Archaeology, Arts and Heritage Sciences of the University of Coimbra and was an Invited Assistant Professor at the Higher School of Education of Coimbra. He is also co-founder and managing-partner of the company THEIA, which works on the application of digital and technological solution to Archaeology and Cultural Heritage.

Ricardo Cabral
ricardo@theia.pt
THEIA; CEAACP Coimbra, Portugal

Ricardo Cabral holds a Licentiate Degree in Archaeology and History and is currently a PhD Candidate in Archaeology at the University of Coimbra. Between 2010 and 2019 he was an Invited Assistant Professor at the Faculty of Letters of the University of Coimbra. He is currently a researcher at the Centre of Studies in Archaeology, Arts and Heritage Sciences of the University of Coimbra, conducting research in Near Eastern Archaeology, where he coordinates the Kani Shaie Archaeological Project (Iraq) and participates in the Iraq Emergency Heritage Management Training Scheme, a British Museum project. He is also co-founder and managing-partner of the company THEIA, which works on the application of digital and technological solution to Archaeology and Cultural Heritage.

https://doi.org/10.37558/gec.v17i1.755

Ge-conservación
Conservação | Conservation

The performance of shelters for the conservation of archaeological sites in dry and warm climates: the case of Complutum

Cristina Cabello Briones

Abstract: Excavated archaeological sites are frequently exposed to damaging environmental conditions, which could lead to rapid decay especially for vulnerable heritage such as mosaics. One of the most common solutions is the construction of shelters; however, some may not behave as expected, either because they do not protect adequately or induce decay. An environmental monitoring programme was undertaken inside and outside the two types of shelters at the Roman archaeological site of Complutum (Alcala de Henares, Spain) from May to September in 2018 and 2019. Hourly temperature and relative humidity readings collected by data loggers, together with rainfall data from a local meteorological station, have been comparatively assessed to better understand the consequences of sheltering in dry and warm areas. The results indicate that both shelters are avoiding further decay by keeping a more stable environment in relation to outside, although the more enclosed structure would be the most suitable one.

Keywords: Preventive conservation, built heritage, archaeological remains, covers, environmental monitoring, temperature, relative humidity

El comportamiento de las cubiertas para la conservación de yacimientos arqueológicos en climas secos y cálidos: el caso de Complutum

Resumen: Los yacimientos arqueológicos excavados se exponen frecuentemente a condiciones ambientales dañinas, que pueden llevar a un rápido deterioro especialmente en el patrimonio vulnerable como los mosaicos. Una de las soluciones más comunes es la construcción de cubiertas; sin embargo, algunas pueden no comportarse como se esperaba, bien porque no protegen adecuadamente bien provocan daño. Se ha realizado un programa de monitoreo ambiental dentro y fuera de los dos tipos de cubiertas del yacimiento arqueológico romano de Complutum (Alcalá de Henares, España) desde Mayo a Septiembre del 2018 y 2019. Las lecturas de temperatura y humedad relativa recogidas cada hora por data loggers, junto con los datos de precipitación de una estación meteorológica local, se han evaluado comparativamente para entender mejor las consecuencias de cubrir en áreas secas y cálidas. Los resultados indican que ambas cubiertas están evitando futuro deterioro al mantener un ambiente más estable en relación con el exterior, aunque la estructura más cerrada sería la más adecuada.

Palabras clave: Conservación preventiva, patrimonio construido, restos arqueológicos, cubiertas, monitoreo ambiental, temperatura, humedad relativa

Introduction

Archaeological excavations imply uncovering the remains; therefore, affect the conservation of both delicate features and archaeological sections (Barrio Martín 2012). Shelters have been largely used as preservation strategies for exposed archaeological sites because, as opposed to other sys-tems such as backfilling, provide with protection and the possibility of still visiting the site during ongoing excavations (Roby 2006). Their main purpose is to act as barriers (Doehne and Price 2010), thus avoiding the rain and reducing, consequently, the moisture content in porous inorganic materials, which primarily composed the archaeological remains that are left *in situ*. Shelters can also stabilize the environmental conditions for long-term conservation; however, if not properly built, they may not provide protection or even induce decay on the remains by, for example, modifying microclimatic parameters and favouring salt crystallization or biocolonisation (Aslan 1997; Cabello Briones 2018). In those situations, improvements should be made, and the possibility of dismantling the shelters considered (Curteis 2018). The evaluation of existing covers must take place regularly to corroborate their protective function and the presentation of results from individual cases, which in general is still very limited, offers significant contributions to current discussions, such as the suitability of the shelter design (Pesaresi and Stewart 2018).

Complutum (40° 28' 26.146" N, 3° 23' 16.49" W) is a Roman archaeological site part of the historic precinct of the modern city of *Alcala de Henares* (Comunidad de Madrid, Spain) [figure 1]. The site, which main construction materials are rammed earth, masonry and brick, is decorated with mural paintings and mosaics. Complutum was declared of cultural interest under the Spanish legislation in 1992, which implies the maximum protection, and included in the UNESCO World Heritage list in 1999. *Alcalá de Henares*, located in the centre of the Iberian Peninsula, is defined as a cold semi-arid climate (BSk) according to the Köppen-Geiger classification. This area is characterised by relatively wet winters, but mainly hot and dry summers. This is important as the climatic location of a site conditions the decay mechanisms (Cabello Briones and Viles 2017).

Currently, there are two areas of the site covered with shelters: the House of Hippolytus and the House of the Griffins [figure 2]. A summary of the construction details is presented in table 1. The House of Hippolytus is a more enclosed structure while the other one, built later in time, is in line with the worldwide tendency of building shelters without lateral claddings (Cabello Briones 2016). A major difference between enclosed and open shelters is that the second ones are usually lighter structures that avoid deep foundations and the subsequent possibility of decay for the unexcavated archaeological remains.

At the start of the study, the conservation state of the ruins inside the shelters at Complutum was identified as stable by visual surveying [figure 3]. This could be related to the regular maintenance carried out by the Archaeological Service in charge of the site since the construction of the shelters. This includes, among other actions, a monthly cleaning of surfaces, and the application of biocides (octyl- isotiazol and aluminium salts) and consolidates (ethyl silicate) at least once per year (Argea Consultores 2017). Conversely, there are relevant signs of long-term and recent decay outside the shelters, mainly in the form of physical and biological deterioration, which indicate that these types of weathering would also affect the covered areas if left exposed.

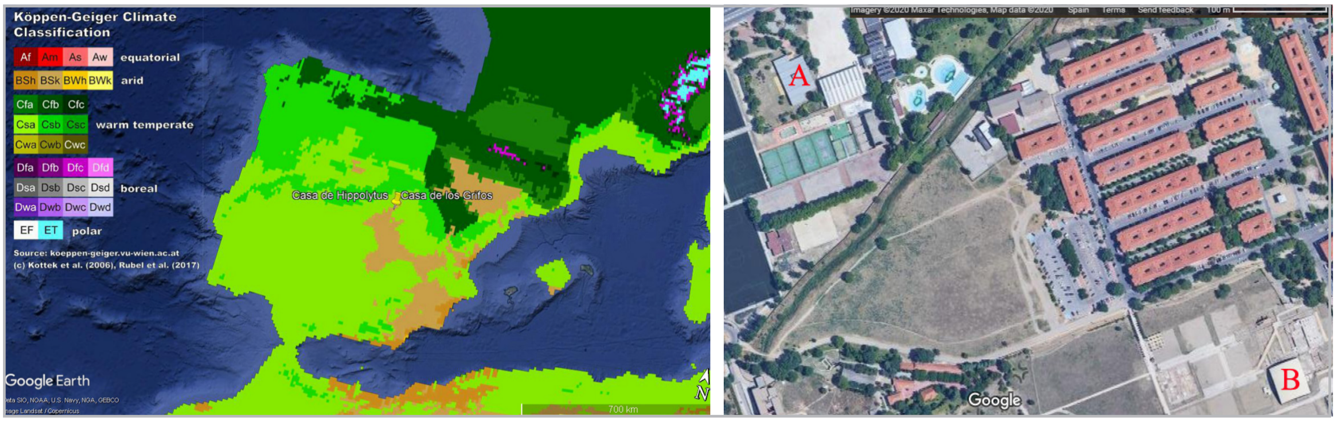


Figure 1.- Geographical location of the site with the Köppen climate classification (left), and an aerial view of the House of Hippolytus (A) and the House of the Griffins (B) (right)

Figure 2.- The shelters at the House of Hippolytus (left) and the House of the Griffins (right) viewed from outside (Photos: C. Cabello Briones)

Table 1.- Comparative between the House of Hippolytus and the House of the Griffins in terms of construction characteristics

	House of Hippolytus	*House of the Griffins*
Year of construction	1999	2011
Covering area	1318 m2 approx.	1300 m2 approx.
Type of shelter	Partially enclosed shelter	Semi open shelter
Description	Enclosure with strip footings and load bearing walls	Dome-shape steel structure with reduced lateral cladding
Construction materials	Cover: galvanized steel sheets in the outer part and hydrophobic agglomerate wooden boards in the inner part. Walls: galvanised expanded metal meshes in the upper part and bricks in the lower part.	Cover: sandwich system of pre-coated steel sheets and 90 mm fiberglass panels. Lateral claddings (hanging from the structure without touching the floor): galvanised expanded metal meshes in the upper part and 1 mm galvanized corrugated sheets.
Architects	Juan Pablo Rodríguez Frade	Pablo Latorre González-Moro and Leandro Cámara Muñoz
References	Rodríguez Frade 2001	Sánchez Montes & Rascón Marqués 2012

Figure 3.- View from inside of the House of Hippolytus (left) and the House of the Griffins (middle), and a detail of the remains located at the House of Mars (right), exposed without covering (Photos: C. Cabello Briones)

It is generally agreed that visual surveys are necessary in order to have an initial understanding of the possible problems affecting a site but the complexity related to the great variety of materials, restoration treatments and condition states of the remains makes them unreliable for an objective comparison. Therefore, in-depth evaluation of the shelters should also imply a monitoring programme over a representative period of time (Pesaresi and Stewart 2018).

Most of the environmental assessments on shelters have studied temperature and relative humidity (RH) (Demas 2013). These variables are involved in wetting and drying events, salt crystallization, biological attack, and hygric and thermal expansion and contraction of building materials and structures (Torraca 2009), which are the mechanisms highly responsible for the decay at exposed archaeological sites (Curteis 2018).

A temperature and RH monitoring, together with a study on rainfall, is especially useful for dry and warm climates, characterised by intense solar radiation, which in the case of central Spain can reach a mean daily of 16MJ/m^2, and sometimes short but intense rain spells (De Castro et al. 2005). Building materials under solar radiation absorb energy during the day, which result in expansion, while at night, contract and release infrared radiation. Thermal cycles, which include both diurnal and seasonal, cause stresses due to the repetitive changes of dimensions, especially in materials with anisotropic thermal behaviours or with different thermal expansion coefficients (Torraca 2009). In addition, high surface temperatures result in a faster drying, which reduces the risk for biocolonisation but favours the crystallization of salts already present in the ruins. Therefore, frequent wet/dry cycling lead to differential stresses, which could induce cracking, detachment or flaking (Doehne and Price 2010).

An environmental assessment primarily based on temperature and relative humidity readings outside and inside the shelters at Complutum has been undertaken during two consecutive years. The data from the warmest months have been comparatively assessed to determine if the shelters are providing adequate conditions for the preservation of the archaeological remains. The results will help to better understand the consequences of sheltering in dry and warm areas, and establish which type of shelter could be the most suitable option in that case.

Research methods

This study presents the results of an environmental monitoring programme of four months per year (from 17th May to 17th September) in 2018 and 2019. The research was undertaking using small data loggers (Lascar Electronics, accuracy= 0.55 °C, 2.25%RH), synchronised to provide with hourly air temperature and RH values, and based on the method used by Cabello Briones (2017). Inside the two shelters, the loggers were placed just under the centre of the cover to obtain representative data of the most protected areas. They were deposited on the top of site columns to avoid losing information by vandalism or perturbing the visitors of the site, which remained open during the monitoring time. Another logger was located outside the House of the Griffins also over a pillar, but in this case, this corresponds to a reconstructed vertical section of the site. For information about precipitation and climatic trends in the area, data was provided by a nearby meteorological station (Red de Calidad del Aire de la Comunidad de Madrid, CAM code 28005002).

Non-parametric Mann-Whitney-Wilcoxon tests were undertaken to compare daily means and standards deviations of temperature and RH. This allowed determining if there were statically significant differences among the studied locations.

Results

—Temperature

Alcalá de Henares is included in the cold semi-arid regime [figure 1], which implies that annual mean temperatures are below 18 ºC. In 2018, the mean temperature was 14.63 ºC, slightly lower than the next year, 15.22 ºC. However, temperatures from just the monitoring period [table 2] keep this site closer to the Mediterranean climate (Csa classification), characterised by extremely dry summers and mean temperatures in the hottest months above 22 ºC (Agencia Estatal de Meteorología 2011).

The hottest months corresponded to August 2018 (max T outside =41.50 ºC) and July 2019 (max T outside =43

Table 2.- Mean temperatures and standard deviations (ºC) outside, and inside the shelters at the House of the Griffins and Hippolytus from May to September 2018 and 2019

		2018			*2019*	
	House of the Griffins	***Outside***	***House of Hippolytus***	***House of the Griffins***	***Outside***	***House of Hippolytus***
May	18.39 (3.24)	18.73 (4.16)	17.96 (2.79)	19.36 (4.80)	19.94 (4.82)	19.04 (4.23)
June	22.49 (5.76)	22.83 (6.31)	22.01 (5.41)	24.55 (5.72)	25.22 (7.66)	24.28 (5.26)
July	26.53 (4.21)	26.65 (4.47)	25.98 (3.71)	28.59 (4.48)	29.60 (4.96)	28.32 (3.95)
August	27.81 (4.54)	28.70 (4.93)	27.18 (3.98)	26.56 (4.61)	27.46 (4.61)	26.28 (4.11)
September	24.48 (4.00)	26.57 (6.12)	23.72 (3.21)	25.26 (4.27)	27.54 (5.01)	24.82 (3.50)

ºC). The number of times the outer temperature exceed 35 ºC during those months was 65 in August (8.74% of total readings for this month) and 119 in July (15.19%). However, high temperatures were also very frequently recorded inside the House of the Griffins: 43 for August 2018 (5.78%) and 55 for July 2019 (7.39%). While the number was considerably reduced inside the House of Hippolytus: 21 (2.82%) and 28 (3.76%) for those months.

Statistical tests on daily mean temperatures certified that temperature outside was significantly warmer than inside both shelters in 2018 and 2019. On the other hand, higher mean temperatures were recorded systematically inside the House of the Griffins in comparison with the other cover ($U=7750$, p-value $< 2.2e^{-16}$ for 2018, and $U=5379.5$, p-value $= 8.2e^{-14}$ for 2019).

In addition to extreme temperature values, another key element in the decay of archaeological sites is the extent of the diurnal differences between maximum and minimum temperatures [table 3], which are associated with solar heating and night cooling events. The greatest diurnal variances were recorded outside, but if both shelters are compared, the data obtained from the House of Hippolytus indicate that this shelter is performing more efficiently, minimising the temperature range.

These differences are clearly seen in the representation of the hourly means of temperature in August 2018 and July 2019, which were the warmest months of the monitoring period [figure 4]. These graphs also show when the minimum and maximum temperatures are reached. From sunrise (at 7:25 in average in August and 6:57 in July), temperatures increase steadily mainly outside of the shelters. On the contrary, the covers avoid direct sunlight on the ruins and keep the inner temperatures lower in relation to outside. However, after sunset (at around 21:42 in August and 21:10 in July), temperatures inside both shelters are slightly higher than outside, revealing a reduced greenhouse effect. The shelters probably limit the transmission to the sky of the IR radiation emitted to the ruins by night, and cause an increase in the temperature inside (Torraca 2009).

Table 3.- Monthly means and standard deviations (ºC) of the daily temperature differences (Tmax-Tmin) outside, and inside the shelters at the House of the Griffins and Hippolytus from May to September 2018 and 2019

		2018			*2019*	
	House of the Griffins	***Outside***	***House of Hippolytus***	***House of the Griffins***	***Outside***	***House of Hippolytus***
May	8.43 (2.33)	10.87 (2.41)	6.77 (1.87)	11.57 (3.71)	11.60 (3.22)	9.50 (2.90)
June	10.22 (2.99)	11.55 (2.35)	8.37 (2.51)	11.60 (2.77)	14.43 (7.89)	9.42 (1.87)
July	12.08 (1.94)	12.35 (1.76)	9.92 (1.54)	12.24 (2.41)	15.71 (6.54)	9.98 (2.22)
August	12.98 (1.80)	13.47 (2.00)	10.00 (1.47)	13.11 (3.07)	13.10 (3.35)	10.21 (1.86)
September	12.00 (2.73)	15.68 (5.91)	7.62 (1.53)	12.75 (3.66)	15.63 (3.71)	9.63 (1.93)

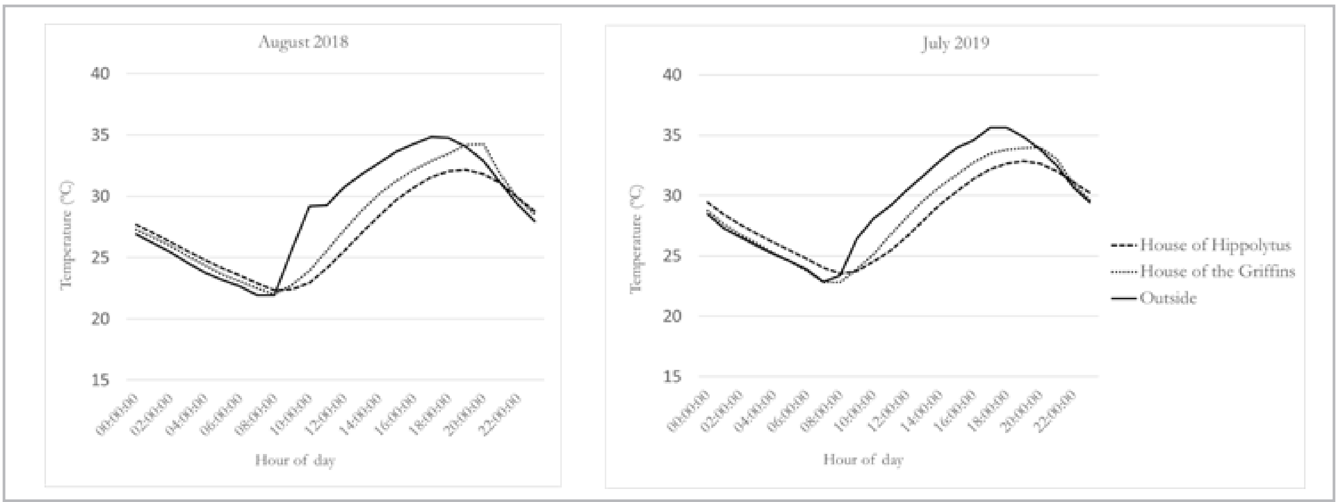


Figure 4.- Hourly means of temperature outside, and inside the shelters at the House of the Griffins and Hippolytus in August 2018 and June 2019, which corresponds to the hottest months of the monitoring programme

The thermal lag between the outdoor and indoor environment during this period was of around 3 hours if maximum temperatures are compared. The temperature peak in August 2018 and July 2019 was recorded at around 17:00 outside and 20:00 inside the shelters [figure 4], without great difference between the covers in this aspect. Together with the expected thermal inertia of the architectural remains, which time-shift and flatten out temperature fluctuations, there is a surprising increase in temperature inside the House of the Griffins around 20:00, which is associated with sunlight coming in from the west side and reaching the ruins under the central part of the shelter. Therefore, the more open structure of this shelter increases the risk of decay for the mural paintings located in that area, vulnerable to sudden heating and ultraviolet radiation (Camuffo 2019).

Additionally, the data concerning the House of the Griffins complement the one obtained by Martínez Garrido et al. (2016) between December 2014 and July 2015. In that study, it was re-corded a daily thermal lag of approximately 5 hours. More specifically, during the warmest months, the highest outdoor temperature was documented at 13:00 and the inner one at 19:00.

—Precipitation and Relative Humidity

The total rainfall in Alcala de Henares from May 2018 to 2019 was 398.60 mm, which confirms that this is a region with a low precipitation rate. In addition, the 70% of the annual precipitation was collected in autumn and winter, so this area can be also classified by its dry summers (Agencia Estatal de Meteorología 2011). Specifically, between May and September 2018, it was recorded 134.50 mm, and 100.20 mm during the same period in 2019. The maximum values of daily rainfall, 17.80 mm and 32.20 mm respectively, were logged at the end of the summer (12th September 2018 and 15th September 2019). During the second case, 21.4 l/m^2 were just collected in an hour (from 13:00 to 14:00) which indicates that around 20% of the total rainfall could concentrate in heavy events.

On the other hand, the mean RH in Alcalá de Henares was 46.16% in 2018, while 37.46% in the following year. Inside the shelters, RH values during the monitoring period were also low (below 65%), mainly in 2019 [table 4], following the annual trend.

Statistical tests on daily mean RH values showed that outside was significantly drier than inside both shelters, especially if compared with the House of Hippolytus (U= 1316.5, p-value = 1.784e^{-10} for 2018, and U= 208, p-value < 2.2e^{-16} for 2019). In addition, there were more variability on the RH data outside than inside the House of Hippolytus, which indicates that the shelter created a more stable environment in this respect. In the case of the House of the Griffins, this was only true for 2018, as there was no significant difference in relation to outside in 2019 (U= 3605, p-value = 0.14). If both shelters are compared, the House of the Griffins had higher RH fluctuations (U= 1149.5, p-value = 1.08e^{-11} for 2018, and U= 512.5, p-value = 2.2e^{-14} for 2019). Nevertheless, as Martínez-Garrido et al. (2016) sustain for the 2014-15 period, it seems for the range of RH variations that the shelter at the House of the Griffins also has a stabilising effect.

As expected for this type of climate, the RH outside drops during daytime because of the intense solar radiation. This effect is less pronounced inside the shelters although both followed the outside environment [figure 5]. Additionally, the maximum values were reached in May 2018 followed by September, so during those months there is a higher probability than RH crosses critical thresholds such as the 71% (at 20ºC) for mirabilite hydration (Viles 2005), which is considered very damaging for stone monuments (Grossi and Esbert 1994).

Table 4.- Monthly means and standard deviations of daily RH values (%) outside, and inside the shelters at the House of the Griffins and Hippolytus from May to September 2018 and 2019

		2018			*2019*	
	House of the Griffins	*Outside*	*House of Hippolytus*	*House of the Griffins*	*Outside*	*House of Hippolytus*
May	63.34 (14.85)	66.40 (21.46)	64.56 (14.26)	39.55 (11.12)	37.34 (10.57)	39.94 (9.97)
June	51.76 (16.63)	52.14 (18.80)	52.61 (16.20)	32.96 (11.14)	31.76 (12.12)	33.13 (10.51)
July	36.17 (11.10)	36.31 (11.80)	36.94 (10.93)	31.67 (9.99)	29.98 (9.79)	32.52 (9.20)
August	36.42 (11.62)	35.63 (12.84)	37.66 (11.84)	36.66 (14.62)	35.38 (14.10)	38.09 (13.95)
September	49.27 (11.62)	46.65 (16.69)	51.09 (12.05)	42.72 (9.83)	38.24 (9.57)	44.16 (9.16)

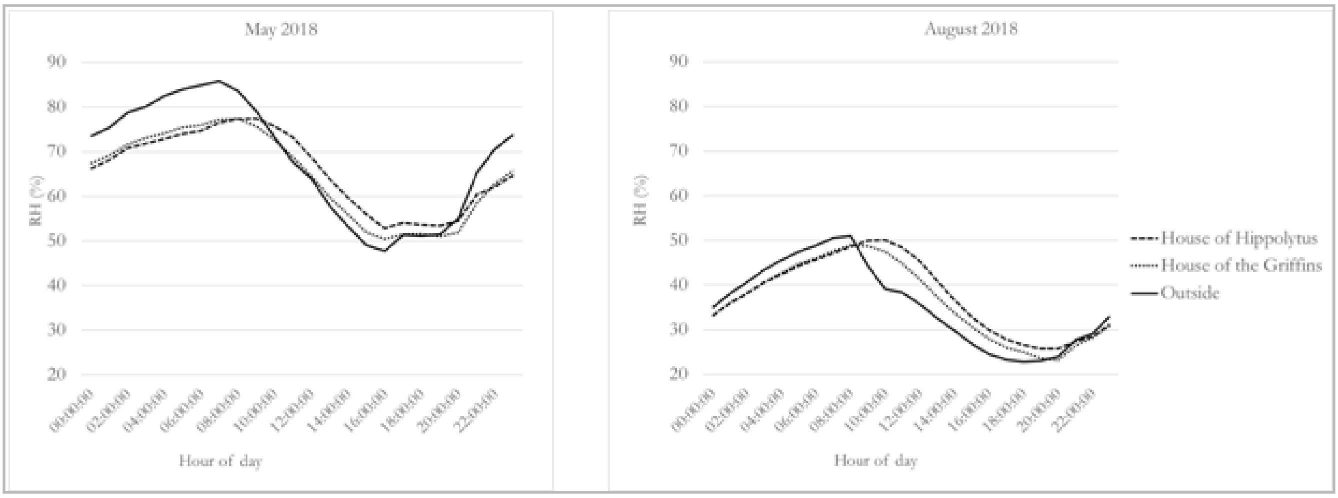


Figure 5.- :Hourly means of RH outside, and inside the shelters at the House of the Griffins and Hippolytus in May and August 2018, which corresponds to the wettest and driest months of the monitoring programme

Discussion

The data from May to September in 2018 and 2019 indicate that outside temperatures represent the most extreme values during days and nights, and shelters were found to have lower maximum temperatures and higher minimum ones in comparison to the outer environment. In addition, these conditions imply a contrasted thermal regime based on large temperature swings between day and night. However, the differences between maximum and minimum temperatures inside the sheltered areas were lower than outside, although relatively high in the House of the Griffins. Nevertheless, a diurnal temperature variance of around 12°C is probably negligible for thermal stress if compared with other studies on stone heritage (Al-Omari *et al.* 2014). Even if surface temperatures are considered equivalent to air temperatures with an approximate increase in 20°C (Bonazza et al. 2009), isolation weathering has only been found relevant for thermal cycles over 40-50°C (Lazzarini and Tabasso 1986; Viles 2005; Brimblecombe 2014) and this threshold is far from the mean temperature variations found at any of the positions in Complutum.

The climatic conditions of the area, characterised by a low precipitation rate, contribute to the dry environment found both outside and inside the shelters. A low RH (below 65% as a generally ac-cepted limit) is beneficial for the conservation of the remains as it avoids biocolonization by many species of fungi, moss or algae (Caneva *et al.* 1991). The environment inside the House of Hippolytus was slightly more humid, as previously showed by Cabello Briones and Barrio Martín (2019), but still below that limit in average.

High temperatures and dry environments favour physical deterioration, specially salt weathering, which is more intense in locations with wide diurnal temperature and RH variations (Gutiérrez Elorza 2005). In this sense, the impact of decay is reduced inside the shelters. However, the regular restoration and maintenance of the site makes it difficult to determine the exact decay mechanism in sheltered areas. The environmental data points to different patterns if compared with exposed conditions. Shorter drying periods outside due to higher temperatures and wide RH ranges could lead to salt efflorescences on the surface while salts may accumulate inside the shelters due to slower evaporation time (Dohene and Price 2010). Although a drier environment means that it is unlikely that critical salt crystallisation thresholds are reached, a further study in this matter, taking into account specific salt mixtures, is recommended.

Therefore, the results show that the environmental conditions inside both shelters mirrored the daily cycles recorded outside but the covers were able to minimise the temperature effects on the ruins reducing the peaks and subsequently the daily range. This has been additionally seen in the study of the House of the Griffins undertaken by Martínez Garrido *et al.* (2016). The explanation may well be that shelters act as a barrier blocking the solar radiation and therefore reducing heating on the remains. This is a benefit also seen in other cases (Cabello Briones, 2016) and represent a key element for warm climates with intense sun and low humidity, making this preventive conservation solution highly suitable for Mediterranean countries.

The two types of shelters built in Complutum represent different approaches towards the conservation of the Roman archaeological site. The cover at House of the Griffins is a partially open shelter while at the House of Hippolytus can be described as a partially enclosed one. If both shelters are compared, the conditions inside the House of the Griffins followed more closely the outer conditions. The more open structure and the insufficient roof insolation of this shelter could be the reason. However, the higher mean temperatures and the diurnal temperature ranges are not enough to consider an imminent damage for the remains. However, isolated temperature peaks from sunlight coming through the sides, as it happened at certain times of the day at the House of the Griffins, support the idea that an open shelter without proper lateral cladding may be a less effective solution for this climate. The deficiencies of this shelter can be related to the fact that it was originally designed as provisional.

Conclusion

The results indicate that outside the shelters there were higher temperatures, more frequent tem-perature and RH fluctuations, and greater diurnal temperature ranges. These conditions are probably the responsible of the physical decay observed in the uncovered ruins and, therefore, the archaeological remains at Complutum would be in worst state of conservation if the shelters had not been built. Therefore, both shelters are avoiding further decay by keeping a more stable environment in relation to outside, although, in sight of the results, the cover at the House of Hippolytus would be the most suitable design.

Warm and dry areas are present in around 40% of the Spanish territory (Agencia Estatal de Meteorología 2011) and other Mediterranean countries with extremely valuable archaeological heritage such as Italy and Tunisia. A partially enclosed shelter with appropriate roof insolation and without restriction of air circulation could be the key for improving shelters in those locations as long as it is able to reduce temperature and RH fluctuations and avoid temperature extremes.

Acknowledgment

The author would like to thank Dr. Joaquín Barrio, Director of the Service for Conservation, Restoration and Scientific Studies of Archaeological Heritage (SECYR-UAM) for his support, and Dr. Sebastián Rascón, Municipal Archaeologist of Alcala de Henares and manager of Complutum for allowing the study at the Roman archaeological site.

References

ARGEA CONSULTORES. (2017). *Servicio de mantenimiento arqueológico y restauración preventiva del conjunto monu-mental de la ciudad romana de Complutum y otros espacios arqueológicos de Alcalá de Henares*. Project report. Alcalá de Henares: Servicio Municipal de Arqueología.

AGENCIA ESTATAL DE METEOROLOGÍA. (2011). *Atlas climático ibérico: temperatura del aire y precipitación (1971-2000)*, Madrid: Instituto Nacional de Meteorología.

AL-OMARI, A., BRUNETAUD, X., BECK, K., AL-MUKHTAR, M. (2014). "Effect of thermal stress, condensation and freezing-thawing action on the degradation of stones on the Castle of Chambord, France", *Environmental Earth Sciences*, 71: 3977-3989. https://doi.org/10.1007/s12665-013-2782-4

ASLAN, Z. (1997). "Protective Structures for the Conservation and Presentation of Archaeological Sites", *Journal of Conservation and Museum Studies*, 3: 16-20.

BARRIO MARTÍN, J. (2012). "Nuevos enfoques y criterios de restauración y conservación del Patrimonio Arqueológico". In *Ensayos en torno al patrimonio cultural y al desarrollo sostenible en Chile y España*, Blánquez, J. *et al.* (coords.). Madrid: Universidad Autónoma, 437-454.

BONAZZA, A., SABBIONI, C., MESSINA, P., GUARALDI, C., DE NUNTIIS, P. (2009). "Climate change im-pact: Mapping thermal stress on Carrara marble in Europe", *Science of the Total Environment*, 407: 4506-4512. https://doi.org/10.1016/j.scitotenv.2009.04.008

BRIMBLECOMBE P. (2014). "Environment and Architectural Stone". In *Stone in Architecture,* Siegesmund, S. and Snethlage, R. (eds.). Berlin: Springer, 317-347. https://doi.org/10.1007/978-3-642-45155-3_5

CABELLO-BRIONES, C. (2016). *The Effects of Open Shelters on the Preservation of Limestone Remains at Archaeological Sites,* Doctoral Thesis, University of Oxford.

CABELLO-BRIONES, C. (2017). "How to evaluate shelters for archaeological sites: some recommendations based on the use of exposure trial", *Ge-conservación*, 11: 34-41. https://doi.org/10.37558/gec.v11i0.442

CABELLO-BRIONES, C., VILES, H.A. (2017). "Deterioration at Archaeological Sites in Different Climatic Locations", *International Journal of Architectural Heritage: Conservation, Analysis, and Restoration*, 11-6: 816-828. https://doi.org/10.1080/15583058.2017.1300710

CABELLO- BRIONES, C. (2018). "Descubrir para cubrir: ¿Son las cubiertas sobre yacimientos arqueológicos realmente beneficiosas?". In *¿Y después? Control y mantenimiento del Patrimonio Cultural, una opción sostenible; Proceedings of the 6th GEIIC Congress (Vitoria, 20-22 September 2018)*. Vitoria: Grupo Español del IIC, 386-390.

CABELLO-BRIONES, C., BARRIO MARTÍN, J. (2019). "Two shelters under review: Preliminary results from the Roman archaeological site of Complutum". In I*nternational Conference of IV International Congress Science and Technology for the Conservation of Cultural Heritage (Seville, 26-30 March 2019)*. Leiden: Balkema/CRC Press. https://doi.org/10.1201/9780429345470-43

CAMUFFO, D. (2019). *Microclimate for Cultural Heritage: Measurement, Risk Assessment, Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*. Amsterdam: Elsevier. https://doi.org/10.1016/C2017-0-02191-2

CANEVA, G., NUGARI, M.P., SALVADORI, O. (1991). *Biology in the Conservation of Works of Art*. Rome: ICCROM.

CURTEIS, T. (2018). "The use of environmental survey and monitoring in the design and evaluation of archaeological shelters". In *Protective shelters for archaeological sites; Proceedings of SYMPOSIUM* (Herculaneum, 23-27 September 2013). Rome: The British School: 40-50.

DE CASTRO, M.J., MARTÍN-VIDE, M., BRUNET, M. (2005). *The climate of Spain: Past, present and scenarios for the 21st century*. Madrid: Publicaciones Ministerio de Medio Ambiente.

DEMAS, M. (2013). "Protective Shelters for Archaeological Sites". In *Mosaics In Situ. An Overview of Literature on Conservation of Mosaics In Situ*, Roby, T. and Demas, M. (eds.). Los Angeles: The Getty Conservation Institute.

DOEHNE, E., PRICE, C. A. (2010). *Stone Conservation: An Overview of Current Research*, Los Angeles: The Getty Conservation Institute.

GROSSI, C.M., ESBERT, R. M. (1994). "Las sales solubles en el deterioro de rocas monumentales. Revisión bibliográfica", *Materiales de Construcción* 44 (235): 15-30.

GUTIÉRREZ ELORZA, M. (2005). "Weathering processes and resulting forms". In *Climatic Geomorphology*. Amsterdam: Elsvier, Chapter 11, 241-258.

MARTÍNEZ-GARRIDO, M.I., ERGENÇ, D., FORT, R. (2016): "Wireless monitoring to evaluate the effectiveness of roofing systems over archaeological sites", *Sensors and Actuators A*, 252: 120–133. https://doi.org/10.1016/j.sna.2016.10.038

LAZZARINI, L., TABASSO LAURENZI, M. (1986). *Il restauro della pietra*, Padova: Cedam.

PESARESI, P., STEWART, J. (2018). "Shelters evaluation, monitoring and maintenance in the context of archaeological site management". In *Protective shelters for archaeological sites; Proceedings of SYMPOSIUM (Herculaneum, 23-27 September 2013)*. Rome: The British School: 58-82.

ROBY, T. (2006). "The Conservation of Mosaics in Situ: Preserving Context and Integrity". In *Stories in Stone. Conserving Mosaics of Roman Africa. Masterpieces from the National Museums of Tunisia*, Abed, A. B. (ed.). Los Angeles: The Getty Conservation Institute: 101-114.

RODRÍGUEZ FRADE, J. P., MADARIAGA MÉNDEZ, A., RASCÓN MARQUÉS, S. (2001). "Cubierta para las ruinas arqueológicas de la Casa de Hippolytus Complutum" [Online], In *Memoria para el Premio Calidad a la Estética, Dirección General de Arquitectura y Vivienda de la Comunidad de Madrid*. http://www.madrid.org/bdccm/premios/PDF/LIBRO2001-2000/T3.pdf (Accessed November 2018).

SÁNCHEZ MONTES, A.L., RASCÓN MARQUÉS, S. (2012). "Musealización del proceso de excavación de la Casa de los Grifos (Alcalá de Henares, Madrid). La Casa de los Grifos en el contexto de los yacimientos musealizados en España". In *VIII Jornadas de Patrimonio Arqueológico en la Comunidad de Madrid, (15-16 November 2011)*. Madrid: Comunidad de Madrid.

TORRACA, G. (2009). *Lectures on Materials Science for Architectural Conservation*. Los Angeles: The Getty Con-servation Institute.

VILES, H.A. (2005). "Microclimate and weathering in the central Namib Desert, Namibia", Geomorphology, 67-2: 189-209.

Author/s

Cristina Cabello Briones
cristina.cabello@uam.es
Servicio de Conservación, Restauración y Estudios Científicos del Patrimonio Arqueológico, Universidad Autónoma de Madrid, Spain

Cristina Cabello Briones holds a PhD in Geography and the Environment from the University of Oxford. Her thesis is on the effects of open shelters on the preservation of limestone remains at archaeological sites. She also has an MA in Preventive Conservation from the University of Northumbria at Newcastle, a BA in Heritage Conservation from Escuela Superior de Conservación y Restauración de Bienes Culturales de Madrid, and a BA in Art History from Universidad Autónoma de Madrid.

https://doi.org/10.37558/gec.v17i1.756

Coberturas sostenibles en excavaciones arqueológicas. Metodología de aplicación al caso de mosaicos en el Conjunto Arqueológico de Itálica (Santiponce, Sevilla)

M. Ordóñez-Martín, J.C. Gómez de Cózar

Resumen: Es conocido que uno de los retos del trabajo arqueológico, es el de evitar o reducir los efectos del llamado "trauma de excavación", donde la modificación acelerada de condiciones higrotérmicas, junto al efecto de la radiación solar, altera las condiciones de equilibrio del objeto soterrado. Esto lleva a la necesidad de cobertura de yacimientos arqueológicos durante la excavación, realizada frecuentemente mediante sistemas fijos o desmontables más propios del mundo productivo o industrial, de alta huella ecológica, y con efecto limitado, garantizando en su mayoría únicamente situaciones de sombra. No obstante, entendemos que es posible dar una solución global desde la arquitectura a los numerosos requerimientos del objeto excavado, tales como: necesidad de coberturas con mínimos apoyos, coberturas ligeras de gran adaptabilidad a la evolución de la excavación, limitación de costes, o necesidad de control de las condiciones higrotérmicas del espacio cubierto mediante procedimientos limpios que minimicen el impacto medioambiental.

Palabras clave: Sostenibilidad, conservación preventiva, coberturas activas, excavación arqueológica, diseño paramétrico, control higrotérmico

Sustainable coverage in archaeological excavations. Methodology of application to the case of mosaics in the Archaeological Ensemble of Italica (Santiponce, Sevilla)

Abstract: One of the challenges of the archaeological work is to prevent or reduce the effects of the "excavation trauma", where the accelerated changes of hygrothermal conditions together with the effect of solar radiation, alter the equilibrium conditions of the buried object. This leads to the need for a coverage during excavation of archaeological sites which is most often performed by fixed or removable systems that come from the productive or industrial world. They have high ecological footprint and limited impact, and ensure, mostly, only shady situations. But we understand that it is possible to provide a global solution from architecture to the numerous requirements of the excavated object, such as: covering systems with minimal supports, light covers highly adaptable to excavation changes, limited budget, or the control of hygrothermal conditions of the covered space through clean procedures that minimize environmental impact.

Keywords: Sustainability, preventive conservation, active coverages, archaeological excavation, parametric design, hygrothermal control

Introducción

Es habitual entender la arquitectura de rápido montaje, como elemento accesorio en las intervenciones patrimoniales, en situaciones transitorias, como "medio auxiliar", por su cualidad de ligereza o poca materialidad. Esta visión, hace que la convivencia de esta arquitectura con el bien patrimonial sea a través de una relación de superposición. Nosotros planteamos, sin embargo, que dichas propiedades de: ligereza, transformabilidad y rápida respuesta, permiten superar el concepto de elemento accesorio, y convertirse en elementos complementarios al objeto a proteger, especialmente en situaciones transitorias, frecuentes en la actividad arqueológica. Esto puede lograrse gracias a sus cualidades de fácil desmontabilidad, reciclabilidad y escasa huella (Gómez de Cózar *et al.* 2019).

Este trabajo, pretende establecer una metodología de intervención asociada a la cobertura de yacimientos arqueológicos, dentro de la conservación preventiva de los mismos, entendiendo esta como la acción de "garantizar la conservación y el mantenimiento de los bienes culturales, aplicando todos los medios posibles externos a los mismos" (Frazzi 2002; 95-111).

En el caso del objeto excavado, la conservación preventiva supondrá las acciones necesarias para atenuar el "trauma de excavación" (Díaz Martínez 2005; 110-130). Los objetos enterrados, permanecen en un ambiente diferente para el que fueron creados, llegando con el paso del tiempo a una situación de equilibrio con las nuevas condiciones mecánicas, físicas, de exposición a luz, temperatura, humedad, microorganismos, presencia de oxígeno, etc. Al excavarse, quedan expuestos a nuevas condiciones de abundancia de oxígeno, CO_2, contaminantes del aire, acidez de lluvias, luz, oscilaciones de temperatura y humedad, etc. Estas nuevas condiciones, suponen un shock para el objeto excavado. Será pues objetivo de la intervención de conservación, evitar al máximo estos procesos de degradación, con medidas que disminuyan los desequilibrios entre el objeto y el nuevo ambiente. (Lacayo 2001;453-457).

La acción de conservación requiere conocer los factores de alteración del objeto excavado, que pueden ser de origen antrópico o ambientales (físicas, químicas o biológicas) (Giles; Bouzas; Pinto 2003).

Desde la arqueología, diversos autores coinciden en que la cobertura es la única actuación que permite la pervivencia de las estructuras y elementos que forman los yacimientos, (Díaz Martínez 2005;119), planteándose los requerimientos de sus coberturas, destacándose los siguientes:

- Intervenciones con mínimos apoyos y grandes luces.
- Solución compatible con la evolución de la excavación, realizadas por fases, con sistemas de tipo modular.
- Cubiertas parciales reversibles que supongan soluciones neutras de fácil desmontaje.
- Coberturas que no compitan con los restos a proteger, diferenciándose claramente los añadidos.
- Coberturas que garanticen una protección solar efectiva.

Objetivos de la investigación.

Teniendo en cuenta que el objetivo primordial de la intervención patrimonial, ha sido la recuperación de la materialidad y los valores del objeto a proteger, a partir de un estudio basado en la metodología pluridisciplinar (Price 1984; Carrera 2018), esta investigación, plantea los siguientes objetivos para establecer una metodología de intervención que permita dar respuesta a los requerimientos de protección de los objetos arqueológicos en proceso de excavación, garantizando unas condiciones de conservación efectivas, evitando los fenómenos de "trauma de excavación" por procesos de: heladicidad, cambios bruscos de temperatura o humedad e incidencia de radiación solar directa, y que permitan abrir dicha intervención, a acciones de interpretación.

Desde el punto de vista especifico, se plantean los siguientes objetivos:

- Uso de la arquitectura ligera y de rápido montaje como elemento no sólo de protección sino de puesta en valor del elemento patrimonial. Tal como se ha indicado anteriormente, los parámetros habituales que definen a este tipo de sistemas (Gómez de Cózar *et al.* 2017) son: capacidad de adaptación a condiciones de contorno variables, reversibilidad y mínimo impacto medioambiental, idóneos para cubrir yacimientos.
- Control ambiental del espacio cubierto durante su intervención, mediante procedimientos pasivos que no requieran energía o que ésta sea mínima y pueda obtenerse mediante fuentes renovables (Hoyano; Jiang 2009;1119-1127).
- Comprobación de la minimización del impacto medioambiental de la solución propuesta mediante herramientas de Análisis del Ciclo de Vida.

Metodología propuesta.

Para alcanzar los objetivos que definen esta aportación, se ha diseñado la siguiente metodología original que, correctamente aplicada, permitirá la intervención en cualquier yacimiento arqueológico que necesite salvaguardar una superficie inferior en condiciones higrotérmicas adecuadas:

- Análisis del yacimiento a cubrir atendiendo a la singularidad de sus restos, naturaleza, posición, geometría, planificación de excavación, potencial de lugares del suelo que pueden ser utilizados como apoyos, condiciones de temperatura y humedad anuales y estudio visual de contorno que permita plantear la posibilidad de que la cobertura permanezca una vez terminadas las tareas de excavación y/o puesta en valor.
- Desarrollo de una cubierta ligera y de rápido montaje basada en un sistema espacial de dos capas sobre mínimos apoyos. A partir de las condiciones de contorno establecidas en el punto anterior, mediante software paramétrico, determinando la geometría específica de la cubierta. Las dos capas permiten generar una cámara de aire (controlada) que posibilitará el control higrotérmico del espacio protegido. Comprobación como estructura de la cubierta para optimizar su materialidad.
- Optimización de la cobertura a partir de software de simulación numérico original, que permite simular condiciones ambientales tanto del interior del recinto como de su suelo a partir del control de la ventilación de la cámara de la envolvente.
- Análisis del Ciclo de Vida de la solución planteada, conforme a las normas ISO 14040 (UNE-EN ISO 14040 2006), ISO 14044 (UNE-EN ISO 14044 2006) y EN 15978 (UNE-EN 15978 2012), atendiendo tanto a energía incorporada como a la operacional en categoría de GWP (calentamiento global) con objeto de validar la solución de diseño. En el caso de que el impacto sea excesivo, la solución deberá reconfigurarse (geometría,

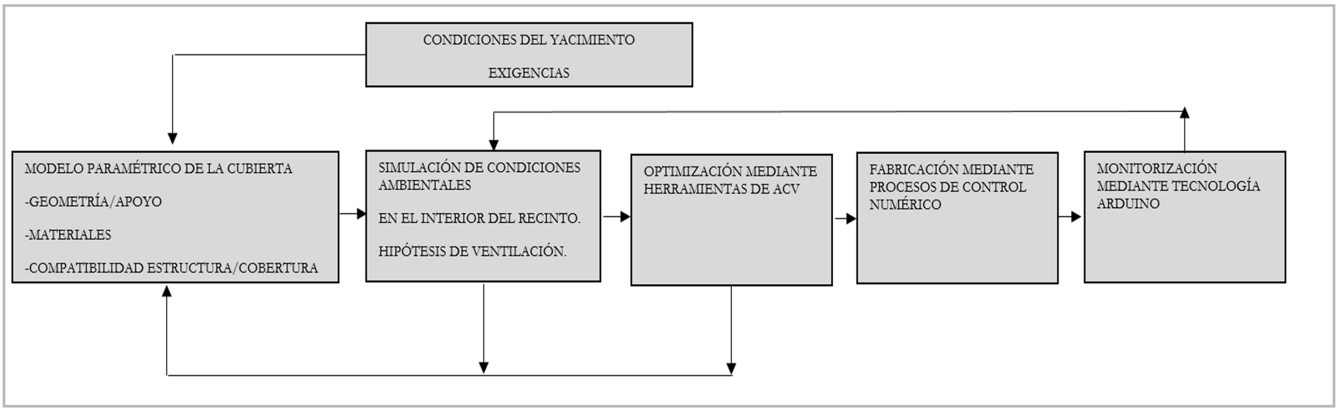


Gráfico 1.- Esquema de la metodología propuesta.

materiales y ciclos de ventilación) para minimizar su impacto.

• Fabricación de la cubierta mediante procedimientos de control numérico, permitiendo un mínimo tiempo de fabricación.

• Control in situ, mediante monitorización basada en tecnología Arduino. De este modo, el modelo numérico de simulación de las condiciones ambientales del recinto podrá calibrarse en función de las condiciones reales del recinto.

Este artículo, desarrolla la metodología descrita atendiendo a los apartados que tienen que ver con la creación paramétrica del modelo, a su simulación numérica y a su comportamiento medioambiental mediante herramientas de ACV. [gráfico 1].

Emplazamiento y estudio de condiciones de contorno

La aplicación de la metodología de estudio se aplicará como primer modelo, en un yacimiento arqueológico del sur de España, concretamente el Conjunto Arqueológico de Itálica, en la localidad de Santiponce, (Sevilla). Dicho estudio surge de las necesidades de protección de mosaicos en procesos de restauración acometidos por el Conjunto. El Plan Director del yacimiento (año 2001) prevé en el apartado de mosaicos, ante la escasez de recursos, su cobertura mediante geotextiles y arena, entendiendo que dos de los agentes generadores de mayor deterioro son los cambios de humedad y temperatura. No obstante, aboga por la implantación de cubiertas físicas en altura previo estudio paisajístico.

Por otra parte, se plantea desde el Conjunto, la idoneidad de implantación de un sistema de cobertura experimental temporal, con el fin de contrastar resultados de monitorización con actuales coberturas efímeras instaladas, cubiertas convencionales a base de estructura metálica y materiales plásticos de sombra.

El emplazamiento elegido responde, además, al estudio de las condiciones de contorno (accesibilidad, estado de conservación, perfil climático, etc.), optándose por mosaico perteneciente a la conocida como "Casa de Neptuno".

Se procederá al levantamiento planimétrico del objeto arqueológico y de su entorno, con el fin de diseñar un prototipo que responda a las condiciones de mínima huella en su instalación, así como de absoluta reversibilidad de la intervención [figura 1].

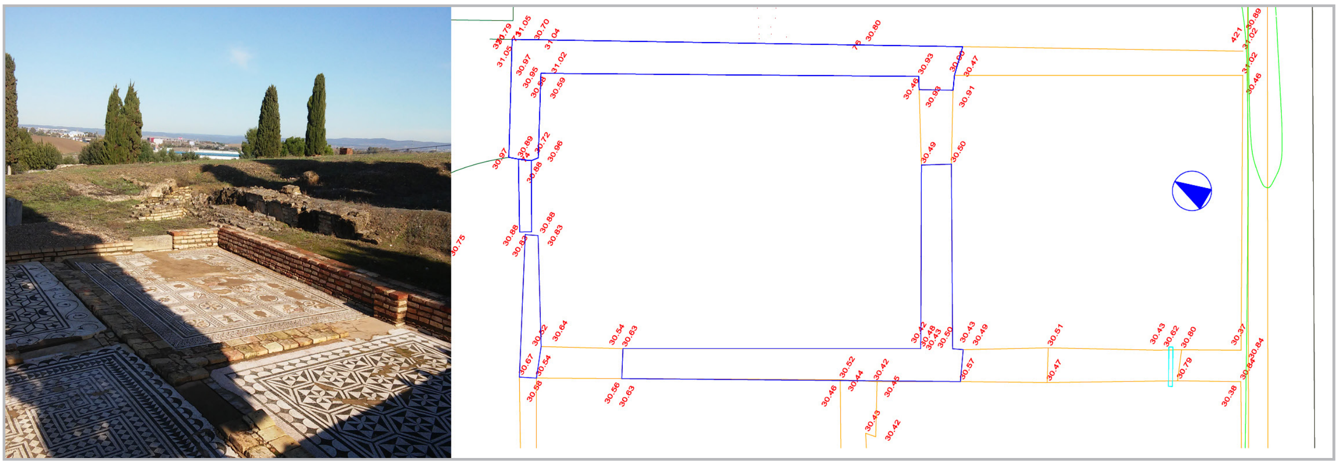


Figura 1.- Fotografía de emplazamiento y levantamiento planimétrico.

El mosaico elegido es adyacente a otros tres pertenecientes al mismo conjunto doméstico, y presenta una delimitación irregular en cuanto a la altura de arranques de muros que lo delimitan, fruto de intervenciones de consolidación realizadas. Esta situación, ligada a la topografía irregular de su entorno inmediato, condicionará la generación del modelo de cobertura.

Generación paramétrica de modelo de cubierta, comprobación estructural y fabricación mediante tecnología CNC.

Una vez definidas las condiciones de contorno, se procede a la generación del modelo geométrico de la cobertura. Para dicha generación, se emplea software original de diseño paramétrico, que permite generar geometrías ilimitadas pudiendo variar en tiempo real los diversos parámetros que las condicionan.

La herramienta de diseño permite actuar sobre los parámetros definitorios del sistema, basado en la "Patente Florín" (Gómez de Cózar; García Diéguez 2001). [figura 2].

Estos son:

• Variación del número de módulos de la malla tridimensional, generando modelos de mayor o menor extensión, adaptándose a la geometría y tamaño del área a proteger.
• Modificación del canto de la malla, lo cual permitirá adecuarse a las necesidades del yacimiento en cuanto a luz máxima entre apoyos, así como a las acciones previstas (peso propio del textil de cobertura, cargas de nieve, etc.).
• Variaciones sobre la curvatura de la malla estructural esférica, permitiendo actuar sobre la estabilidad, limitando las deformaciones, especialmente ante acciones eólicas.

Posteriormente a la generación, será necesaria la comprobación estructural de la malla y el dimensionado de las distintas barras que la componen (rombos, aspas y diagonales).

Igualmente, se deberán dimensionar los apoyos de dicha cubierta, condicionados a la geometría del terreno existente, con la premisa de ejecutar un número mínimo de apoyos, y siempre externos al objeto excavado.

Para dicho dimensionado, se emplea software de cálculo matricial espacial de mallas de barras, desarrollado por Cype Ingenieros S.A. Dicha herramienta, permite el dimensionado de las barras de la malla estructural en limitando los estados límites últimos y de servicio para materiales como acero, aluminio o madera. En el caso de estudio, se fijarán los parámetros de resistencia mecánica relativos a panel de fibras de densidad media (MDF), previendo la ejecución de barras y nudos mediante la combinación de piezas de dicho material, hasta conseguir la sección resistente necesaria. Se chequearán igualmente las deformaciones debidas especialmente a

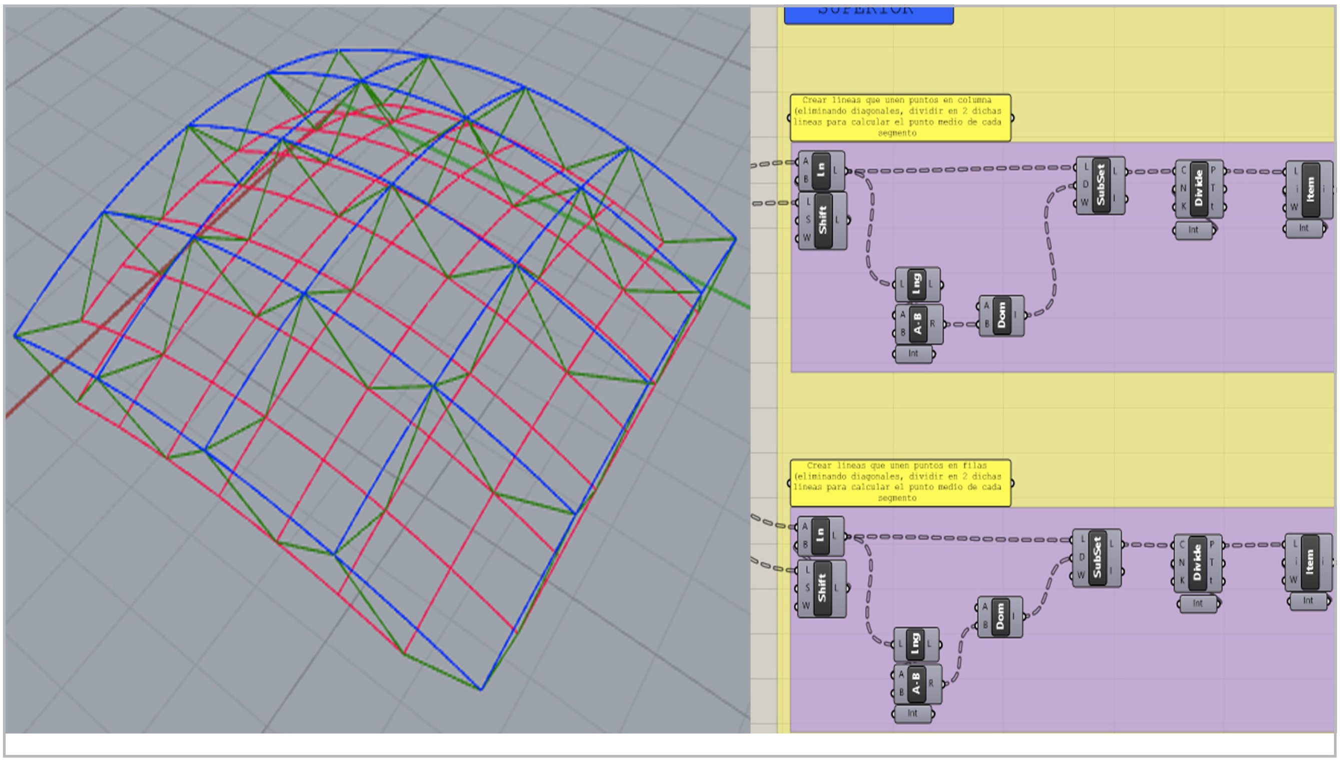


Figura 2.- Pantalla de control de parámetros de generación de la malla estructural, *Sistema Florín*, de la cubierta mediante herramienta Grasshopper.

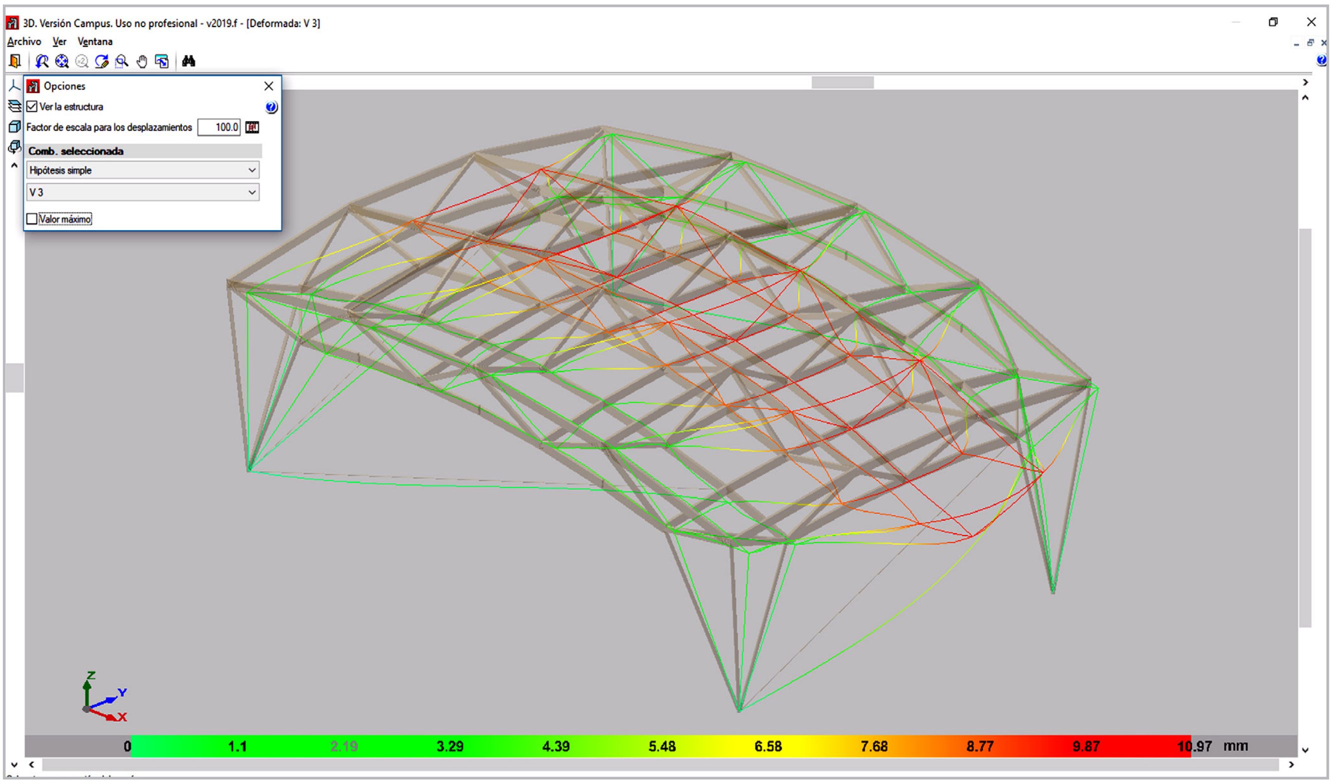


Figura 3.- Salida de resultados de software de cálculo matricial (deformada ante acción eólica).

la acción de viento, [figura 3], considerando si procede la colocación de sistemas ligeros de arriostramiento mediante atirantado, ya que se trata de un sistema de uniones articuladas, consiguiendo con ello apoyos sencillos de escasa incidencia en el suelo.

Como consecuencia del dimensionado estructural, y trasladando los resultados de secciones de barras y nudos al modelo generado paramétricamente, se contará con un modelo virtual con dimensiones reales que puede ser trasladado al sistema de fabricación correspondiente.

Para el caso de estudio, y con el fin de limitar el empleo de material en base a criterios de ligereza y mínima huella ecológica, se opta por el diseño de secciones de barras formadas por dos perfiles separados, unidos puntualmente en el centro de la luz de los mismos, consiguiendo la inercia necesaria. Para el caso de los nudos, se opta por la unión de dos piezas de forma directa atornilladas, lo cual confiere rigidez al mismo, y facilita la unión con el sistema de barras [figura 4].

Finalmente, la generación paramétrica del modelo, y la obtención de un modelo físico digital, permite la fabricación del prototipo de cubierta del yacimiento mediante sistemas de fabricación industrializados, garantizando unos cortos tiempos de fabricación con alta exactitud dimensional de los elementos. Por otra parte, permitirá el rápido trasporte y montaje del mismo, ya que se trata de sistema modular ensamblable configurado para unas condiciones de contorno concretas.

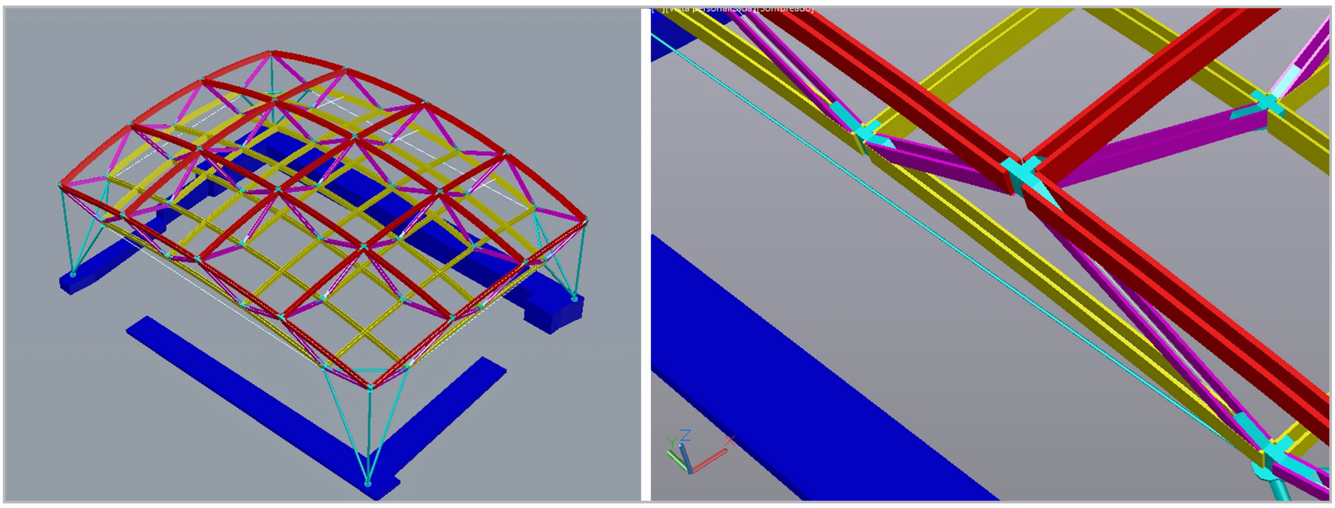


Figura 4.- Evolución del modelo alámbrico al modelo físico dimensionado.

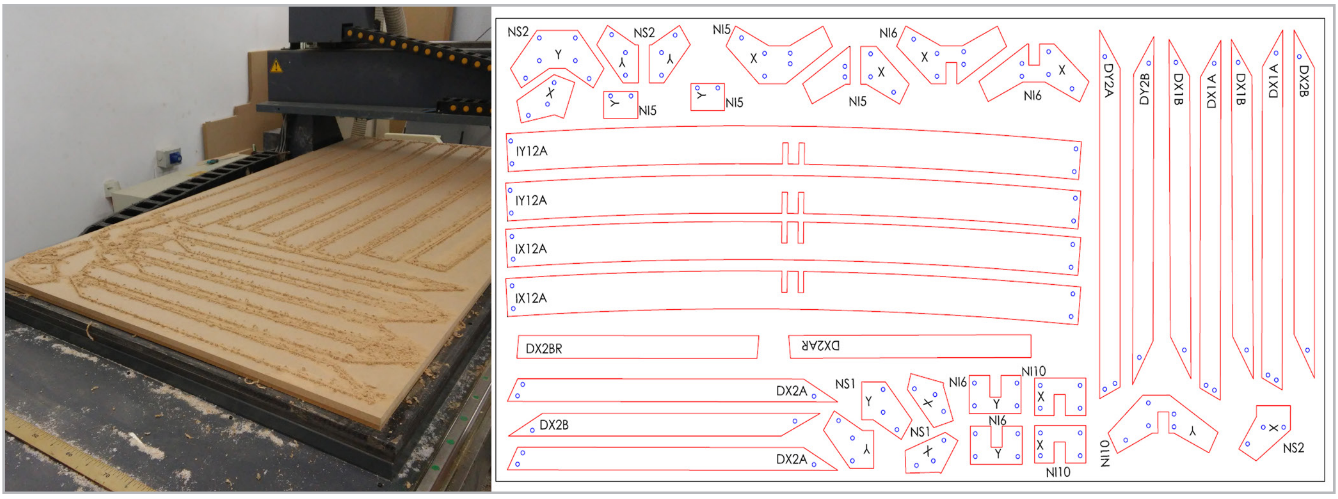


Figura 5.- Panel de despiece codificado y proceso de fabricación en fresadora de control numérico.

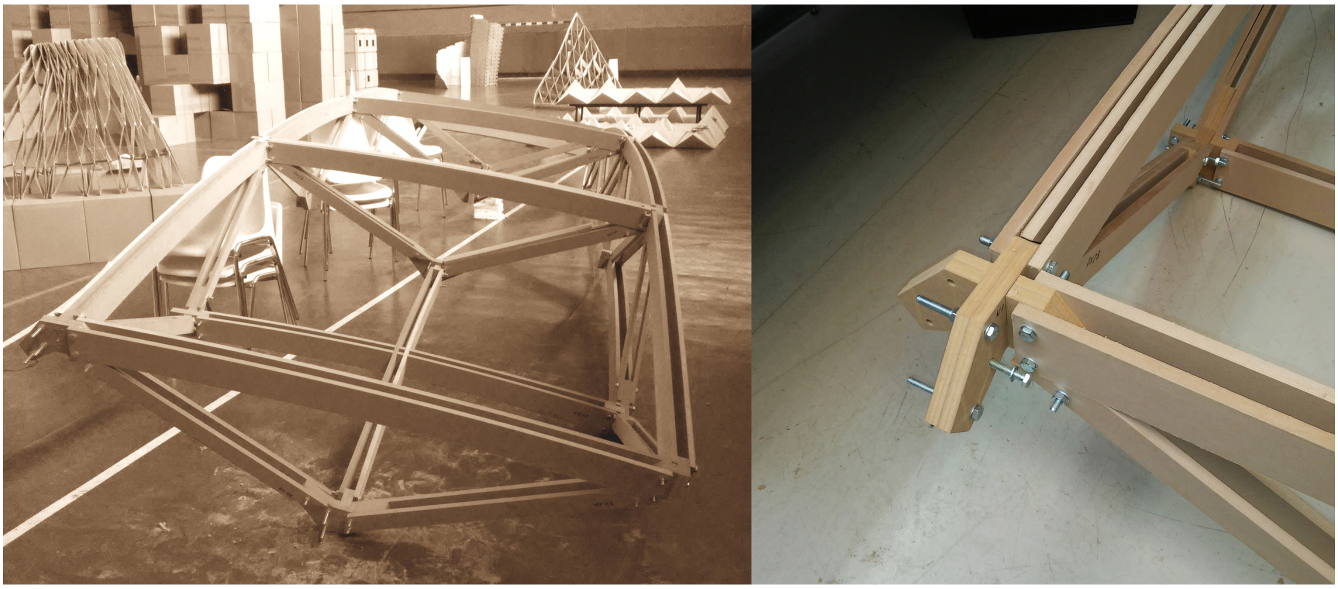


Figura 6.- Fase de montaje de tres módulos de cubierta en taller/ detalle de unión atornillada en cara superior.

La prefabricación en taller de elementos modulares, permite igualmente realizar las correcciones del modelo necesarias debidas a modificación de parámetros durante las labores previas a los trabajos de montaje, incluso debidas a necesidades surgidas durante el proceso de rehabilitación, permitiendo en tiempo real, la modificación de parámetros geométricos de la cubierta (luz, número de módulos, canto de la mallas, etc.), e incluso la extensión de la misma en casos de ser necesario, realizándose la modificación de parámetros en la herramienta de generación, y la nueva obtención del modelo físico digital para su envío a taller.

Como sistema de fabricación, se opta por el empleo de equipo de fresado por control numérico (CNC). Dicho equipo, propio de la pequeña industria de taller metálico y de carpintería, permite el empleo de pequeños recursos con gran economía de fabricación. En el caso de este estudio, se ha empleado el equipo de fresado existente en el Taller de Fabricación Digital de la Escuela Técnica Superior de Arquitectura de Sevilla.

Para la fabricación se han empleado paneles de tablero de densidad media (MDF), de 20 mm de espesor, con dimensiones adaptadas al equipo de fabricación (1,22 x 2,44 m). El modelo digital, ha sido despiezado en paneles codificados que son interpretados por la tecnología CNC. La codificación permitirá su posterior instalación en obra como kit de montaje [figura 5].

Con el fin de chequear el proceso, se ha realizado un test de montaje de un primer prototipo en taller, permitiendo la verificación de la coordinación dimensional de barras y nudos, así como la calibración de tolerancias dimensionales en el montaje de las uniones atornilladas. Igualmente, se ha realizado chequeo de estabilidad de los módulos ante solicitaciones previstas, así como ante fenómenos de segundo orden como es el caso del pandeo local de barras, previéndose los rigidizadores necesarios. Igualmente se han instalado los elementos para el futuro anclaje y tensado de las láminas textiles estructurales que constituirán la envolvente. [figura 6].

Simulación mediante CFD

Paralelamente al proceso de fabricación del prototipo, se ha diseñado una herramienta de cálculo original que permita procesos de simulación energética. El estudio tiene como objetivo, elaborar un método analítico que permita documentar la capacidad de las envolventes de doble capa previstas como material de cobertura en yacimientos, para garantizar un control efectivo de variables ambientales mediante sistemas pasivos de mínimo consumo energético.

Será pues necesario, para la aplicación de la metodología de conservación preventiva basada en: diagnóstico, cuantificación de agentes potenciales, estimación de riesgos, proposición de medidas correctoras y monitorización (Carrera 2018), la posibilidad de cuantificar y modelizar los siguientes parámetros ambientales, aplicando un método microclimático (Baglioni; Cacace; Valpuesta 2018):

- Temperatura seca exterior.
- Temperatura seca en el interior del espacio cubierto y en el interior de la cámara de aire formada por la envolvente de doble capa.
- Temperatura superficial de la envolvente y del objeto a proteger (mosaico).
- Humedad relativa interior en espacio cubierto y cámara de la envolvente.
- Velocidad del aire exterior, en interior de la cámara y en interior del espacio cubierto.
- Radiación solar incidente sobre la cubierta.

Para la citada simulación, se ha desarrollado una herramienta de cálculo basada en software de código abierto (PDE), concretamente se empleará la aplicación FreeFem (Chacón 2010), consistente en software para resolver ecuaciones diferenciales empleando método de elementos finitos (FEM).

El modelo de cálculo parte de la definición de límites o bordes cuyos nodos de contacto comparten valores idénticos, permitiendo generar mapas de evolución de parámetros higrotérmicos mediante ecuaciones de continuidad, empleando la dinámica de fluidos computacional (CFD).

Los límites o bordes serán los correspondientes a las diversas capas de textil estructural formado por entramado de fibra de poliéster y protección de polifluoruro de vinilideno de 0.78 mm de espesor que constituyen la envolvente de doble capa prevista, y que envuelve a la estructura soporte del prototipo. Tendremos pues cuatro límites o bordes que encerrarán las áreas de cálculo (bordes interior y exterior de cubierta, y bordes interior y exterior de envolvente vertical) [figura 7].

La densidad de la malla de nodos y la discretización de las áreas o dominios de cálculo se ajustará a la geometría y a la necesidad de definición de puntos singulares como son las aberturas de admisión-extracción de aire previstas en el modelo [figura 8].

La herramienta diseñada, permite la simulación de variación de parámetros como Tª y humedad relativa, mediante actuación sobre la velocidad del aire en la cámara que forman las dos capas de la envolvente, partiendo de parámetros de condiciones ambientales: Tª exterior, húmedas relativa, radiación solar incidente, velocidad del viento, etc., así como de las características propias de la envolvente (transmitancia térmica, trasmisión, reflexión y absorción solar, factor solar y porcentaje de paso de la luz).

Se ensayan en el modelo de flujos, diversas opciones de admisión y extracción de aire forzado mediante pequeños ventiladores en línea axiales [figura 7], disponiendo aberturas en puntos singulares (envolvente vertical y cubierta), según hipótesis prediseñadas y a ejecutar en el futuro modelo físico a escala 1:1. Detallamos a continuación algunas hipótesis consideradas:

- H1: Admisión forzada unilateral en envolvente vertical y extracción libre en extremo contrario de dicha envolvente.
- H2: Admisión forzada bilateral en envolvente vertical, y extracción libre en envolvente de cubierta.
- H3: Admisión forzada unilateral en envolvente vertical y extracción forzada en extremo contrario de dicha envolvente.
- H4: Admisión forzada bilateral en envolvente vertical, y extracción forzada en envolvente de cubierta.

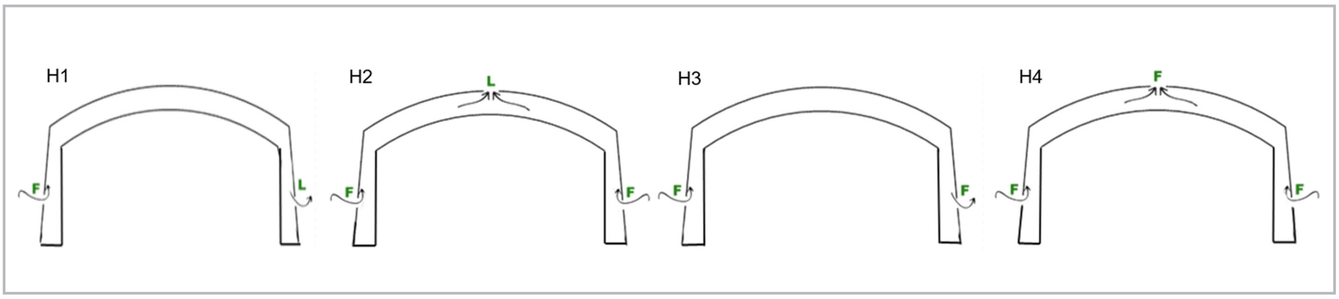


Figura 7.- Esquema de bordes e hipótesis de flujos de aire forzados (F), y libres (L).

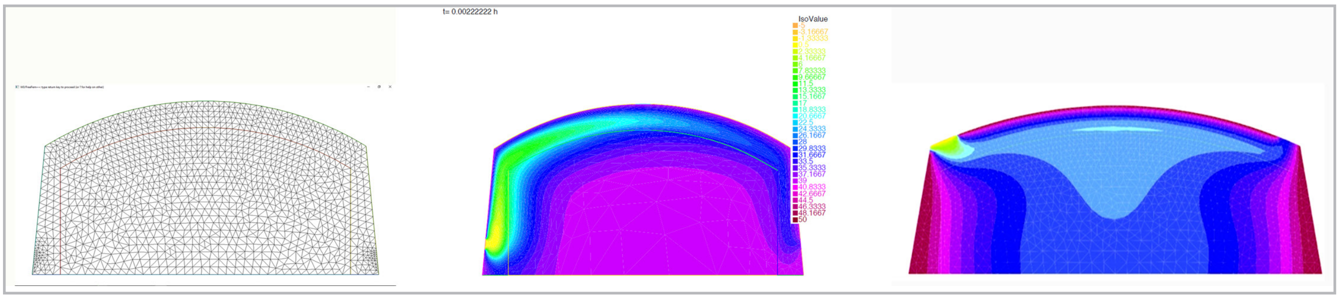


Figura 8.- Modelo de malla discretizada, y modelos de mapas de Tª y velocidad del aire para hipótesis forzada.

Para cada hipótesis, el modelo reporta mapas de evolución estacional y horaria de distribución de temperatura y velocidad de aire, tanto en espacio cubierto como en cámara, ante los diversos flujos estáticos (únicamente debidos a fenómenos de convección por diferencia de temperatura en el espacio cubierto), y ante flujos dinámicos (con circulación de aire forzada en el interior de la cámara formada por la envolvente de doble capa, con diversidad de posición de aberturas [figura 8].

ACV de la solución propuesta

Tal como se ha indicado, este trabajo se enmarca en una línea de investigación que vincula el diseño del elemento arquitectónico a su influencia en la minimización de su impacto medioambiental en todas las fases de su ciclo de vida (Gómez de Cózar, 2019).

El siguiente cuadro ilustra el modelo arquitectónico utilizado y su relación con las diferentes fases del ciclo de vida de una edificación a efecto de minimizarlas.
En un trabajo anterior (Gómez de Cózar, 2017) se procedió

FABRICACIÓN	⟶	LIGEREZA
CONSTRUCCIÓN	⟶	RÁPIDO MONTAJE
USO	⟶	ESTRATEGIAS PASIVAS ENERGÍAS RENOVABLES
DEMOLICIÓN	⟶	REVERSIBLE
DISPOSICIÓN FINAL	⟶	RECICLABLE

a comparar el impacto medioambiental, mediante herramientas de ACV, de una cubierta resuelta con el *Sistema Florín* frente a otros sistemas cotidianos y usuales que tenían las mismas dimensiones y cubrían la misma superficie. En el estudio reseñado, la estructura de la cubierta *Florín*, estaba resuelta de forma íntegra en acero galvanizado. En este artículo, se actualiza el análisis en función de la materialidad elegida para la estructura (fundamentalmente, paneles de MDF y tornillería de acero zincadas) asumiendo que todos los modelos que se comparan tienen la misma envolvente (doble capa de membrana textil de malla y urdimbre del poliéster revestida con PVC).

El análisis se ha realizado conforme a ISO 14040 (UNE-EN ISO 14040 2006), ISO 14044 (UNE-EN ISO 14044 2006) y EN 15978 (UNE-EN 15978 2012), siguiendo el siguiente procedimiento:

Alcance y objetivos (Scope and goal definition)

El objetivo fundamental en todos los casos analizados ha sido determinar el impacto medioambiental de la edificación proyectada. Siguiendo la bibliografía más actual (Galán Marín *et al.* 2015), (Asdrubali, F. *et al.* 2017) se ha considerado el *Riesgo de calentamiento global* (GWP), como el indicador de impacto más relevante.

Límites del sistema

En función de EN 15978 (UNE-EN 15978 2012) se han seleccionado las fases más relevantes para el análisis del ciclo de vida de una edificación:

- Fase de producción. Incluye materias primas (A1), transporte de materiales a fábrica (A2) y fabricación de materiales (A3).

- Fase de construcción/deconstrucción. Incluye transporte a lugar de construcción/montaje/obra (A4), proceso constructivo (A5), proceso de de-construcción (C1) y transporte a lugar de disposición final (C2).

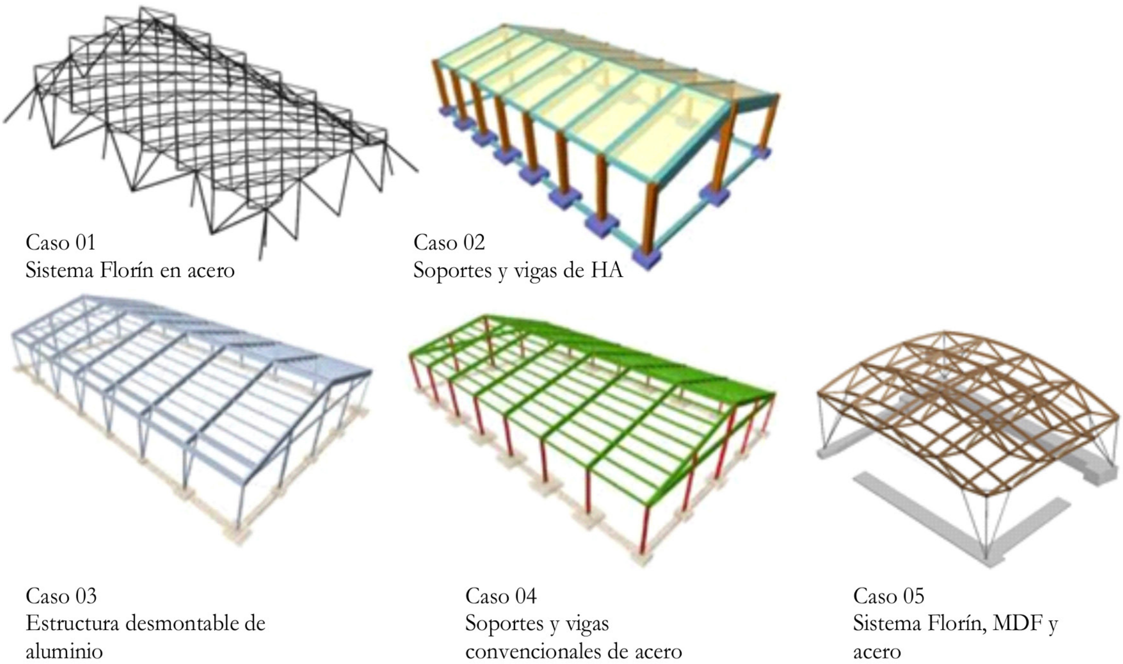
- Fase de final de vida. Incluye procesado de residuos para reúso, recuperación y/o reciclado (C3) y disposición final (C4).

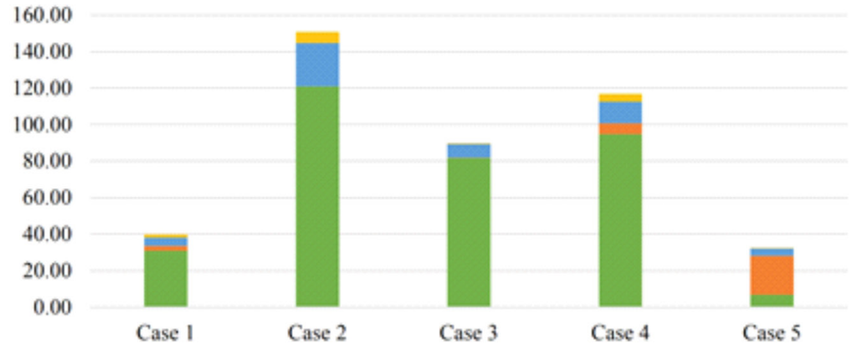
En todos los casos se ha considerado una duración de la edificación de 50 años.

Las etapas B1 a B7, relacionadas con fase de uso (energía operacional) no se van a incluir en el presente estudio porque, gracias al uso de estrategias pasivas de diseño, su impacto es despreciable.

Asignación

Se ha elegido un escenario de reciclado de todos los materiales. Los impactos unitarios asociados a esta fase se han obtenido de la base de datos Ecoinvent 2.0 (Frischknecht, R *et al.* 2007).





GWP (kgCo2-eq/m2)

	Case 1	Case 2	Case 3	Case 4	Case 5
Production	30,85	120,86	81,83	94,69	6,80
Workshop	2,74	0,00	0,13	5,94	21,46
Const./Disassem.	4,62	23,88	7,37	11,93	3,97
End of Life	1,48	6,02	0,37	4,29	0,19
Total	**39,70**	**150,76**	**89,70**	**116,86**	**32,42**

Gráfico 2.- Evaluación del impacto del ciclo de vida. Modelos comparados y resultados.

Unidad funcional

En todos los casos se ha considerado como unidad funcional el sistema constructivo/estructural completo incluyendo su cimentación. En todos los casos, los resultados de expresan por metro cuadrado de edificación cubierta.

Limitaciones y suposiciones

Para la cuantificación de la energía demandada durante las fases de construcción y deconstrucción se han cuantificado todos los procesos. En todos los casos se ha considerado un escenario de disposición final de reciclaje de todos los productos empleados.

1. *Inventario del ciclo de vida* (life cycle inventory, LCI): Consiste en la cuantificación de materiales, procesos y elementos incluidos en el sistema según ISO 14044 (UNE-EN ISO 14044 2006). Se siguen las indicaciones de García Martínez (García Martínez, A. 2010), clasificando el inventario en tres fases:
- Inventario de materiales.

- Inventario de transportes y procesos de construcción y deconstrucción.
- Inventario de procesos de final de vida.

Los valores de impacto asociados a transportes, construcción y deconstrucción se obtienen a partir del inventario de procesos que se han seguido en las operaciones referenciadas y de los valores de impacto unitarios asociados a cada proceso.

2. *Evaluación del impacto del ciclo de vida* (life cycle impact assessment, LCIA): A partir de la cuantificación de materiales y de procesos, la evaluación del impacto del ciclo de vida se ha calculado a partir de los diferentes valores unitarios de impacto, según la categoría considerada, establecidos en la base de datos Ecoinvent 2.0. Siendo esta la base de datos de uso más extendido entre la comunidad científica europea. Contiene los valores de impacto asociados a los materiales, elementos y procesos en cada etapa de su ciclo de vida.

3. *Interpretación de resultados:* En cada caso se han interpretado los resultados estableciendo relaciones entre el modelo arquitectónico/constructivo planteado y los diferentes valores de impacto medioambiental obtenidos.

Los resultados se han repercutido por metro cuadrado de superficie edificada: Modelos 1, 2, 3 y 4: 610,00 m^2; Modelo 5: 40,32 m^2.

Conforme a los criterios establecidos en el punto anterior, comparando los resultados obtenidos con tres sistemas diferentes y también utilizados con frecuencia (estructura de hormigón armado, estructura de aluminio y estructura de acero laminado), los resultados obtenidos ponen de manifiesto que el diseño realizado es el que más minimiza el impacto medioambiental respecto a las opciones restantes. En el gráfico 2 se observan los resultados obtenidos.

Discusión de resultados

Tras los primeros procesos de generación paramétrica, simulación estructural, higrotérmica y de análisis de ciclo de vida, del modelo, podemos realizar el siguiente análisis:

• Desde el punto de vista del diseño, optimización y comportamiento mecánico: En la optimización estructural, se han seguido criterios de diseño y elección de perfiles basado en: elección de secciones con inercia suficiente y mínimo consumo de material que garanticen la ligereza del sistema, unificación de secciones que permitan fabricación y montaje de mínima complejidad, o uniones entre elementos de rápido montaje y desmontaje, obteniendo como solución óptima la compuesta por trípodes de apoyo a base de perfiles tubulares de acero, y malla de cubierta a base de perfiles dobles de tablero MDF de igual sección en la totalidad de los módulos, previéndose perfil triple únicamente en una barra en los módulos de apoyo en los trípodes. La citada solución supone un peso total de la estructura de 226,50 kg, con una repercusión por superficie cubierta de 5,61 kg/m^2.

Realizando la comparativa con opciones de fabricación en materiales tradicionales de la construcción ligera como el acero y el aluminio, se obtiene una masa total de 500,90 Kg en caso del empleo de perfiles huecos tubulares de sección circular, y de 299,23 Kg en caso de emplear perfilería tubular de aluminio extruido, suponiendo una repercusión de 12,42 y 7,42 kg/m^2 respectivamente, revelándose la solución elegida como la óptima para los parámetros de partida.

•En cuanto a control higrotérmico en el espacio cubierto y objeto arqueológico: Tras la primera fase de simulación, con las hipótesis de aperturas y forzado de flujos de aire descritos [figura 8], podemos analizar los primeros resultados, destacando los siguientes:

En cuanto a valores obtenidos en periodo estival, se observa que el movimiento de aire en el interior de la cámara de la envolvente, permite la disminución de la temperatura interior del espacio cubierto entre 0,5 y 4 ºC, y en torno a 2ºC a nivel del suelo (objeto excavado), para velocidades iniciales de impulsión de aire en la cámara de 13 m/s, y un periodo máximo de funcionamiento del sistema de 4 horas, obteniéndose lo valores máximos de atenuación para la hipótesis H4 [figura 8], siendo forzada tanto la admisión por envolvente vertical, como la extracción por cubierta, consiguiendo una distribución más uniforme de Tª interior del espacio cubierto, así como una velocidad de aire residual más elevada en el interior de la cámara, en torno a 6,5 m/s.

En lo que se refiere al periodo de invierno, las primeras simulaciones han revelado que el mantenimiento de velocidades de aire bajas (inferiores a 0,50 m/s según escala de Beaufort), mediante el cierre de aberturas de la envolvente, permite que no exista disminución de la Tª debida a efectos eólicos en el interior de la cámara, favoreciendo el recalentamiento del aire ocluido en la misma debido a la radiación solar directa, con la consiguiente trasmisión de calor a través de la capa textil interior, y el mantenimiento de la Tª seca del espacio cubierto en valores positivos en dicho periodo.

• Relativas a minimización del impacto medioambiental en función de su comparación a otros sistemas constructivos: Como se puede observar en el gráfico 2, las diferentes soluciones que se han comparado aumentan el impacto medioambiental 1,21 veces (caso 1, Sistema Florín resuelto en acero), 4,54 veces (caso 2, hormigón armado), 2,77 veces (caso 3, aluminio) y 3,57 veces (caso 4, acero laminado) respecto a la solución diseñada (caso 5).

Las causas fundamentales de la reducción de impacto son:

-Naturaleza de los materiales elegidos. Las propiedades naturales del material elegido y su mínima industrialización plantean un potencial mínimo de impacto unitario. La ventaja de poder conseguir cantidades suficientes en un radio de acción cercano minimiza los impactos asociados a transportes.

-Extrema ligereza de la solución. Gracias al diseño de la malla espacial, en función del proceso de optimización que se ha seguido, se consigue un elemento muy ligero. La ligereza repercute en las tareas de fabricación, transportes y montaje.

-Se trata de un sistema de rápido montaje que potencia el trabajo en taller y minimiza el trabajo en obra.

-El sistema es reversible y reciclable al 100,0%.

Cuando se comparan las dos soluciones (casos 1 y 5) que se han resuelto con Sistema Florín, se observa que la solución realizada en madera mejora los resultados que se obtienen con la solución en acero (1,21 veces). Esta situación todavía podría mejorar más en función del tipo de tratamiento que se dé a la madera a efectos de garantizar su durabilidad en ambientes húmedos (clases de servicio 2 y 3 conforme a CTE DB SE M.

De este modo, se pone de manifiesto el beneficio medioambiental que se obtiene al utilizar el modelo constructivo desarrollado en función a otras alternativas posibles.

Conclusiones

Tras el desarrollo de la metodología propuesta y del análisis de los resultados obtenidos, se concluye lo siguiente:

• El uso de sistemas ligeros y de rápido montaje, como el Sistema Florín, construidos a partir de materiales adecuados, se configura como la opción más idónea de cobertura de yacimiento. La elección de materiales en cada caso de estudio será fundamental atendiendo no sólo a la naturaleza de éstos sino también a su necesidad de ser protegidos con otros productos para garantizar su durabilidad. Las herramientas de diseño paramétrico creadas, unidas a la fabricación digital, permiten obtener soluciones originales y optimizadas en cada caso en función de las necesidades particulares de cada yacimiento. En cada caso, aunque el sistema sea el mismo, la geometría final estará adaptada a las condiciones reales del yacimiento.

• La incorporación de doble capa de membrana a un sistema constructivo que fue creado con ese fin, permite tener un control higrotérmico aceptable del espacio cubierto sin apenas consumo energético, empleado medidas pasivas de acondicionamiento ambiental.

Figura 9.- Sondas y equipamiento a instalar en el prototipo construido.

Las simulaciones que se han realizado a partir de las herramientas originales creadas ponen de manifiesto el beneficio de esta tecnología a la hora de conseguir temperaturas adecuadas tanto en el interior del recinto como en su suelo.

• Se ha demostrado, como los dos puntos anteriores tienen gran repercusión en el Análisis del Ciclo de Vida realizado en cuanto a la minimización del impacto medioambiental conseguido. Cuando se sigue la metodología propuesta, se ha podido comprobar que el elemento resultante es el que menos impacto produce en relación a otros sistemas habituales, en las mismas condiciones de uso, con los que se ha comparado.

Desarrollos posteriores a la redacción de este artículo. Futuras líneas de investigación

Dentro del estudio del prototipo, y una vez sea instalado en el emplazamiento propuesto, se procederá a la monitorización del mismo, con el fin de contrastar los datos de simulación del modelo de cálculo CFD. Para ello, se recurrirá a tecnología compatible con software de código abierto "Arduino" (Evans 2007), colocándose sondas de temperatura y humedad en el exterior del mismo, en interior de cámara de la envolvente textil, y en el interior del espacio cubierto. Igualmente se prevé el uso de dinamómetro y piranómetro, para obtener lectura de parámetros exteriores de velocidad del aire y radiación solar incidente, así como de pequeños equipos de ventilación que permitan modificar la velocidad del aire en la cámara, e incluso la trasferencia de aire de la misma al espacio interior [figura 9]. La comparación de los datos obtenidos por el conjunto de sondas y equipamiento permitirá la gestión de una gran base de datos de parámetros de condiciones ambientales del espacio cubierto ante la variabilidad de las condiciones exteriores estacionales, y las condiciones activas de intervención sobre el mismo, permitiendo así la calibración del modelo de cálculo.

Referencias

AA.VV. (2008). *Deplorable Emergency System*. La Coruña: Netbiblo S.L.

AA.VV. (2003). *Taller de Conservación Preventiva en Excavaciones Arqueológicas in Situ*. Cádiz: Instituto Andaluz de Patrimonio Histórico, Colegio Oficial de Doctores y Licenciados en Filosofía y Letras de Cádiz.

ASDRUBALI, F., *et al.* (2017), "Abrevies of Structure, Termo-Physical. Acoustic, and Environmental Propperties of Wooden Materials for Buiding Applications", *Building and Environment*, 114: 307-332.

BAGLIONI, R., CACACE, C., VALPUESTA, S. (2018). "Diseño y Evaluación de una Metodología de Estudio y Gestión Medioambiental de Bienes Culturales". En *VI Congreso GE IIC*, Vitoria-Gasteiz: Grupo Español del IIC: 198-205.

CARRERA, F. (2018). "Conservación Preventiva en Yacimientos Arqueológicos, ¿Empezamos?". En *VI Congreso GE IIC*, Vitoria-Gasteiz: Grupo Español del IIC: 376-384.

CHACÓN, E. (2010). "Notas sobre FreeFem++2D y 3D: traducción del manual de F. Hecht, en Departamento de Ecuaciones Diferenciales y Análisis Numérico, Facultad de Matemáticas, Universidad de Sevilla. http://freefem.org/ff++/ftp/freefem++Spanish.pdf

DÍAZ MARTÍNEZ, S. (2005). "La Conservación de los Yacimientos Arqueológicos In Situ", *Boletín Arkeolan*, 13: 110-130.

EVANS, B. (2007). *Arduino Programming Notebbok*. San Francisco: Creative Commons.

FRAZZI, P. (2002). "Conservación preventiva para objetos arqueológicos históricos en contextos urbanos", *Estudios Ibero Americanos de la Universidad Pontificia de Rio Grande do S*, 26 vol XXVIII: 95-111.

FRISCHKNECHT, R., JUNGBLUTH, N., HANS-JÖRG, A., *et. al.* (2017). *Implementación of life cycle impacto assessment métodos: data v2.0*. Dübendorf: Rolf Frischknecht, Niels Jungbluth.

GALÁN MARÍN, C., RIVERA GÓMEZ, C., GARCÍA MARTÍNEZ A. (2015). "Embodied Energy on convencional load-Bea ring salles versus natural stabilized e Art ha blocs", *Energy and Building*, 97: 146-154.

GARCÍA MARTÍNEZ, A. (2010). *Análisis de Ciclo de Vida (ACV) de edificios. Propuesta metodológica para la elaboración de Declaraciones Ambientales de Viviendas en Andalucía*. Sevilla: Universidad de Sevilla.

GÓMEZ DE CÓZAR, J. C., GARCÍA DIÉGUEZ, R. (2001). *Sistema Florín. Estructuras Desplegables de Dos Capas*. Sevilla: DCA1 Universidad de Sevilla.

GÓMEZ DE CÓZAR, J. C. (2007). "Textile Architecture?". En *III International Conference on Textile Composites and Inflatable Structures*, Barcelona: International Centre for Numerical Methods in Engineering: 293-296.

GÓMEZ DE CÓZAR, J. C., GARCÍA MARTÍNEZ A., ARIZA LÓPEZ, I., *et. al.* (2017). "Lightweight and Quickly Assembled: the Most Eco-Efficient Model for Architecture", *International Journal of Computational Methods and Experimental Measurements*, Vol. 5. Núm. 4: 539-550. https://doi.org/10.2495/CMEM-V5-N4-539-550

GÓMEZ DE CÓZAR, J. C., GARCÍA MARTÍNEZ A., ARIZA LÓPEZ, I., *et. al.* (2019). "Life cycle assessment as a decision-making tool for selecting building systems in heritage intervention: Case study of Roman Theatre in Itálica, Spain", *Journal of Cleaner Production*, 206: 27-39. https://doi.org/10.1016/j.jclepro.2018.09.169

JIANG, HE., AKIRA, HOYANO. (2009). "Measurement and simulation of the thermal environment in the built space under a membrane structure", *Building and Environment* ,44: 1119-1127. https://doi.org/10.1016/j.buildenv.2008.08.003

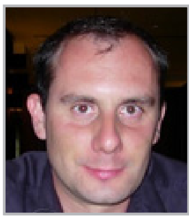
KRAUEL, J. (2010). *Arquitectura Digital, Innovación y Diseño*. Barcelona: S.A. Leading International Key Services

KRONENBURG, R. (2008). *Portable architecture: design and technology*. Basel: Birkhäuser.

LACAYO, T.E. (2001). "Factores de Alteración in-Situ. Conservación Preventiva del Material Arqueológico". En *XV Simposio de Investigaciones Arqueológicas en Guatemala*, Guatemala: J.P. Laporte, H. Escobedo y B. Arroyo: 453-457.

PRICE, S. (1984). *La Conservación en Excavaciones Arqueológicas*. Roma: ICCROM.

Autor/es



Manuel Ordóñez Martín
maormarq@us.es
Universidad de Sevilla. E.T.S. Arquitectura

Profesor Asociado Universidad. Máster en Arquitectura y Patrimonio Histórico. 2012. Profesor Máster en Proyecto de Instalaciones en Arquitectura. (2011- actualidad). Departamento de Construcciones Arquitectónicas 1. Universidad de Sevilla. E.T.S. Arquitectura. Grupo de Investigación TEP 130: Arquitectura, Patrimonio y Sostenibilidad: Acústica, Iluminación, Óptica y Energía. Doctorando con tesis en redacción: Análisis y Desarrollo de Coberturas Temporales Eficientes en Yacimientos Arqueológicos. Producción científica más relevante.
https://investigacion.us.es/sisius/sis_showpub.php?idpers=7429

Juan Carlos Gómez de Cózar
gcozar@us.es
Universidad de Sevilla. E.T.S. Arquitectura

Profesor Titular de Universidad. Director del Master Universitario en Innovación en Arquitectura: Tecnología y Diseño. Departamento de Construcciones Arquitectónicas 1. Universidad de Sevilla. E.T.S. Arquitectura. Grupo de Investigación TEP 130: Arquitectura, Patrimonio y Sostenibilidad: Acústica, Iluminación, Óptica y Energía. Autor de varias patentes y de numerosos trabajos de transferencia que desarrollan la línea de investigación: "Forma, materialidad y arquitectura. búsqueda de modelos constructivos ligeros, de rápido montaje y reversibles que minimicen el impacto medioambiental". Producción científica más relevante:
https://investigacion.us.es/sisius/sis_showpub.php?idpers=5478

https://doi.org/10.37558/gec.v17i1.757

Ge-conservación
Conservação | Conservation

Evaluación de riesgos, monitorización y simulación de edificios patrimoniales

Carmen M.ª Muñoz González, Ángel Luis León Rodríguez, Jaime Navarro Casas, Jonathan Ruiz Jaramillo, Catherine Teeling

Resumen: Los edificios religiosos son una parte importante del patrimonio cultural, son documentos de nuestra herencia y tenemos la necesidad de preservarlos. Las condiciones ambientales en el que están inmersos estos edificios son determinantes para la preservación y conservación del patrimonio mueble que contiene. Originalmente, la mayoría de estos espacios no estaban acondicionados, pero actualmente, estos edificios están siendo climatizados para proporcionar el confort térmico a los feligreses y para mejorar las condiciones del clima interior y la preservación del patrimonio mueble. El objetivo principal de esta investigación ha sido analizar las condiciones ambientales de edificios religiosos en un clima Mediterráneo, mediante el uso de monitorización y simulación para evaluar y mejorar la preservación del patrimonio cultural de estos edificios. Este estudio aporta las herramientas para la optimización de la calidad ambiental para la preservación y conservación del patrimonio mueble e inmueble y para su aplicación en futuros proyectos de rehabilitación patrimonial.

Palabras clave: Patrimonio, monitorización, simulación, riesgo, condiciones ambientales

Evaluación de riesgos, monitorización y simulación de edificios patrimoniales

Abstract: The churches are an important part of Cultural Heritage; these need to be preserved. The indoor environmental conditions of these spaces are decisive for the preservation and conservation of the movable heritage The originally churches were not conditioned, but currently, these buildings are being air-conditioned to provide thermal comfort to parishioners and to improve indoor weather conditions. The main objective of this research project has been to analyse the environmental conditions of religious buildings in a Mediterranean climate, through the use of monitoring and simulation to evaluate and improve the preservation of the Cultural Heritage of these buildings. Finally, this study provides the subject expert, the tools for the optimization of environmental and energy quality, in the refurbishment project.

Keywords: Heritage, monitoring, simulation, risk, environmental conditions

Introducción

El estudio higrotérmico de espacios religiosos proto-barrocos se enmarca dentro una fase de estudios de investigación que tiene por objeto la futura rehabilitación de dichos espacios, y se pretende sirva de base para conocer el estado de conservación, los fenómenos de degradación que sufren algunas obras de arte y analizar previamente las consecuencias de las posibles intervenciones en los edificios.

Los procesos de degradación son resultado de la interacción de diversos parámetros ambientales tanto del exterior como el interior (Muñoz-Gonzalez 2016).

Uno de los objetivos de este estudio fue aportar datos que pudieran dar explicación a la degradación actual de los espacios religiosos analizados, debido a las condiciones ambientales interiores, a los factores climatológicos, el uso actual, etc. La observación de los parámetros ambientales interiores (obtenidos con una previa monitorización del espacio de estudio) desde un punto de vista de la dinámica ambiental, permite conocer el funcionamiento ambiental del espacio interior (Erhardt & Mecklenburg 1994), (Magrini 2016). Debido a la naturaleza oscilante del clima, el proceso de monitorización se debe realizar para un periodo de varios años lo que permite un conocimiento más detallado de la interacción de los materiales y obras de arte con el clima interior (Wessberga & Vyhlídal). Igualmente, debido a la influencia de la masa humana en la degradación y el confort térmico del espacio, este estudio ahonda en el conocimiento más detallado del uso de estos espacios y la interacción de las personas con el ambiente interior (Camuffo *et al.* 2010).

Un elevado porcentaje de edificios patrimoniales son contenedores de una riqueza inestimable de nuestro patrimonio cultural. Estos espacios albergan un patrimonio mueble, tan importante como el que se puede encontrar en espacios expositivos, los museos. En este ámbito poco a poco se han ido imponiendo diferentes estrategias de conservación, al menos como planteamiento teórico. Sin embargo, otros espacios como por ejemplo, los religiosos, son instituciones que no disponen de estructuras técnicas y administrativas permanentes para la conservación de los bienes que acopian, a pesar de que en la mayoría de los casos, muchos de ellos están inscritos en el Registro General de Bienes de Interés Cultural o forman parte del Inventario General de Bienes Muebles (DIRECCIÓN GENERAL DE BELLAS ARTES Y BIENES CULTURALES Y DE ARCHIVO Y BIBLIOTECA 2009).

Además de las carencias en medios técnicos, es preciso considerar otra particularidad que puede determinar de forma importante la conservación del patrimonio, que es su carácter de patrimonio en uso. Generalmente, los espacios de culto están vinculados a ritos y tradiciones con un importante seguimiento popular en el que enlazan, además, elementos del patrimonio inmaterial que requieren asimismo una aproximación especial en cuanto a los requerimientos de conservación.

En los últimos treinta años, las iglesias están disminuyendo drásticamente, sobre todo en el occidente de Europa. Asimismo, muchos de estos espacios han tenido que ser usados para fines alternativos con el fin de disponer de algunos ingresos extras. El uso original de las iglesias está siendo modificado y actualmente a estos espacios, hoy por hoy, no se les exigen un acondicionamiento ambiental, como al resto de otras edificaciones que albergan actividades de uso público. Hoy en día muchas de ellas se utilizan para conciertos y otros eventos musicales, exposiciones, etc. (Mosoarca *et al.* 2017)

Durante siglos el clima interior de las iglesias había venido determinado principalmente por el clima exterior. Sin embargo, en la actualidad muchos de estos espacios están siendo equipados con novedosas tecnologías (diseñadas para una arquitectura contemporánea) para mejorar las condiciones de confort de los feligreses (Berardinis, Rotilio & Capannolo 2017).

Igualmente, si el funcionamiento de estas técnicas ambientales fuese continuo, existiría una alta demanda de energía debido al gran volumen e inercia térmica que presentan estos edificios. Precisamente por razones económicas la mayoría de las iglesias emplean un sistema de climatización para períodos de tiempo limitados, concretamente cuando las personas están presentes. Pero esta estrategia de climatización puede tener un efecto adverso sobre la conservación del edificio y sus objetos interiores (Balocco & Colaianni 2018).

Los problemas a los que se enfrenta la conservación de estos espacios están relacionados con la evaluación de riesgos, la aplicación de control y el seguimiento de las condiciones ambientales, una vez implementados los sistemas de acondicionamiento ambiental. En la mayoría de los casos, la implantación de las instalaciones de acondicionamiento ambiental deriva de dos necesidades principales, una es la económica (de la instalación, uso y mantenimiento) y la segunda es el confort térmico. Sin embargo, los requisitos de conservación en pocas ocasiones son considerados (Muñoz 2016).

Por esto, resulta relevante el presente trabajo, donde se propone profundizar en el conocimiento del acondicionamiento higrotérmico de espacios religiosos. Se pretende con ello, ofrecer a los técnicos competentes las pautas de diseño que le permitan predecir la conducta higrotérmica de estos espacios antes y después de la aplicación de técnicas ambientales.

Metodología

Este trabajo de investigación se desarrolló siguiendo un método experimental, depurado durante años de trabajo por parte de miembros del grupo de investigación TEP 130, adscrito al Instituto Universitario de Arquitectura y ciencias de la Construcción (IUACC) de la Universidad de Sevilla. Este método combina las formulaciones analíticas, las medidas experimentales realizadas *in situ* y la utilización de técnicas de simulación mediante ordenador para conocer y predecir el comportamiento higrotérmico de los espacios.

El método desarrollado para el análisis de cada iglesia objeto de estudio puede ser desglosado en cinco fases, las cuales se suceden cronológicamente.

• En la primera etapa del estudio se realiza una recopilación de información básica de la muestra de estudio. La documentación histórica permite conocer las circunstancias que propiciaron la construcción del edificio, su propia evolución y del entorno hasta nuestros días.

• Una segunda etapa, el seguimiento del ambiente interior cuya finalidad es proporcionar datos objetivos de parámetros higrotérmicos para realizar la evaluación y diagnosis del estado de conservación el patrimonio cultural y el confort térmico. Las iglesias fueron monitorizadas durante veintidós meses, excepto la iglesia de nuestra señora de la Victoria, que por mantenimiento

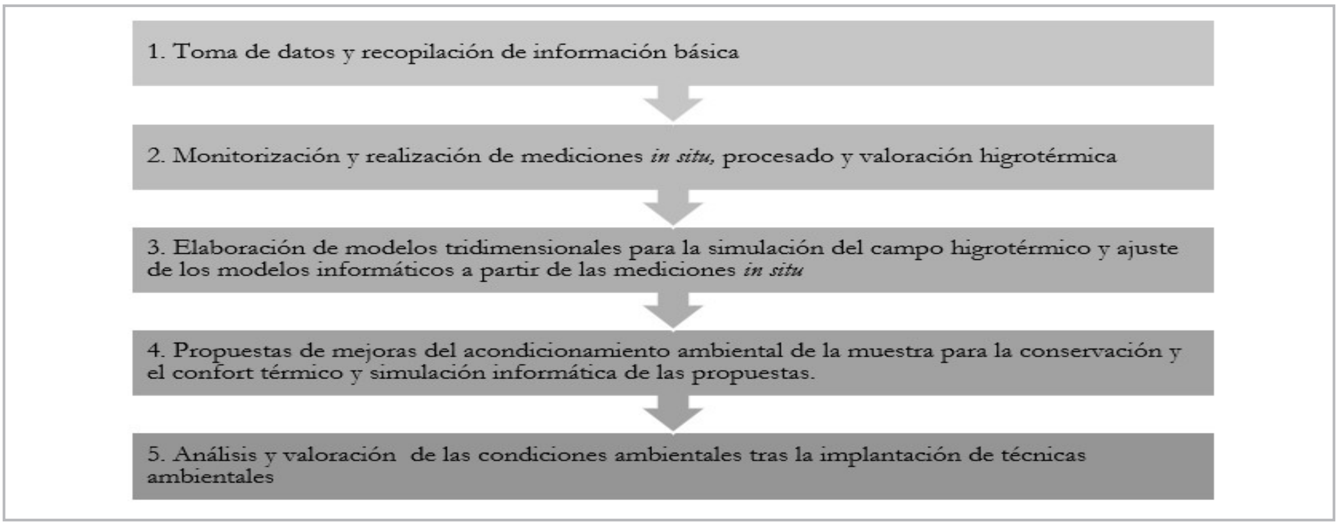


Figura 1.- Fotografía de emplazamiento y levantamiento planimétrico.

y obras solo se pudo hacer un seguimiento ambiental durante dieciséis meses.

• En la tercera etapa se elaboran los modelos tridimensionales para la simulación del campo higrotérmico. Los datos de la monitorización se emplean para generar los modelos de simulación informática, elaborando modelos digitales tridimensionales de cada caso de estudio. Estos modelos espaciales reproducen cada edificio y su entorno, desde el punto de vista geométrico, climático y constructivo, empleando para ello el programa informático Design Builder.

Este modelo informático se valida a partir de las mediciones *in situ*. La metodología de validación se basa en la comparación de un importante número de datos horarios registrados *in situ* con los resultados obtenidos de la simulación informática una vez generado el modelo.

• Una cuarta etapa donde se desarrollan propuestas de mejoras del acondicionamiento ambiental de la muestra mediante la aplicación de técnicas ambientales pasivas y activas en los modelos de simulación, para la conservación y el confort térmico.

• Finalmente, en la quinta etapa se analiza y valora los resultados obtenidos de los modelos informáticos para determinar la adecuación de las condiciones ambientales para la conservación, confort térmico y eficiencia energética.

El esquema propuesto para la gestión de las condiciones ambientales en ningún caso tiene como objetivo proporcionar soluciones específicas o reglas sobre cómo conseguir estándares de niveles estrictos de dichas condiciones, sino que pretende proporcionar una metodología de trabajo normalizados que permite tomar decisiones adecuadas y coordinadas sobre futuras intervenciones en edificios históricos, sin poner en riesgo el bien patrimonial.

Caso de estudio

Para este estudio se analizaron tres espacios religiosos que se encontraban en un mismo ámbito geográfico y por lo tanto tenían unas condiciones climatológicas externas muy similares. Los espacios religiosos se encontraban en la localidad de Morón de la Frontera, en la provincia de Sevilla (España). Estas iglesias, forman parte del patrimonio inmueble de Andalucía, algunas de las mismas declaradas BIC (Bien de Interés Cultural), con la categoría de monumento, como es el caso de la Iglesia de San Francisco de Asís

Las iglesias, pertenecían a un mismo periodo constructivo, comprendido entre 1550-1650 para poder realizar un estudio comparativo. Estas presentaban variaciones en cuanto a forma de planta, sistema constructivo de cubierta, huecos de ventanas, etc., factor que enriquecía el estudio, ya que se podía determinar la influencia de estas características sobre el comportamiento higrotérmico en las mismas.

En la figura 2, se muestran las tres iglesias de estudio, la primera, la iglesia de San Francisco de Asís del año 1550, presenta una planta en forma cajón, cubierta por una bóveda de cañón y lunetos reforzados por pares de arcos fajones. La planta está orientada de manera que los muros longitudinales, se encuentran, con una ligera desviación al norte. En los alrededores de la iglesia están adosados las demás dependencias como capillas, casa parroquial y sobre una de las medianeras se levanta el claustro del antiguo monasterio. La segunda, la iglesia Nuestras Señora de la Merced del 1638, de planta cruz latina con una falsa bóveda de cañón con arcos fajones y lunetos que cubren los brazos del crucero, mientras que una bóveda semiesférica sobre pechinas cubre el crucero. Por último, la iglesia Nuestra Señora de la Victoria del año 1584, formada por una nave de cinco tramos, con capillas unidas mediante arcos de medio punto. La nave se cubre con tejado a dos aguas cuyo interior está cubierto con un artesonado de madera. A continuación, se muestra las características constructivas de las iglesias analizadas, véase [tabla 1].

Figura 2.- Muestra de las iglesias de estudio. 1) Iglesia de San Francisco 2) Iglesia de Nª Señora de la Merced 3) Iglesia de Nª Señora de la Victoria.

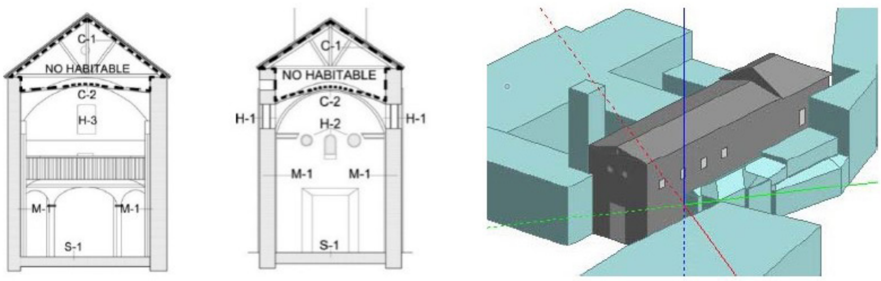


Figura 3.- Modelos tridimensionales. 1) Iglesia de San Francisco 2) Iglesia de Nª Señora de la Merced 3) Iglesia de Nª Señora de la Victoria.

Tabla 1.- Características constructivas de las iglesias

	San Francisco	Ntr.ª. Señora de la Merced	Ntr.ª. Señora de la Victoria
Muros externos	Mampostería y ladrillos	Mampostería y ladrillos	Mampostería y ladrillos
Bóveda	Piedra y madera	Piedra y madera	-
Cubierta	Tejas árabes, madera y cañizos	Tejas árabes, madera y cañizos	Tejas árabes, vigas de acero, artesonado de madera
Suelos	Mármol	Mármol	Mármol
Ventanas	Vidrio simple	Vidrio doble	Vidrio simple

Elaboración de modelos tridimensionales para la simulación del campo higrotérmico

El interior de estos espacios religiosos fue monitorizado para realizar un seguimiento del ambiente interior para proporcionar así datos objetivos para realizar una evaluación de diagnosis del estado de conservación del patrimonio inmueble y mueble. Igualmente, uno de los avances en este estudio, fue que estos datos obtenidos de mediciones de temperatura del aire, temperatura superficial, humedad relativa y absoluta y velocidad de aire interior se utilizarían como referencia real para los procesos de validación de las simulaciones de modelos virtuales. Esto nos permitió, tener una herramienta fundamental dentro de la metodología aplicada a los criterios de diseño del acondicionamiento ambiental de edificios patrimoniales.

Los datos de monitorización se emplearon para generar los modelos de simulación informática, elaborando modelos digitales tridimensionales de cada iglesia de estudio. Se realizaron varios modelos espaciales que reproducían cada iglesia y su entorno, desde el punto de vista geométrico, climático y constructivo, empleando el programa informático Design Builder.

Los modelos informáticos tridimensionales tenían un comportamiento higrotérmico muy similar al que había en la realidad. La validación de un modelo consistió en la comparación de los resultados simulados con los datos reales recogidos en un período de tiempo. La metodología de validación se basó en la comparación de un importante número de datos horarios registrados *in situ* con los resultados obtenidos de la simulación informática una vez generado el modelo. Un modelo era válido cuando la variación de las mediciones in situ y las del modelo virtual, difería menos de 1 ºC de temperatura y 1.5 g/m^3 de humedad absoluta durante el 95 % del tiempo y menos del 5 % de humedad relativa durante el 90 % del tiempo. Véase [figura 4]

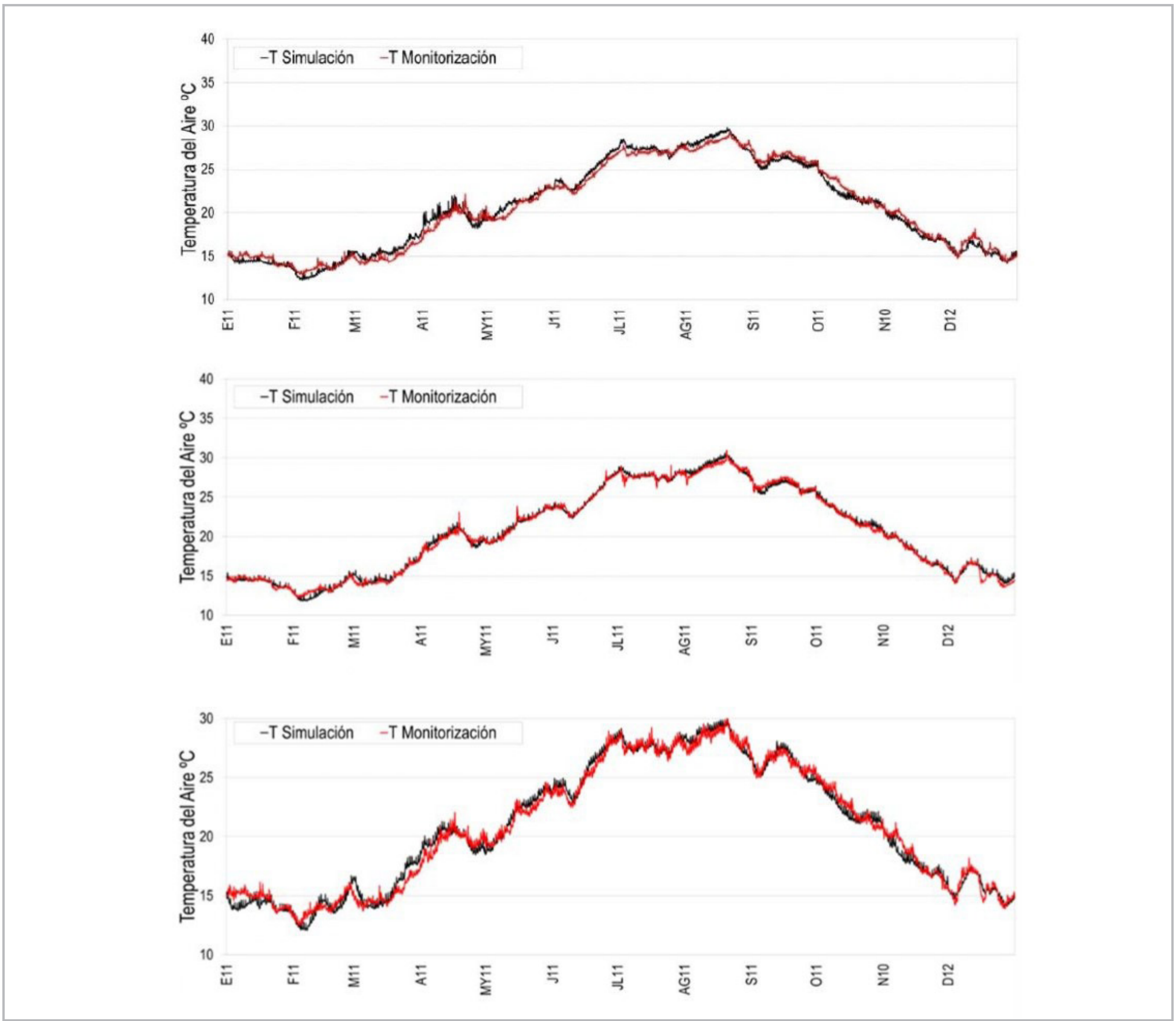


Figura 4.- Validación de modelo tridimensionales, temperatura del aire. 1) Iglesia de San Francisco 2) Iglesia de Nª Señora de la Merced 3) Iglesia de Nª Señora de la Victoria.

Resultados y discusión

A continuación, se muestran los resultados y el análisis global del comportamiento higrotérmico de la muestra en el caso de la aplicación de las técnicas ambientales activas y mixtas.

—Monitorización y realización de mediciones in situ, procesado y valoración higrotérmica

Las medidas higrotérmicas llevadas a cabo in situ en cada una de las iglesias objeto de estudio, nos permitió evaluar y caracterizar su comportamiento higrotérmico. Estos edificios se caracterizaban por presentar una elevada inercia térmica, derivada de sus sistemas constructivos. Asimismo, al estar rodeadas de otras edificaciones, la incidencia e influencia solar sobre sus cerramientos exteriores era mínima.

Las mediciones reflejaron que las diferencias de temperatura y humedad relativa interiores (valores promedios) no eran significativos, excepto en los meses más cálidos (finales de primavera, verano y principios de otoño). Véase [figura 5].

En verano, o cuando las temperaturas interiores eran más elevadas, la humedad absoluta interior aumentaba sensiblemente por la evaporación del agua contenida en el suelo y parte inferior de muros (humedad de capilaridad). Los meses más fríos y en primavera la temperatura interior tenía una mayor incidencia sobre la humedad absoluta.

Igualmente, se caracterizó la temperatura radiante interior de la muestra de iglesias mediante el empleo de equipos de medida infrarrojas. En los ensayos realizados se observó que en invierno se producía un ligero gradiente térmico vertical en los muros que era apreciable principalmente a últimas horas del día. Esa diferencia de temperatura entre las partes baja y alta se debía a la estratificación del aire y a la influencia de la radiación solar sobre las cubiertas [figura 6]. La diferencia de temperatura oscilaba entre 0.5 º C. En verano, el gradiente térmico era más acusado entre las zonas altas y bajas de la iglesia, en torno a 2.5ºC.

Como era esperable, los únicos flujos de calor significativos de la envolvente se observaban en los elementos constructivos de menor resistencia e inercia térmica: huecos de muros y cubierta.

En todas las iglesias se detectaron humedades de capilaridad en la parte baja de los muros que provocaban evaporación de agua y aumento la de la humedad ambiental interior.

El suelo de las iglesias era la superficie que presentaba una temperatura radiante más baja (entre 21 ºC en verano y 14 ºC en invierno). Esto generaba que, en verano, este elemento actuara como disipador de cargas térmicas y regulador de temperatura interior.

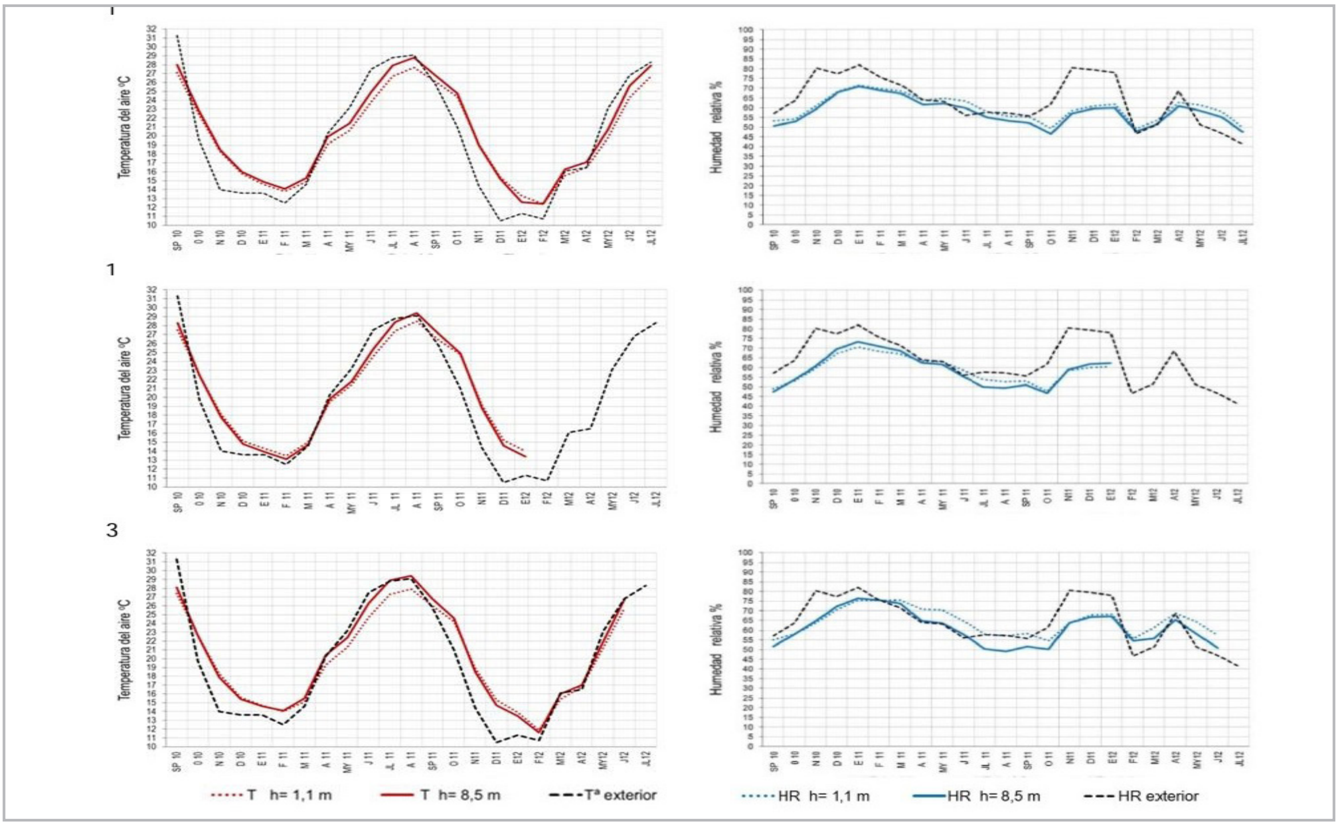


Figura 5.- Valores medidos de T y HR (Promedios mensuales). 1) Iglesia de San Francisco 2) Iglesia de Nª Señora de la Merced 3) Iglesia de Nª Señora de la Victoria.

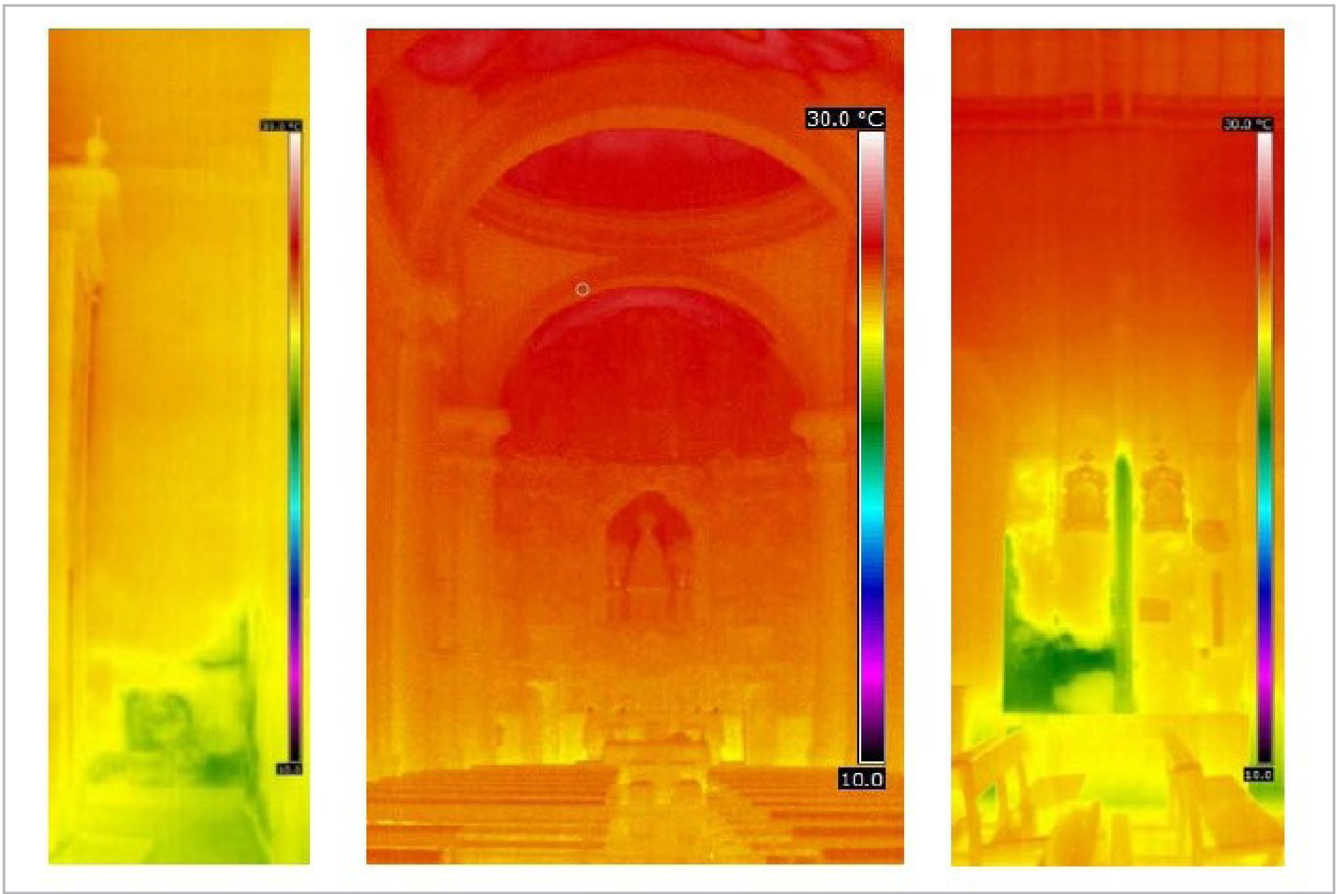


Figura 6.- Temperatura radiante en el mes de junio. 1) Iglesia de San Francisco 2) Iglesia de Nª Señora de la Merced 3) Iglesia de Nª Señora de la Victoria.

IGLESIA SAN FRANCISCO DE ASÍS				
	OTOÑO	INVIERNO	PRIMAVERA	VERANO
Sin riesgo	19%	23%	15%	0%
Riesgo bajo	80%	77%	55%	88%
Riesgo alto	1%	0%	30%	12%
IGLESIA NUESTRA SEÑORA DE LA MERCED				
	OTOÑO	INVIERNO	PRIMAVERA	VERANO
Sin riesgo	24%	25%	20%	0%
Riesgo bajo	74%	75%	73%	98%
Riesgo alto	2%	0%	7%	2%
IGLESIA NUESTRA SEÑORA DE LA VICTORIA				
	OTOÑO	INVIERNO	PRIMAVERA	VERANO
Sin riesgo	14%	13%	6%	14%
Riesgo bajo	81%	87%	69%	81%
Riesgo alto	5%	0%	25%	5%

Tabla 2.- Porcentaje de tiempo en riesgo biodeterioro.

En cuanto al riesgo de biodeterioro del contenido mueble de las diferentes iglesias [tabla 2], el análisis de las mediciones in situ puso de manifiesto que durante los meses de primavera y verano era cuando tenía lugar los mayores periodos de riesgo al biodeterioro.

Igualmente, la pluviometría tenía una notable influencia en el aumento del riesgo al biodeterioro. En los años más lluviosos, el porcentaje de datos con riesgo alto al biodeterioro era mayor.

Del análisis del riesgo mecánico sobre el patrimonio mueble de las iglesias se concluyó que las desviaciones de la humedad relativa tenían una mayor incidencia sobre la preservación de las obras de arte, pues el porcentaje de tiempo en riesgo era mayor que en las desviaciones de temperatura. En general, las estaciones que presentan un mayor porcentaje de tiempo en riesgo, debido a las variaciones de la humedad relativa, eran otoño, invierno y primavera.

— *Elaboración de modelos tridimensionales para la simulación del campo higrotérmico y ajuste de los modelos informáticos a partir de las mediciones in situ*

Para validar los modelos de simulación higrotérmica en este tipo de edificios, fue básico fijar adecuadamente la temperatura del terreno, ya que tenía gran influencia en los resultados. A diferencia de otros investigadores, que proponen considerar los suelos en contacto con el terreno como elementos adiabáticos, en el caso que nos ocupa se comprobó que cuando incluíamos este como adiabático no se validaban los modelos de simulación, especialmente en verano, ya que este componente constructivo actuaba como disipador de calor (Huijbregts, Schellen, Schijndel & Ankersmit 2015). Esto es una condicionante del clima, Mediterráneo, debido a las elevadas temperaturas en los meses de primavera y verano. Para poder validar los modelos de simulación, fue necesario medir in situ la temperatura superficial del suelo y fijar para el terreno una temperatura 2 ºC por debajo.

La humedad contenida en los materiales de construcción, que es bastante frecuente en estas construcciones, dificultaba la validación de los modelos, ya que alteraba las condiciones ambientales por el efecto de evaporación del agua en el interior del edificio. Por ello, se consideró necesario utilizar herramientas que permitieran simular este efecto. Así pues, en edificios históricos que presenten humedad en los muros por capilaridad, es necesario utilizar herramientas de simulación que permitan variar la humedad absoluta.

— Propuestas de mejoras del acondicionamiento ambiental de la muestra para la conservación y el confort térmico y simulación informática de las propuestas

Las diferentes propuestas de estudio se dividieron en varios bloques, técnicas ambientales pasivas: (conjunto de acciones de rehabilitación de la envolvente de la iglesia); técnicas ambientales activas (implementación de sistemas de climatización permanente).

En función a la evaluación de estas técnicas, las especificaciones ambientales para cada edificio tuvieron en consideración un amplio rango de materiales y sus combinaciones. La humedad relativa fue el parámetro más crítico en este campo y en consecuencia debía mantenerse en un nivel determinado tan estable como fuera posible. Al definir el límite del rango definitivo, se supuso las variaciones de HR para limitar daños mecánicos ocasionados por el microclima en materiales orgánicos higroscópicos de acuerdo con la Norma UNE-EN 15757 (UNE-EN 15757, 2011). Igualmente se fijaron los límites superiores para HR para evitar un biodeterioro por mohos, pudriciones, insectos, etc. Finalmente, según las normativas anteriores y la UNE-E-EN 15759-1 (UNE-E-EN 15759-1 2012) se establecieron los siguientes valores:

El modo de funcionamiento de los diferentes sistemas de climatización vino determinado principalmente por la necesidad de encontrar un equilibrio entre los requisitos para la conservación y el confort térmico, el tipo de utilización del edificio y la eficiencia energética. Los tipos de funcionamiento propuesto fueron los siguientes:

Funcionamiento 24 horas: El objetivo era proporcionar un microclima especificado de forma permanente, durante todo el año. El sistema de climatización funcionaba las 24 horas del día.

Funcionamiento 12 horas: Se proporcionaba un microclima especificado durante un periodo de tiempo limitado. En este caso el sistema funcionaba sólo durante el día, de 9.00 a.m. hasta 22.00 p.m.

Funcionamiento régimen de uso de la iglesia: Proporcionaba unas condiciones ambientales adecuadas únicamente cuando se utilizaba la iglesia, durante la celebración del culto. Debido a la inercia térmica de la iglesia, los sistemas debían encenderse al menos una hora antes de que comenzara la misa.

—Análisis y valoración de las condiciones ambientales tras la implantación de técnicas ambientales

Después de aplicar y combinar distintas técnicas ambientales pasivas y activas se observó que las propuestas de acondicionamiento ambiental que solían llevarse a cabo en los espacios religiosos situados en zonas climáticas más frías (norte y centro de Europa), no tenían la misma validez de aplicación en climas templados (clima Mediterráneo), debido a que las primeras estaban orientadas básicamente para condiciones extremas durante invierno.

Las distintas técnicas ambientales pasivas consideradas en esta investigación no garantizaban el confort a lo largo de un año, especialmente durante las estaciones de invierno y primavera. Las propuestas de rehabilitación que utilizaban exclusivamente técnicas ambientales pasivas no conseguían eliminar totalmente el riesgo mecánico y el riesgo al biodeterioro de los materiales que forman parte del patrimonio mueble.

Tabla 3.- Condiciones interiores de diseño para la conservación y el confort humano

Condiciones típicas	Temperatura operativa			Velocidad			Humedad relativa
	mínima	óptima	máxima	mínima	óptima	máxima	
Invierno	20	22	24	0,05	0,15	0,25	30-65%
Verano	23	25	27	0,1	0,25	>0,50	30-65%

Cuando se aplicaban simultáneamente varias técnicas pasivas se lograba paliar los efectos anteriores. La combinación que conseguía los mejores resultados para la preservación del patrimonio era la que contempla la utilización de doble ventana, aislamiento de las cubiertas (bóvedas o artesonados), aislamiento térmico de muros y suelo.

Las intervenciones que incorporaban aislamiento térmico en el suelo de las iglesias repercutían desfavorablemente en el confort térmico de los feligreses, ya que se eliminaba su efecto como disipador térmico durante gran parte del año.

La aplicación de técnicas ambientales activas, en combinación con las pasivas, en régimen de funcionando durante 24 h y 12 h, mejoraba las condiciones ambientales originales y disminuía el riesgo de degradación, no existiendo datos propicios para que se produjera el biodeterioro de los de las obras de arte.

Los sistemas activos estudiados que no realizan un control absoluto de la humedad interior (humectación o deshumectación), como era el caso de equipo autónomo, UTA (Unidad de Tratamiento del Aire) a dos tubos y solo ventilación agravaban la situación inicial, ya que los límites establecidos para este parámetro se superaban en primavera, verano y otoño, existiendo, por tanto, riesgo de deterioro del patrimonio mueble.

Cuando los sistemas activos de acondicionamiento ambiental actuaban únicamente cuando el edificio estaba ocupado (régimen de uso), existía riesgo de biodeterioro principalmente en primavera, en torno al 5% del tiempo.

El riesgo de daño mecánico sobre el patrimonio mueble de la muestra, no se producía si los sistemas activos funcionaban durante las 24 h, excepto en aquellos casos donde los equipos no controlan la HR, o cuya función exclusiva era la ventilación de las iglesias. Cuando el periodo de funcionamiento era de 12 h, existía la posibilidad de que las obras sufrieran daños mecánicos durante el 10%-15% del tiempo y con el funcionamiento en régimen de uso durante el 5% -10% del tiempo.

Conclusiones

Los edificios religiosos son una parte importante del patrimonio cultural, son documentos de nuestra herencia y tenemos la necesidad de preservarlos para el presente y para las futuras generaciones.

Las características esenciales de estos edificios son sus sistemas constructivos (antiguas técnicas de edificación); que no fueron diseñados como viviendas o como espacios de trabajo con un uso discontinuo, y que por su decoración son edificios vulnerables.

Originalmente, la mayoría de los lugares históricos de culto no estaban acondicionados, pero actualmente, estos edificios están siendo climatizados para proporcionar el confort térmico a los fieles y visitantes y para mejorar las condiciones del clima interior para la conservación de los edificios y de su contenido o para lograr una combinación de ambas. No obstante, los requisitos normales de climatización para el confort térmico pueden estar en conflicto con los de la conservación, y por lo tanto se necesita llegar a un equilibrio.

Muchos de estos recintos están siendo equipados de sistemas de acondicionamiento ambiental y, en muchos casos, de forma inadecuada. Así pues, para tratar estas cuestiones debemos cambiar la manera de intervenir en estos edificios existentes, de modo que reduzcamos los impactos negativos en su preservación y en el medioambiente.

Así que, con el fin de hacer frente a estos retos, se desarrolló una metodología que identificara el modo más adecuado de acondicionar estos espacios. La metodología utilizada en este estudio pudo evaluar la aplicación de técnicas ambientales pasivas y activas en las iglesias históricas localizadas en un clima Mediterráneo.

Con este trabajo de investigación se ha procurado contribuir en el aporte de soluciones a un problema funcional que se está produciendo hoy en día y donde las técnicas que se están aplicando no están presentando, en general, resultados óptimos. La aplicación de un método experimental contrastado permitió afirmar que la implementación de las propuestas de rehabilitación ambiental mejoraría las condiciones ambientales para la preservación del patrimonio y el confort humano. Igualmente, se pudo determinar el consumo de la instalación y estudiar previamente la viabilidad del sistema.

El presente trabajo, ha propuesto profundizar en el conocimiento del acondicionamiento higrotérmico de espacios religiosos para ofrecer a los técnicos competentes las pautas de diseño que le permitan predecir la conducta higrotérmica de estos espacios antes y después de la aplicación de técnicas ambientales.

Referencias

BALOCCO, C., COLAIANNI, A. (2018)."Assessment of energy sustainable operations on a historical building. The Dante Alighieri High School in Florence". *Sustainability*, 10 (6), 2054: 1-24. https://doi.org/10.3390/su10062054

BERARDINIS, P., ROTILIO, M., CAPANNOLO, L. (2017). "Energy and Sustainable Strategies in the renovation of existing buildings: an Italian Case Study". *Sustainability*, 9 (8) 1472: 1-20. https://doi.org/10.3390/su9081472

CAMUFFO, D., PAGAN, E., RISSANEN,S., BRATASZ, L., KOZLOWSKI, R., CAMUFFO, M. V. (2010). "An advanced church heating system favourable to artworks a contribution to European standardisation". *Journal of Cultural Heritage,* 11: 205-219. https://doi.org/10.1016/j.culher.2009.02.008

DIRECCIÓN GENERAL DE BELLAS ARTES Y BIENES CULTURALES Y DE ARCHIVO Y BIBLIOTECA. (2009). "*Conservación preventiva en lugares de culto*". Actas de las jornadas celebradas en el Instituto del Patrimonio Cultural de España. Madrid: Ministerio de Educación, Cultura y Deporte.

ERHARDT, D., MECKLENBURG, M. (1994). "Relative Humidity re-examined en Preventive conservation. Practice, Theory and Research". London: *The contributions to the Ottawaz II Congress*. Roy, Ashok and Smith, Perry: 32-38.

HUIJBREGTS, Z., SCHELLEN, H., SCHIJNDEL, J., ANKERSMIT, B. (2015). " Modelling of heat and moisture induced strain to assess the impact of present and historical indoor climate conditions on mechanical degradation of a wooden cabinet". *Journal of Cultural Heritage*, 16: 419-427. https://doi.org/10.1016/j.culher.2014.11.001

MAGRINI, A. Y. (2016). "The energy performance improvement of historic buildings and their environmental sustainability assessment". *Journal Cultural Heritage*. 21: 834-841. https://doi.org/10.1016/j.culher.2016.03.012

MOSOARCA, M., *et. al.* (2017). "Failure analysis of historical buildings due to climate change". *Engineering Failure analysis,* 82:666-680. https://doi.org/10.1016/j.engfailanal.2017.06.013

MUÑOZ, C. (2016). "Air conditioning and passive environmental techniques in historic churches in Mediterranean climate. A proposed method to assess damage risk and thermal comfort pre-intervention, simulation". *Energy and Buildings,* 130: 567-577. https://doi.org/10.1016/j.enbuild.2016.08.078

MUÑOZ-GONZALEZ, C. (2016). "Study of the implantation of the technologies of hygrothermal conditioning in the refurbishment project of churches. The case of Baroque churches in Moron de la Frontera". [PhD thesis]. Sevilla.

UNE-E-EN 15759-1.(2012). "Conservación del patrimonio cultural. Clima interior. Parte 1: Recomendaciones para la calefacción de iglesias, capillas y otros lugares de culto". Madrid.

UNE-EN 15757. (2011). "Conservación del patrimonio cultural. Especificaciones de temperatura y humedad relativa para limitar los daños mecánicos causados por el clima a los materiales orgánicos higroscópicos ". Madrid.

WESSBERGA, M., VYHLÍDAL, T. (2019). "A model-based method to control temperature and humidity in intermittently heated massive historic buildings". Sweden: *Building and Environment,* 159 (15): 1-16. https://doi.org/10.1016/j.buildenv.2019.03.024

Autor/es

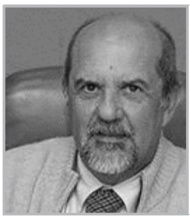
Carmen M.ª Muñoz González
carmenmgonzalez@uma.es
Departamento de Construcciones Arquitectónicas. Profesora Sustituta Interina. Universidad de Málaga

En el año 2008 finalizó sus estudios en la E.T.S de Arquitectura. Compaginando con el trabajo como arquitecta en estudios de arquitectura comenzó el Máster de Arquitectura y Patrimonio Histórico en el año 2008. Ese mismo año se incorporó como colaboradora en el Departamento de Construcciones Arquitectónicas I de la E.T.S.A. de la Universidad de Sevilla. Actualmente trabaja como profesora en del Departamento de Construcciones Arquitectónicas del a Universidad de Málaga y forma parte del grupo de investigación denominado TEP130: Arquitectura, Patrimonio y sostenibilidad: Acústica, Iluminación, Óptica y Energía, perteneciente al Plan Andaluz de Investigación, Desarrollo e Innovación (PAIDI). Ha trabajado como investigadora en varios proyectos de investigación desde el año 2010 hasta la actualidad, TECNOCAI-ACCIONA, Caracterización arquitectónica del parque de ascensores y su huella ecológica, SUB-UMBRA y Rehabitar el Carmen, Plan de rehabilitación energética del patrimonio residencial malacitano. En el año 2012 comenzó su doctorado con mención internacional, el cual finalizó en 2016. Su trayectoria en el campo de investigación se ha centrado en la línea de Building, Environment & Energy, y especialmente en dos líneas: Energy Efficiency and Lighting.

Ángel Luis Rodríguez León
leonr@us.es
Departamento de Construcciones Arquitectónicas Profesor Titular Universidad de Sevilla

Desde el año 1996, fecha en la que finalizo sus estudios en la E.T.S. de Arquitectura, forma parte del grupo de investigación denominado TEP130: Arquitectura, Patrimonio y Sostenibilidad: Acústica, Iluminación, Óptica y Energía, perteneciente al Plan Andaluz de Investigación, Desarrollo e Innovación. Mantiene una actividad docente e investigadora desde hace 22 años. Ha sido responsable de varias asignaturas de Acondicionamiento ambiental e Instalaciones del título de Arquitecto, siendo profesor en varios cursos de doctorado y títulos oficiales de máster, tanto de carácter nacional e internacional. En la actualidad es director del Título Propio de la US denominado Máster en Proyecto de Instalaciones en arquitectura: diseño, cálculo y eficiencia energética. Su trayectoria dentro del citado grupo de investigación se ha centrado en la línea: Building, Environment & Energy, y específicamente en dos sub-líneas: Room Acoustics y Energy Efficiency.

GRUPO ESPAÑOL de CONSERVACIÓN
International Institute for Conservation of historic and artistic works



Jaime Navarro Casas
jnavarro@us.es
Departamento de Construcciones Arquitectónicas
Catedrático

Es doctor arquitecto y Catedrático de Construcciones Arquitectónicas desde 1984. Ha sido director del Instituto Universitario de Ciencias de la Construcción (I.U.A.C.C) de la Universidad de Sevilla, director de la Escuela Técnica Superior de Arquitectura de Sevilla y además de miembro de la Comisión de Investigación de dicha Universidad. Forma parte del grupo de investigación denominado TEP130: Arquitectura, Patrimonio y Sostenibilidad: Acústica, Iluminación, Óptica y Energía, perteneciente al Plan Andaluz de Investigación. Actualmente, es el arquitecto de la Catedral de Sevilla. Es miembro de la comisión Docente del Máster Arquitectura y Restauración del Patrimonio Histórico. Su trayectoria dentro del citado grupo de investigación se ha centrado en la línea: Building, Environment & Energy, y específicamente en dos sub-líneas: Room Acoustics y Energy Efficiency and Artificial and Natural Lighting.

Jonathan Ruiz Jaramillo
jonaruizjara@uma.es
Departamento de Construcciones Arquitectónicas Profesor Ayudante Doctor
Universidad de Málaga

Arquitecto por la Universidad de Sevilla y Master en peritación y reparación de edificios. Doctor Arquitecto desde 2012, su tesis doctoral titulada "Comportamiento sísmico de edificios históricos. Las iglesias mudéjares de Sevilla" obtiene el premio Focus-Abengoa en el año 2013. Su labor investigadora se inicia en el año 2006 obteniendo una beca de formación de personal investigador (FPI) en el Departamento de Construcciones Arquitectónicas en la E.T.S. de Arquitectura de Sevilla en el marco del proyecto de investigación "Obtención de un método que garantice y optimice el empleo de elementos de madera al exterior frente a los agentes medioambientales". En el año 2011 se incorpora como profesor del Área de Construcciones Arquitectónicas de la ETS de Arquitectura de la Universidad de Málaga, donde en la actualidad desarrolla su actividad docente e investigadora. Ha participado en diversos proyectos de investigación como "Comportamiento sísmico de edificios construidos con técnicas tradicionales (fábrica de piedra, ladrillo, adobe, tapial, madera, etc.). Evaluación de la seguridad estructural. Propuesta de técnicas de rehabilitación no destructivas"; "Obtención de un método no contaminante y sustentable que permita la conservación de edificios antiguos construidos en madera. Aplicación al centro histórico de Morelia (México)"; "Restauración de bienes muebles e inmuebles en madera"; "Caracterización de materiales, componentes y estimación de características resistentes de iglesias altiplánicas (adobe y quincha), museo del olivo en quinto (tapial), restos tartésicos del carambolo"; "Norma sísmica. Análisis previo y rehabilitación ante daños de edificios e infraestructuras existentes". En la actualidad, junto a Luis García Pulido, es investigador principal del proyecto "Las atalayas que defendieron el reino nazarí de Granada. Análisis y documentación científica (NAZALAYA)". .

Catherine Teeling
catherine.teeling@port.ac.uk
Department Portsmouth School of Architecture. Lecture.Creative and Cultural Industries. Universidad de Portsmouth

After a career in practice of over 12 years and following the completion of a masters degree in 'Computation in Design' in 1996, Catherine has been working in academia as a senior lecturer in Architecture, firstly at the University of Greenwich teaching post grad level Architecture & as course leader for Masters in Urban Design. Where she secured 249K funding from HEFCE (Higher Education Funding Council of England) for a three year best practice learning and teaching project exploring the 'Creative use of Computers in Design' and established the first Electronic Design Studio (EDS) within a School of Architecture in the UK. The culmination of the project resulted in the first International Symposium on Digital Creativity in 2000. Catherine has worked at UCLA and undertook a six-month sabbatical as a visiting professor at Massachusetts Institute of Technology (MIT) in Boston, USA. Where she worked within the Computation Research Group and taught in the School of Architecture MIT. From 2003 she has been a Principal Lecturer and Course Director for masters in Architecture and undergraduate Interior Architecture & Design, at the Canterbury School of Architecture now the University of the Creative Arts.

https://doi.org/10.37558/gec.v17i1.758

Ge-conservación
Conservação | Conservation

Environmental degradation of Modern non-balanced glasses

Teresa Palomar, Alexandra Rodrigues

Abstract: Crizzling is an alteration pathology related to non-balanced glasses (high content of flux oxides and low content of stabilizer ones), which can produce an intense damage such as transparency losses, appearance of drops on the surface or cracking. In this study two case studies (outdoor and indoor environment) were presented. The main alteration agent for these glasses was the water (rain, condensation and environmental humidity). In the outdoor environment, the rain washed away the $[OH^-]$ ions formed during the alteration; however, the exposure to cyclic conditions accelerated its alteration rate. In the indoor environment, early stages revealed to consist of an alkali leaching that concentrates on the surface, on specific areas, that were related to water adsorption and consistent with the weeping phenomenon. Cracking and flaking of the surface represents a later stage, occurring specifically in unbalanced compositions.

Keywords: Glass, crizzling, natural environment, degradation mechanism

Degradación ambiental de vidrios modernos no equilibrados

Resumen: El *crizzling* es una patología de alteración relacionada con vidrios no equilibrados (con elevado contenido de óxidos fundentes y bajo de óxidos estabilizantes), que puede producir graves daños como pérdida de transparencia, aparición de gotas en la superficie o fisuras. En este estudio, se presentan dos casos de estudio (ambiente exterior e interior). El principal agente de alteración de estos vidrios es el agua (lluvia, condensación y humedad ambiental). En ambiente externo, la lluvia lavó los iones $[OH^-]$ formados durante la alteración; sin embargo, la exposición a condiciones cíclicas aceleró su velocidad de degradación. En ambientes interiores, se observó el estado inicial consistente en la lixiviación de los alcalinos a la superficie, en áreas relacionadas con la adsorción de agua y el fenómeno de *weeping*. La formación de fisuras y el desprendimiento de la superficie corresponden a un estado más avanzado que ocurre específicamente en composiciones no equilibradas..

Palabras clave: Vidrio, *crizzling*, ambiente natural, mecanismo de degradación

Introduction

Glass is usually related to a material with high chemical durability. However, its stability depends on the chemical composition and, therefore, the strength and distribution of the chemical bonds in the glass matrix.

Historical glasses are formed by a former oxide (SiO_2), flux oxides which decrease the melting temperature of the glass (Na_2O and K_2O), and stabilizer oxides which create bridges in the structure to increase the chemical stability (CaO and MgO). The presence of a low content of alkaline oxides, alkaline ions with low ionic radius ($Li^+ < Na^+ < K^+$) and the replacement of alkaline ions by Ca^{2+} or Mg^{2+} induce a high structural packing of the glass that favors their chemical durability (Fernández Navarro 2003). However, if the chemical composition of the glass is not balanced (high content of flux and low content of stabilizers), the chemical resistance decreases, accelerating the degradation rate. These low stable formulas can be due to an incorrect production technology, an over-purification of raw materials or a wrong batch formulation (Kunicki-Goldfinger 2003).

Another important factor for glass alteration is the environmental conditions. In outdoor environments, there are several factors that can react with the glass surface. The most aggressive ones are rain, wind, pollution, and aerosols (Woisetschläger *et al*. 2000; Munier *et al.* 2002; Melcher and Schreiner 2005; Melcher *et al.* 2008; Gentaz *et al.* 2011; Lombardo *et al*. 2014; Palomar *et al.* 2018; Palomar *et al.* 2019). In an indoor environment, these alteration agents are minimized; however, high environmental humidity and volatile organic compounds (VOCs), mainly the formic acid from the wood of the furniture, can accelerate the alteration mechanism.

The non-balanced glasses are especially susceptible to be altered. Their fast degradation frequently produces transparency loss, color change, the appearance of drops on the surface, salts, alteration layers, cracking, peeling and fracture, among others (Kunicki-Goldfinger 2008). This process, denominated crizzling, has been observed in soda, potash, mixed-alkali and lead silicate glass with low content of CaO and MgO, and predominantly in glasses from the 17^{th} to 19^{th} centuries from Italy, UK, and Central Europe. The crizzling is a severe pathology on glasses, observed generally in indoor environments; however, it can be also produced in external environments.

The main objective of this study is to characterize the effect of two different atmospheres on historical unbalanced glasses. For that, two sets of historical samples from the Cathedral of Girona, Spain (outdoor environment) and Museu Nacional de Arte Antiga (MNAA), Portugal (indoor environment) were characterized and compared.

Characterization techniques

The glass samples studied were characterized by the following techniques: optical microscopy (OM), X-ray fluorescence (XRF) spectrometry, and micro energy dispersive XRF, besides visual inspection.

OM was carried out by a Leica MZ16 reflected light microscope equipped with a Leica DC300 camera for Girona samples. The microscopic documentation in the case of MNAA replica samples was carried out using a light microscope (Axioplan 2, Zeiss) with digital camera (Nikon DMX). The whole surface area was observed in order to identify surface features.

For Girona samples, semi-quantitative chemical analysis by XRF was carried out by a PANalytical Axios wavelength dispersed X-ray spectrometer equipped with a tube of rhodium of 4 kW and 60 kV. Analytical determinations were undertaken through the standard-less analytical software IQ+ (PANalytical) based on fundamental parameters from synthetic oxides and well-characterized natural minerals. In addition, Sheffield glass nos. 7 and 10 (Society of Glass Technology) are commonly used as internal routine control standards. Powder samples (1 g approx.) for bulk XRF analysis were prepared by grinding body glass fragments, with their most external surfaces removed by polishing, in an agate mortar. After that, pressed boric acid pellets were made, using a mixture of n-butylmethacrylate and acetone (10:90 wt. %) as binding medium. This methodology agrees with the recommendation of the *Corpus Vitrearum* for the stained-glass analyses.

For MNAA glassworks, the analyses had to be done in situ in the museum, by non-invasive techniques such as portable micro-X-ray fluorescence (μ-EDXRF). The analyses were therefore achieved using a portable spectrometer ArtTAX 800, Bruker (Billerica, MA, USA). It operates with a molybdenum (Mo) X-ray source, focusing polycapillary lens and electro-thermally cooled xFlash (Si drift) detector, with 170 eV resolution. The accurate positioning system and polycapillary optics enabled a small area of primary radiation (70 μm) at the sample. The excitation and detection paths can be purged with helium to allow the detection of low Z elements down to aluminium. Spectra were acquired under the following conditions: voltage 40 kV, intensity 0.6 mA and live time of 360 s. Helium purging was used to allow the determination of elements down to aluminium. Each glass was analysed in (at least) three different areas. Quantitative analyses were carried out with the WinAXIL program, making use of spectra obtained from glass standards (A, B, C, and D from Corning Museum of Glass, Corning, NY, USA). All CMOG glass standards were used to validate the quantitative procedure.

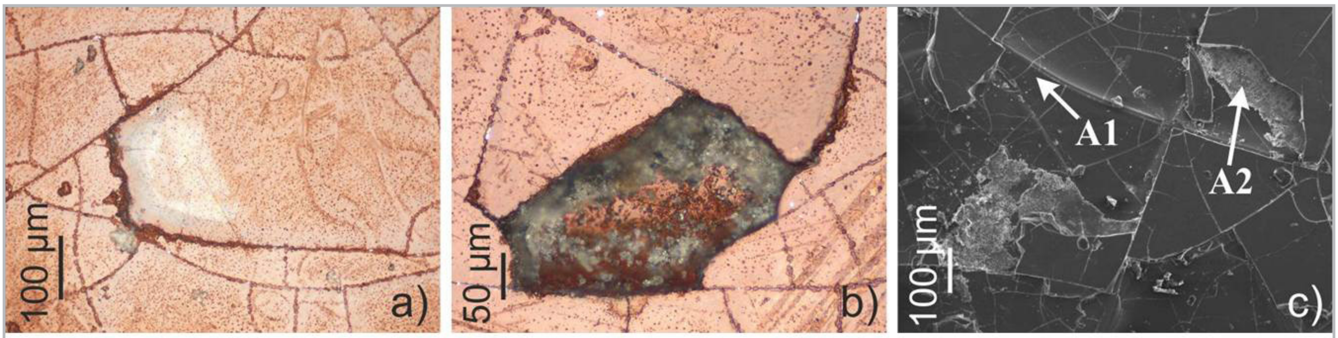
In-depth characterization of the corrosion processes were obtained with the production and use of replica samples, with similar composition to the historical materials. The methodology used for this study was adopted in VICARTE (Glass and Ceramics for the Arts) Research Unit since 2012 (Rodrigues *et al.* 2014), where through historical techniques – by blowing and fire-polishing the surfaces – they become as close as possible to the real historic ones. This revealed to be an important factor for the understanding of the alteration of these surfaces in the initial state, hence the composition of the glass surface is considered, as well as the chemistry of surface layers formed during the glass samples production.

Case Studies

—Crizzling in an outdoor environment: Cathedral of Girona

The stained-glass rose window "La Asunción de la Virgen María" ("Assumption of the Virgin Mary") is located in the west façade of the Cathedral of Girona since the 18^{th} century. According to some documents from the cathedral, their glasses were imported from Venetia (Italy) (Palomar *et al*. 2011; Palomar 2013).

All the analyzed samples presented an advance state of alteration on their external surface. They showed several fissures and crystalline deposits inside some cracks [figure 1 a]. Even, the accumulation of deposits raised the dealkalinized areas that caused their detachment [figure 1 b]. The morphology of the cavity, with conchoidal form,



Analyses	Na_2O	Al_2O_3	SiO_2	SO_2	Cl^-	K_2O	CaO
A1	0.6	1.9	84.2	1.6	0.3	4.9	6.4
A2	6.7	--	5.3	40.3	--	47.8	--

Figure 1.- a) Salts inside the fissures, b-c) detachment produced by salts growth. The attached table shows the results of the EDS microanalyses (wt. %).

pointed out that the detachment was mechanical instead of chemical, where the alteration front use to be continue or semispherical (Palomar 2018). It was also observed new fissures inside some cavities as result of the recurrence of the degradation process. The cracked surface presented a high content of SiO_2, result of an advanced state of dealkalinization, with crystals of K_2SO_4 [figure 1 c]. The formation of this salt was due to the reaction of the K^+-ions leached from the glass and the SO_2 from the polluted environment. K_2CO_3 was not detected because it has a higher solubility in aqueous solutions than K_2SO_4 (Palomar *et al.* 2017).

Regarding the surfaces exposed to the indoor environment, the surface of the sample G1 was completely fissured, as the outdoor surface, instead of the other three glasses that showed a net of aligned pits [figure 2 a and b]. This uncommon pathology could also be related to the same alteration mechanism but in a lesser degree. The humidity and condensation inside the building produced the dealkalinization process. The tensions between the silica gel layer and the bulk glass were liberated forming fissures. In this indoor environment, the fissures can trap the condensed humidity creating a stationary state inside them. The basic species formed inside the fissures as result of the alkaline attack caused the dynamic breakage of the glass, which forms the aligned pits (Palomar and Llorente 2016).

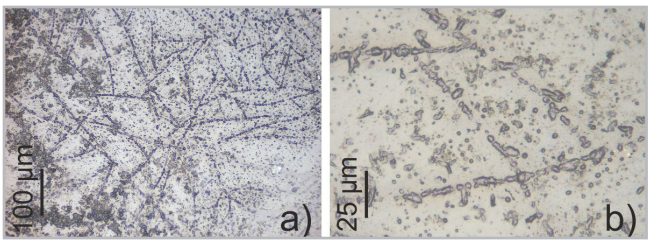


Figure 2.- a-b) Net of aligned pits.

This different mechanism is directly related to the chemical composition of the glasses. All of them were potash-lime silicate glasses with a high content of K_2O (~23 wt. %), SiO_2 (~65 wt. %), and relatively low content of CaO (~ 5 wt. %) [table 1]. However, small differences in their proportions are responsible for their different degree of alteration. The sample G1 has a higher ratio of alkaline oxides and silica ($[K_2O+Na_2O]/SiO_2$ = 0.42) and the highest ratio between the potash and the calcium oxides (K_2O/CaO = 4.72). This relatively higher content of alkaline oxides introduced several points of reticular discontinuity that promote hydration and surface dealkalinization, accelerating the degradation process.

Table 1.- Chemical composition of the stained glasses from the Cathedral of Girona

Samples	Chemical composition (wt%)				
	Na_2O	SiO_2	K_2O	CaO	Others
G1	2.26	62.71	24.01	5.09	5.93
G2	2.20	66.69	22.60	5.29	3.22
G3	1.41	64.55	24.36	5.19	4.49
G4	2.16	67.51	21.68	5.89	2.76

—Crizzling in an indoor environment: Museu Nacional de Arte Antiga (Portugal)

The glass objects in Museu Nacional de Arte Antiga (MNAA), Lisbon, Portugal, presented a high variability of compositions. The case study of the group of glassworks collected by Ferdinand II of Portugal is an especially valuable one. This collection represents a chronology which spanned many centuries, as well as multiple and widespread European production centers (Rodrigues and Martinho 2015). The glass objects with unbalanced compositions in this case were selected from 17th and 18th century productions, both Na- and K-rich compositions from the Venetian (or *façon de Venise*) and Bohemian types.

These unbalanced compositions exposed to an indoor environment presented signs of alteration. Museum objects, both with high Na_2O and K_2O content, evidenced weeping and crizzling of the surfaces [figure 3 a-d].

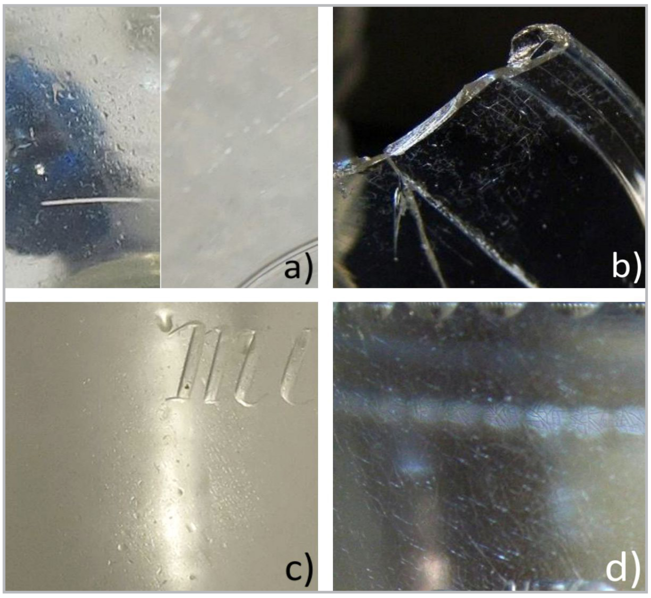


Figure 3.- a) Weeping (droplets on the surface, left) and crizzling (cracking of the glass, right) on object MNAA1074vid, a Na-rich glass; b) crizzling on object MNAA1079vid, a Na-rich glass; c) weeping phenomenon on MNAA1009vid, probably K-rich glass; d) crizzling phenomenon on MNAA 1043vid, a K-rich glass with PbO.

Due to the impossibility to observe these glasses under the OM, or to perform more invasive analyses, some compositions similar to analyzed glasses were replicated [Table 2] and aged under museum-like conditions (45%, 55%, 65% and 75% RH and room temperature) for the understanding of the early stages of the alteration processes.

The observations made under OM [figure 4 a and b] revealed that in the early stages (1 year exposure), the formations on the surface were consistent with the weeping phenomenon, which often precedes the crizzling (Koob, 2006). This occurred to both Na-rich and K-rich glass types, although to different extents. No crizzling was observed in these early stages.

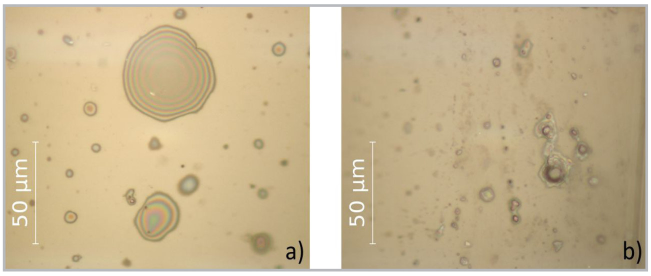


Figure 4.- OM analyses to the MNAA replica materials aged over 1 year. a) Na1 glass; b) K1 glass.

It seems that the cracking and flaking of the surface represents a later stage in an indoor environment, occurring specifically in unbalanced compositions. Moreover, crizzling was also more visible after washing, such as it was in the case of MNAA1079vid [figure 3 b]. When no run-off occurs (indoor environment), the alkaline species can still be partially retained in the alteration layer (Alloteau *et al*., 2017). If some run-off occurs or if the surfaces are washed, leached and probably even partially retained alkali is removed from the surface. The µ-EDXRF analyses performed on the surface of MNAA1079vid and MNAA1043vid clearly evidence a decrease in the alkaline species concentration, and an increase in silica (to around 80 wt. %, which could not have been the original glass composition) [table 3].

Table 2.- Chemical composition of the glassworks and replica materials from MNAA, Lisbon.

Samples	Chemical composition (wt%)				
(n=3)	Na_2O	SiO_2	K_2O	CaO	Others
MNAA1079vid	13.8*	79.0	2.73	3.47	1.0
Na1	17.2	70.5	3.00	5.00	4.3
Na2	14.8	70.5	3.15	5.25	6.3
MNAA1043vid	n.d.	80.0	7.5	1.9	10.6**
K1	–	69.1	18.0	3.5	9.4**

* - both Na2O and MgO, obtained through µ-XRF semi-quantification. /** - includes addition of PbO /n.d. - not detected /§ - replica materials were produced taking into consideration that the historic glass surfaces analyzed were depleted in alkali and enriched in SiO_2, as can be seen in the analyses in Figure 1

Table 3.- Chemical composition of two very different areas of the surface of the glasswork MNAA1079vid.

Samples			Chemical composition (wt%)				
(n=1)			Na_2O	SiO_2	K_2O	CaO	Others
MNAA1079vid	Min. values	More leached	5.7	84.8	2.7	3.5	3.3
	Max. values	Less leached	14.1	78.3	2.7	3.5	1.4

Discussion

In both environments, water was the main alteration agent of the unbalanced glasses. The rain (outdoor environment), the condensation water and the high humidity (indoor and outdoor environments) favor the leaching of the alkaline oxides from the glass lattice by the hydrolytic attack (Reaction 1) and the ionic exchange (Reaction 2). As result, a hydrated surface layer and drops of alkaline hydroxide were formed on the surface.

$$\equiv Si\text{-}O\text{-}Si\equiv + H_2O \longleftrightarrow 2 \equiv Si\text{-}OH \quad \text{Reaction 1)}$$
$$\equiv Si–O–X + H_2O \longrightarrow \equiv Si–O–H + XOH \text{ (X: Na, K) (Reaction 2)}$$

In an outdoor environment, the rainwater can wash the leached ions (alkaline, alkaline-earth and hydroxyl ions) from the glass surface. The removal of hydroxyl ions favors the maintenance of a neutral pH in the glass surface (Palomar *et al*. 2019). In addition, during the drought periods, the alkaline ions leached from the glass can react with the atmospheric gases (CO_2, SO_2, NO_X), solubilized in rainwater to form crystalline deposits (Reaction 3) (Melcher and Schreiner 2006).

$$2K^+ + SO_2 + 2OH^- \longrightarrow K_2SO_4 + H_2 \quad \text{(Reaction 3)}$$

In the indoor environment, the accumulation of the species $[OH^-]$ in the surface can cause two different alteration mechanisms. In a humid environment, the hygroscopicity of the alkaline hydroxide (KOH and NaOH) can attract more water accelerating the ionic exchange and the hydrolytic attack (Reaction 1 and 2) (Rodrigues *et al*. 2018a; Rodrigues *et al*. 2018b) and, therefore, the advance of the alteration layer to the glass bulk. However, if the content of $[OH^-]$ ions increases pH > 9, the siloxane bonds can be broken by the alkaline mechanism (Reaction 4). In both situations, the result is the formation of a thick alteration layer on the glass surface, and, in the worst scenario, it can produce the complete loss of the piece.

$$\equiv Si\text{-}O\text{-}Si\equiv + OH^- \longrightarrow \equiv SiOH + \equiv SiO^- \text{ (Reaction 4)}$$

If the altered glass piece is moved to an environment with lower humidity, the alteration layer could be fissured and cracked, favoring the detachment of the external layer [figure 1 b] and the drying of the surface drops. If salts are crystallized inside the fissures, they could force the cracks progression and the layer detachment.

In a more controlled and mild environment such as a museum, the evolution of the deterioration processes over time is dependent on the equilibrium (or fluctuations) of the humidity, temperature and its influence to a certain composition. On the other hand, the composition can be determinant for the reactivity with the water in the surrounding environment. This occurs since the hydration of the glass is much dependent on the alkali content (Reaction 2) and type (energies of complexation and hydration vary) (Alloteau *et al*., 2019). Due to the lack of washing away of the $[OH^-]$ ions trapped in the H-bonding network (or of their precursor H_2O species H-bonded to non-bringing oxygens), a self-catalytic effect of the system towards hydrolysis can sometimes occur (Alloteau *et al*., 2019). This is enhanced if the alkali content is high, since H-bound species are found in the alkali vicinity. Moreover, if not followed by repolymerization or rearrangement of the structure – being some structure more prone to form a passivation layer than other –, the leaching of the alkali ions can likely contribute to the opening of the porosity of the network and/or to the entrance of more environmental water molecules attracted to the surface by the leached species.

Conclusions

Glasses with unbalanced composition (flux vs. formers and stabilizers) are very susceptible to environmental agents, mainly the water (rainwater, condensation, and humidity). The excess of alkaline oxides and the low percentage of calcium and magnesium oxides in these glasses favors the ionic-exchange mechanism between the environmental water and the alkaline ions from the glass, which favors the formation of a silica gel layer on the surface. In an indoor environment, alkaline drops are formed and they stay on the surface favoring the alkaline attack, capable of breaking the siloxane Si–O–Si bonds in the glass. However, in outdoor environment, the contact with the rainwater is higher but it also removes the basic species. The formation of salts in dry atmospheres is also dangerous since they can force the detachment of the external alteration layer.

Acknowledgments

The authors acknowledge to Fernando Cortés (Cathedral of Canterbury) for supplying the glass samples and the Cathedral of Santa Maria Foundation of Vitoria-Gasteiz and Cervitrum research group (Institute of History, CSIC) for supporting the study of glass samples. Likewise, they acknowledge the partial financial support of the Fundación General CSIC (ComFuturo Programme), and of the Portuguese Science Foundation (projects Pest-OE/EAT/UI0729/2011, Pest-OE/EAT/UI0729/2014, and SFRH/BD/84675/2012). The authors also wish to acknowledge professional support of the CSIC Interdisciplinary Thematic Platform Open Heritage: Research and Society (PTI-PAIS).

References

ALLOTEAU, F., LEHUÉDÉ, P., MAJÉRUS, O., BIRON, I., DERVANIAN, A., CHARPENTIER, T., CAURANT, D., (2017) "New insight into atmospheric alteration of alkali-lime silicate glasses", *Corrosion Science* 122: 12–25. https://doi.org/10.1016/j.corsci.2017.03.025

ALLOTEAU, F., MAJÉRUS, O., BIRON, I., LEHUÉDÉ, P., CAURANT, D., CHARPENTIER, T., SEYEUX, A., (2019) "Temperature-dependent mechanisms of the atmospheric alteration of a mixed-alkali lime silicate glass", *Corrosion Science*. Elsevier, 159: p. 108129. https://doi.org/10.1016/j.corsci.2019.108129

FERNÁNDEZ NAVARRO, J. M. (2003). *El vidrio*, Madrid: Editorial CSIC - CSIC Press.

GENTAZ, L., LOMBARDO, T., LOISEL, C., CHABAS, A. VALLOTTO, M. (2011). "Early stage of weathering of medieval-like potash–lime model glass: evaluation of key factors", *Environmental Science and Pollution Research*, 18: 291-300. https://doi.org/10.1007/s11356-010-0370-7

GIBSON, L. T., WATT, C. M. (2010). "Acetic and formic acids emitted from wood samples and their effect on selected materials in museum environments", *Corrosion Science,* 52: 172-178. https://doi.org/10.1016/j.corsci.2009.08.054

GIN, S., COLLIN, M., JOLLIVET, P., FOURNIER, M., MINET, Y., DUPUY, L., MAHADEVAN, T., KERISIT, S., DU, J. (2018). "Dynamics of selfreorganization explains passivation of silicate glasses", *Nat. Commun*. 9: 1–9. https://doi.org/10.1038/s41467-018-04511-2

KOOB, S. (2006) *Conservation and care of glass objects*. Archetype.

KUNICKI-GOLDFINGER, J. 2003. "Preventive conservation strategy for glass collections. Identification of glass objects susceptible to crizzling" In: KOZLOWSKI, R. (ed.) *Proceedings of the 5th EC Conference 'Cultural Heritage Research: a Pan-European Challenge'*. Cracow, Poland: Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, European Community: 301-304.

KUNICKI-GOLDFINGER, J. J. (2008). "Unstable historic glass: symptoms, causes, mechanisms and conservation", *Studies in Conservation*, 53: 47-60. https://doi.org/10.1179/sic.2008.53.Supplement-2.47

LOMBARDO, T., CHABAS, A., VERNEY-CARRON, A., CACHIER, H., TRIQUET, S., DARCHY, S. (2014). "Physico-chemical characterisation of glass soiling in rural, urban and industrial environments", *Environmental Science and Pollution Research*, 21: 9251-9258. https://doi.org/10.1007/s11356-014-2853-4

MELCHER, M., SCHREINER, M. (2005). "Evaluation procedure for leaching studies on naturally weathered potash-lime-silica glasses with medieval composition by scanning electron microscopy", *Journal of Non-Crystalline Solids*, 351: 1210-1225. https://doi.org/10.1016/j.jnoncrysol.2005.02.020

MELCHER, M., SCHREINER, M. (2006). "Leaching studies on naturally weathered potash-lime–silica glasses", *Journal of Non-Crystalline Solids*, 352: 368-379. https://doi.org/10.1016/j.jnoncrysol.2006.01.017

MELCHER, M., SCHREINER, M., KREISLOVA, K. (2008). "Artificial weathering of model glasses with medieval compositions–an empirical study on the influence of particulates", *Physics and Chemistry of Glasses - European Journal of Glass Science andTechnology Part B,* 49: 346-356.

MUNIER, I., LEFÈVRE, R., GEOTTI-BIANCHINI, F. , VERITÀ, M. (2002). "Influence of polluted urban atmosphere on the weathering of low durability glasses", *Glass Technology*, 43: 225-237.

PALOMAR, T. (2013). *La interacción de los vidrios históricos con medios atmosféricos, acuáticos y enterramientos*. PhD dissertation, Universidad Aunónoma de Madrid (Spain).

PALOMAR, T. (2018). "Chemical composition and alteration processes of glasses from the Cathedral of León (Spain)", *Boletín de la Sociedad Española de Cerámica y Vidrio*, 57: 101-111. https://doi.org/10.1016/j.bsecv.2017.10.001

PALOMAR, T., AGUA, F., GARCÍA-HERAS, M., VILLEGAS, M. A. (2011). "Chemical degradation and chromophores of 18th century window glasses", *Glass Technology - European Journal of Glass Science and Technology Part A*, 52: 145-153. https://doi.org/10.13039/501100004837

PALOMAR, T., CHABAS, A., BASTIDAS, D. M., DE LA FUENTE, D. & VERNEY-CARRON, A. (2017). "Effect of marine aerosols on the alteration of silicate glasses", *Journal of Non-Crystalline Solids,* 471: 328-337. https://doi.org/10.1016/j.jnoncrysol.2017.06.013

PALOMAR, T., DE LA FUENTE, D., MORCILLO, M., ALVAREZ DE BUERGO, M., VILARIGUES, M. (2019). "Early stages of glass alteration in the coastal atmosphere", *Building and Environment,* 147: 305-313. https://doi.org/10.1016/j.buildenv.2018.10.034

PALOMAR, T., LLORENTE, I. (2016). "Decay processes of silicate glasses in river and marine aquatic environments", *Journal of Non-Crystalline Solids*, 449: 20-28. https://doi.org/10.1016/j.jnoncrysol.2016.07.009

PALOMAR, T., REDOL, P., CRUZ ALMEIDA, I., PEREIRA DA SILVA, E., VILARIGUES, M. (2018). "The influence of environment in the alteration of the stained-glass windows in Portuguese monuments", *Heritage*, 1: 25. https://doi.org/10.3390/heritage1020025

ROBINET, L., HALL, C., EREMIN, K., FEARN, S., TATE, J. (2009). "Alteration of soda silicate glasses by organic pollutants in museums: Mechanisms and kinetics", *Journal of Non-Crystalline Solids*, 355: 1479-1488. https://doi.org/10.1016/j.jnoncrysol.2009.05.011

RODRIGUES, A., GUTIERREZ-PATRICIO, S., MILLER, A. Z.; SAIZ-JIMENEZ, C., WILEY, R., NUNES, D., VILARIGUES, M., MACEDO, M. F (2014). "Fungal biodeterioration of stained-glass windows", *International Biodeterioration & Biodegradation*, 90: 152–160. https://doi.org/10.1016/j.ibiod.2014.03.007

RODRIGUES, A., MARTINHO., B. (2015) "The Assemblage of a Distinct Glass Collection – The creation and display of the glass and stained-glass collection of Ferdinand II of Portugal", *Revista de História da Arte,* 2: 76–93.

RODRIGUES, A., FEARN, S., PALOMAR, T., VILARIGUES, M. (2018a). "Early stages of surface alteration of soda-rich-silicate glasses in the museum environment", *Corrosion Science*, 143: 362-375. https://doi.org/10.1016/j.corsci.2018.08.012

RODRIGUES, A., FEARN, S., VILARIGUES, M. (2018b). "Historic K-rich silicate glass surface alteration: Behaviour of high-silica content matrices", *Corrosion Science*, 145: 249-261. https://doi.org/10.1016/j.corsci.2018.10.010

TÉTREAULT, J., SIROIS, J., STAMATOPOULOU, E. (1998). "Studies of lead corrosion in acetic acid environments", *Studies in Conservation*, 43: 17-32. https://doi.org/10.1179/sic.1998.43.1.17

THICKETT, D., LEE, L. R. (2004). *Selection of materials for the storage or display of museum objects,* London: The British Museum

VERHAAR, G., VAN BOMMEL, M. R, TENNENT, N. H. 2016. "Weeping Glass: The Identification of Ionic Species on the Surface of Vessel Glass Using Ion Chromatography". In: ROEMICH, H. & FAIR, L. (eds.) *Recent advances in glass and ceramics conservation 2016*. Paris: International Council of Museums - Committee for Conservation (ICOM-CC).

WOISETSCHLÄGER, G., DUTZ, M., PAUL, S., SCHREINER, M. (2000). "Weathering phenomena on naturally weathered potash-lime-silica-glass with Medieval composition studied by Secondary Electron Microscopy and Energy Dispersive Microanalysis", *Microchimica Acta,* 135: 121-130. https://doi.org/10.1007/s006040070001

Author/s

Teresa Palomar
t.palomar@csic.es
Institute of Ceramic and Glass (ICV-CSIC)

Doctor in Chemistry in the Autonoma University of Madrid in 2013 and Master in Conservation Science in the Pablo de Olavide University (Sevilla) in 2016. She has developed her scientific career in the Spanish National Research Council (CSIC), the Spanish Centre Foundation of Glass (FCNV) and the Research Unit VICARTE "Glass and Ceramic for the Arts" (Portugal). Currently, she is a postdoctoral researcher in the Institute of Ceramic and Glass (ICV-CSIC) with a contract to the Program Comfuturo "Un COMpromiso público privado con la ciencia y el FUTURO". Her scientific career has been focused on the conservation of inorganic materials from cultural heritage, especially on glass and metal. She has received the Special Mention in the Young Researcher on Conservation Science Award 2018 organized by the Spanish group of the International Institute for Conservation of Historic and Artistic Works.

Alexandra Rodrigues
aj.rodrigues@campus.fct.unl.pt
VICARTE Research Unit "Glass and Ceramic for the Arts"

Master and Ph.D. in Conservation and Restoration, specialization in Conservation Science, by Faculty of Science and Technology NOVA University of Lisbon (FCT-NOVA), in 2019. She has developed her scientific career in FCT-NOVA (Dep. Conservation and Restoration and Research Unit VICARTE "Glass and Ceramic for the Arts"), in collaboration with national cultural institutions such as Museu Nacional de Arte Antiga and National Palace of Pena (Portugal). She is currently a research fellow on the project NanoCStoneH (collaboration between Instituto Superior Técnico, Universidade de Lisboa, and Instituto Politécnico de Setúbal) granted by the Portuguese Foundation for Science and Technology, focused on the development of nanocomposite materials for consolidation of carbonate stone, and a VICARTE research member. Her scientific career has been focused on the conservation of inorganic materials from cultural heritage, especially on glass and stained-glass (study and characterization of collections; of materials and production techniques; and of glass corrosion processes), and currently also on stone preservation.

https://doi.org/10.37558/gec.v17i1.690


Ge-conservación
Conservação | Conservation

Laser-Induced Fluorescence mapping of pigments in *a secco* painted murals

Auxiliadora Gómez-Morón, Rocío Ortiz, Francesco Colao, Roberta Fantoni, Javier Becerra, Pilar Ortiz

Abstract: Laser-induced fluorescence is a remote analysis tool, successfully applied to real-time diagnosis of historical artworks, allowing the observation of features invisible to naked eye, as traces of retouches or presence of modern consolidants. Aim of the present paper is to introduce an historical database of pigments with respective binders and consolidants, realized to support the remote identification and mapping of these materials onto a mural in the least invasive way. To this aim, a monochromatic ultraviolet laser source emitting at 266nm with remote scanning has been used in combination with reflectance. Wall painted models have been built with *a secco* technique according to traditional recipes of XVII century. Digital image analysis, principal component analysis and spectral angle mapping have been carried out on data to get the mapping of two selected pigments, blue smalt and red carmine, in a real mural painting (XVII century). This non-invasive technique allowed us to operate remotely, a distance up to 11 m from the artwork. Results are consistent with traditional microanalysis performed to identity major pigments.

Keywords: Laser Induced Fluorescence, *a secco* technique database, surface mapping of pigments, smalt and carmine, non-invasive technique, cultural heritage application

Mapeo de fluorescencia inducida por láser de pigmentos *a secco* de pintura mural

Resumen: La fluorescencia inducida por láser es una técnica de análisis a distancia, aplicada con éxito en tiempo real para el diagnóstico de obras de arte, permitiendo la observación de características invisibles al ojo humano, como rastros de retoques o la presencia de consolidantes modernos. El objetivo de este artículo es generar una base de datos de pigmentos históricos con sus respectivos aglutinantes y consolidantes, realizada para respaldar la identificación remota y el mapeo de estos materiales en un mural de la forma menos invasiva posible. Para este objetivo, se ha utilizado una fuente láser monocromática ultravioleta que emite a 266nm con escaneado remoto en combinación con reflectancia. Se realizaron modelos de pintura mural en técnica *a secco* de acuerdo con las recetas tradicionales del siglo XVII. Análisis digital de imagen, análisis de componentes principales y mapeado de ángulo espectral ha sido llevado a cabo para obtener los datos de mapeado de dos pigmentos seleccionados, azul esmalte y rojo carmín en una pintura mural real (siglo XVII). Esta técnica no invasiva nos permitió trabajar de manera remota, a una distancia de 11 m de la obra de arte. Los resultados son consecuentes con los microanálisis tradicionales llevados a cabo para identificar pigmentos mayoritarios.

Palabras clave: Fluorescencia ultravioleta inducida por láser, base de datos de técnica *a secco*, mapeado superficial de pigmento, esmalte y carmín, técnica no invasiva, aplicación en patrimonio cultural

Introduction

Pigments characterization on different painted artwork surfaces has been already proposed by means of several optical and spectroscopic tools, among which there are reflectance (Acquaviva *et al*. 2008), micro-Raman (Bruni *et al.* 2002) and Laser Induced Breakdown Spectroscopy (LIBS) (Fotakis, Anglos & Couris 1997) techniques, utilized either alone or better in combination. However, their categorization based on invasive character and remote applicability, is the most various. In fact, LIBS and micro-Raman are mostly used in-situ at short distance, being the former micro-destructive and only the latter non -destructive at commonly utilized laser powers. Currently only reflectance is suitable to perform a true non-invasive remote application. The development of additional spectroscopic techniques suitable to remote imaging is therefore advisable.

Laser-induced fluorescence (LIF) resulted a very useful tool in non-destructive analysis in Cultural Heritage (CH) for painted surfaces analysis including pigments with organic binders (Borgia *et al.* 1998; Fotakis *et al*. 1996) and consolidants (Borgia *et al*. 1998; Fiorani *et al.* 2010). Former researches showed the successful application of this technique to identification of protein based media (Nevin & Anglos 2006; Nevin *et al*. 2006), pigment and acrylic resins (Domingo et al. 2001) and biological degradation (Colao *et al*. 2008; Lognoli *et al*. 2002;). The combination of LIF and Fourier Transform Raman Spectroscopy (FT-RS) was already proposed for pigments and patina investigations (Domingo *et al*. 2001; Oujja *et al*. 2012) and also time resolved operating mode was introduced to carry out specific diagnosis on painted surfaces (Comelli *et al.* 2004; Comelli *et al.* 2011). Fast remote scanning of large surfaces by LIF technique was already demonstrated (Cecchi *et al*. 2000), resulting in the major advantage of the technique whenever in situ measurements or sampling are not feasible. The state of the art on LIF application to material recognition and mapping in murals can be summarized as follows:

- Mapping pigments, whose identification is based on Raman or X-Ray Fluorescence (XFR) in situ measurements at selected points.

- Identifying and mapping consolidants, with support of time resolved LIF data acquisition and occasional combination with Raman in situ measurements at selected points.

- Mapping biodegradation with support of time resolved data acquisition and occasional combination local sampling and bio-chemical analysis for classification.

The equipment employed in this work for LIF (LidArt) is a lidar fluorosensor (optical radar detecting LIF signals (Lognoli *et al.* 2003)) capable to collect and spectrally analyse the fluorescence induced by ultraviolet (UV) laser on remote surfaces. It is suitable to fast process data by means of digital image analysis procedures (Carcagnì *et al*. 2007) for an optimal space-resolved model (Colao *et al*. 2008) on artworks, in which chemical characteristics invisible to the naked eye are highlighted. Its first version, patented in 2007 (Colao *et al*. 2007) and 2010 with improved tools (Caneve *et al.* 2010), has been employed in the Baptistery of Padua (Fantoni *et al*. 2013). In its latter version this equipment allows to scan surfaces in reflectance and fluorescence mode until 30 m distance with a spatial resolution better than 1 cm, collecting respective hyperspectral images.

The huge amount of collected data implies the use of advanced statistical tools and digital image analysis to process the spectra. In this case, grey scale and false-colour images reconstruction, principal component analysis (PCA) (Rencher 2002) and spectral angle mapping (SAM) (Girouard *et al.* 2004; Rashmi *et al*. 2014) have been employed to process the data acquired on the scanned surfaces.

In spite of the large efforts spent to extract and identify significant features from an automatic image analysis, in some cases the complex structure of the examined painted surface can make difficult to select specific spectral features to work with: these are the cases in which it is worthwhile to have at our disposal a series of reference spectra prepared according to historical recipes and restoration procedures. Preliminary studies on LIF of pigments following deep UV excitation were already conducted before the development of lidar fluorosensor systems, considering spectrally (Fantoni et al. 2000) and/or time resolved (Giardini-Guidoni et al. 2000) techniques. Organic molecules, characterized by the presence of conjugated double bonds, metal-aromatics cages, condensed aryl rings, usually have significant fluorescence fingerprints, although their emission wavelength and intensity can be strongly affected by the environmental condition (aggregation state, pH, etc.). This kind of molecules, usually soluble, are prevailing used as colorants in modern products (paints and inks), however a few natural derivatives (e.g. lakes from plants or animals) are well known colorants since the antiquity and are usually classified as organic pigments. Conversely the use of most inorganic pigments, except some of the modern synthetic pigments, date back to very early time in the past, even to the Palaeolithic age (e.g. iron oxides).

In spite of weak luminescence shown by most inorganic pigments alone upon near UV or visible excitation (Burrafato et al. 2004), a set of reference spectra prepared according to historical recipes for wall paintings can be extremely useful to support the identification of original materials and to investigate their distribution. Plaster, historically used binders and modern consolidants are indeed fluorescent upon deep UV excitation; the presence of pigments can give rise to additional bands or characteristic modulations in the detected emission due to selective re-absorption, with a mechanism which implies the pigment acting as a kind of "inner filter" (de la Rie & de la Rie 1982). A LIF database of historical pigments including non-fluorescing or scarcely fluorescing inorganic substances is useful provided that it takes into account these considerations.

The novelty in this paper is based on the realization of a database with LIF spectra of historical pigments, prepared according to traditional receipts, together with their binders in order to assess the possibility to map the distribution of pigments on real artwork painted surfaces, such as the one here considered as case study.

Methods and materials

—*Experimental Apparatus*

The lidar fluorosensor used for this study was already operated to collect hyperspectral fluorescence images of large artwork surfaces (e.g. frescos, decorated facades, paintings on different substrates) upon UV excitation either at 266 nm or at 355 nm (Fantoni *et al.* 2013).

The instrument detected the spectral LIF signature characteristic of different chemical compounds laying on the examined surface, including the effect of their mutual interference in the emission – re-absorption pattern, thus producing a fingerprint suitable to identify different materials utilized on the surface, as needed in planning restoration. In the present work the instrument was operated at 266 nm, which does give rise to fluorescence for most surface coatings and background plaster.

The sensor is based on an imaging spectrograph (Jobin-Yvon CP240) coupled with an intensified charge coupled device (ICCD - Andor iStar DH734) as light detector. The prototype is able to scan an image of 0.7×2.5 m^2 in less than 2 minutes when placed at 11.2 m average distance from the target.

The optical arrangement was characterized by having the spatial and spectral information on two mutually orthogonal directions imaged on the detector's sensitive area, with about 1 mm spatial resolution at 1 m distance and a spectral resolution better than 2 nm. In the setup used for the present measurements, the overall system specifications are: line scanning, horizontal resolution 640 pixels, 0.1 mrad angular resolution, minimum acquisition time per line 200 ms and field-of-view (FOV) aperture 5.7 deg.

In the utilized laser fluence range (< 0.01 mJ/cm^2) the instrument does not produce any photo-damage on surfaces painted with the *a fresco* or *a secco* technique, as formerly tested in laboratory samples (Colao *et al*. 2008; Raimondi *et al*. 2015). The absence of any photo-degradation on known photo-labile samples (such as white lead paint (Raimondi *et al.* 2015)) in the present database was furtherly checked by optical microscopy inspection after the UV irradiation needed to process LIF signals.

Reference data are acquired by the LIF scanning sensor; the system setup was such to have a spatial resolution of approximately 3x3 mm, and the samples in powder form were put in circular holder with a clear aperture 18 mm approx. In such a way we have not less than 20 spectra simultaneously acquired from the same sample and under the same excitation conditions. The average spectrum is computed as arithmetic mean to increase the S/N ratio.

This lidar fluorosensor can also acquire spectrally resolved reflectance spectra when an appropriate illuminating light is used; from this data a red-green-blue (RGB) reconstructed image in the visible range is produced. To operate in reflectance mode the laser is switched off, a halogen lamp with at less 1000W power is turned on and the optical detector shutter remains opened for the time needed to acquire the image. After calibration, the collected spectra can be used for the computation of standard CIE/lab colorimetric measurements.

—*Operating modes*

During the measurement campaign here reported, the system was sequentially operated in either modes: fluorescence and reflectance mode.

Off line processing of the acquired data is performed to take into account both the wavelength dependent detector efficiency and the spatially dependent collection efficiency. After the calibration we assume to produce images with an efficiency and spatial resolution that are nominally uniform in the entire examined spectral range.

—*LIF Data analysis*

The spectra have been studied by chemometric techniques (PCA) (Rencher 2002) and projection operators (SAM) (Girouard *et al.* 2004; Rashmi *et al.* 2014) and coupled to digital image analysis in order to permit a rapid mapping of the surface by emitted signal similarity.

Major spectral features in LIF spectra are identified by PCA. Although the principal components (PCs) do not possess any direct physical meaning, they can conveniently be described in terms of bands since the overall LIF spectra due to the presence of different surface constituents result from linear combination of PC with appropriate weights (scores).

In the present study PCA is aimed at the identification of prominent spectral features, thus avoiding a manual time-consuming examination of each single spectrum acquired. This procedure has the advantages to be fast and run in a semiautomatic mode, however it has the inconvenience to supply only a global analysis, possibly ignoring the local peculiarities lacking enough statistical significance to be represented in the considered PC. To overcome this drawback, a detailed local analysis can additionally be performed on subsets of the scanned areas, with a separate analysis of the PCs. Once identified, spectral bands are sought for in the acquired LIF spectra, completing the data analysis.

A different method used in the analysis of spectral images, concerns the identification of pixels having a specific spectral content. A typical case is the identification of a given constituent: such task is accomplished either by a band analysis based on spectral deconvolution, or by using spectral mapper algorithms as SAM. This case requires the availability of reliable reference spectra, possibly measured in an analogous matrix in order to account also for interactions among different painted layers. Although the mapper algorithms perform well with a low computational cost, their results based on a partial information are of course less accurate with respect to the complete band analysis procedures, and their application often follows the latter only once major features have been identified.

—*Database models*

Modelling of the wall painting with a secco technique has been performed according to researches carried out by the Andalusian Institute of Cultural Heritage (IAPH) in the wall painted of Domingo Martínez from the XVII century (Gómez Morón 2008), relevant to the considered case study, and Cenino Cenini´s recipes (Cennini 1859) widely used in the Renaissance and the successive periods until the end of XVIII century. The employ of linseed oil as a medium for mural painting was a common practise during the Spanish Baroque, being described this technique by Francisco Pacheco in his treatise *The Art of Painting* in 1649 (Pacheco 1871).

More than forty plaster models have been built in the laboratory to emulate the surfaces of these murals [figure 1] over a primer layer of gypsum. With this purpose, several bricks have been covered with a mixture of gypsum and sand with animal glue binder. The preparation was done with sand from Guadalquivir River (near to Seville) and gypsum in relationship 1:6. The sand has a fineness of 11.2±3.6 µm. The animal glue (rabbit skin glue) was previously heated with a water bath to acquire a pasty consistency, and then it was added to the mixture gypsum/sand or to the gypsum until saturation

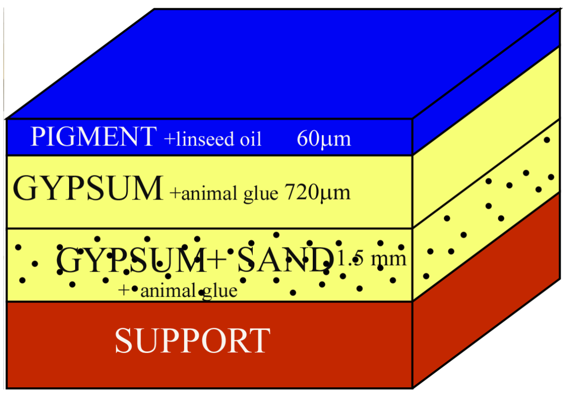


Figure 1.- Laboratory preparation of the plaster for *a secco* painted model scheme of composition and thickness of the plaster respective layers.

in the layer of plaster. The plaster layers were dried a room temperature for two weeks. These layers were the substrate upon which different pigments from KREMER historic pigments [table 1] and products from CTS Srl, have been applied with linseed oil. The colour layer was applied with pigment and linseed oil in ratio 3 (pigment): 1 (linseed). Each model has a surface near 15x5 cm, so it was possible to obtain their LIF signal signature in the considered matrix from the scanned surface. Table I shows the model samples, the mixture compositions and pigments are grouped according to their colours.

The bricks covered by the wall painted models were examined three months after preparation, in order to take into account at least fast aging effects. Note that the binder used, linseed oil in a layer of approximately 60 µm thickness, is known to be fluorescent upon UV laser excitation, giving rise to a spectrum that for the pure sample is slowly changing in intensity and peak position with ageing, where the early effects mostly correspond to blue intensity increase (Miyoshi 1985). For LIF spectral characterization the painted brick has been allocated in a vertical support and scanned at 7 m distance.

All samples listed in Table I showed significant luminescence signal in the examined near UV-visible range, with characteristic modulation (emission or re-absorption) which can be associated to pigments presence in the considered matrix. In order to show examples of the spectra collected, only those relevant to the examined case study (sect. 3.2) are reported in this paper, but the entire data set is available on line as additional material and can be consulted to evaluate the possibility of identifying a single pigment in the presence of others characterized by a similar colour in a real historical sample.

In order to possibly discriminate effects relevant to a specific pigment with respect to those related to

Table 1.- Colour, composition and pigments for Database of a secco technique wall painting models. All materials were applied on plaster, as described in the text, with addition of linseed oil. (*)

Layer color	Common or chemical name (id.#, Kremer order number)
No pigment	Plaster (P1); P1+ linseed oil (P2); P1+ benzyl gel (P22); P1+ tea (P23); P1+ Ammonium citrates (P24, P25); P1+ Paraloid B72 in nitrotoluene -15%- (P26); P1+ DMSO (P27)
White	Lead White (P3, 460009); Calcium White (P4, 58720); Lead Sulfate (P5, 46050); Lithopone (P33, 46100)
Yellow	Lead Tin Yellow (P6, 101009); Orpigment (P35, 10700); Naples Yellow (P17, P32, 431229); Massicot (P36, 43010)
Red/Organge/ Brown	Cinnabar (P7, P21, 10624); Haematite (P8, 48651); Carmine Naccarat made of cochineal (P9, 42100); Red Lead, Minium (P10, 425009); Armenian bole (P28, 40503); Raw Sienna (P11, P12, 40400); Realgar (P31, 10800); Madder Lake (P40, 372141)
Blue	Ultramarine Blue (P13, 45000); Smalt (P14, 10000); Lapis Lazuli (P15, 10500); Azurite (P16, 10200)
Green	Malachite (P18, 10300); Cyprus Green Earth (P29, 17400); Verona Green Earth (P30, 11000); Bavarian Green Earth (P38, 11100); Copper Resinate (P39, 12200)
Black	Manganese Black (P19, 47500); Verdigris (P34, 44450) Ivory Black (P20, 12000); Grape Black (P37, 12015), Furnace Black (P41)

(*) all spectra collected are available online as additional material its presence in the considered matrix, the spectral acquisitions were repeated over layers of each pure pigment in powder. Samples were prepared by gently and uniformly pressing a few mm thick layer of each pigment powder in order to fill (2 cm^2 x 2 mm) cylindrical holes on aluminium foil used as holders, which were allocate at 7 m from LIF equipment for remote spectra collection. Comments on pure pigments spectra are reported here only for selected samples (ivory and furnace black, azurite and smalt blue, carmine nacarat made of cochineal, madder lake and cinnabar red) relevant to the real case studied in the on-site application.

—*On-site application*

On-site measurements were carried out in the vault of the Chapel Our Lady of Good Air that is part of the Palace of Saint Elmo in Seville, the residence of the president of the Andalusian Government. This Chapel of the XVII century had just been restored by the IAPH, employing different non-destructive techniques for diagnosis and restoration monitoring.

Namely, this work presents the application of LIF database to pigments mapping on the wall paintings the Glorification of the Virgin from Domingo Martinez after its restoration.

Three images acquisitions were performed on the virgin silhouette [figure 2]; table II shows the image acquisition setting in each scan. The wall painting scanned area was about 2.5 m^2, while image size in pixel is 128 pixels in height and a variable number of pixels in width [table II].

Table II.- Image acquisition settings for three scans

Scans	1-2	3
Gate	500ms	500ms
Gain	230	230
Laser current	100A	OFF
Halogen lamp	OFF	2000W
Optical f-number	3	22
Spectral focus	UV-VIS	VIS
Back-ground	No	No
Lines	600	600
Scan width	11000	11000
Distance	11.2m	11.2m

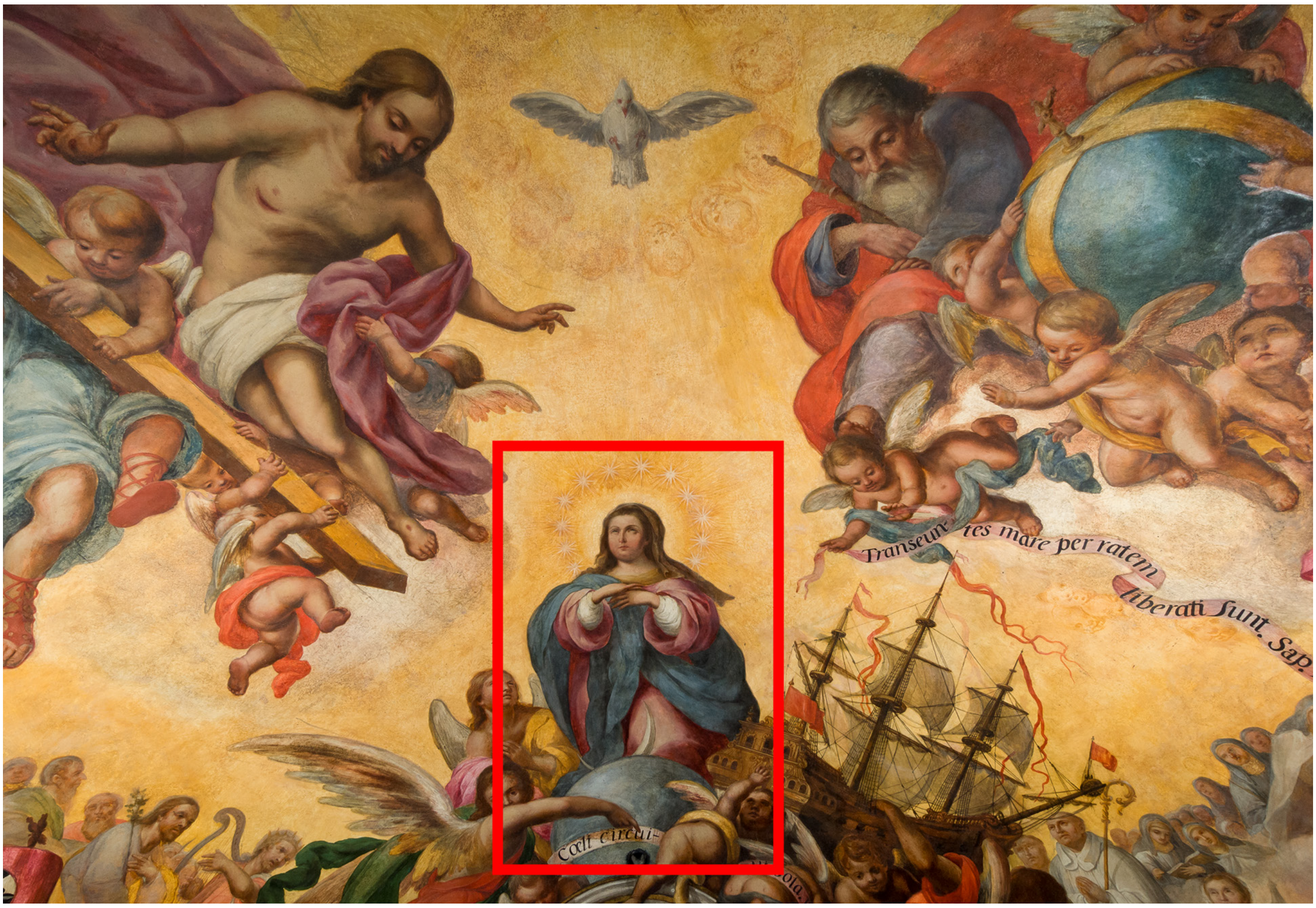


Figure 2.- Scanned zone of the vault of the Our Lady of Good Air (Seville).

— *Traditional Analysis*

To validate the results obtained, the LIF identification was compared with traditional analysis after the sampling performed following the recommendations of the standard UNE-EN-16085:2014 (AENOR 2014). Micrometer-sized samples were taken to analyse the pigment layers. Sampled specimens were examined by optical microscopy (OM), Scanning electron microscopy/energy dispersive X-ray (SEM-EDX) spectroscopy and X-Ray Fluorescence (XRF) to characterize the substrate; Fourier-transform infrared spectroscopy (FTIR) and gas chromatography with mass spectrometry (GC-MS) were applied to the binder analysis and to detect occasional presence of modern resins used as consolidants.

It is worth mentioning that, twenty-two samples taken in the vaults correspond to less than 1 cm^2 of investigated surface and sampling required the installation of scaffolding, on the other hand the LidArt apparatus allowed to scan quickly near 7 m^2 without any damage to the murals and without any scaffolding.

Results and discussion

—LIF study on laboratory samples

The fluorescence spectra from sample models were collected upon laser excitation at 266 nm. Figures 3 A-F and 4 A-C show the spectra acquired on selected painted plasters, possible references for the case study discussed in the following, and on some involved pure pigments, respectively. The database with all the LIF spectrum of pigments/colorants on plaster with linseed oil has been enclosed as Annex 1.

The spectral emissions, once well distinct features are present, allow for the identification of different pigment/binder mixtures. From sample to sample we observed variations in absolute fluorescence intensity of more than one order of magnitude, however the signal to noise ratio was higher than 20 in all the reported measurements and normalized spectra are plotted.

In case of pigments layered on plaster [figures 3A-F] the fluorescence consists of a broad band centred at 450 nm

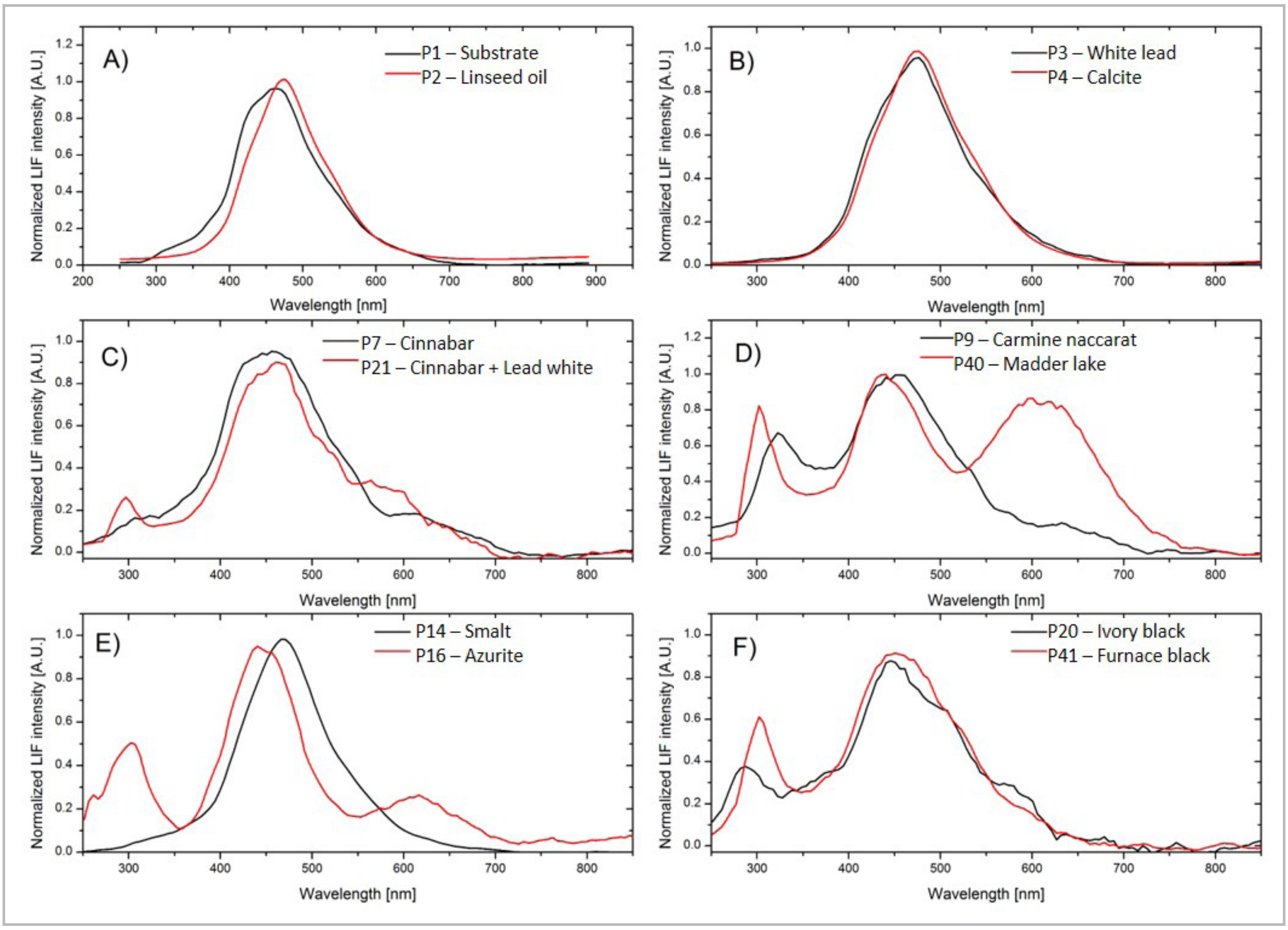


Figure 3.- Normalized LIF spectra of painted substrates: A – substrate samples: alone (P1, black line) and with linseed oil (P2, red line); B - white samples: lead white (P3, black line) and calcite (P4, red line); C - cinnabar samples: alone (P7, black line) and with lead white (P21 red line); D – red samples: carmine naccarat made of cochineal (P9, black line) and madder lake (P40, red line); E – blue samples: smalt (P14, black line) and azurite (P16, red line); F - black samples: ivory black (P20, black line) and furnace black (P41, red line).

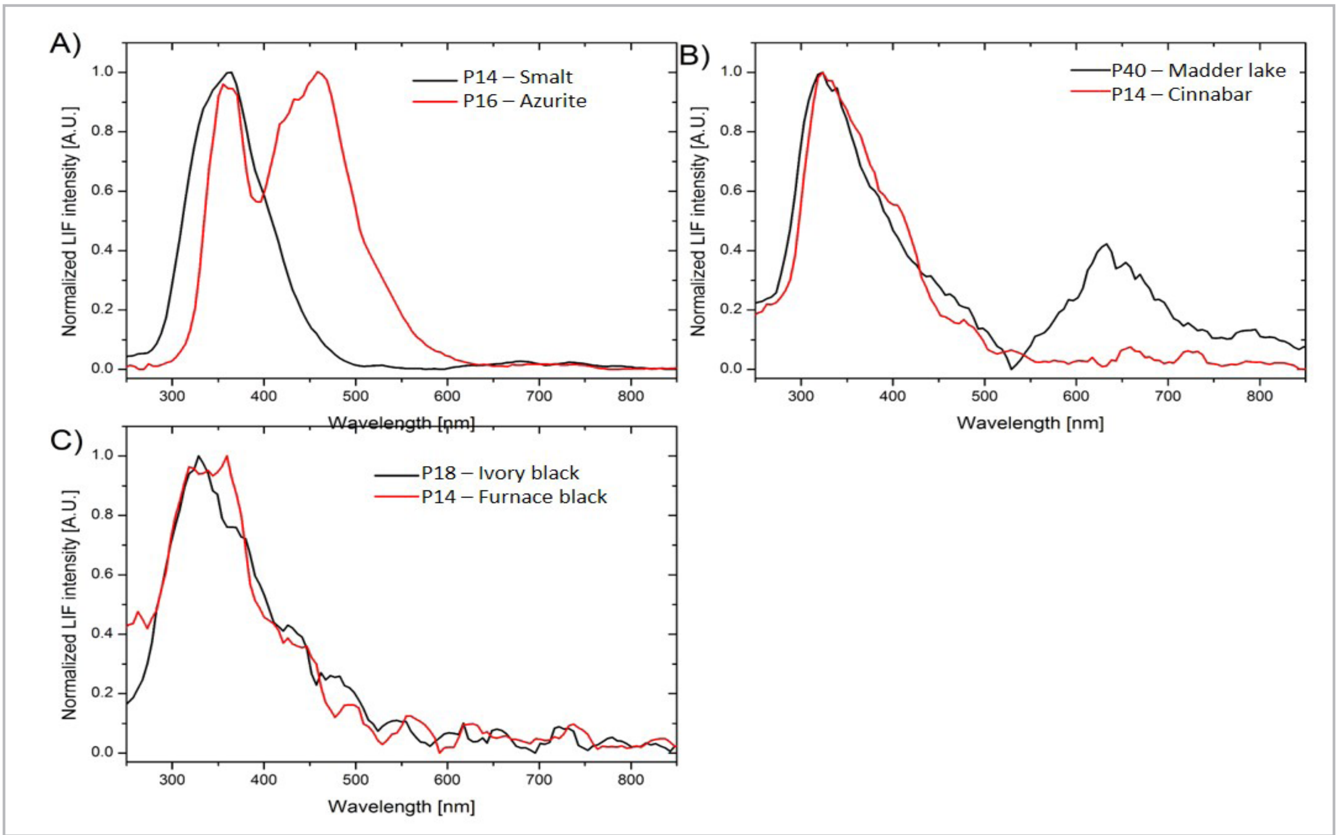


Figure 4.- LIF spectra of pigments in powder form: A – blue pigments: smalt (P14, black line) and azurite (P16, red line); B - red pigments: madder lake (P40, black line) and cinnabar (P7, red line); C - black pigments: ivory black (P20, black line) and furnace black (P41, red line).

and width of 200 nm. The substrate and binding media [figures 3A-B] contribute to the total fluorescence with a broadband emission; in particular the spectrum recorded for the substrate alone (curve P1 in figure 3A) shows an emission peaked at around 450 nm. From this observation we deduce that the main contribution to the emitted band is due to the fluorescence of matrix, that is due to the mixture of substrate (gypsum, quartz and calcite) and binding media (animal glue and linseed oil); over the matrix's band, other spectral emissions are due to the pigments and consolidant components.

As an example, figure 3A shows the difference from the white layer of the plaster alone (P1) and its overlap with the binder, linseed oil (P2); while the effect of the presence of calcite and lead white (P3 and P4) applied with linseed oil on the plaster is shown in figure 3B. In both figures the linseed oil application corresponds to a reduction in the intense plaster UV band peaked at 320-400 nm probably for a selective re-absorption (Verri *et al.* 2008; Simonot, Thoury & Delaney 2011). The presence of the considered white pigments, although causing some attenuation, does not seem to further affect the plaster spectral shape; although the lead white has a characteristic broad emission peaked at 400 nm (Giardini-Guidoni *et al.* 2000) which overlaps to the former.

Differences related to various pigment addition can be observed in figures 3 C-F. As a specific feature some pigments, especially organic pigments such as different types of red, present an additional UV emission band peaked around 300 nm, which is missing for smalt and cinnabar. This band can give a strong indication of the presence of an additional pigment even in small quantity, for instance of lead white to obtain pink from cinnabar red [figure 3C]. The effect of a layer of cinnabar, added either pure or in mix with lead white (curve P7 and curve P21, respectively in figure 3C), is the presence of a characteristic weak band peaked at 610 nm according to Mounier *et al.* (2014), while the addition of white lead give rise to the mentioned UV band and causes some changes in the spectral zone between 450 and 500 nm and a significant reduction of intensity, with the observed increase in signal/noise ratio (SNR).

The spectra of red organic pigments, reported in figure 3D, show distinct features: madder lake samples (P40) has broad bands similar to those describes by Comelli et al. (2011) for madder lake (between 600 and 615 nm), while in carmine nacarat made of cochineal (P9) the intense band peaked at 610 nm is replaced by a significant broad shoulder with a maximum around 635 nm. This emission maximum is identified by Comelli *et al.* (2011) as an anthraquinone-based lake of animal origin, for example, cochineal or kermes. These spectral signatures would allow identifying between some red organic pigments and even its origin, although the remote fluorescence cannot compete with micro-spectrofluorimetry coupled to chemometrics (Nabais *et al.* 2018) in the identification of manufacturing receipt. The relative intensity recorded on the red band between 610-640 nm is however in both cases larger than for the red band of cinnabar red, which is definitely peaked at a longer wavelength (around 650 nm).

Figure 3E shows the difference of spectral features between two inorganic blue pigments: smalt and azurite. Both pigments originate a broad band, not assigned, peaked between 400 and 500 nm. However, in the case of azurite this band appears blue shifted, it is accompanied by secondary emission at longer wavelengths and there is an emerging UV tail from plaster background. Thus, it will be possible to distinguish smalt from azurite. Discrimination of smalt from other blue pigments would be not so straightforward from LIF spectra alone (see supplementary material).

Figure 3F reports results for black pigments: furnace black (P41 curve) and ivory black (P20 curve). The weak spectra recorded in both cases are dominated by the rather uniform absorption of both pigments in the entire visible range (see again the SNR increase with respect to the plaster curve), the only distinct feature seems to be the most intense tail of UV emission peaked around 300 nm recorded for P41 (furnace black), which might be related to the plaster background, so it is difficult to carry out an identification.

From figures 3C-F we can conclude that each coloured layer, although characterized by a weak overall emission, has a spectral signature, as a fingerprint, resulting from the interaction between layers and components with different absorption/emission behaviour in the considered sample model.

The fluorescence observed from each of the pigments painted on the plaster substrate, closely follows what obtained in the measurements from the corresponding pigment in powder form (pure pigment) reported in figure 4, where it should be noticed the lack of the emission band typical of the plaster substrate.

On the powder pigments, despite the peculiar low SNR, some characteristic signatures appear in the visible at least for the considered blue and red colorants [figures 4A-B]. Note that the observed features are not system artefacts, as checked on Spectralon, a standard material which gave rise only to a flat background. The spectra of blue inorganic pigments, azurite and smalt respectively [figure 4A], present distinct features: the smalt spectrum has a single broad band at peaked 390 nm while the azurite shows a second band with comparable peaked at 480 nm. On the other hand, the black pigments considered appear undistinguishable also from their pure pigment spectra [figure 4C].

The difference between the red pigments: cinnabar and madder lake [Figure 4B] is fully consistent with what observed in case of the same pigments with the binder on plaster, the second band of madder lake peaked at 610 nm emerging very clearly. Two different trends are consistently observed when the spectrum of pure pigments and layers are compared in all analysed samples: on one hand we observe a decrease of the fluorescence emission in the ultraviolet region between 290 and 400 nm on plaster samples, while on the other hand the band at 450-500 nm is modulated because of the simultaneous contributions from pigment emission/absorption and plaster emission. Spectral features emerge clearly on red tail where the plaster contribution is negligible.

These observations suggest that the presence of the substrate alter in a significant way the emitted spectrum related to pigment fluorescence. It is confirmed that an appropriate deconvolution is required to separate the contribution arising from different components, whenever it is possible. Alternatively, a database built with appropriate matrix is necessary to take in account re-absorption and other secondary effects. In fact, strong UV-visible absorption from some pigments may also be responsible for complex features, generating a lack of intensity that cannot be reproduced by a deconvolution based on a simple superposition of positive components.

Summarising, the fluorescence from the plaster alone for a secco technique wall painting, and from the plaster and binder plus pigments, was examined in different experiments, to isolate their spectral contributions in historical matrices. The emission feature of the plaster is an intense band at 450-500nm, and each mixture has an own spectra or fingerprint due to the contribution of different components on the layers. The reference spectra from our laboratory model [figure 3], containing ancient pigments and colorants with their binder on plaster, are proposed to be used as guidelines to select SAM endpoints on on-site wall painted scanned by LIF to discriminate the presence of pigments in the artwork under investigation. A quantitative agreement cannot be expected due to possible differences in the various historical receipts, to long-term aging effects and to possible presence of modern consolidant on the real surface which are known to alter the spectral signatures.

— *LIF database application on-site*

The application of the above described database was carried out on the vault of the Chapel Our Lady of Good Air in Seville (Spain) scanned by our LidArt prototype.

The interpretation of the spectra was simplified by PCA. Five PCs [figure 5A bottom left] show most of the variance of the spectrum in each point analysed of the surface. These PCs have relationship with the main chemical products presents onto the surfaces, they could be considered as a spectral signature (Fiorani *et al.* 2010) containing the spectral information needed to look for at our pigments-on-plaster database. PCA shows a clear peak at 360nm due to the presence of acrylic products (Paraloid, database P26), as reported in former studies (Fiorani *et al.* 2010; Fantoni *et al.* 2013).

A significant tail on the red, extending above 600 nm in PC3, suggests the widespread presence of a red organic pigment. Other contributions, with signatures between 400 and 500 nm, that are more difficult to understand, require the use of our database with standards on plaster.

With this purpose a spectral analysis was carried out in fixed zones at different points of the images. Spectra collected in the standard database were utilized to perform a two-step mapping procedure based on the SAM algorithm projected onto the entire scanned surface, as described in the following.

The area studied was first digitalized in a false colour fluorescence image [figure 5A, top] in order to evaluate the spatial accuracy of the scans and to achieve an overview of pigments distribution. Internal reference spectra with characteristic signatures are shown in figure 5B-C (bottom). These spectra have been utilized as endpoints for SAM projections on the entire image with the purpose to better identify different areas. Two regions can be clearly identified [figures 5B-C, top].

Figures 5B-C (bottom) report the spectral signature associated to smalt blue peaked at shorter wavelengths [figure 3E curve P14] and carmine naccarat made of cochineal spectra, the latter characterized by the secondary long wavelength structure peaked around 410 nm [figure 3D curve P9]. The omitted fluorescence emission at 610 nm allowed us to discard the use of madder lake. Despite the evident contribution of a red lake of animal origin (i.e. cochineal), the presence of other red pigments, e.g. cinnabar with a weaker but broader red emission, cannot be ruled out with current LIF measurements.

Red and blue pigments maps [figures 5B and 5C top] match greatly with blue and red colours in the image [figure 2]. The first figure shows the use of blue pigment found in the mantle, meanwhile the second one demonstrates the use of red organic pigment mostly in the red robe, though it appeared also used in other zones as part of colour mixtures specially to create some contrast to the background. The possible identification of red organic pigment as lake of animal origin (probably cochineal) is consistent with the wall painting dating, because of the diffusion of the Mexican cochineal in European countries after the discovery of America (Cardon 2007), although it is well known that cochineal lake was previously used in Europe, for example, Polish, Armenian or Ararat cochineals (Eastaugh *et al*. 2004).

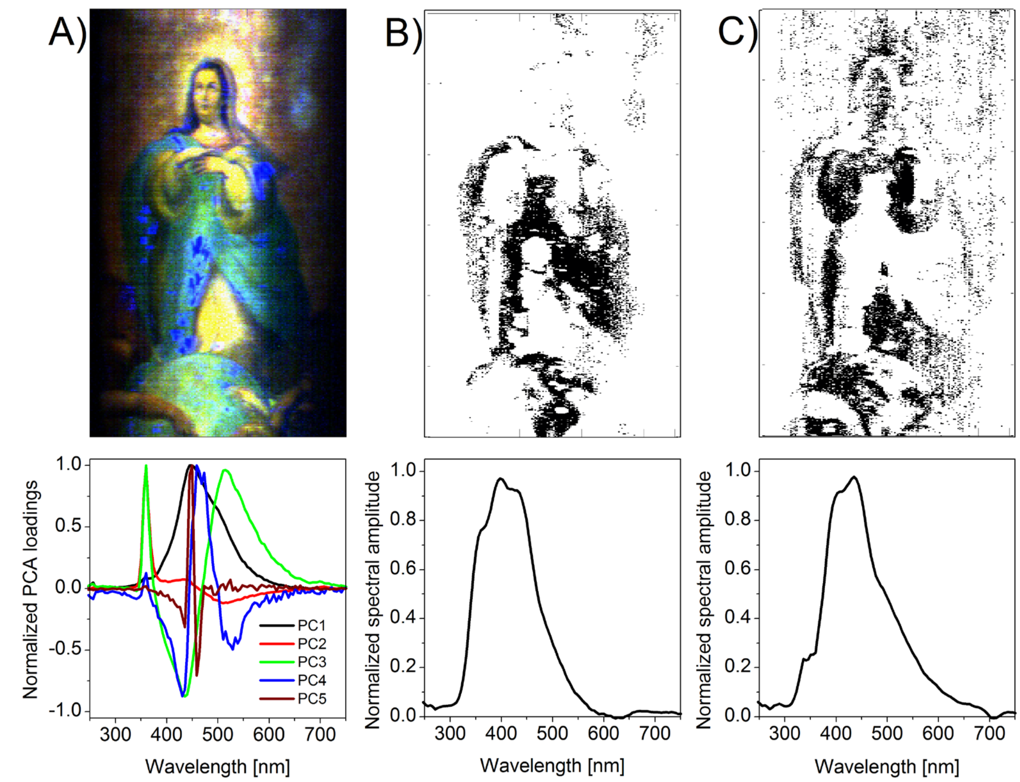


Figure 5.- Results from the fluorescence image analysis performed on the scanned wall painting representing the Glorification of the Virgin. A) top figure - RGB false colour image obtained by combining the fluorescence intensities emitted at 515, 445 and 360 nm; bottom figure - PCA of spectra from image; B) top figure - Similarity image mapping with SAM on blue pigmented areas (mainly blue smalt); bottom graph - endpoint spectrum for SAM; C) top figure - Similarity image mapping with SAM on red pigmented areas (mainly carmine); bottom graph - endpoint spectrum for SAM.

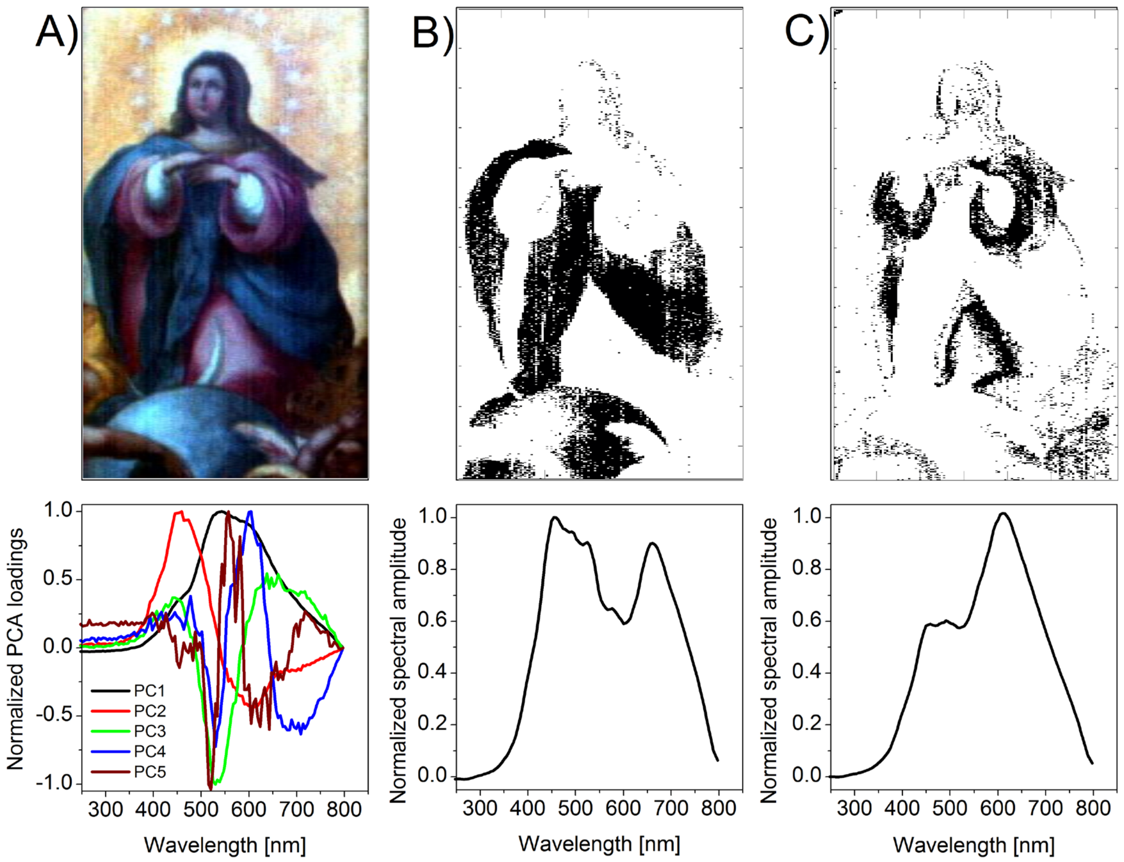


Figure 6.- Results from the reflectance image analysis performed on the scanned wall painting representing the Glorification of the Virgin. A) top figure - RGB image obtained by combining the reflectance intensities emitted at 600, 500 and 400 nm; bottom graph - PCA of the entire reflectance image; B) top figure - Similarity image mapping obtained on the reflectance with SAM on blue pigmented areas (mainly blue smalt); bottom graph - endpoint spectrum for SAM; C) top figure - Similarity image mapping obtained on the reflectance with SAM on red pigmented areas (mainly carmine); bottom graph - endpoint spectrum for SAM.

For sake of comparison the same type of analysis here reported for fluorescence signatures was also performed with reflectance spectra, available from our remote scanning instruments [figure 6]. In this case no detection of acrylic consolidant was obtained from spectral analysis. Furthermore, although it was possible to map most of the red and the blue components where they dominate, no information on the red addition to background was achieved in this case. This observation stresses the power of the proposed method based on fluorescence as a fingerprint of the entire painted outer layers, since the mapping accounts also for the presence of week contributions from the red pigment used.

In order to overcome the scarce selectivity of the spectral features appearing in the fluorescence database for some specific cases, such as for instance the examined black pigments, work is in progress to merge data from fluorescence and reflectance spectra since they are sequentially recorded by our instrument in similar environmental conditions and from the same point of view.

In the selected case study was not possible to identify other pigments in the current database, even by using the combination of fluorescence and reflectance spectra. This is due to the fact that in most of the cases characteristic pigment fluorescence band excited at 266 nm are weak, or even absent, and possibly hindered by matrix effect; in these conditions it is not easy to detect those pigments which are not major components of the examined surface and thus responsible at least for absorption in case of negligible fluorescence.

In summary, the data base has been built with the aim to support pigment identification on real historical surfaces. The considered case study offered the chance to identify three families of major pigment: red, blue and black. Results have been obtained on identification (as carmine and smalt) and mapping red and blue, with better sensitivity than in reflectance for the red carmine.

— *Identification of pigments by traditional techniques*

Traditional techniques have been employed, not only to design the database, but also to evaluate the accuracy of the results. Conventional micro-analysis and X-rays techniques revealed that the primer wall painted layer

Table III.- Colour Palette of the wall painting vault titled "The Glorification of the Virgin"

White	Blue	Red	Ochre, brown, sienna	Green	Black	Metallic
Lead White, Calcite, Barite	Smalt blue	Red Earth, Cinnabar, Carmine (possible from cochineal)	Yellow pigments with lead and chromium (due to a restoration)	Malachite	Lamp Black, carbon	Gold, Silver, Copper

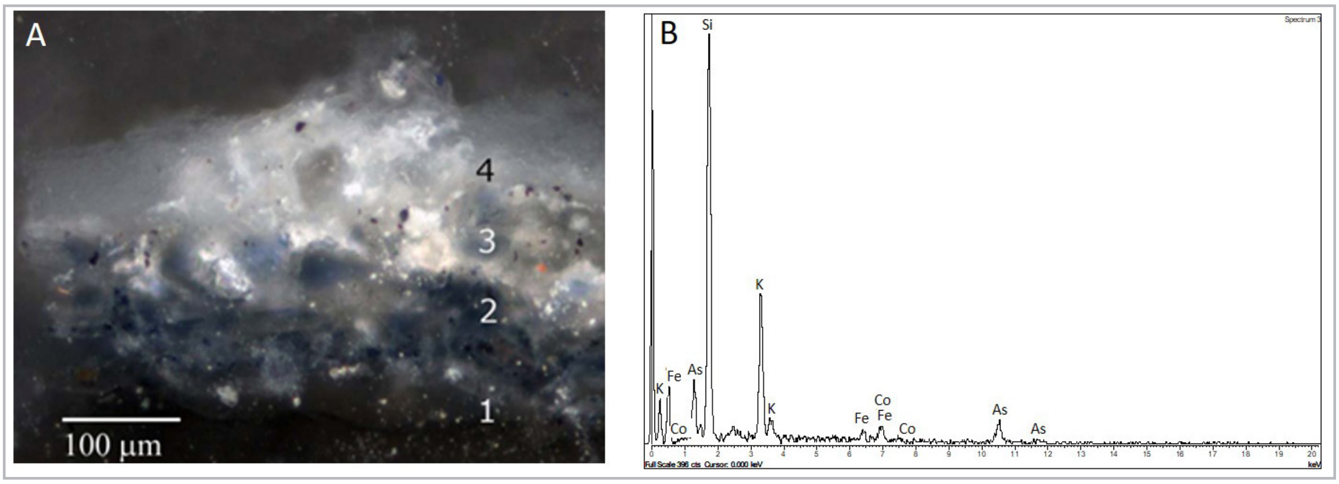


Figure 7.- A-Stratigraphy of blue sample: White primer of plaster (layer 1), Calcite, lead white and blue smalt (layer 2), grains of lead white, calcite and blue smalt (layer 3) in smaller quantities than those identified in layer 2, very thin white layer of calcite (layer 4). B – EDX spectrum where is identified smalt blue (Si, Co, As, K and Fe).

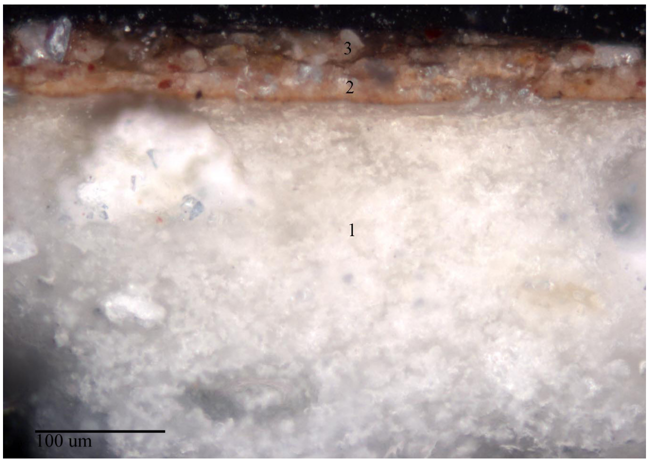


Figure 8.- Stratigraphy of red sample: Plaster composed by gypsum (layer 1), lead white, red earth, calcite, carmine and a few grains of gypsum (layer 2), red layer with the same composition of second layer (layer 3).

was formed by a support of gypsum of different thickness mixed with earths, oxalates, quartz and calcite. Domingo Martinez used a secco technique what was confirmed by GC-MS. The binder analysis revealed the presence of animal glue and linseed oil in the outsider surface, meanwhile traces of resins appeared on the outer surfaces in sporadic zones (Gómez Morón 2008). Since gypsum, quartz, calcite (P4) and animal glue are the basis of our reference models while linseed oil is the binder used to mix the pigments, we expect the best correlation between remote LIF data and results from present *in situ* sampling.

The table III summarises the colour palette of the vault, as deduced from the sampling. Mainly inorganic pigments were found: lead white, smalt blue, red earth, cinnabar, yellow lead and chromium, green malachite (copper hydroxi-carbonate), however the organic compound carmine, possible from cochineal, has been utilized as well in most of the red zones. Relevant for this research was the confirmation of the LIF characterization made for the blue pigment of the mantle and the red pigment of the robe of the Virgin. The smalt blue was determined by SEM-EDX with the presence of silicon, arsenic, potassium, iron and copper [figure 7]. In the case of the robe [Figure 8], a punctual analysis of its stratigraphic section by FTIR identified the use of an organic pigment as red colour.

Conclusions

The work here presented supports the use of database according ancient recipes as LIF standards to carry out LIF mapping on painted surfaces. The results show that LIF is a great diagnostic tool, having the ability to perform spectral analysis on-site and with high speed on very large real painted surfaces, also having the possibility to analyse both organic and inorganic pigments even in the case of not well known fluorescence emission bands on pure substances. Most important from the point of view of the conservators, LIF remote imaging is a completely non-destructive analysis. The availability of a validated LIF spectra database allows minimizing samples collection on wall painting following ICOMOS (International Council on Monuments and Sites) recommendations (ICOMOS 2003).

The LIF technique is demonstrated to be an effective diagnostic tool on the considered case study (a XVII century *a secco* mural paint). In fact, based on the historical database built, the assignment of two main pigments (smalt and carmine) was confirmed and their distribution onto the image was obtained, furthermore the capability of mapping the identified red pigment was significantly improved with respect to the reflectance imaging. Note that the distribution on a large area of a specific material achieved by LIF imaging, either original pigment or modern consolidant, is a valuable information for conservation scientists even in the least favourable case of not-straightforward assignment requiring additional in situ measurements or samplings.

Nevertheless, LIF remote imaging still requires further study to complete the database of historical pigments of interest, which have not been formerly investigated with detail upon laser excitation in the UV region. The problem of identifying and/or discriminate contribution for plaster and binders could be possibly solved by using multiple UV/visible excitation wavelengths. Possibilities of combined remote utilization, together with other laser spectroscopies (e.g. Raman) are under investigation to detect by vibrational signatures the presence of characteristic non fluorescent groups at the investigated painted surfaces. Moreover, further studied about ageing and fading must be carried out to complete the database.

Acknowledgements

This study has been supported by the agreements IAPH-UPO & UPO-ENEA, José Castillejo (2010) and Technoheritage (2013) grants of Pilar Ortiz and the Project of Excellence of Junta de Andalusia HUM-6775 (RIVUPH). Part of the data analysis was conducted during the COBRA (Conservation of Cultural Heritage based on Radiations and Enhabling Technologies) Regional project n. 1031 (LR13/2008) funded by Latium Region.

References

ACQUAVIVA, S., D'ANNA, E., DE GIORGI, ML, DELLA PATRIA, A., PEZZATI, L. (2008). "Optical characterization of pigments by reflectance spectroscopy in support of UV laser cleaning treatments." *Applied Physics A*. 92(1):223–227. https://doi.org/10.1007/s00339-008-4486-2

AENOR (2014). UNE-EN 16085. *Conservation of Cultural property. Methodology for sampling from materials of cultural property. General rules*.

ANGLOS, D., SOLOMIDOU, M., ZERGIOTI, I., ZAFIROPULOS, V., PAPAZOGLOU, TG., FOTAKIS, C. (1996). "Laser-Induced Fluorescence in Artwork Diagnostics: An Application in Pigment Analysis." *Applied Spectroscopy*. 50(10):1331–1334. https://doi.org/10.1366/0003702963904863

BORGIA, I., FANTONI, R., FLAMINI, C., DI PALMA, TM., GUIDONI, AG., MELE, A., GIARDINI GUIDONI, A., MELE, A. (1998). "Luminescence from pigments and resins for oil paintings induced by laser excitation." *Applied Surface Science*. 127–129:95–100. https://doi.org/10.1016/S0169-4332(97)00616-8

BRUNI, S., CARIATI, F., CONSOLANDI, L., GALLI, A., GUGLIELMI, V., LUDWIG, N., MILAZZO, M. (2002). "Field and Laboratory Spectroscopic Methods for the Identification of Pigments in a Northern Italian Eleventh Century Fresco Cycle. *Applied Spectroscopy*. 56(7): 827–833. https://doi.org/10.1366/000370202760171482

BURRAFATO, G,. CALABRESE, M., COSENTINO, A., GUELI, AM., TROJA, SO., ZUCCARELLO, A. (2004). "ColoRaman project: Raman and fluorescence spectroscopy of oil, tempera and fresco paint pigments". *Journal of Raman Spectroscopy*. 35(10):879–886. https://doi.org/10.1002/jrs.1229

CANEVE, L., COLAO, F., FIORANI, L., PALUCCI, A. (2010). *Patent No. RM2010A000606*.

CARCAGNÌ, P., DELLA PATRIA, A., FONTANA, R., GRECO, M., MASTROIANNI, M., MATERAZZI, M., PAMPALONI, E., PEZZATI, L. (2007). "Multispectral imaging of paintings by optical scanning". *Optics and Lasers in Engineering*. 45(3):360–367. https://doi.org/10.1016/j.optlaseng.2005.02.010

CARDON, D. (2007). N*atural Dyes - Sources, Tradition, Technology and Science*. London, U.K.: Archetype Publications Ltd.

CECCHI, G., PANTANI, L., RAIMONDI, V., TOMASELLI, L., LAMENTI, G., TIANO, P., CHIARI, R. (2000). "Fluorescence lidar technique for the remote sensing of stone monuments". *Journal of Cultural Heritage*. 1(1):29–36. https://doi.org/10.1016/S1296-2074(99)00120-X

CENNINI, C. 1859. *Il libro dell'arte, o Trattato della pittura*. G. Milanesi. & F. Le Monnier, Eds. Firenze.

COLAO, F., FANTONI, R., FIORANI, L., PALUCCI, A. (2007). *Patent No. RM2007A000278*.

COLAO, F., CANEVE, L., FANTONI, R., FIORANI, L., PALUCCI, A., FANTONI, R., FIORANI, L. (2008). Scanning hyperspectral lidar fluorosensor for fresco diagnostics in laboratory and field campaigns. In *Lasers in the Conservation of Artworks - Proceedings of the International Conference LACONA 7*. CRC Press. 149–155. https://doi.org/10.1201/9780203882085.pt3

COMELLI, D., D'ANDREA, C., VALENTINI, G., CUBEDDU, R., COLOMBO, C., TONIOLO, L. (2004). "Fluorescence lifetime imaging and spectroscopy as tools for nondestructive analysis of works of art". *Applied Optics*. 43(10):2175–2183. https://doi.org/10.1364/ao.43.002175

COMELLI, D., NEVIN, A., VALENTINI, G., OSTICIOLI, I., CASTELLUCCI, EM., TONIOLO, L., GULOTTA, D., CUBEDDU, R. (2011). "Insights into Masolino's wall paintings in Castiglione Olona: Advanced reflectance and fluorescence imaging analysis." *Journal of Cultural Heritage*. 12(1):11–18. https://doi.org/10.1016/j.culher.2010.06.003

DOMINGO, C., SILVA, D., GARCÍA-RAMOS, JV., CASTILLEJO, M., MARTÍN, M., OUJJA, M., TORRES, R., SÁNCHEZ-CORTÉS, S. (2001). "Spectroscopic Analysis of Pigments and Binding Media of Polychromes by the Combination of Optical Laser-Based and Vibrational Techniques". *Applied Spectroscopy*, Vol. 55, Issue 8, pp. 992-998. 55(8):992–998. https://doi.org/10.1366/0003702011953135

EASTAUGH, N., WALSH, V., CHAPLIN, T. & SIDDALL, R. (2004). *Pigment Compendium: A Dictionary of Historical Pigments - Nicholas Eastaugh, Valentine Walsh, Tracey Chaplin, Ruth Siddall - Google Books*. 3th ed. New York: Elsevier Butterworth-Heinemann.

FANTONI, R., PALUCCI, A., RIBEZZO, S., BORGIA, I., BACCHI, E., CAPONERO, MA., BORDONE, A., BUSINARO, L., FERRI DE COLLIBUS, M., FORNETTI, GG., POGGI, C. (2000). "Laser diagnostics developed for conservation and restoration of cultural inheritance". In *SPIE Proceed. Conf. ALT'99*. V. 4070. V.I. Pustovoy & V.I. Konov, Eds. Bellingham: V.I. Pustovoy and V.I. Konov Eds. 2–7. https://doi.org/10.1117/12.378139

FANTONI, R., CANEVE, L., COLAO., F, FIORANI, L., PALUCCI, A., DELL'ERBA, R., FASSINA (2013). "Laser-induced fluorescence study of medieval frescoes by Giusto de' Menabuoi". *Journal of Cultural Heritage*. 14(3 SUPPL):S59–S65. https://doi.org/10.1016/j.culher.2012.10.025

FIORANI, L, CANEVE, L, COLAO, F, FANTONI, R, ORTIZ, P, GÓMEZ & MA, VÁZQUEZ. 2010. "Real-Time Diagnosis of Historical Artworks by Laser-Induced Fluorescence." *Advanced Materials Research*. 133–134:253–258. https://doi.org/10.4028/www.scientific.net/AMR.133-134.253

FOTAKIS, C., ANGLOS, D., COURIS, S. (1997). "Laser Diagnostics of Painted Artworks: Laser-Induced Breakdown Spectroscopy in Pigment Identification". *Applied Spectroscopy*, Vol. 51, Issue 7, pp. 1025-1030. 51(7):1025–1030. https://doi.org/10.1366/0003702971941421

GIARDINI-GUIDONI, A., VENDITTELLI, M., FLAMINI, C., FANTONI, R., SCIUTI, S., MELE, A. (2000). "Experimental comparison of three nondestructive testing diagnostics on pigments and ligands." In *Proceedings of the SPIE*, Volume 4070, p. 8-17 (2000). V. 4070. V.I. Pustovoy & V.I. Konov, Eds. 8–17. https://doi.org/10.1117/12.378149

GIROUARD, G., BANNARI, A., HARTI, A., EL., DESROCHERS, A. (2004). "Validated spectral angle mapper algorithm for geological mapping: comparative study between QuickBird and Landsat-TM". In *XXth ISPRS Congress. Istambull*. 599–604.

GÓMEZ MORÓN, MA. (2008). *Analytical report of the paintings of the San Telmo vaults "Informe analítico de las pinturas de las bóvedas de San Telmo"*. (Internal report). Sevilla (Spain).

ICOMOS (2003). *Principles for the preservation and conservation-restoration of wall paintings*. Victoria Falls (Zimbabwe): 14a Asamblea General del ICOMOS.

DE LA RIE, ER 1(982). "Fluorescence of Paint and Varnish Layers (Part III)". *Studies in Conservation*. 27(3):102. https://doi.org/10.2307/1506145

LOGNOLI, D., LAMENTI, G., PANTANI, L., TIRELLI, D., TIANO, P., TOMASELLI, L. (2002). "Detection and characterization of biodeteriogens on stone cultural heritage by fluorescence lidar". *Applied optics*. 41(9):1780–7. https://doi.org/10.1364/ao.41.001780

LOGNOLI, D,. CECCHI, G., MOCHI, I., PANTANI, L., RAIMONDI, V., CHIARI, R., JOHANSSON, T., WEIBRING, P., HEDNER, H., SVANBERG, S. (2003). "Fluorescence Lidar imaging of the cathedral and baptistery of Parma". *Applied Physics B: Lasers and Optics*. 76(4):457–465. https://doi.org/10.1007/s00340-003-1126-6

MIYOSHI, T. (1985). "Fluorescence from Oil Colours, Linseed Oil and Poppy Oil under N2 Laser Excitation". *Japanese Journal of Applied Physics*. 24(Part 1, No. 3):371–372. https://doi.org/10.1143/JJAP.24.371

MOUNIER, A., LE BOURDON, G., AUPETIT, C., BELIN, C., SERVANT, L., LAZARE, S., LEFRAIS, Y., DANIEL, F. (2014). Hyperspectral imaging, spectrofluorimetry, FORS and XRF for the non-invasive study of medieval miniatures materials. *Heritage Science*. 2(1):24. https://doi.org/10.1186/s40494-014-0024-z

NABAIS, P., MELO, MJ., LOPES, JA., VITORINO, T., NEVES, A. CASTRO, R. (2018). "Microspectrofluorimetry and chemometrics for the identification of medieval lake pigments." *Heritage Science*. 6(1):1–11. https://doi.org/10.1186/s40494-018-0178-1.

NEVIN, A. ANGLOS, D. (2006). "Assisted Interpretation of Laser-Induced Fluorescence Spectra of Egg-Based Binding Media Using Total Emission Fluorescence Spectroscopy". *Laser Chemistry*. 2006:1–5. https://doi.org/10.1155/2006/82823

NEVIN, A., CATHER, S., ANGLOS, D., FOTAKIS, C. (2006). "Analysis of protein-based binding media found in paintings using laser induced fluorescence spectroscopy". *Analytica Chimica Acta*. 573–574:341–346. https://doi.org/10.1016/j.aca.2006.01.027

OUJJA, M., VÁZQUEZ-CALVO, C., SANZ, M., DE BUERGO, MÁ,. FORT, R., CASTILLEJO, M. (2012). "Laser-induced fluorescence and FT-Raman spectroscopy for characterizing patinas on stone substrates". *Analytical and Bioanalytical Chemistry*. 402(4):1433–1441. https://doi.org/10.1007/s00216-011-5319-2

PACHECO, F. (1871). *The Art of painting "El arte de la pintura"*. Revised ed ed. Madrid: Librería de D. León Pablo Villaverde.

RAIMONDI, V., ANDREOTTI, A., COLOMBINI, MP., CUCCI, C., CUZMAN, O., GALEOTTI, M., LOGNOLI, D., PALOMBI, L., PICOLLO, M. TIANO, P. (2015). Test measurements on a secco white-lead containing model samples to assess the effects of exposure to low-fluence UV laser radiation. *Applied Surface Science*. 337:45–57. https://doi.org/10.1016/j.apsusc.2015.02.062

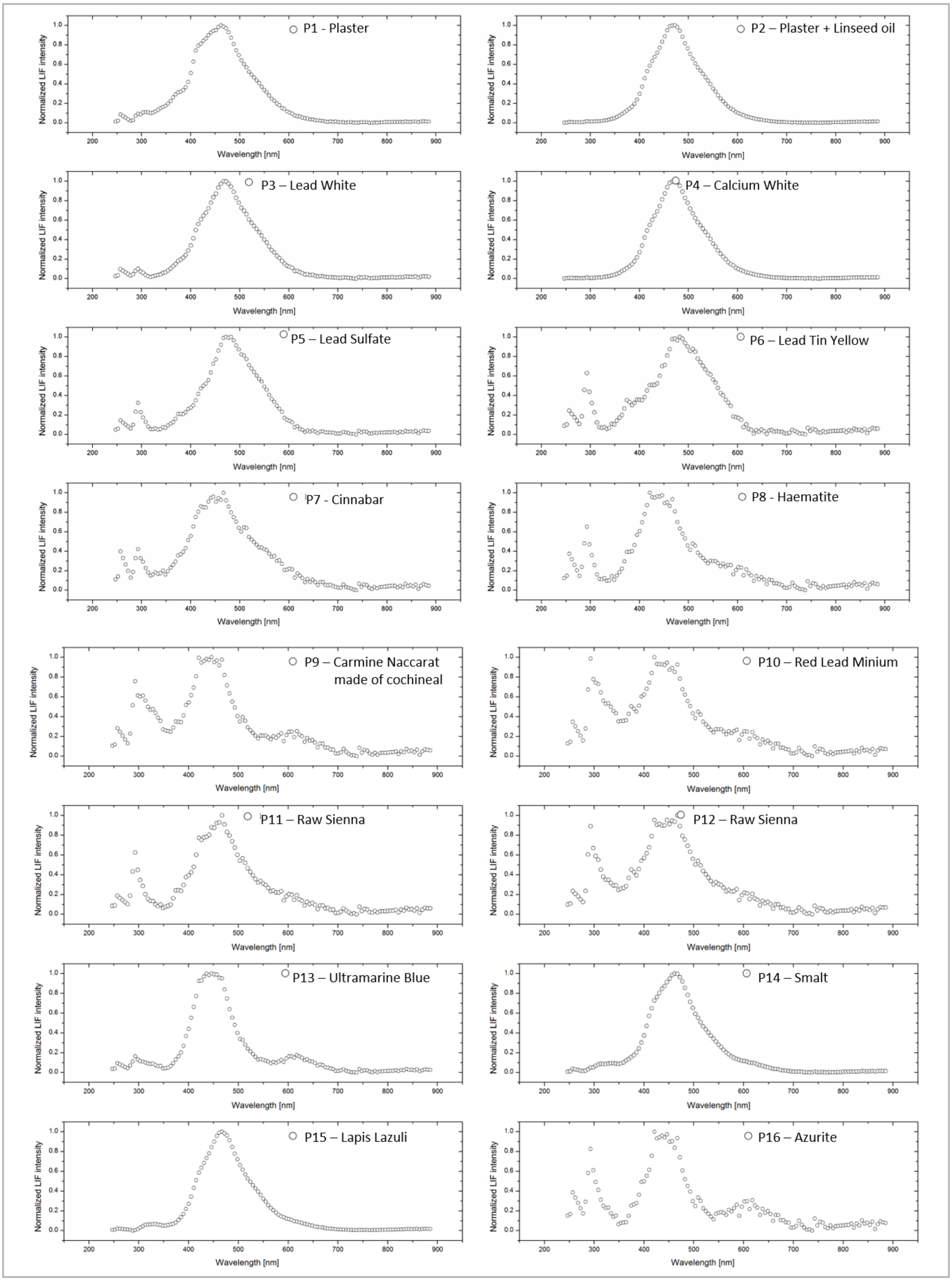
RASHMI, S., ADDAMANI, S., VENKAT, RAVIKIRAN, S. (2014). "Spectal Angle Mapper Algorithm for remote Sensing Image Classification". International Journal of Innovative Science, *Engineering & Technology*. 1(4):201–205.

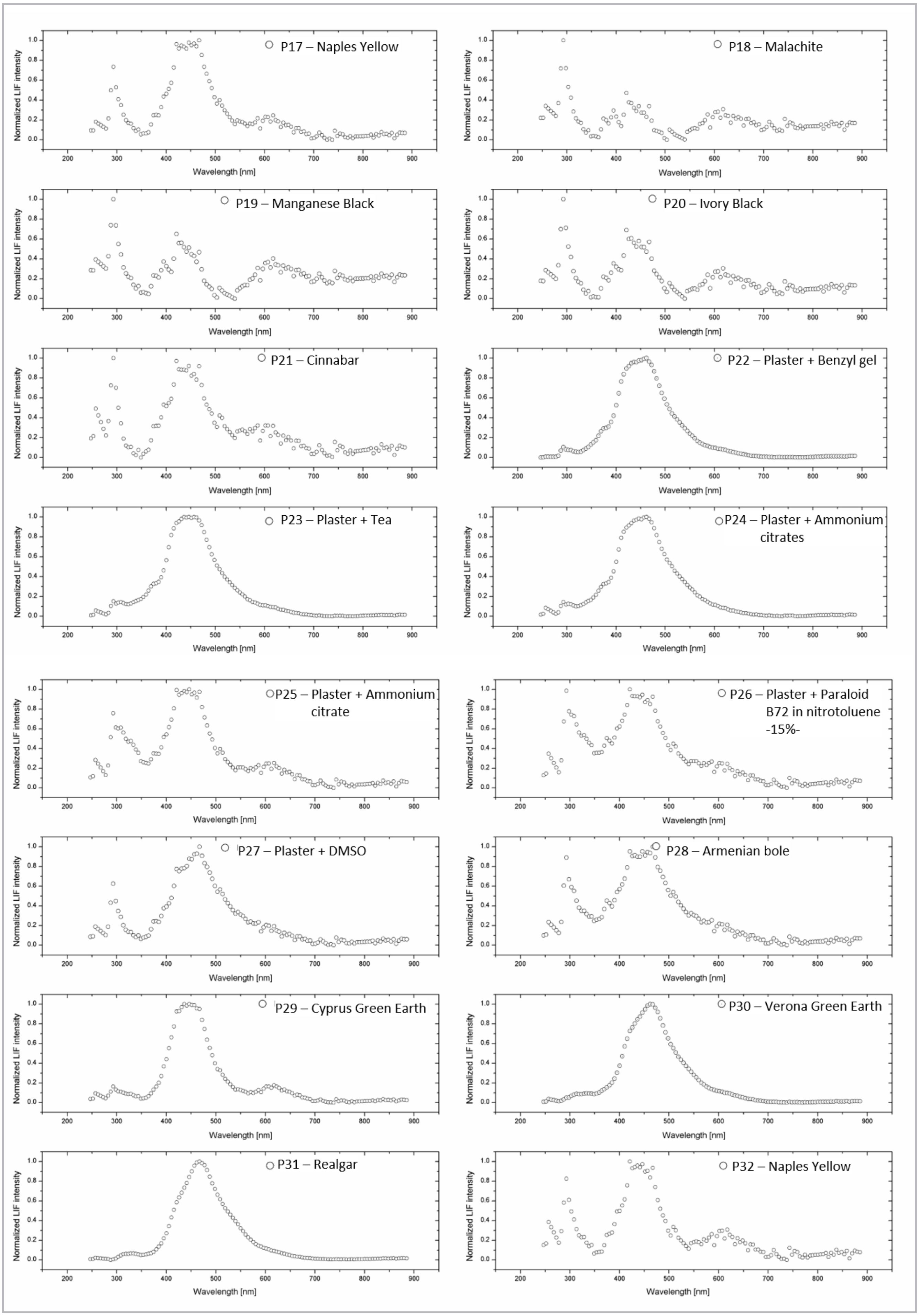
RENCHER, AC. (2002). *Methods of Multivariate Analysi*s. 2nd ed. New York: Wiley Interscience.

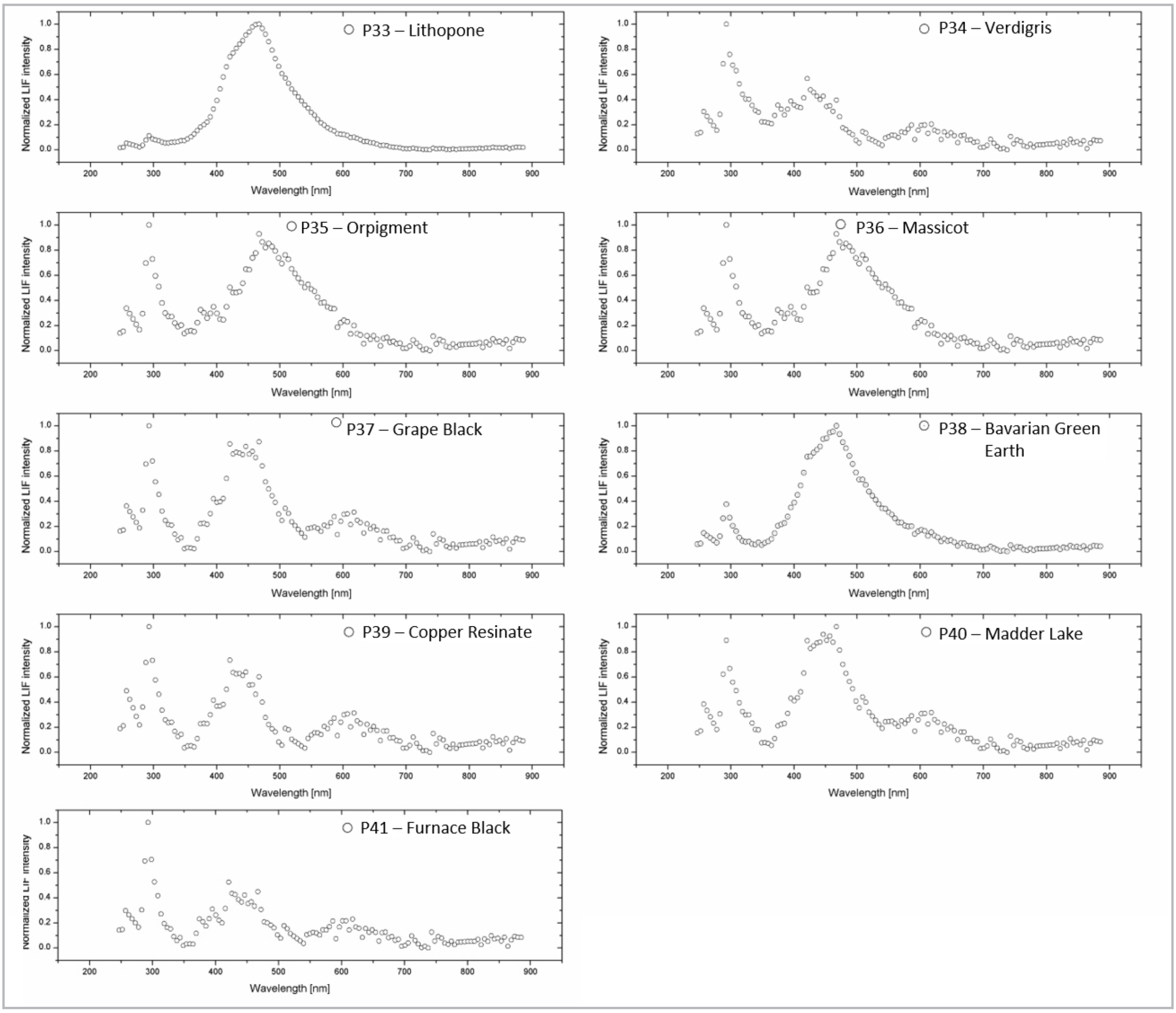
SIMONOT, L., THOURY, M., DELANEY, J. (2011). "Extension of the Kubelka–Munk theory for fluorescent turbid media to a nonopaque layer on a background." *Journal of the Optical Society of America A*. 28(7):1349. https://doi.org/10.1364/JOSAA.28.001349

VERRI, G., CLEMENTI, C., COMELLI, D., CATHER, S., PIQUÉ, F. (2008). "Correction of Ultraviolet-Induced Fluorescence Spectra for the Examination of Polychromy". *Applied Spectroscopy*. 62(12):1295–1302. https://doi.org/10.1366/000370208786822296

Annex 1.- LIF spectrum of pigments/colorants on plaster with linseed oil. The name of the pigment and the occasional presence of other additives is specified in Table I. Data are normalized on the maximum, an indication on the relative intensity can be derived from SNR (data scattering around the best fit curve).




P17 – Naples Yellow
P18 – Malachite
P19 – Manganese Black
P20 – Ivory Black
P21 – Cinnabar
P22 – Plaster + Benzyl gel
P23 – Plaster + Tea
P24 – Plaster + Ammonium citrates
P25 – Plaster + Ammonium citrate
P26 – Plaster + Paraloid B72 in nitrotoluene -15%-
P27 – Plaster + DMSO
P28 – Armenian bole
P29 – Cyprus Green Earth
P30 – Verona Green Earth
P31 – Realgar
P32 – Naples Yellow
Normalized LIF intensity
Wavelength [nm]



Author/s

María Auxiliadora Gómez-Morón
mariaa.gomez.moron@juntadeandalucia.es
Instituto Andaluz del Patrimonio Histórico (IAPH), Seville, Spain

BSc Chemistry 1989-1994 and Master "Quimilaser. Laser application in Chemistry" 2012 (University of Sevilla). Member, since 2016, of the project "Art-Risk (Artificial Intelligence applied to preventive conservation of heritage buildings)" to investigate and develop a new computerized tool for preventive conservation of heritage in urban centres based on models of artificial intelligence. Art-Risk will be available to organizations and companies dedicated to the restoration and rehabilitation. Member, since 1995, of the research group "Remote Sensing and Geochemistry", with long-term experience in the research line in Archaeometry. Socrates grant at the University la Sapienza, where she worked in the project "Testaccio" (1999). An 18 months training grant at the IAPH (Andalusian Institution for Historical Heritage), from 1.11.1999 to 30.4.2001. A grant for conservation and restoration of cultural heritage at the Institution for Spanish Historical Heritage (2001). Since 2001, she works at IAPH (Andalusian Institution for Historical Heritage), where she takes part in projects such as Giraldillo's restoration and is responsible of the project for application of non-destructive analytical techniques for Historical Heritage. Part time professor at University Pablo de Olavide (Sevilla) since 2009, where she has taught three editions of the on-line course of non-destructive analytical techniques for Historical Heritage.

Rocío Ortiz
rortcal@upo.es
Department Physical, Chemical and Natural Systems, University Pablo de Olavide, Seville, Spain

Graduated in Architecture in 2001, she obtained a Master's degree in Protection of Built Heritage with a project oriented to a case study in Marchena in 2012. In 2014 she earned a Ph.D with European mention in University Pablo de Olavide (Seville).

She is currently working as Professor at the UPO, where she develops research focus on the fields of: Preventive Conservation; Risks and Vulnerability of Patrimony She is also director of the Mater in Diagnosis of the state of preservation of Cutural Heritage and is responsible of the area of crystallography and mineralogy of the same University. Dr. Ortiz's expertise is in diagnosis of Cultural Heritage, management, e-learning, and her scientific works appeared in 30 books, conference proceedings, and journals. Her research projects have been supported by the European Union, national and regional governments, and private organizations. Dr. Ortiz's research interests have focused on risk and vulnerability of Cultural Heritage, GI applied to Cultural Heritage studies, Construction materials, Urban Planning and hazards and innovation in science teaching with the emphasis on cultural heritage diagnosis

Franceso Colao
francesco.colao@enea.it
Department for Fusion and Nuclear Safety Technologies, Division Physical Technologies for Security and Health, ENEA, Frascati, Italy

Specialist in laser applications, signal processing and data acquisition, current interests concern the development of fluorescence lidar for the analysis of pigments, binders and consolidants. Since 1987 he is researcher at ENEA, carrying out research in design and development of remote sensing laser-based systems for atmospheric studies. Known expert in the field of laser spectroscopy and diagnostics, including lidar for atmospheric studies, Raman spectroscopy, visible/UV emission spectroscopy, Laser Induced Fluorescence (LIF). He gained large experience of remote sensing systems for different applications: environmental control of pollutants, and remote diagnostic in the field of cultural heritage. Currently the main activities in the latter field are related to the development of fluorescence lidar, used to monitor the water quality (chemical and biochemical pollution) and the vegetation health (both on phytoplankton species and on green plants), cultural heritage (analysis of pigments, binders and consolidants), application of laser induced breakdown spectroscopy (LIBS) and lidar remote sensing of the statosphere. He was involved in the study of LIBS and its application to the field of laser matter interaction and monitoring of soil and water. He has been responsible for several research projects, among these it is worth of mention the followings: application of LIBS to identification of asbestos' fibres in environmental samples (ISPESL programme 2003-04), development of a LIBS system for extraterrestrial soil analysis (ASI programme 2001-02), study of polar stratospheric clouds by lidar remote sensing (2006, 2017-19), development of a LIBS system for use in hostile environment (MURST programme 2004-07) , development of an integrated system for drug discovery by laser spectroscopy (CUSTOM – EU FP7 2010-2012), development of LIF system for forensic investigation (FORLAB– EU FP7 2011-2013), development of standoff Raman system for prompt identification of explosive substances (NATO project RADEX 2014-16, EXTRAS 2018-20). He has been tutoring of thesis and has given lectures to universities and research centers. The results of his researches have been presented at international conferences and published in peer review journals in more than fifty regulars.

Roberta Fantoni
roberta.fantoni@enea.it
Department for Fusion and Nuclear Safety Technologies, Division Physical Technologies for Security and Health, ENEA, Frascati, Italy

Dr. Roberta Fantoni is the head of the division "Technology Applications for Security and Health" at Fusion and Technology for Nuclear Safety and Security (ENEA). Her role is to coordinate researches in the field of development of applications of ionizing and non-ionizing radiations, including processes and diagnostics based on lasers and particles (electrons, protons) beams for the Industry, Environment, Cultural Heritage and Bio-medicine, and Micro-Nanotechnology. After a degree in chemistry she became a specialist in optoelectronics dealing with laser applications. She is a known expert in the field of laser spectroscopy and diagnostics. Major activities concern applications of the spectroscopic techniques as on-line diagnostics during different process. Recently she coordinated the regional project COBRA dedicated to innovation and technology transfer in Cultural Heritage conservation. Author of 164 scientific papers of peer review papers and 25 book chapters in the field of spectroscopy and laser applications.

Javier Becerra
jbeclun@upo.es
Department Physical, Chemical and Natural Systems, University Pablo de Olavide, Seville, Spain

PhD in History and Humanities: Europe, America, Arts and Language, degree in Conservation and Restoration and MSc Diagnosis of the State of Preservation of the Historical Heritage. Now, Javier is researcher at the Pablo de Olavide University in Seville, Spain. His research activity has focused on a) studies of new conservation-restoration treatments, especially based on nanomaterials b) vulnerability and risk studies in cultural heritage and c) diagnosis, analytical techniques and interventions in cultural heritage. This scientific production has resulted in a patent, 15 journal publications (10 in high impact indexed journals) and 12 book chapters. The results of the investigations carried out have been presented at 10 international conferences with a total of 18 communications. He has collaborated in the diagnosis of samples from national and international monuments (Villa Adriana in Rome, Medina Azahara, archaeological museum of Écija, churches in Seville, contemporary buildings in La Havana, historical buildings in Oxford and Panama City, etc.) and has participated in analytical reports of national and international artworks requested from institutions such as the Andalusian Institute of Historical Heritage or the Pablo de Olavide University. Finally, his research activity has been recognized with different awards at national and international level.

Pilar Ortiz
mportcal@upo.es
Department Physical, Chemical and Natural Systems, University Pablo de Olavide, Sevi-lle, Spain

The research and teaching experience developed has been focused on the diagnosis, preservation and conservation of cultural heritage. For this task, she has collaborated with museums and cultural institutions, such as the IVCR+i, IAPH, Cádiz Museum, Écija Museum, etc. Additionally, I have developed works related to cultural heritage issues in several countries, i.e., the United Kingdom, Belgium, Italy, Romania, Cuba, Peru, Colombia, Panama, etc. Her scientific production can be summarized in 38 publications on indexed journals; 50 books and book chapters, more than 25 attendances to international congresses, chairman and member of scientific committee in several international congresses, etc. She has worked at the University of Amberes (Belgium) as assistant lecturer, invited professor at the University of Oxford (UK), and invited researcher at ENEA (Italy). She has participated in 24 national and international projects, contracts and agreements and has the head researcher in 16 of those projects, highlighting a Project of Excellence of the Junta de Andalucía, a RETOS project of the Government of Spain, an International Cooperation project of the Junta de Andalucía and International Erasmus+. She has opened and leadership important research lines as the application of Lasers techniques for in situ diagnosis in cultural heritage materials, the development of non-destructive techniques for diagnosis of cultural heritage, or the application of risk maps, vulnerability index and artificial intelligence to the preventive conservation of cultural heritage. Dr. Ortiz is member of the International Excellency Campus of the University of Jaén in cultural and natural heritage, of the "Cambio" work group in the International Excellency Campus of the Pablo de Olavide University (UPO), of the Andalusian Council of Cultural Heritage and Dean of the faculty of Experimental Sciences of the UPO.

https://doi.org/10.37558/gec.v17i1.759

Ge-conservación
Conservação | Conservation

Técnicas analíticas para la caracterización de documentos: una revisión bibliográfica

Gemma Mª Contreras, Javier Becerra

Resumen: El interés por la conservación de manuscritos ha crecido en las últimas décadas, bien por su valor artístico o por la información única que custodian. Para ello, es preciso conocer tanto los materiales empleados, como las alteraciones presentes, a fin de discernir el mejor tratamiento de restauración según sus características.

La implementación de técnicas analíticas aplicadas a este campo de estudio ha permitido mejorar el conocimiento sobre el patrimonio documental y bibliográfico. De este modo, se pueden emplear técnicas elementales (energías dispersivas de rayos X, fluorescencia de rayos X, etc.) o moleculares (espectroscopía infrarroja, espectroscopía Raman, etc.) para analizar los materiales inorgánicos u orgánicos. Si bien muchos de estos estudios han estado encaminados a estudiar manuscritos iluminados, es importante prestar especial atención a los estudios publicados sobre la caracterización de tintas metalográficas, las cuales se relacionan con la preservación de la información y con la degradación del soporte. El empleo de técnicas de imagen (microscopía óptica, fotografía infrarroja, microscopía electrónica, etc.) permite complementar los estudios de diagnóstico e identificación de materiales. Sin embargo, un conocimiento pormenorizado del manuscrito estudiado requiere del diseño de un protocolo de estudio en el que se complemente la información obtenida mediante la selección de las técnicas más adecuadas en función de las características del manuscrito y la disponibilidad de estas.

El objetivo principal de este artículo es simplificar la toma de decisiones en torno a la selección de técnicas analíticas y no solo dar una revisión bibliográfica de los principales estudios sobre el análisis de soportes y materiales respaldados. Además, se ha diseñado un protocolo que facilita al restaurador la selección de técnicas analíticas en función del material a caracterizar y los recursos disponibles

Palabras clave: Técnicas analíticas, manuscritos, caracterización, diagnóstico

Analytical techniques for the characterization of documents: a bibliographic review

Abstract: The interest in the conservation of manuscripts has grown in recent decades, either for their artistic value or for the unique information they hold. For this, it is necessary to know both the materials used and their alterations, in order to discern the best restoration treatment according to their characteristics.

The implementation of analytical techniques applied to this field of study has allowed us to improve knowledge about documentary and bibliographic heritage. Thus, elementary techniques (X-ray dispersive energies, X-ray fluorescence, etc.) or molecular techniques (infrared spectroscopy, Raman spectroscopy, etc.) can be used to analyze inorganic or organic materials. Although many of these studies have been aimed at studying illuminated manuscripts, it is important to take into consideration the published studies on the characterization of metallographic inks, which are related to the preservation of information and to the degradation of the support. The use of imaging techniques (optical microscopy, infrared photography, electron microscopy, etc.) makes it possible to complement diagnostic and material identification studies. However, a detailed knowledge of the studied manuscript requires the design of a protocol that complements the information obtained by selecting the most appropriate techniques based on the characteristics of the manuscript and the availability of them.

The main objective of this paper is simplified the maker decision around the selection of analytical techniques and not only giving a bibliographical review of the main studies about the analysis of supports and supported materials, Additionally, a protocol have been designed to make easier to the restorer the choose of analytical techniques according to the materials to characterized and the available sources.

Keywords: Analytical techniques, manuscripts, characterization, diagnosis

Introducción

El patrimonio documental y bibliográfico abarca un conjunto de bienes de creciente interés tanto por la información custodiada como por su valor histórico-artístico. Desde hace décadas, se han incrementado los estudios tendentes a identificar y conocer tanto los materiales estructurales y sustentados, así como los productos de alteración, con el objetivo de mejorar los métodos para su conservación y restauración. Estos estudios son difundidos por diversas fuentes, destacando las bases de datos bibliográficas como Scopus o Dialnet, editoriales como Elsevier o Taylor & Francis, o las publicaciones realizadas bajo el amparo de instituciones de reconocida trayectoria profesional, tales como el Instituto del Patrimonio Cultural de España (IPCE), el Instituto Valenciano de Conservación, Restauración e Investigación (IVC+i) o el Instituto Andaluz del Patrimonio Histórico (IAPH).

El conjunto de técnicas analíticas que pueden emplearse para estudiar manuscritos es muy amplio, abarcando desde complejas técnicas para obtener la composición de los materiales empleados, como las espectroscopías infrarroja o Raman, la fluorescencia de rayos X o las técnicas cromatográficas (Zappalà *et al*. 1996; Derbyshire & Wheeler 2002; Stuart 2007; Manso & Carvalho 2009), a ensayos más rudimentarios que pueden ser aplicados en el propio taller de restauración, por ejemplo, el test de batofenantrolina, de Molish o de Lugol (Matteini & Moles 2001; Stuart 2007; Neevel 2009). En este sentido, el conservador-restaurador debe tener una visión general de las técnicas analíticas más importantes empleadas en el estudio de documentos y material de archivo, de tal forma que se posean los conocimientos oportunos para discernir la técnica más adecuada en función de las necesidades del bien y los recursos disponibles en cada momento.

Un aspecto relevante a la hora de seleccionar una técnica analítica es la posibilidad de tomar muestras para realizar el análisis (Larsen 2002), así como la necesidad de operar *in situ*. Parece obvio que un método en el que no sea necesario la toma de muestras, y posibilite operar en el mismo archivo o biblioteca, es un sistema ideal. Sin embargo, según Clarke (2002), la técnica escogida debe ser capaz de identificar completamente un material desconocido, sensible a muestras muy pequeñas, capaz de diferenciar entre materiales, inmune a posibles interferencias, rápido y capaz de identificar componentes de mezclas de manera individualizada, entre otros.

Con este artículo se pretende, no sólo ofrecer una visión detallada de las investigaciones realizadas sobre análisis de soportes y elementos sustentados, sino simplificar la labor de futuros estudios en los que se deba seleccionar un método analítico. Los sistemas de análisis han sido clasificados en técnicas de imagen y técnicas analíticas de identificación, así como un último grupo de pruebas que, al no requerir de complejos equipamientos, pueden ser aplicadas al papel en el taller de restauración. Sin embargo, una caracterización completa de este tipo de bienes culturales requiere del empleo de diferentes métodos analíticos debido a la amplia variedad de materiales que los componen, tanto orgánicos como inorgánicos. Para finalizar esta revisión bibliográfica, se han recogido diferentes estudios en los que es posible observar cómo estas técnicas analíticas se complementan unas con otras, a fin de establecer un protocolo básico de actuación teniendo en cuenta los recursos disponibles en cada momento.

Técnicas de imagen

El empleo de técnicas de imagen en el estudio de documentos manuscritos permite obtener información morfológica de los materiales constitutivos, así como evaluar el estado de deterioro de estos (James 2010).

Mediante microscopía óptica (MO) es posible obtener imágenes amplificadas de hasta 500 aumentos [figura 1.a y b], lo que permite analizar tanto las fibras del papel (Stuart 2007) como la presencia de biodeterioro (Pinzari, Pasquariello & De Mico 2006). Además, el desarrollo de microscopios portátiles que llegan a alcanzar los 900 aumentos facilita su empleo in situ, sin la necesidad de toma de muestras. Para obtener imágenes de mayor magnificación es necesario recurrir a la microscopía electrónica de barrido (SEM). Esta técnica utiliza un haz de electrones para formar una imagen acromática de hasta 300.000 aumentos [figura 1.c y d]. El haz de electrones es generado por el calentamiento de un filamento de tungsteno, volframio o hexaboruro de lantano, e irradiado sobre la muestra que se sitúa en una cámara al vacío (Matteini & Moles 2001), en la que también se sitúan los diversos detectores que generan la imagen utilizando las interacciones electrón-muestra (Goodhew, Humphreys & Beanland 2014; Moropoulou et al. 2019). Esta técnica requiere de toma de muestras y ha sido empleada, por ejemplo, para el estudio de la morfología de la superficie del papel (Goltz *et al*. 2010) o la presencia de biodeterioro (Pinzari, Pasquariello & De Mico 2006). En efecto, la comparativa entre imágenes MO y SEM, permite apreciar como el aumento de la magnificación de estas últimas facilita la labor de identificación, por ejemplo, al apreciarse de manera nítida la torsión del hilo de algodón [figura 1.c] o las dislocaciones de la fibra de cáñamo [figura 1.d].

En el caso de que se fuese necesario realizar un rastreo topográfico de la superficie puede recurrirse al empleo de la microscopía de fuerza atómica (AFM), tal y como realizan Piantanida, Bicchieri & Coluzza (2005) para estudiar las reacciones químicas en superficie y la degradación de la celulosa por envejecimiento y ataque biológico.

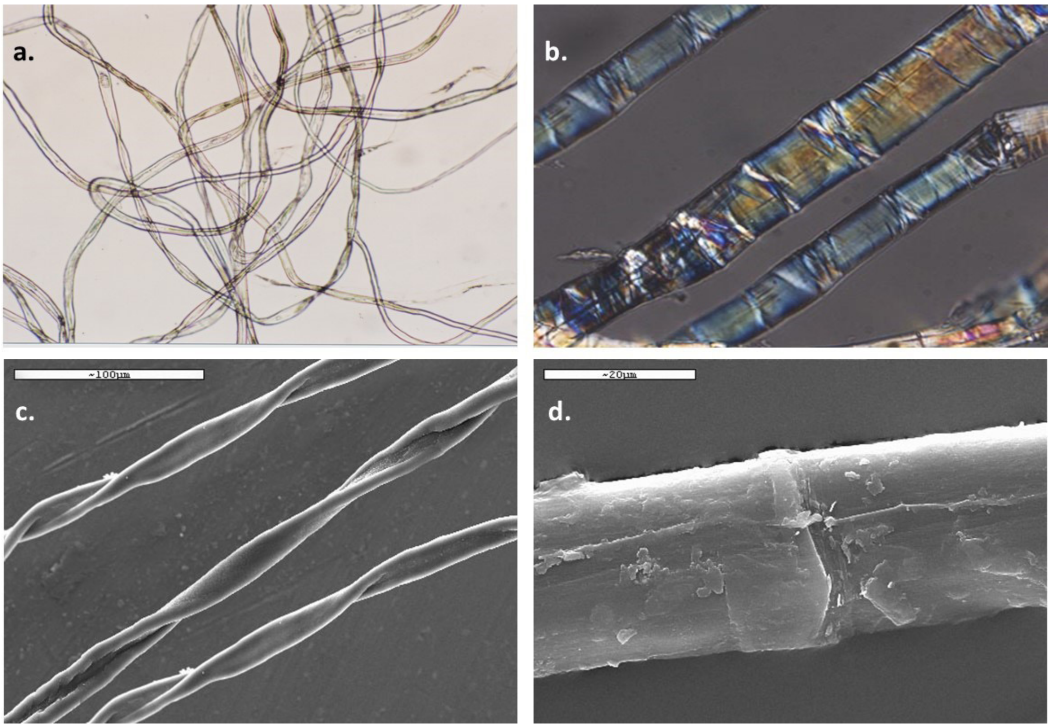


Figura 1.- Fibra de algodón (a) y cáñamo (b) observadas mediante microscopía óptica. Fibra de algodón (c) y cáñamo (d) observadas mediante microscopía electrónica de barrido. Fuente: IVCR+i.

El empleo de la fotografía a diferentes longitudes de onda mediante filtros de paso permite evaluar la degradación de manuscritos. En este sentido, mediante fotografía infrarroja es posible distinguir tintas sepia y metalogálica de las de bistre o carbón (Colbourne 2001) o los dibujos subyacentes de las miniaturas [figura 2], mientras que con fotografía ultravioleta, la fluorescencia de los materiales es empleada para leer manuscritos con la tinta muy desvaída o estudiar su oxidación y degradación (Mairinger 2000; Knox & Easton 2003; Stuart 2007; Easton, Christens-Barry & Knox 2011; Montani *et al.* 2012).

La fotografía infrarroja de falso color ha sido empleada por varios autores (Clarke 2001; Colbourne 2001) para distinguir pigmentos inorgánicos con similar espectro. Sin embargo, en la actualidad, son las técnicas basadas en imágenes espectrales las que están tomando un mayor auge. Es el caso de la imagen multiespectral, cuyos equipos permiten capturar información sobre diferentes bandas del espectro electromagnético, desde el ultravioleta hasta el infrarrojo cercano, por cada píxel de la imagen. Por tanto, las imágenes multiespectrales están compuestas por diferentes bandas, generalmente de 3 a 20, que no han de ser contiguas. Con el empleo de esta técnica se han identificado tintas, su distribución y su corrosión (Havermans, Aziz & Scholten 2003; Scholten et al. 2005), así como dibujos subyacentes de ilustraciones (McGillivray & Duffy 2017). A diferencia de la imagen multiespectral, las imágenes hiperespectrales están formadas por un mayor número de bandas contiguas, lo que permite obtener el espectro de cada píxel. Se han realizado diferentes aproximaciones al empleo de esta técnica en el estudio de manuscritos, especialmente para evaluar cambios

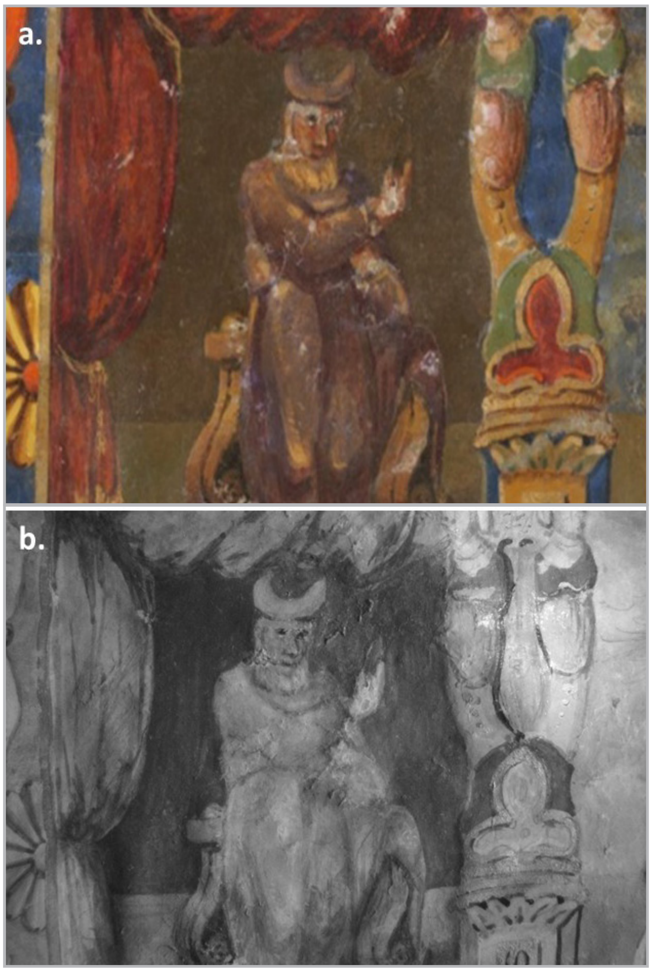


Figura 2.- Fotografía a color (a) y fotografía infrarroja (b) sobre una miniatura procedente de un cantoral del Colegio del Corpus Christi. Fuente: IVCR+i.

ópticos en los documentos, durabilidad de la tinta y del papel o procesos de restauración, así como estudiar tintas o la degradación de pergaminos (Scholten *et al*. 2005; Aalderink *et al*. 2008; Goltz *et al*. 2009; Giacometti *et al.* 2012; Mindermann 2018).

Técnicas analíticas de identificación

Las técnicas analíticas de identificación permiten estudiar la composición química de los diferentes materiales empleados en el patrimonio documental y bibliográfico, así como su grado de alteración o la aparición de productos de neoformación. Estos estudios se pueden llevar a cabo mediante el estudio de los elementos químicos o las moléculas presentes en los diferentes materiales.

—*Técnicas de identificación de elementos químicos*

Entre las técnicas de análisis elemental caben destacar las técnicas basadas en la fluorescencia de rayos X. En ellas se emplea una fuente de excitación (electrones, protones, rayos X, fuentes radiactivas, etc.) que excita el material induciendo la emisión de fluorescencia de rayos X por parte de los átomos excitados, aportando información cuantitativa y cualitativa de los elementos que lo constituyen (análisis multielemental).

La fluorescencia de rayos X (EDXRF) es una técnica no destructiva, rápida, precisa y fiable, y cuyo espectro puede ser simple o de varios elementos. En el caso de material documental y bibliográfico, ha sido utilizada para estudiar tintas metalogálicas y su degradación, identificar la aparición de foxing o analizar halos y filigranas (Ferrero *et al.* n.d.; Zappalà *et al*. 1996; Kanngießer *et al*. 2004; Rožić, MačEfat & Oreščanin 2005; Stuart 2007; Van Der Snickt *et al.* 2008; Čechák *et al.* 2010; Chaplin *et al*. 2010; Deneckere *et al.* 2011; Dietz *et al.* 2012; Pessanha *et al.* 2012; Alcántara García, Ruvalcaba Sil & Vander Meeren 2014; Manso *et al.* 2014). Una variación de esta técnica es la radiación sincrotrón de fluorescencia de rayos X (XSRXRF) y que ha sido utilizada para caracterizar materiales de dibujo, tintas impresas, pigmentos, etc. (Kolar & Strlič 2006; Bataglia *et al.* 2011). Sin embargo, para obtener una mayor sensibilidad en la detección de elementos químicos, es recomendable recurrir a la fluorescencia de rayos X por reflexión total (TXRF), por la cual el objeto es excitado por rayos X primarios que inciden de manera oblicua sobre la muestra. Su ventaja frente al XRF es que tiene una mayor sensibilidad de medición elemental. Klockenkämper, Von Bohlen, and Moens (2000) y Pessanha, Manso, and Carvalho (2012) la han empleado para la caracterización de tintas, pigmentos inorgánicos e impurezas en manuscritos.

Otra técnica muy utilizada en la caracterización de manuscritos es la espectroscopia dispersiva de rayos X (EDX), la cual aparece acoplada a un microscopio electrónico. Permite realizar el análisis químico elemental semicuantitativo [figura 3], por lo que es adecuada para analizar elementos inorgánicos, tintas manuscritas e impresas, la degradación de pergaminos y pigmentos o la oxidación de tintas (Matteini & Moles 2001; Kolar *et al*.2006; Goltz *et al*. 2010; Espejo Arias *et al*. 2011; Pessanha *et al.* 2012).

La técnica de emisión de rayos X inducida por partículas (PIXE) permite reconocer elementos de bajo número atómico, generalmente a partir del sodio (Plossi, Zappalà & Zappalà 2007). Su funcionamiento se basa en detectar los rayos X procedentes de la desexcitación de los átomos tras ser ionizados con un haz de protones. A pesar de que se puede aplicar sin dañar prácticamente los documentos, su uso presenta algunas limitaciones como la profundidad del perfil de la tinta depositada en el papel frente al alcance de los protones, el peso de las concentraciones de los elementos en el papel, la no homogeneidad en la distribución, la rugosidad de la superficie del papel, y el hecho de que la decisión dependa del elemento químico analizado con errores entre el 5 y el 20% (Budnar et al. 2006). A pesar de

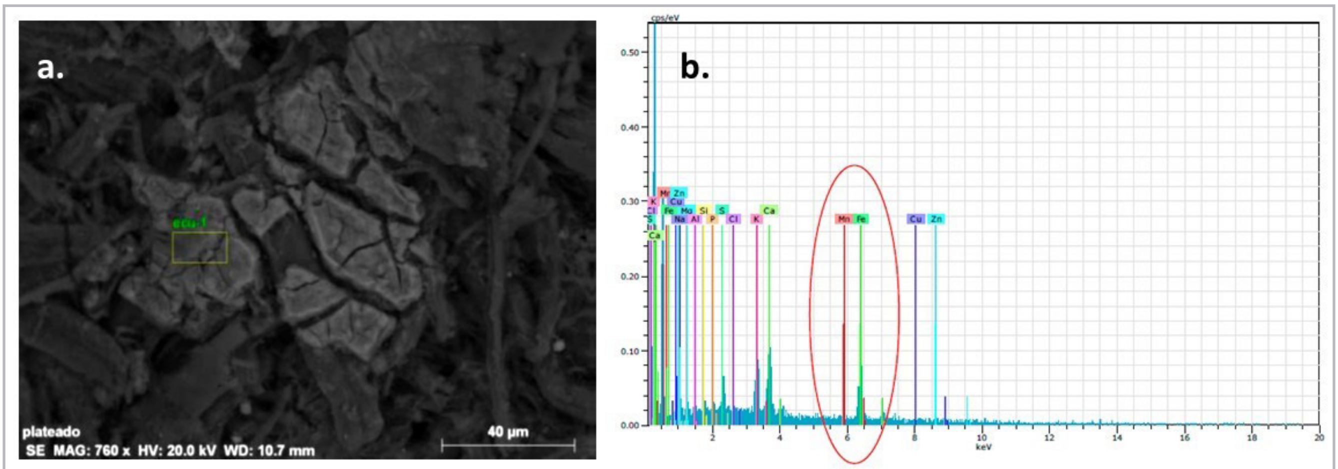


Figura 3.-Muestra de tinta de un manuscrito procedente del Archivo Nacional de Ecuador estudiada por SEM (a) y EDX (b). En este caso se puede determinar que se trata de una tinta ferrogálica con trazas de calcio y potasio. Fuente: Gemma Mª Contreras.

esto, se trata de una técnica ampliamente utilizada para el estudio de tintas impresas y manuscritas (distribución de metales, migración proporción de elementos, deterioro), pigmentos inorgánicos o el deterioro de papel, papiros, pergaminos y vitelas (Del Carmine *et al.* 1996; Lucarelli & Mandò 1996; Budnar *et al.* 2001; Budnar *et al*. 2004; Wagner *et al.* 2001; Budnar *et al.* 2006; Olsson *et al.* 2001; Kolar *et al.* 2006; Plossi & Zappalà 2007; Stuart 2007; Manso & Carvalho 2009; Kakuee *et al.* 2012; Pessanha *et al*. 2012).

El empleo de equipos láser en patrimonio documental y bibliográfico es muy común tanto en procesos de limpieza como en la caracterización de los materiales constituyentes (Clarke 2001; Kaminska *et al*. 2007; Nevin, Spoto & Anglos 2012). En el caso de la caracterización de este tipo de bienes culturales destaca el uso de la espectrometría de emisión atómica con inducción de plasma (IPC-AES), que ha sido utilizada para estudiar la influencia del hierro y el cobre en la degradación del papel (Kolar & Strlič 2006), y la espectrometría de masas con fuente de plasma de acoplamiento inductivo (IPC-MS), la cual ha sido empleada para determinar elementos traza de los papeles y las tintas (Wagner *et al.* 1999; Stuart 2007). La espectroscopia de ablación inducida por láser (LIBS) permite hacer análisis cualitativo y cuantitativo de los elementos químicos presentes en una muestra (Mateo *et al.* 2019) al analizar el plasma producido por un pulso láser en la superficie del material a estudias. Se trata, por tanto, de una técnica microdestructiva, aunque con una alta sensibilidad, que permite determinar pigmentos, tintas manuscritas e impresas, papel y pergamino (Häkkänen *et al.* 2001; Melessanaki *et al*. 2001; Ochocińska *et al*. 2003; Oujja *et al*. 2005; Dolgin *et al.* 2006; Dolgin *et al*. 2008; Bicchieri *et al.* 2011; Pessanha *et al.* 2012; Król, Kowalska & Kościelniak 2018).

De este modo, y en base a las técnicas de caracterización elemental, se puede concluir que el empleo de SEM-EDX aporta la ventaja de unificar dos tipos de ensayos sobre una misma muestra, al obtenerse una imagen de alta magnificación, así como el análisis elemental de la muestra. Además, esta unificación de técnicas permite realizar un mapeado composicional y, por tanto, analizar la distribución de los diferentes elementos. Sin embargo, se trata de una técnica que requiere la toma de muestras y cuya sensibilidad a la hora de identificar elementos es de 1000 ppm, frente a otras técnicas como FRX (100 ppm) y LIBS (10-50 ppm) (Kearton & Mattley 2008). De este modo, para la identificación de elementos trazas sería recomendable el empleo de FRX, de la cual existen modelos que permiten el análisis in situ y sin toma de muestras, o LIBS, la cual es una técnica mínimamente invasiva. Finalmente, en el caso de ser necesaria la identificación de elementos de bajo peso molecular que no puedan ser identificados con las técnicas anteriores, se podría recomendar el empleo de PIXE.

—*Técnicas de identificación a nivel molecular*

Dentro de las técnicas de identificación a nivel molecular aplicadas al estudio del patrimonio documental y bibliográfico destacan la espectroscopía infrarroja y la espectroscopía Raman.

Las espectroscopías infrarrojas son una serie de técnicas con numerosas aplicaciones en el patrimonio cultural (Derrick 2000), que analizan las vibraciones de los enlaces moleculares producidas por fotones de radiaciones infrarrojas, y cuyas longitudes de onda de excitación son características en función del tipo de molécula. En el caso de la espectroscopia infrarroja transformada de Fourier (FTIR), la distribución de la radiación infrarroja es alterada por un espejo y pasada por un interferómetro donde es grabada la señal, es decir, se graba la cantidad de radiación infrarroja detectada. Mediante la transformada de Fourier, técnica de procesamiento de estos datos, los datos son transformados en un espectro. Esta técnica ha sido utilizada para identificar cargas (carbonatos y sulfatos), tintas metalogálicas (carbonatos, sulfatos, taninos, presencia de goma arábiga) e impresas, papeles (fibras, cargas, adhesivos, impurezas ácidas…) y pergaminos, colonias de microorganismos, oxidación por tintas metaloácidas y tratamientos de restauración (Colbourne 2000; Calvini, Gorassini & Chiggiato 2006; Trafela et al. 2007; Ferrer & Sistach 2007; Plossi & Zappalà 2007; Sivakoval, Beganskiené & Kareiva 2008; Zotti, Ferroni & Calvini 2008, 2011; Gonzalez & Wess 2008; Ursescu, Malutan & Ciovica 2009; Manso & Carvalho 2009; Bicchieri *et al*. 2011; Da Costa *et al*. 2013; Doherty *et al.* 2013; Vetter, Pöllnitz & Schereiner 2014; Doncea & Iona 2014; Nodari & Ricciardi 2019). A pesar de las ventajas que presenta esta técnica, autores como da Costa et al. (2013) y Remaizelles, Quillet & Bernard (2000) han detectado ciertas limitaciones a la hora de caracterizar pigmentos orgánicos, tintes y tintas. En el caso de las tintas metalogálicas, sólo es posible detectar el espectro de los taninos, no así de los complejos completos de las tintas.

En cuanto a la espectrometría Raman, se trata de un método analítico que se basa en la dispersión inelástica o Raman, y aporta información sobre los modos vibracionales de las moléculas. Su aplicación en el estudio de manuscritos está relacionada con la identificación de pigmentos orgánicos e inorgánicos, tintas y tintes, degradación y oxidación de las fibras, cargas de la celulosa, preparación original de pergaminos (Clark 1995; Burgio, Ciomartan & Clark 1997; Burgio, Clark & Hark 2010; Clarke 1999, 2001; Wehling *et al.* 1999; Mannucci *et al.* 2000; Bicchieri, Nardone & Sodo 2000; Bicchieri *et al*. 2006; Bicchieri *et al*. 2008; Bicchieri *et al.* 2011; Magistro *et al*. 2001; Bruni *et al*. 2001; Bruni *et al.* 2008; Derbyshire & Wheeler 2002; Chaplin *et al.* 2005; Chaplin *et al*. 2006; Aceto *et al*. 2006; Baraldi *et al*. 2009; Trentelman & Turner 2009; Bioletti *et al*. 2009; Guedes & Prieto 2012; Nastova *et al.* 2012 Marucci *et al.* 2018). Una de las principales limitaciones de esta técnica viene causada por el problema de la fluorescencia, fenómeno que aumenta en tintas históricas (Lee, Mahon & Creagh 2006), en tintes y papel (Stuart 2007), y en pergamino (Bersani *et al*. 2006). El empleo de la espectroscopia Raman activada por superficie aumentada (SERS) permite aumentar la intensidad de las bandas Raman y reducir el efecto de la fluorescencia del material debido a la interacción del analito con la superficie rugosa de los metales nobles. De este modo, autores como El Bakkali *et al.* (2013), Castro *et al.* (2014)o Roldán, Centeno & Rizzo (2014) han podido mejorar la identificación de pigmentos, lacas o tintas.

Mediante espectrometría UV-Vis es posible identificar los grupos funcionales presentes en una molécula al excitar los electrones del enlace con radiación ultravioleta-visible. La variante de esta técnica más utilizada es la espectrometría de reflexión de fibra óptica (FORS), en la que se observa la reflectancia generada por el material en función de la longitud de onda del haz incidente, desde el ultravioleta hasta el infrarrojo cercano. En el caso de los pigmentos, cada uno tiene su propia curva de reflectancia espectral, por lo que es posible identificarlos (Clarke 2001; Matteini & Moles 2001; Aceto *et al.* 2012). Las limitaciones de este sistema aparecen cuando los pigmentos son mezclas y no puros (Aceto *et al.* 2012).

La espectrometría de resonancia magnética nuclear (NMR) permite estudiar las estructuras moleculares. Suele emplearse para evaluar el estado de conservación de materiales celulósicos, los deterioros ocasionados por las tintas metaloácidas o la efectividad de tratamientos de restauración (Blümich *et al*. 2003; Casieri *et al.* 2004; Castro *et al.* 2008)

En el caso de técnicas moleculares, por tanto, destaca su empleo para la identificación de pigmentos, cargas, tratamientos de restauración, tipos de papel, etc. Algunos pigmentos y cargas pueden ser identificados con técnicas elementales, siendo recomendable el uso de estas técnicas moleculares cuando no es posible realizar una identificación correcta con las primeras, como es el caso de los pigmentos orgánicos. Lejos de establecer una prelación entre las técnicas espectroscópicas, cabe destacar que estas son complementarias en multitud de casos, ya que, si bien el análisis por infrarrojo suele ser más sencillo, los espectros Raman permiten una mejor identificación de algunos componentes orgánicos. Sólo en el caso de pigmentos orgánicos que se encuentren en un estado más o menos puro, especialmente lacas y tintes, sería recomendable el empleo de FORS para confirmar su correcta identificación.

Otras técnicas analíticas de identificación

Los sistemas de cromatografía permiten separar componentes estrechamente relacionados en mezclas complejas [figura 4]. Existen diferentes técnicas cromatográficas siendo las más utilizadas en los estudios sobre patrimonio documental la cromatografía líquida de alta eficacia (HPLC) y la cromatografía de gases/espectrometría de masas (GS-MS). La primera técnica es un método muy rápido, eficaz y preciso que se aplica principalmente al estudio de muestras orgánicas como el material proteico, aglutinantes, aprestos, etc. (Striegel & Hill 1996; Matteini & Moles 2001; Romera *et al*. 2013; Kurouski *et al*. 2014). En la GS-MS, la muestra es volatilizada para hacerla recorrer la columna cromatográfica. Es capaz de separar mezclas orgánicas complejas y complejos organometálicos, así como determinar cualitativa y cuantitativamente sus componentes (Matteini & Moles 2001; Stuart 2007). Además, el espectrómetro de masas identifica las moléculas, las cuales son previamente ionizadas con un haz de electrones (Clarke 2001). Estas técnicas también son utilizadas para evaluar el envejecimiento de tintas (EL-Sabbah *et al.* 2019)

Mediante difracción de rayos X (XRD) es posible identificar minerales gracias a su estructura cristalina ya que los rayos X irradiados a la muestra son difractados por los electrones cuando su longitud de onda es del mismo orden que el radio atómico. De este modo, se obtiene información sobre la posición y tipo de átomos, ya que

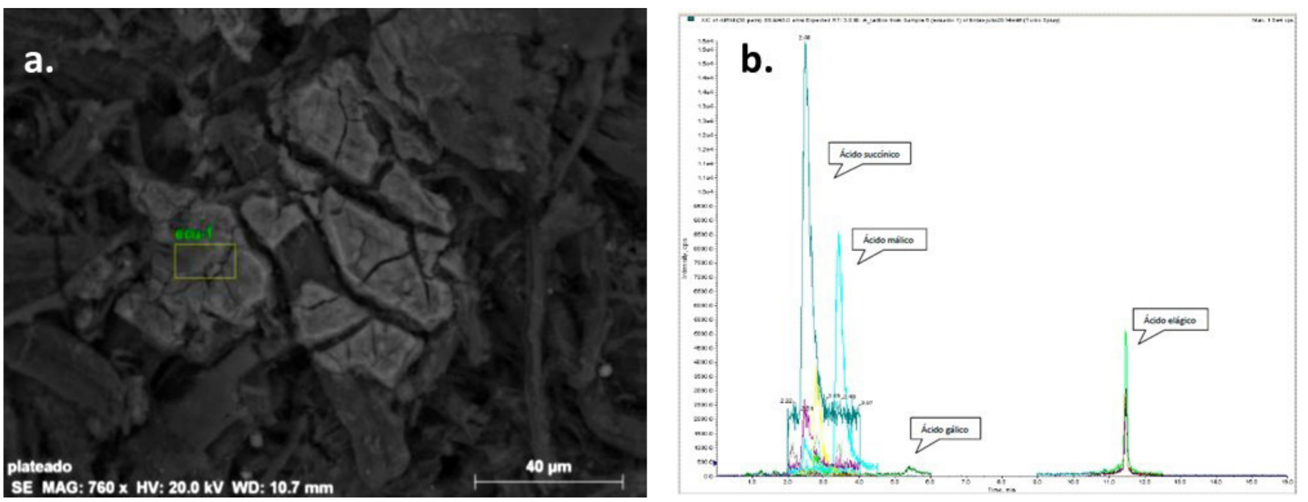


Figura 4.-Imagen SEM (a) de una muestra de tinta procedente de un manuscrito de Archivo Nacional de Ecuador y cromatograma (b) en el que se observan los diferentes ácidos presentes en la tinta. Fuente: Gemma Mª Contreras.

las estructuras cristalinas dispersan elásticamente los haces de electrones y los amplifica por interferencia constructiva. Se trata de una técnica que permite caracterizar pigmentos inorgánicos y tintas, así como evaluar su alteración (Matteini & Moles 2001; Wess et al. 2001; Stuart 2007; Duran et al. 2009; Cucos et al. 2011; Rueangyodjantana & Buntem 2017).

Finalmente, cabe destacar el empleo de los procesos de extracción de ADN para la determinación del origen animal de los pergaminos empleados como soporte documental. Este tipo de análisis requiere de la toma de micromuestras, las cuales son tratadas para la extracción del gen empleado para la identificación de la especie mediante el uso de primers. Tras la obtención de la secuencia genómica, se procede a su comparación con bases de datos para así determinar la especie (Bower *et al.* 2010). Sin embargo, el empleo de esta técnica para identificar la especie en pergaminos históricos posee la desventaja de que el ADN se encuentra degradado, para lo cual se recomienda el uso de la secuencia nucleótidica del gen del citocromo b (Espejo, Alvarez-Cubero & Saiz 2011).

Empleo de las técnicas analíticas en el patrimonio documental

La especificidad de cada técnica analítica [tabla I] hace que la mayoría de los investigadores opten por la suma de las ventajas de varias técnicas, bien para estudiar elementos diferentes, como pigmentos orgánicos o inorgánicos, o bien para ratificar el resultado de unas técnicas con otras. Este es el caso de la espectroscopía Raman, una de las técnicas más empleadas para el estudio de los componentes de los manuscritos iluminados. Por ejemplo, Plossi & Zappala (2007) la utiliza en combinación con EDXRF, al igual que Aceto *et al.* (2008) en la caracterización de tintas metalogálicas, en las que la presencia de un alto contenido en cobre puede corresponder a una preparación conjunta de sulfato de hierro y sulfato de cobre. Esta combinación de técnicas se ha empleado ampliamente para el estudio códices medievales (Vandenabeele et al. 2002; Burgio *et al.* 2010), libros renacentistas italianos (Burgio, Clark & Hark 2010) o manuscritos islámicos (Burgio *et al.* 2008). Además, estos estudios pueden llevarse a cabo mediante equipos portátiles, lo que facilita su empleo in situ (Wehling *et al.* 1999; Duran *et al.* 2011; Hamdan, Alawadhi & Jisrawi 2012).

Estas técnicas, a su vez, pueden verse complementadas por otras, por ejemplo, el uso de FORS para identificar pigmentos como el azul ultramar o el cinabrio (Aceto *et al.* 2012), SEM-EDS para determinar la presencia de cobre y sales de cobre en tintas manuscritas o estudiar manuscritos iluminados (Aceto et al. 2006; Chaplin *et al.* 2010) o FTIR para estudiar tintas metalogálicas (Bicchieri *et al*. 2008) y las sales e impurezas que contienen (Piantanida *et al.* 2013). De hecho, este tipo de combinaciones, no sólo son utilizadas para la caracterización de materiales constitutivos, sino también para la evaluación de la reversibilidad de tratamientos de restauración (Bicchieri *et al.* 2012). Para la identificación de pigmentos, Andalò *et al.* (2001) proponen el empleo de microespectroscopía Raman y PIXE, aunque sólo obtuvieron la identificación de pigmentos inorgánicos.

Tras la espectroscopía Raman, es muy común encontrar estudios en los que se emplea la combinación de EDXRF y FTIR para estudiar la composición química del papel (Doncea *et al.* 2010) o para el estudio del cobre como agente acelerador del deterioro tanto de tintas como de pigmentos (Faubel *et al.* 2007). El uso de EDXRF y FORS ha permitido a Aceto *et al.* (2012) y a Picollo *et al.* (2011) realizar estudios in situ y sin toma de muestras de tintas sobre pergamino o pigmentos.

Gambaro *et al.* (2009) utilizan FTIR para identificar tintas, SEM/EDX para obtener la morfología y composición de las tintas y GC/MS para identificar los componentes metalogálicos, de tal manera que se pueda trazar la continuidad en el uso de tintas metalogálicas en el siglo

Tabla I.- Principales técnicas analíticas y su empleo para la caracterización de los materiales constitutivos del patrimonio documental.

	MO	SEM	EDXRF	EDX	PIXE	LIBS	FTIR	Raman	FORS	HPLC	GS-MS	XRD
Inorgánicos			■	■	■	■	■	■		■		
Orgánicos						■	■	■		■	■	
Morfología	■	■										
Biodeterioro		■					■					
Pergamino		■			■	■	■	■				
Pigmentos			■	■	■	■	■	■	■			■
Tintas			■	■	■	■	■	■				
Oxidación							■	■				
Cargas							■	■		■		
Adhesivos							■			■	■	

XIX. Estos mismos autores introducen el empleo de la cromatografía para el estudio de los extractos orgánicos del papel y la determinación de la presencia de ácido vinílico y de lignina (Ganzerla et al. 2009). En otros casos, junto a FTIR y SEM/EDX, se emplea la XRD para determinar la antigüedad de papeles (Rueangyodjantana & Buntem 2017).

Finalmente, la combinación de LIBS con imagen multiespectral ha resultado eficaz en el estudio no invasivo de pigmentos en manuscritos iluminados (Melessanaki *et al*. 2001); mientras que junto con espectrometría atómica (AAS) ha permitido identificar la presencia de hierro y cobre en tintas (Wagner *et al.* 1999).

Test químicos para la aproximación a la composición de materiales constitutivos

En ocasiones, el empleo de técnicas analíticas es difícil de asumir por el conservador-restaurador. Para ello, se puede recurrir al empleo de test químicos, los cuales darán una aproximación a los compuestos presentes en una obra. Estas pruebas son de carácter cualitativo, por lo que sólo indicarán la presencia o ausencia de un material, aunque no su cuantificación en la muestra analizada. Estas pruebas requerirán de la aplicación de una gota del reactivo, por lo que se han de realizar en zonas poco vivible del documento y de manera controlada. Entre los test más utilizados para la identificación de los soportes cabe destacar:

Test de Molish: Determina la presencia de celulosa y sus derivados. Para ello, se disuelve una pequeña muestra del soporte en acetona y se le agregan varias gotas de 2 wt-%1-naftol en etanol. Se depositan dos gotas de ácido sulfúrico concentrado cerca de la muestra, de tal forma que su vapor reaccione con la muestra. Si tras 10-15 minutos aparece un color rojo-marrón significa que la muestra posee celulosa. La tinción hacia un tono verdoso indica la presencia de nitrato de celulosa, mientras que entre marrón y negro puede ser debida a la presencia de lignina u otros azúcares (Odegaard, Carroll & Zimmt 2005; Stuart 2007).

Test para determinar la presencia de celulosa: En un tubo de ensayo, se añade a la muestra una gota de concentrado de ácido fosfórico, se tapa con filtro de papel y se añade una gota de acetato de anilina (se añaden a la anilina 1:1 ácido acético glacial y agua destilada). El tubo se calienta y, en presencia de celulosa, se aprecia un color rosa (Odegaard Carroll & Zimmt 2005; Stuart 2007).

Test para determinar la presencia de lignina: Se deposita sobre la muestra una gota de una solución de fluroglucinol en metanol (4 g. de fluroclucinol en 50 ml de metanol) y, a continuación, una gota de una solución de ácido clorhídrico en metanol al 50% en volumen. La presencia de lignina teñirá la muestra de un color rojo-violeta (Vergara Peris 2002; Stuart 2007).

Test de Buiret: Para identificar la presencia de proteínas. Se añade una gota de 2 wt-% de sulfato de cobre a una pequeña cantidad de muestra. Al cabo de unos minutos, la muestra se vuelve ligeramente azul, mientras que en presencia de proteínas, virará hacia un tono púrpura (Stuart 2007).

Test de Lugol: Permite determinar la presencia de almidón al adquirir la muestra una tonalidad azul tras depositar sobre esta una gota de lugol (0.13 g. de yodo y 2,6 g. de yoduro de potasio en 5 ml de agua destilada) (Matteini & Moles 2001; Stuart 2007). Una variable de este test se encuentra en Vergara Peris (2002), quien aplica una gota de solución de yodo/yoduro al 50%.

Test para determinar la presencia de alumbre: Se deposita una gota de una solución de aluminón (0,1 g. de aluminón en 100 ml de agua destilada) en la superficie de la muestra y se deja secar. La tinción hacia un tono rojo-rosado indica la presencia de iones de aluminio en el papel (Odegaard, Carroll & Zimmt 2005; Stuart 2007).

La identificación de tintas mediante el uso de test químicos suele ser una tarea más complicada, ya que se podrá determinar la presencia de determinados compuestos e intuir su naturaleza a grandes rasgos. Debe tenerse en cuenta que existe una gran cantidad de recetarios de tintas, en la que la presencia de determinados compuestos ha favorecido a su mayor o menor grado de deterioro (Contreras 2015). En este sentido, es posible detectar la presencia de tintas ferrogálicas mediante la identificación de la presencia de hierro, o hierro y cobre.

Test de batofenantrolina: Permite identificar la presencia de hierro (II) al poner en contacto unas tiras empapadas en batofenantrolina con la muestra. No es un sistema apto para otros metales (Neevel 2009; Belhadj *et al.* 2014).

Test para determinar la presencia de tintas ferrogálicas: Consiste en aplicar sobre la tinta una microgota de α,α′-dipiridilo al 2 wt-% en ácido tioglicólico. Si aparece un color rosa o rojo significa que hay presencia de hierro, ya que este reactivo reduce Fe^{3+} en Fe^{2+} (Stuart 2007).

Test para determinar la presencia de iones de cobre: Se aplica en unas tiras de papel con una solución de 5N-α-PAN en 1,4 dioxano (Kolar & Strlič 2006).

Protocolo de actuación para la identificación de materiales presentes en documentos

A la hora de abordar la caracterización de documentos es importante tener en cuenta una serie de premisas que condicionarán la selección de las técnicas a emplear. Entre estos condicionantes cabe destacar la necesidad de identificar los diversos materiales presentes en el documento debido a su valor histórico-cultural, su estado de conservación o la selección del tratamiento

Figura 5.-Protocolo de actuación en función de los medios disponibles y el tipo de material a caracterizar

de restauración; los medios y recursos disponibles o la posibilidad de toma de muestras.

La figura 5 muestra, a modo de esquema, un protocolo de actuación general que facilita la labor de selección de técnicas y estudios a la hora de abordar la caracterización de un documento bibliográfico. En el eje superior, se establece una prelación de técnicas en función de los recursos y medios disponibles, desde las técnicas más básicas, hasta la caracterización mediante técnicas más complejas pero que aportan un mayor de precisión a la hora de proceder a la determinación de los materiales y los productos de alteración. El eje vertical, determina el empleo de técnicas en función del tipo de material a analizar, distinguiendo especialmente entre soportes y materiales sustentados.

La aplicación de este protocolo de actuación permite al conservador-restaurador realizar una aproximación a los materiales presentes en el documento de manera autónoma, así como seleccionar la técnica que mejor se ajuste a su necesidad de identificar determinados materiales. El grado de precisión requerido, generalmente aparece asociado a la importancia y valor del documento, así como la disponibilidad material y económica para llevar un mayor número de estudios.

Conclusiones

Los bienes culturales que constituyen el patrimonio documental están conformados por materiales de diversa composición química y propiedades. Es por ello que, para garantizar su preservación es necesaria su correcta identificación. El desarrollo de las técnicas analíticas de identificación, así como su puesta a punto para el análisis de documentos, garantiza un amplio espectro de posibilidades a la hora de abordar este tipo de estudios. De este modo, la elección de la técnica dependerá de diversos factores entre los que destacan el objetivo del estudio o material a caracterizar, la posibilidad o no de toma de muestra, los recursos y medios disponibles, etc.

Es importante tomar en consideración que el empleo de una única técnica analítica difícilmente podría servir para la realización de una caracterización general de los materiales que conforman un documento. De este modo, es necesario conocer el tipo de información que facilita cada técnica analítica, así como las técnicas que servirían para confirmar el resultado o para complementarlo. En este sentido, se ha establecido un protocolo de actuación que facilita la labor del restaurador a la hora de llevar a cabo la elección de técnicas en función del material a caracterizar. Debido a la dificultad que entraña para muchos conservadores-restauradores el acceder a este tipo de técnicas analíticas, se ha dotado al protocolo de una primera aproximación mediante pruebas químicas que pueden ser desarrolladas en el propio taller.

Finalmente, es importante resaltar que la correcta caracterización de los materiales presentes en un documento no sólo aporta datos histórico-artísticos o de diagnóstico de la obra, sino que facilita la selección de los tratamientos de restauración y la implementación de los estándares de la conservación preventiva en función de las características del bien estudiado.

Agradecimientos

Este trabajo ha sido desarrollado gracias a la colaboración de los doctores David Juanes y Livio Ferrazza. Los autores también están agradecidos al Institut València de Conservació, Restauració i Investigació (IVCR+i).

Referencias

AALDERINK, BJ., KLEIN, ME., PADOAN, R., DE BRUNI, G., STEEMES, T. (2008). "Quantitative Hyperspectral Imaging Technique for Condition Assessment and Monitoring of Historical Documents". In *9th International Conference on NDT of Art*. Jerusalem, Israel.

ACETO, M., AGOSTINO, A., BOCCALERI, E., CRIVELLO, F., GARLANDA, AC. (2006). "Evidence for the degradation of an alloy pigment on an ancient Italian manuscript". In *Journal of Raman Spectroscopy*. V. 37: 1160–1170. https://doi.org/10.1002/jrs.1604

ACETO, M., AGOSTINO, A., BOCCALERI, E., GARLANDA, AC. (2008). "The Vercelli gospels laid open: An investigation into the inks used to write the oldest Gospels in Latin". *X-Ray Spectrometry*. 37(4):286–292. https://doi.org/ 10.1002/xrs.1047

ACETO, M., AGOSTINO, A., FENOGLIO, G., GULMINI, M., BIANCO, V., PELLIZZI, E. (2012). "Non invasive analysis of miniature paintings: Proposal for an analytical protocol". *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*. 91:352–359. https://doi.org/10.1016/j.saa.2012.02.021

ALCÁNTARA GARCÍA, J., RUVALCABA SIL, JL., VANDER MEEREN, M. (2014). "XRF study of Mexican iron gall inks: Historical and geographical overview of their chemistry". In Materials Research Society Symposium Proceedings. V. 1618. *Materials Research Society*: 31–41. https://doi.org/10.1557/opl.2014.453

ANDALÒ, C., BICCHIERI, M., BOCCHINI, P., CASU, G., GALLETTI, GC., MANDÒ, PA., NARDONE, M., SODO, A., PLOSSI ZAPPLÀ, M. (2001). "The beautiful "Trionfo d'Amore" attributed to Botticelli: A chemical characterisation by proton-induced X-ray emission and micro-Raman spectroscopy". *Analytica Chimica Acta*. 429(2):279–286. https://doi.org/10.1016/S0003-2670(00)01292-7

EL BAKKALI, A., LAMHASNI, T., HADDAD, M., AIT LYAZIDI, S., SANCHEZ-CORTES, S., DEL PUERTO NEVADO, E. (2013). "Non-invasive micro Raman, SERS and visible reflectance analyses of coloring materials in ancient Moroccan Islamic manuscripts". *Journal of Raman Spectroscopy*. 44(1):114–120. https://doi.org/10.1002/jrs.4154

BARALDI, P., MOSCARDI, G., BENSI, P., ACETO, M., TASSI, L. (2009). "An investigation of the palette and techniques of some High Medieval codices by Raman microscopy". *e-Preservation science*. 6:163–168.

BATAGLIA, M., ALIDORI BATAGLIA, M., CELESTRE, R., DENES, P., DOERNING, D., KIM, TS., ZALUSLY, S. (2011). "The application of SR-XRF to the analysis of manuscript illumination. A case of study". *Revista de História da Arte. Medieval Colours between beauty and meaning*. I:245–252.

BELHADJ, O., PHAN TAN LUU, C., JACOBI, E., MESLET-STRUYVE, S., VEZ, S., REISSLAND, B. ROUCHON, V. (2014). "The Dutch Fe-Migration Mending Test". *Journal of PaperConservation*. 15(1):9–15.

BERSANI, D, LOTTICI, PP, VIGNALI, F & ZANICHELLI, G. 2006. "A study of medieval illuminated manuscripts by means of portable Raman equipments". In *Journal of Raman Spectroscopy*. V. 37. V. 37:1012–1018. John Wiley & Sons, Ltd. https://doi.org/10.1002/jrs.1593

BICCHIERI, M., NARDONE, M., SODO, A. (2000). "Application of micro-Raman spectroscopy to the study of an illuminated medieval manuscript". *Journal of Cultural Heritage*. 1(2):S277–S279. https://doi.org/10.1016/S1296-2074(00)00175-8

BICCHIERI, M., SODO, A., PIANTANIDA, G., COLUZZA, C. (2006). "Analysis of degraded papers by non-destructive spectroscopic techniques". In *Journal of Raman Spectroscopy*. V. 37:1186-1192. John Wiley & Sons, Ltd. https://doi.org/10.1002/jrs.1603.

BICCHIERI, M., MONTI, M., PIANTANIDA, G., SODO, A. (2008). "All that is iron-ink is not always iron-gall!" In *Journal of Raman Spectroscopy.* V. 39:1074-1078. John Wiley & Sons, Ltd. https://doi.org/10.1002/jrs.1995

BICCHIERI, M., MONTI, M. PIANTANIDA, G., PINZARI, F. & SODO, A. (2011). "Non-destructive spectroscopic characterization of parchment documents". *Vibrational Spectroscopy.* 55(2):267–272. https://doi.org/10.1016/j.vibspec.2010.12.006

BICCHIERI, M., MONTI, M., PIANTANIDA, G., PINZARI, F., IANNUCCELLI, S., SOTGIU, S., TIRENI, L. (2012). "The Indian drawings of the poet Cesare Pascarella: Non-destructive analyses and conservation treatments". *Analytical and Bioanalytical Chemistry*. 402(4):1517–1528. https://doi.org/10.1007/s00216-011-5229-3

BIOLETTI, S., LEAHY, R., FIELDS, J., MEEHAN, B. & BLAU, W. (2009). "The examination of the Book of Kells using micro-Raman spectroscopy". *Journal of Raman Spectroscopy.* 40(8):1043–1049. https://doi.org/10.1002/jrs.2231

BLÜMICH, B., ANFEROVA, S., SHARMA, ., SEGRE, AL., FEDERICI, C. (2003). "Degradation of historical paper: Nondestructive analysis by the NMR-MOUSE". *Journal of Magnetic Resonance*. 161(2):204–209. https://doi.org/10.1016/S1090-7807(03)00034-X

BOWER, MA., CAMPANA, MG., CHECKLEY-SCOTT, C., KNIGHT, B., HOWE, CJ. (2010)." The potential for extraction and exploitation of DNA from parchment: a review of the opportunities and hurdles". *Journal of the Institute of Conservation*. 33(1):1–11. https://doi.org/10.1080/19455220903509937

BRUNI, S., CARIATI, F., CASADIO, F., GUGLIELMI, V. (2001). "Micro-Raman identification of the palette of a precious XVI century illuminated Persian codex". *Journal of Cultural Heritage*. 2(4):291–296. https://doi.org/10.1016/S1296-2074(01)01131-1

BRUNI, S., CAGLIO, S., GUGLIELMI, V., POLDI, G. (2008). "The joined use of n.i. spectroscopic analyses - FTIR, Raman, visible reflectance spectrometry and EDXRF - To study drawings and illuminated manuscripts". *Applied Physics A: Materials Science and Processing*. 92(1):103–108.

BUDNAR, M, VODOPIVEC, J, MANDÒ, PA, CASU, FLG & SIGNORINI, O. 2001. Distribution of chemical elements of iron-gall ink writing studied by the PIXE method. *Restaurator*. 22(4):228–241. https://doi.org/10.1515/REST.2001.228

BUDNAR, M,. SIMČIČ, J., RUPNIK, Z., URŠIČ, M., PELICON, P., KOLAR, J., STRLIČ, M. (2004). "In-air PIXE set-up for automatic analysis of historical document inks". In *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms. V*. 219–220. North-Holland. 41–47. https://doi.org/10.1016/j.nimb.2004.01.025

BUDNAR, M., URŠIČ, M., SIMČIČ, J., PELICON, P., KOLAR, J., ŠELIH, VS., STRLIČ, M. (2006). "Analysis of iron gall inks by PIXE. Nuclear Instruments and Methods". In *Physics Research, Section B: Beam Interactions with Materials and Atoms*. 243(2):407–416. https://doi.org/10.1016/j.nimb.2005.10.013

BURGIO, L., CIOMARTAN, DA., CLARK, RJH. (1997). "Pigment identification on medieval manuscripts, paintings and other artefacts by Raman microscopy: Applications to the study of three German manuscripts". *Journal of Molecular Structure*. 405(1):1–11. https://doi.org/10.1016/S0022-2860(96)09422-7

BURGIO, L., CLARK., RJH., MURALHA, VSF., STANLEY, T. (2008). "Pigment analysis by Raman microscopy of the non-figurative illumination in 16th- to 18th-century Islamic manuscripts". *Journal of Raman Spectroscopy*. 39(10):1482–1493. https://doi.org/10.1002/jrs.2027

BURGIO, L., CLARK, RJH., HARK, RR. (2010). "Raman microscopy and x-ray fluorescence analysis of pigments on medieval and Renaissance Italian manuscript cuttings". Proceedings of the National *Academy of Sciences of the United States of America*. 107(13):5726–5731. https://doi.org/10.1073/pnas.0914797107

CALVINI, P., GORASSINI, A., CHIGGIATO, R. (2006). "Fourier transform infrared analysis of some Japanese papers." *Restaurator*. 27(2):81–89. https://doi.org/10.1515/REST.2006.81

DEL CARMINE, P., GIUNTINI, L., HOOPER, W., LUCARELLI, F., MANDÒ, PA. (1996). "Further results from PIXE analysis of inks in Galileo's notes on motion". *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*. 113(1–4):354–358. https://doi.org/10.1016/0168-583X(95)01335-0

CASIERI, C., BUBICI, S., VIOLA, I., DE LUCA, F. (2004). "A low-resolution non-invasive NMR characterization of ancient paper". *Solid State Nuclear Magnetic Resonance*. 26(2):65–73. https://doi.org/10.1016/j.ssnmr.2004.02.001

CASTRO, K., PROIETTI, N., PRINCI, E., PESSANHA, S., CARVALHO, ML., VICINI, S., CAPITANI, D., MADARIAGA, JM. (2008). "Analysis of a coloured Dutch map from the eighteenth century: The need for a multi-analytical spectroscopic approach using portable instrumentation". *Analytica Chimica Acta*. 623(2):187–194. https://doi.org/10.1016/j.aca.2008.06.019

CASTRO, R., POZZI, F., LEONA, M., MELO, MJ. (2014). "Combining SERS and microspectrofluorimetry with historically accurate reconstructions for the characterization of lac dye paints in medieval manuscript illuminations". *Journal of Raman Spectroscopy*. 45(11–12):1172–1179. https://doi.org/10.1002/jrs.4608

ČECHÁK, T., TROJEK, T., MUSÍLEK, L., PAULUSOVÁ, H. (2010). "Application of X-ray fluorescence in investigations of Bohemian historical manuscripts". *Applied Radiation and Isotopes*. 68(4–5):875–878. https://doi.org/10.1016/j.apradiso.2009.10.039

CHAPLIN, TD., CLARK, RJH., JACOBS, D., JENSEN, K., SMITH, GD. (2005). "The Gutenberg Bibles: Analysis of the illuminations and inks using Raman spectroscopy". *Analytical Chemistry*. 77(11):3611–3622. 3611-3622. https://doi.org/10.1021/ac050346y

CHAPLIN, TD., CLARK, RJH., MCKAY, A., PUGH, S. (2006). "Raman spectroscopic analysis of selected astronomical and cartographic folios from the early 13th century Islamic «Book of Curiosities of the Sciences and Marvels for the Eyes». *Journal of Raman Spectroscopy*. 37(8):865–877. https://doi.org/10.1002/jrs.1536

CHAPLIN, TD., CLARK, RJH., MARTINÓN-TORRES, M. (2010). "A combined Raman microscopy, XRF and SEM-EDX study of three valuable objects - A large painted leather screen and two illuminated title pages in 17th century books of ordinances of the Worshipful Company of Barbers, London". *Journal of Molecular Structure*. 976(1–3):350–359. https://doi.org/10.1016/j.molstruc.2010.03.042

CLARK, RJH. (1995). "Raman microscopy: Application to the identification of pigments on medieval manuscripts". *Chemical Society Reviews*. 24(3):187–196. https://doi.org/10.1039/CS9952400187

CLARKE, M. (1999). "A new technique for the non-destructive identification of organic pigments, dyes and inks in–situ on early mediaeval manuscripts, using 3–D fluorescence reflectance spectroscopy". *International conference on non-destructive testing and microanalysis for the diagnostics and conservation of the cultural and environmntal heritage*. 2:1421–1436.

CLARKE, M. (2001)."The analysis of medieval Eupopean manuscripts". *Reviews in Conservation*. 2:3–17. https://doi.org/10.1179/sic.2001.46.Supplement-1.3

CLARKE, M. (2002). "The analysis of manuscript pigments". Why, what and how?". *Gazette du livre médiéval*. 40(1):36–44. https://doi.org/10.3406/galim.2002.1555

COLBOURNE, J. (2001). "A survey of methods used in the technical examination and analysis of brown inks". In *The iron gall ink meeting, Newcastle upon Tyne, 4th & 5th September*. University of Northumbria. 37–45.

CONTRERAS, G. (2015). *La tinta de escritura en los manuscritos de archivo valencianos, 1250-1600. Análisis, identificación de componentes y valoración de su estado de conservación*. Universidad de Valencia.

DA COSTA, ACA., DA FONSECA, NF., DE CARVALHO, SS., DOS SANTOS, FCSC., BARKI, L., DE FREITAS, DS., HERBST, MH., LUTTERBACH, MTS. (2013). "Archaeometric investigations on naturally and thermally-aged iron-gall inks using different tannin sources". *Central European Journal of Chemistry*. 11(11):1729–1739. https://doi.org/10.2478/s11532-013-0303-7

CUCOS, A., BUDRUGEAC, P., MIU, L., MITREA, S., SBARCEA, G. (2011). "Dynamic mechanical analysis (DMA) of new and historical parchments and leathers: Correlations with DSC and XRD". *Thermochimica Acta*. 516(1–2):19–28. https://doi.org/10.1016/j.tca.2011.01.006

DENECKERE, A., DE REU, M., MARTENS, MPJ., DE COENE, K., VEKEMANS, B., VINCZE, L., DE MAEYER, P., VANDENABEELE, P., MOENS, L. (2011). "The use of a multi-method approach to identify the pigments in the 12th century manuscript Liber Floridus". In *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*. V. 80. Elsevier. 125–132. https://doi.org/10.1016/j.saa.2011.03.005

DERBYSHIRE, A., WHEELER, M. (2002). "Further applications of Raman microscopy in paper conservation". *Conservation Journal*. Spring(40).

DIETZ, G, KETELSEN, T, HOSS, M, SIMON, O, WINTERMANN, C, WOLFF, T, RABIN, I & HAHN, O. (2012). "The Egmont Master phenomenon: X-ray fluorescence spectrometric and paper studies for art history research". *Analytical and Bioanalytical Chemistry.* 402(4):1505–1515. https://doi.org/10.1007/s00216-011-5309-4

DOHERTY, B., DAVERI, A., CLEMENTI, C., ROMANI, A., BIOLETTI, S., BRUNETTI, B., SGAMELLOTTI, A., MILIANI, C. (2013). "The Book of Kells: A non-invasive MOLAB investigation by complementary spectroscopic techniques". *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*. 115:330–336. https://doi.org/10.1016/j.saa.2013.06.020

DOLGIN, B., CHEN, Y., BULATOV, V., SCHECHTER, I. (2006). "Use of LIBS for rapid characterization of parchment". *Analytical and Bioanalytical Chemistry*. 386(5):1535–1541. https://doi.org/10.1007/s00216-006-0676-y

DOLGIN, B., BULATOV, V., CHEN, Y., SCHECHTER, I. (2008). "Characterization of historical parchment using laser-induced breakdown spectroscopy". *American laboratory*. 40(6):24–27.

DONCEA, SM., IONA., RM. (2014). "FTIR (DRIFT) analysis of some printing inks from the 19th and 20th centuries". *Revue Roumaine de Chimie.* 59(3–4):173–183.

DONCEA, SM., ION, RM., FIERASCUI, RC., BACALUM, E., BUNACIU, AA., ABOUL-ENEIN, HY. (2010). "Spectral methods for historical paper analysis: Composition and age approximation". *Instrumentation Science and Technology*. 38(1):96–106. https://doi.org/10.1080/10739140903430271

DURAN, A., PEREZ-RODRIGUEZ, JL., ESPEJO, T. FRANQUELO, ML., CASTAING, J., WALTER, P. (2009). "Characterization of illuminated manuscripts by laboratory-made portable XRD and micro-XRD systems". In *Analytical and Bioanalytical Chemistry*. V. 395. 1997–2004. https://doi.org/10.1007/s00216-009-2992-5

DURAN, A., FRANQUELO, ML., CENTENO, MA., ESPEJO, T., PEREZ-RODRIGUEZ, JL. (2011). "Forgery detection on an Arabic illuminated manuscript by micro-Raman and X-ray fluorescence spectroscopy". *Journal of Raman Spectroscopy*. 42(1):48–55. https://doi.org/10.1002/jrs.2644

EASTON, R.L. CHRISTENS-BARRY, W.A., KNOX, K.T. (2011). "Spectral image processing and analysis of the Archimedes Palimpsest". In *European Signal Processing Conference*. Barcelona. 1440–1444. https://doi.org/10.5281/zenodo.42360

EL-SABBAH, M.M.B., GOMAA, A.Z., EL-HEFNY, D.E., AL-HAWARY, A.S. (2019). "Dating the ballpoint pen inks using gas chromatography-mass spectrometry technique". E*gyptian Journal of Chemistry*. 62(3):385–400. https://doi.org/10.21608/ejchem.2018.4812.1427

ESPEJO, T., ALVAREZ-CUBERO, M.J., SAIZ, M. (2011). "Determinación del origen animal de pergaminos históricos a través de análisis de ADN". In *XVIII Congreso Internacional Conservación y Restauración de Bienes Culturales*. Granada: Universidad de Granada. 10–13.

ESPEJO ARIAS, T., LAZAROVA STOYTCHEVA, I., CAMPILLO GARCÍA, D., DURÁN BENITO, A., JIMÉNEZ DE HARO, MC. (2011). "Caracterización material y proceso de conservación de la colección de documentos árabes manuscritos del archivo histórico provincial de granada". *Al-Qantara*. 32(2):519–532.

FAUBEL, W., STAUB, S., SIMON, R,. HEISSLER, S., PATAKI, A., BANIK, G. (2007). "Non-destructive analysis for the investigation of decomposition phenomena of historical manuscripts and prints". *Spectrochimica Acta - Part B Atomic Spectroscopy*. 62(6–7 SPEC. ISS.):669–676. https://doi.org/10.1016/j.sab.2007.03.029

FERRER, N., SISTACH, MC. (2007). "FTIR Technique Used to Study Acidic Paper Manuscripts Dating from the Thirteenth to the Sixteenth Century from the Archive of the Crown of Aragón". *The Book and Paper Group Annual*. 26:21–25.

FERRERO, J.L., ROLDAN, C., JUANES, D., LLUCH, J.L., ARDID, M. *Evolucion de la instrumentacion de fluorescencia de rayos-X en la unidad de arqueometria del ICMUV.* GEIIC.

GAMBARO, A., GANZERLA, R., FANTIN, M., CAPPELLETTO, E., PIAZZA, R., CAIRNS, WRL. (2009). "Study of 19th century inks from archives in the Palazzo Ducale (Venice, Italy) using various analytical techniques". *Microchemical Journal.* 91(2):202–208. https://doi.org/10.1016/j.microc.2008.11.002

GANZERLA, R., GAMBARO, A., CAPPELLETTO, E., FANTIN, M., MONTALBANI, S., ORLANDI, M. (2009). "Characterization of selected paper documents from the archives of Palazzo Ducale (Venice), Italy using various analytical techniques". *Microchemical Journal*. 91(1):70–77. https://doi.org/10.1016/j.microc.2008.08.003

GIACOMETTI, A., CAMPAGNOLO, A., MACDONALD, L., MAHONY, S., TERRAS, M., ROBSON, S., WEYRICH, T., GIBSON, A. (2012). "Cultural Heritage Destruction: Documenting Parchment Degradation via Multispectral Imaging". *Proc. of Electronic Visualisation and the Arts (EVA 2012)*. BCS Learning & Development. https://doi.org/10.14236/ewic/EVA2012.52

GOLTZ, D, ATTAS, M, CLOUTIS, E, YOUNG, G & BEGIN, P. (2009). "Visible (420–720 nm) Hyperspectral imaging techniques to assess inks in historical documents". *Restaurador*. 30:199–221. https://doi.org/10.1515/rest.013

GOLTZ, D., CHIN, J., HIEBERT, R., ABSALAN, G. (2010). Micro-extraction and determination of transition metals in historical ink. *Microchimica Acta*. 170(1):127–133. https://doi.org/10.1007/s00604-010-0375-4

GONZALEZ, L., WESS, T. (2008). "Use of attenuated total reflection-fourier transform infrared spectroscopy to measure collagen degradation in historical parchments". *Applied Spectroscopy*. 62(10):1108–1114. https://doi.org/10.1366/000370208786049196

GOODHEW, PJ., HUMPHREYS, J., BEANLAND, R. (2014). *Electron Microscopy and Analysis,* Third Edition. CRC Press.

GUEDES, A., PRIETO, AC. (2012). "Raman Spectroscopy for the Characterisation of Inks on Written Documents". *Infrared and Raman Spectroscopy in Forensic Science*. Chichester, UK: John Wiley & Sons, Ltd. 137–151.

HÄKKÄNEN, H., HOUNI, J., KASKI, S., KORPPI-TOMMOLA, JEI. (2001). "Analysis of paper by laser-induced plasma spectroscopy". *Spectrochimica Acta - Part B Atomic Spectroscopy*. 56(6):737–742. https://doi.org/10.1016/S0584-8547(01)00210-5

HAMDAN, NM., ALAWADHI, H., JISRAWI, N. (2012). "Integration of µ-XRF, and u-Raman techniques to study ancient Islamic manuscripts". *IOP Conference Series: Materials Science and Engineering*. V. 37. IOP Publishing. 012006. https://doi.org/10.1088/1757-899X/37/1/012006

HAVERMANS, J., AZIZ, HA., SCHOLTEN, H. (2003). "Non Destructive Detection of Iron-Gall Inks by Means of Multispectral Imaging - Part 2: Application on Original Objects Affected with Iron-Gall-Ink Corrosion". *Restaurator*. 24(2):88–94. https://doi.org/10.1515/REST.2003.88

JAMES, C. (2010). *Visual identification and analysis of old master drawing techniques*. Olschki.

KAKUEE, O., FATHOLLAHI, V., OLIAIY, P., LAMEHI-RACHTI, M., TAHERI, R., JAFARIAN, HA. (2012). External PIXE analysis of an Iranian 15th century poetry book. In *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*. V. 273:178-181. North-Holland. https://doi.org/10.1016/j.nimb.2011.07.069

KAMINSKA, A., SAWCZAK, M., KOMAR, K., ŚLIWIŃSKI, G. (2007). "Application of the laser ablation for conservation of historical paper documents". *Applied Surface Science*. 253(19):7860–7864. https://doi.org/10.1016/j.apsusc.2007.02.094

KANNGIEßER, B., HAHN, O., WILKE, M., NEKAT, B,. MALZER, W., ERKO, A. (2004). "Investigation of oxidation and migration processes of inorganic compounds in ink-corroded manuscripts". *Spectrochimica Acta - Part B Atomic Spectroscopy*. V. 59. Elsevier. 1511–1516. https://doi.org/10.1016/j.sab.2004.07.013

KEARTON, B. MATTLEY, Y. (2008). "Laser-induced breakdown spectroscopy: Sparking new applications". *Nature Photonics*. 2(9):537–540. https://doi.org/10.1038/nphoton.2008.173

KLOCKENKÄMPER, R., VON BOHLEN, A., MOENS, L. (2000). "Analysis of Pigments and Inks on Oil Paintings and Historical Manuscripts Using Total Reflection X-ray Fluorescence Spectrometry". *X-Ray Spectrometry*. 29(1):119–129. https://doi.org/10.1002/(SICI)1097-4539(200001/02)29:1<119::AID-XRS400>3.0.CO;2-W

KNOX, KT., EASTON, RL. (2003). Recovery of Lost Writings on Historical Manuscripts with Ultraviolet Illumination. In *The Fifth International Symposium on Multispectral Color Science* (Part of PICS 2003 Conference). 301–306. http://www.imaging.org/IST/store/epub.cfm?abstrid=8535 (Accessed 14 February 2020).

KOLAR, J., STRLIČ, M. (2006). *Iron gall inks: on manufacture characterisation, degradation and stabilisation*. Ljubljana: National and University Library.

KOLAR, J., ŠTOLFA, A., STRLIČ, M., POMPE, M., PIHLAR, B., BUDNAR, M., SIMČIČ, J., REISSLAND, B. (2006). Historical iron gall ink containing documents - Properties affecting their condition. *Analytica Chimica Acta*. 555(1):167–174. https://doi.org/10.1016/j.aca.2005.08.073

KRÓL, M., KOWALSKA, D., KOŚCIELNIAK, P. (2018). "Examination of Polish Identity Documents by Laser-Induced Breakdown Spectroscopy". *Analytical Letters*. 51(10):1592–1604. https://doi.org/10.1080/00032719.2017.1384833

KUROUSKI, D., ZALESKI, S., CASADIO, F., VAN DUYNE, RP., SHAH, NC. (2014). "Tip-enhanced raman spectroscopy (TERS) for in situ identification of indigo and iron gall ink on paper". *Journal of the American Chemical Society*. 136(24):8677–8684. https://doi.org/10.1021/ja5027612

LARSEN, R. (2002). *Microanalysis of parchment*. Archetype.

LEE, AS., MAHON, PJ., CREAGH, DC. (2006). "Raman analysis of iron gall inks on parchment". *Vibrational Spectroscopy*. 41(2):170–175. https://doi.org/10.1016/j.vibspec.2005.11.006

LUCARELLI, F., MANDÒ, PA. (1996). "Recent applications to the study of ancient inks with the Florence external-PIXE facility". *Nuclear*

Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms. 109–110:644–652. https://doi.org/10.1016/0168-583X(95)00985-X

MAGISTRO, F., MAJOLINO, D., MIGLIARDO, P., PONTERIO, R., RODRIQUEZ, MT. (2001). "Confocal Raman spectroscopic study of painted medieval manuscripts". *Journal of Cultural Heritage*. 2(3):191–198. https://doi.org/10.1016/S1296-2074(01)01121-9

MAIRINGER, F. (2000). "The ultraviolet and fluorescence study of paintings and manuscripts". *Radiation in Art and Archeometry*. Elsevier. 56–75. https://doi.org/10.1016/B978-044450487-6/50050-X

MANNUCCI, E., PASTORELLI, R., ZERBI, G., BOTTANI, CE., FACCHINI, A. (2000). "Recovery of ancient parchment: Characterization by vibrational spectroscopy". *Journal of Raman Spectroscopy*. 31(12):1089–1097. https://doi.org/10.1002/1097-4555(200012)31:12<1089::AID-JRS649>3.0.CO;2-C

MANSO, M., CARVALHO, ML. (2009). "Application of spectroscopic techniques for the study of paper documents: A survey." *Spectrochimica Acta - Part B Atomic Spectroscopy*. 64(6):482–490. https://doi.org/10.1016/j.sab.2009.01.009

MANSO, M., CARDEIRA, AM., SILVA, M., LE GAC, A., PESSANHA, S., GUERRA, M., CALDEIRA, AT., CANDEIAS, A., CARVALHO, ml. (2014). "The mysterious halos in iron gall ink manuscripts: an analytical explanation". *Applied Physics A: Materials Science and Processing*. 118(3):1107–1111. https://doi.org/10.1007/s00339-014-8924-z

MARUCCI, G., BEEBY, A., PARKER, AW., NICHOLSON, CE. (2018). Raman spectroscopic library of medieval pigments collected with five different wavelengths for investigation of illuminated manuscripts. *Analytical Methods*. 10(10):1219–1236. https://doi.org/0.1039/C8AY00016F

MATEO, M., BECERRA, J., ZADERENKO, AP., ORTIZ, P., NICOLÁS, G. (2019). "Laser-induced breakdown spectroscopy applied to the evaluation of penetration depth of bactericidal treatments based on silver nanoparticles in limestones". *Spectrochimica Acta Part B: Atomic Spectroscopy*. 152:44–51. https://doi.org/10.1016/j.sab.2018.11.010

MATTEINI, M., MOLES, A. (200)1. *Ciencia y restauración : método de investigación*. Hondarribia (Guipuzcoa): Nerea.

MCGILLIVRAY, M., DUFFY, C. (2017). "New light on the Sir Gawain and the green knight manuscript: Multispectral imaging and the Cotton Nero A.x. Illustrations". *Speculum*. 92(October):S110–S144.

MELESSANAKI, K., PAPADAKIS, V., BALAS, C., ANGLOS, D. (2001). "Laser induced breakdown spectroscopy and hyper-spectral imaging analysis of pigments on an illuminated manuscript". *Spectrochimica Acta - Part B Atomic Spectroscopy*. 56(12):2337–2346. https://doi.org/10.1016/S0584-8547(01)00302-0

MINDERMANN, S. (2018). *Hyperspectral Imaging for Readability Enhancement of Historic Manuscripts.* Munich.

MONTANI, I., SAPIN, E., PAHUD, A., MARGOT, P. (2012). Enhancement of writings on a damaged medieval manuscript using ultraviolet imaging. *Journal of Cultural Heritage*. 13(2):226–228. https://doi.org/10.1016/j.culher.2011.09.002

MOROPOULOU, A., ZENDRI, E., ORTIZ, P., DELEGOU, ET., NTOUTSI, I., BALLIANA, E., BECERRA, J., ORTIZ, R. (2019). "Scanning Microscopy Techniques as an Assessment Tool of Materials and Interventions for the Protection of Built Cultural Heritage". *Scanning*. 2019:1–20. https://doi.org/10.1155/2019/5376214

NASTOVA, I., GRUPČE, O., MINČEVA-ŠUKAROVA, B, TURAN, S., YAYGINGOL, M., OZCATAL, M., MARTINOVSKA, V., JAKOVLEVSKA-SPIROVSKA, Z. (2012). "Micro-Raman spectroscopic analysis of inks and pigments in illuminated medieval old-Slavonic manuscripts". *Journal of Raman Spectroscopy*. V. 43. John Wiley & Sons, Ltd. 1729–1736. https://doi.org/10.1002/jrs.4084

NEEVEL, JG. (2009). "Application issues of the bathophenanthroline test for iron(II) ions". *Restaurator*. 30(1–2):3–15. https://doi.org/10.1515/rest.002

NEVIN, A., SPOTO, G., ANGLOS, D. (2012). "Laser spectroscopies for elemental and molecular analysis in art and archaeology". *Applied Physics A: Materials Science and Processing*. 106(2):339–361. https://doi.org/10.1007/s00339-011-6699-z

NODARI, L., RICCIARDI, P. (2019). "Non-invasive identification of paint binders in illuminated manuscripts by ER-FTIR spectroscopy: a systematic study of the influence of different pigments on the binders' characteristic spectral features". *Heritage Science*. 7(1):7. https://doi.org/10.1186/s40494-019-0249-y

OCHOCIŃSKA, K., SAWCZAK, M., MARTIN, M., BREDAL-JORGENSEN, J., KAMIŃSKA, A., ŚLIWIŃSKI, G. (2003). "LIPS spectroscopy for the contamination analysis and laser cleaning diagnostics of historical paper documents". *Radiation Physics and Chemistry*. V. 68. Elsevier Ltd. 227–232. https://doi.org/10.1016/S0969-806X(03)00289-5

ODEGAARD, N., CARROLL, S., ZIMMT, WS. (2005). *Material Characterization Tests for Objects of Art and Archaeology*. London: Archetype Publications. http://books.google.com/books?id=BaZ1QgAACAAJ&pgis=1 (Accessed 07 April 2020).

OLSSON, AM., CALLIGARO, T., COLINART, S., DRAN, JC., LÖVESTAM, NEG, MOIGNARD, B., SALOMON, J. (2001). "Micro-PIXE analysis of an ancient Egyptian papyrus: Identification of pigments used for the "Book of the Dead". Nuclear Instruments and Methods in *Physics Research, Section B: Beam Interactions with Materials and Atoms*. 181(1–4):707–714. https://doi.org/10.1016/S0168-583X(01)00545-6

OUJJA, M., VILA, A., REBOLLAR, E., GARCÍA, JF., CASTILLEJO, M. (2005). "Identification of inks and structural characterization of contemporary artistic prints by laser-induced breakdown spectroscopy". *Spectrochimica Acta - Part B Atomic Spectroscopy*. V. 60. Elsevier. 1140–1148. https://doi.org/10.1016/j.sab.2005.05.021

PESSANHA, S., MANSO, M., CARVALHO, ML. (2012). "Application of spectroscopic techniques to the study of illuminated manuscripts:

A survey". *Spectrochimica Acta - Part B Atomic Spectroscopy. V.* 71–72. Elsevier. 54–61. https://doi.org/10.1016/j.sab.2012.05.014

PIANTANIDA, G., BICCHIERI, M., COLUZZA, C. (2005). "Atomic force microscopy characterization of the ageing of pure cellulose paper". *Polymer*. 46(26):12313–12321. https://doi.org/10.1016/j.polymer.2005.10.015

PIANTANIDA, G., MENART, E., BICCHIERI, M., STRLIČ, M. (2013). Classification of iron-based inks by means of micro-Raman spectroscopy and multivariate data analysis. *Journal of Raman Spectroscopy*. 44(9):1299–1305. https://doi.org/10.1002/jrs.4351

PICOLLO, M., ALDROVANDI, A., MIGLIORI, A., GIACOMELLI, S., SCUDIERI, M. (2011). "Non invasive XRF and UV-Vis-Nir reflectance spectroscopyAnalysis of materials used by Beato Angelico in the manuscript graduale N.558". *Revista de História da Arte*. 219–227.

PINZARI, F., PASQUARIELLO, G., DE MICO, A. (2006). "Biodeterioration of paper: A SEM study of fungal spoilage reproduced under controlled conditions". *Macromolecular Symposia*. V. 238. John Wiley & Sons, Ltd. 57–66. https://doi.org/10.1002/masy.200650609

PLOSSI, M., ZAPPALÀ, A., ZAPPALÀ, A. (2007). *Libri e documenti : le scienze per la conservazione e il restauro*. V. 13,StudiGo. Biblioteca statale Isontina.

REMAIZELLES, C., QUILLET, V., BERNARD, J. (2000). "FTIR techniques applied to iron gall inked damaged paper". *15th World Conference on NDT*. Roma.

ROLDÁN, ML., CENTENO, SA., RIZZO, A. (2014). "An improved methodology for the characterization and identification of sepia in works of art by normal Raman and SERS, complemented by FTIR, Py-GC/MS, and XRF". *Journal of Raman Spectroscopy*. 45(11–12):1160–1171. https://doi.org/10.1002/jrs.4620

ROMERA, D., SANCENÓN, J., GAMON, M., CONTRERAS, G., JUANES BARBER, D., FERNÁNDEZ, G. (2013). "La espectrometría de masas en tándem. Aplicación a la caracterización de las tintas en manuscritos del siglo XV al siglo XIX". *La ciencia y el arte IV: ciencias experimentales y conservación del patrimonio*, 2013, págs. 70-92. 70–92.

ROŽIĆ, M., MAČEFAT, MR., OREŠČANIN, V. (2005). Elemental analysis of ashes of office papers by EDXRF spectrometry. Nuclear Instruments and Methods in *Physics Research, Section B: Beam Interactions with Materials and Atoms*. 229(1):117–122. https://doi.org/10.1016/j.nimb.2004.11.011

RUEANGYODJANTANA, J., BUNTEM, R. (2017). "Studies on the deterioration of ancient Thai manuscripts". *Key Engineering Materials*. 757 KEM:19–23. https://doi.org/10.4028/www.scientific.net/KEM.757.19

SCHOLTEN, JH., KLEIN, ME,. STEEMERS, TAG., DE BRUIN, G. (2005). Hyperspectral imaging-A Novel non-destructive analytical tool in paper and writing durability research. In *Proceedings of Art'05 – 8th International Conference onNon Destructive Investigations and Microanalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage*. C. Parisi, G. Buzzanca, & A. Paradisi, Eds. Lecce, Italy.

SIVAKOVAI, B., BEGANSKIENÉ, A., KAREIVA, A. (2008). "Investigation of damaged paper by Ink Corrosion". *Materials Science* (Medziagotyra). 14:51–54.

VAN DER SNICKT, G., DE NOLF, W., VEKEMANS, B., JANSSENS, K. (2008). "μ-XRF/μ-RS vs. SR μ-XRD for pigment identification in illuminated manuscripts". *Applied Physics A: Materials Science and Processing*. 92(1):59–68. https://doi.org/10.1007/s00339-008-4447-9

STRIEGEL, MF., HILL, J. (1996). T*hin-layer chromatography for binding media analysis*. Los Angeles: Getty Conservation Institute.

STUART, BH. (2007). *Analytical Techniques in Materials Conservatio*n. J.& S. Wiley, Ed.

TRAFELA, T., STRLIČ, M., KOLAR, J., LICHTBLAU, DA., ANDERS, M., MENCIGAR, DP., PIHLAR, B. (2007). "Nondestructive analysis and dating of historical paper based on IR spectroscopy and chemometric data evaluation". *Analytical Chemistry*. 79(16):6319–6323. https://doi.org/10.1021/ac070392t

TRENTELMAN, K., TURNER, N. (2009). "Investigation of the painting materials and techniques of the late-15th century manuscript illuminator Jean Bourdichon". *Journal of Raman Spectroscopy.* 40(5):577–584. http://doi.wiley.com/10.1002/jrs.2186.

URSESCU, M., MALUTAN, T., CIOVICA, S. (2009). "Iron gall inks influence on papers' thermal degradation". *FTIR spectroscop applications. European Journal of Science and Theology*. 5(3):71–84.

VANDENABEELE, P., WEHLING, B., MOENS, L., DE REU, M., VAN HOOYDONK, G., VON BOHLEN, A., KLOCKENKÄMPER, R. (2002). *Characterization of pigments in Mercatellis manuscripts by total-reflection X-ray flourescence and Raman-microscopy. In Archaeometry '98: proceedings of the 31st international symposium on archaeometry*, Budapest, 26 April-3 May 1998. p.825-827

VERGARA PERIS, J. (2002). *Conservación y restauración de material cultural en archivos y bibliotecas*. Valencia: Biblioteca Valenciana.

VETTER, W., PÖLLNITZ, G., SCHEREINER, M. (2014). "Examination of historic parchment manuscripts by non-invasive Reflection-FTIR. Possibilities and limitations". *3TH Inernational Congress Chemistry for Cultural Heritage*. Viena.

WAGNER, B., GARBOŚ, S., BULSKA, E., HULANICKI, A. (1999). "Determination of iron and copper in old manuscripts by slurry sampling graphite furnace atomic absorption spectrometry and laser ablation inductively coupled plasma mass spectrometry". *Spectrochimica acta, Part B: Atomic spectroscopy*. 54(5):797–804. https://doi.org/10.1016/S0584-8547(99)00025-7

WAGNER, B., BULSKA, E., HULANICKI, A., HECK, M., ORTNER, HM. (2001). "Topochemical investigation of ancient manuscripts". *Fresenius' Journal of Analytical Chemistry*. V. 369. Springer-Verlag. 674–679. https://doi.org/10.1007/s002160100750

WEHLING, B., VANDENABEELE, P., MOENS, L., KLOCKENKÄMPER, R., VON BOHLEN, A., VAN HOOYDONK, G., DE REU, M. (1999). "Investigation of pigments in medieval manuscripts by micro Raman spectroscopy and total reflection X-Ray fluorescence spectrometry". *Mikrochimica Acta*. 130(4):253–260. https://doi.org/10.1007/BF01242913

WESS, T., DRAKOPOULOS, M., SNIGIREV, A., WOUTERS, J., PARIS, O., FRATZL, P., COLLINS, M., HILLIER, J., NIELSEN, K. (2001). The Use of Small-Angle X-Ray Diffraction Studies for the Anal sis of Structural Features in Archaeological Samples. *Archaeometry*. 43:117–129. https://doi.org/10.1111/1475-4754.00007

ZAPPALÀ, A., BAJT, S., GIGANTE, GE., HANSON, AL. (1996)."Applications of EDXRF in the conservation of acid papers using a synchrotron light microbeam". Nuclear Instruments and Methods in *Physics Research, Section B: Beam Interactions with Materials and Atoms*. 117(1–2):145–150. https://doi.org/10.1016/0168-583X(96)00221-2

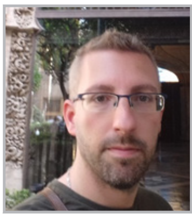
ZOTTI, M., FERRONI, A., CALVINI, P. (2008). Microfungal biodeterioration of historic paper: Preliminary FTIR and microbiological analyses. *International Biodeterioration and Biodegradation*. 62(2):186–194.

ZOTTI, M, FERRONI, A & CALVINI, P. 2011. Mycological and FTIR analysis of biotic foxing on paper substrates. *International Biodeterioration and Biodegradation*. 65(4):569–578.

Autor/es

Gemma María Contreras
contreras_gem@gva.es
Subdirección General del Institut Valencià de Conservació, Restauració i Investigació (IVCR+i) Generalitat Valenciana.

Gemma Mª Contreras Zamorano has a degree in Geography and History, specialized in Art, by the University of Valencia, where she obtained the DEA and the PhD degree with a research about inks of Valencian manuscripts between 1250 and 1600. In addition, she has a degree in Fine Arts, specialized in conservation and restoration of cultural heritage, by the Polytechnic University of Valencia. She is currently a professor in the master of Diagnosis of the State of Preservation of the Historical Heritage at the Pablo de Olavide University (Seville), which she previously studied. Since 1999, she has worked for the Generalitat Valenciana as a restorer of graphic works and archival material. In 2008, she got the position of section head of this department at the Valencià Institute of Conservation and Restoration. Since November 2015, she is director of this institution. She has two books about cultural heritage and conservation, and 50 articles about paper restoration and research on materials and application techniques. She has conducted several courses about conservation and restoration of graphic artworks and archival materials at Spanish and international universities (Basque Country, Seville, Managua-Nicaragua, Quito-Ecuador), as well as other public institutions such as the Alhambra in Granada, Arxiu de la Seu d'Urgell, Suleymaniye Library (Istanbul), CIRMA (Guatemala), INHCA (Nicaragua).



Javier Becerra
jbeclun@upo.es
Department Physical, Chemical and Natural Systems, University Pablo de Olavide, Seville, Spain

PhD in History and Humanities: Europe, America, Arts and Language, degree in Conservation and Restoration and MSc Diagnosis of the State of Preservation of the Historical Heritage. Now, Javier is researcher at the Pablo de Olavide University in Seville, Spain. His research activity has focused on a) studies of new conservation-restoration treatments, especially based on nanomaterials b) vulnerability and risk studies in cultural heritage and c) diagnosis, analytical techniques and interventions in cultural heritage. This scientific production has resulted in a patent, 15 journal publications (10 in high impact indexed journals) and 12 book chapters. The results of the investigations carried out have been presented at 10 international conferences with a total of 18 communications. He has collaborated in the diagnosis of samples from national and international monuments (Villa Adriana in Rome, Medina Azahara, archaeological museum of Écija, churches in Seville, contemporary buildings in La Havana, historical buildings in Oxford and Panama City, etc.) and has participated in analytical reports of national and international artworks requested from institutions such as the Andalusian Institute of Historical Heritage or the Pablo de Olavide University. Finally, his research activity has been recognized with different awards at national and international level.

https://doi.org/10.37558/gec.v17i1.760

La incidencia de la opinión social en el grado de vulnerabilidad de los edificios patrimoniales. El caso del centro histórico de Popayán (Colombia)

Mª Isabel Turbay Varona, Rocío Ortiz, María Arana, Pilar Ortiz

Resumen: El patrimonio urbano y arquitectónico de muchas ciudades en Hispanoamérica es vulnerable frente a amenazas de diversa índole; la exposición a fenómenos naturales y antrópicos son muchas veces las causas de su destrucción, sin embargo, uno de los factores más importantes que sin duda tiende a debilitarlo, es su relación directa e indirecta con las sociedades comprometidas y por tanto, el valor que ellas han de asignarle; por este motivo, la opinión de los ciudadanos se convierte en un elemento constituyente de la preservación o destrucción del patrimonio histórico. Este trabajo se centra en analizar la opinión social de los habitantes de Popayán, Colombia, sobre el patrimonio arquitectónico de su centro histórico. El instrumento Las encuestas fueron diseñadas por un equipo interdisciplinario de arquitectos, ambientalistas, químicos, historiadores, matemáticos, ingenieros, ... que trabajan en Inteligencia Artificial aplicada a la conservación preventiva de edificios patrimoniales, y fueron revisadas por un sociólogo. Los resultados se analizaron como parte del insumo para la construcción de herramientas para determinar los factores involucrados en el grado de debilidad que sufren los edificios históricos y estimar la vulnerabilidad y peligrosidad, ante distintas amenazas.

Palabras clave: Conservación, grado de vulnerabilidad, opinión social, valor del patrimonio

The incidence of social opinion on the degree of vulnerability of heritage buildings. The case of the historic center of Popayán (Colombia)

Abstract: The urban and architectural heritage of many cities in Latin America is vulnerable to threats of various kinds; exposure to natural and anthropic phenomena are many times the causes of its destruction, however, one of the most important factors that undoubtedly tends to weaken it, is its direct and indirect relationship to committed societies and, therefore, the value that they assign it, because of that, the citizen opinion becomes a constituent element of cultural heritage preservation or destruction. This work focuses on analyzing the social opinion of the inhabitants of Popayan (Colombia), about the architectural heritage of the historical center. The surveys were designed by an interdisciplinary team of architects, environmentalists, chemists, historians, mathematics, engineering, … that work on Artificial Intelligence applied to the preventive conservation of heritage buildings, and were revised by a sociologist. The results were analyzed as a tool to determine the factors involved in the degree of weakness that historical buildings suffer and estimate the vulnerability and hazards, facing different threats.

Keywords: Conservation, grade of vulnerability, social opinion, heritage value

Introducción

Para precisar el valor patrimonial de un bien es importante entender, el concepto de significación cultural, desde las recomendaciones de las cartas internacionales, como la carta de Burra (ICOMOS 1999), donde se especifica que los conjuntos de valores asignados a los monumentos, incluyen el valor estético, histórico, científico, social o espiritual que toman su forma en los lugares, en su materialidad, en el entorno, en el uso, en asociaciones, significados, registros, sitios relacionados y objetos relacionados. Por tanto la percepción acerca de estos valores, implica el reconocimiento y representatividad de las características y cualidades de los objetos, por parte de determinados grupos o individuos, que a su vez, establecen conexiones direccionadas a fortalecer, o no, la identidad comunitaria de los pueblos y que pueden emplearse también, como una función social en la cual una población, las toma, no solo como referente identitario, sino también como fuente potencial de desarrollo y relacionamiento social cotidiano (Llull Peñalba 2005).

Es necesario abordar también la relación entre el valor patrimonial y la conservación, lo cual se interpreta como un campo complejo (Manzini 2011), en el que puede ser determinante la evaluación de la opinión social. Explica Caraballo (Caraballo Perichi 2008) que alrededor de la significación acumulativa y en concordancia con la permanencia y evolución de los monumentos, se integra el contexto físico y temporal; mientras Garré (Garré 2001) establece que, el atributo (objeto) que representa ese valor, pudo en otro momento haber representado otros, incluso contradictorios, al que en el presente se le asigna; este proceso de re-significación resulta a partir de la evolución cultural de las comunidades que intervienen en este proceso y de su percepción acerca del patrimonio. Por tanto, el concepto de valor cultural tiene que ver directamente con el de la conservación del patrimonio, como describe García Canclini (García Canclini 1999). Es evidente que la interpretación social de los edificios y lugares puede tener diferentes matices en un rango de valor, según los grupos o individuos, y donde se involucran los intereses propios, cuestionados en diferentes entornos y estados, ocasionando la falta de comprensión del significado del patrimonio, asociada a la obsolescencia, abandono o pérdida de los monumentos (Manzini 2011) o por el contrario puede servir como instrumento de salvaguarda al patrimonio mismo y de reafirmación de la identidad en un conjunto social.

Las investigaciones dirigidas a identificar y medir los riesgos del patrimonio histórico son imprescindibles en la generación de insumos para la gestión de los entornos y los edificios históricos. En los avances en este campo, son la clave para garantizar la conservación, las propuestas de metodologías que identifiquen las debilidades del patrimonio, con el uso de herramientas que permitan la toma de decisiones.

La inclusión del valor social asociado a la vulnerabilidad no puede evaluarse solo en función de un listado de valores culturales implícitos a la normativa de los sitios. En la actualidad, las normativas de muchos países implican la catalogación de los monumentos, estos inventarios de valores intrínsecos reconocidos y protegidos, deben considerarse incompletos para la conservación del patrimonio; como se aborda en el estudio sobre la vulnerabilidad sísmica en Chile (Diaz Fuentes 2017), y es por tanto necesario involucrar la opinión de la sociedad, para otorgar mayor legitimidad hacia el valor que representa el patrimonio; de lo contrario, es más probable que aunque un bien esté reconocido desde el ámbito formal no cuente con la apropiación social suficiente y por tanto no se pueda garantizar su preservación en el futuro.

En los manuales de riesgo, la vulnerabilidad suele recogerse como la susceptibilidad de los bienes culturales ante una perturbación, es decir la debilidad inherente del patrimonio (UNESCO 1977) por tanto, la opinión de la sociedad no puede ser subvalorada ante la fragilidad de los monumentos, ya que puede ser reflejo de vitalidad o quebranto ante las diferentes amenazas. La importancia de este valor social del patrimonio se ha podido observar a nivel internacional tras el incendio de la Catedral de Notre Dame de París en 2019.

Este estudio complementa las metodologías propuestas por diversos autores (Ortiz y Ortiz 2016; Prieto *et al.* 2020; Turbay, Ortiz y Ortiz 2019) que tienen como objetivo calcular las vulnerabilidad en edificios históricos para minimizar los riesgos y la pérdida de elementos patrimoniales. Este tipo de investigaciones de evaluación de riesgos y estimación de la vulnerabilidad, incluyen estudios sistemáticos en los que se verifican las amenazas de tipo natural y antrópico, valorando el grado de afección mediante matrices de vulnerabilidad o inferencias calculadas por medio de inteligencia artificial; en los que se analizan un conjunto de variables. La opinión social del patrimonio histórico es una variable hasta ahora no incluida, que puede ser relevante como factor en la aproximación de escenarios de riesgo.

El modelo de evaluación de la opinión social que se aplicó en Popayán, tuvo como objetivo identificar la opinión de los ciudadanos como un factor que incide en la vulnerabilidad, y estimarlo como una nueva variable directamente proporcional a la debilidad o fortaleza del patrimonio ante las amenazas naturales o antrópicas. Este nuevo factor podría, a su vez, agregarse a las metodologías propuestas por varios autores (Ortiz y Ortiz 2016; Prieto et al. 2020; Turbay, et al. 2019) para la estimación de la vulnerabilidad de edificios históricos.

Metodología

La opinión social se ha evaluado mediante una encuesta de carácter anónimo, llevada a cabo en el casco histórico de la ciudad, específicamente en algunos puntos estratégicos del centro como son el Parque Caldas, uno de los lugares de mayor concurrencia, y en tres plazoletas de iglesias donde también se evidencia alto flujo peatonal diario (Alcaldía de Popayán 2015).

Las encuestas estuvieron dirigidas a ciudadanos colombianos o extranjeros, mayores de 18 años residentes en la ciudad, esto abarca a la población que ha establecido su domicilio de manera permanente en esa área y no incluye a la población que ejerce movilidad temporal o no definitiva, a través de movimientos diarios por distintas razones (trabajo, estudio, recreo, comercio, …), y que puede implicar el traspaso de fronteras municipales como es el caso de Popayán, ya que es el principal centro urbano del departamento (Ministerio de Ambiente, Vivienda y desarrollo territorial 2004).

Para evaluar la muestra necesaria para que los resultados fuesen representativos, se tuvo en cuenta la población total estimada para Popayán (Colombia) en 2018, cercana a las 277.270 personas en la zona urbana, según los resultados del censo nacional de población y vivienda

(DANE 2019); la muestra se segmentó por medio de las variables de sexo y edad de acuerdo a los datos de la pirámide poblacional. El total de encuestas fue de 384, para obtener un 5% de error muestral y un 95% de confianza, de estas, 201 dirigidas a mujeres y 183 a hombres, de las cuales a su vez estuvieron distribuidos en 8 rangos de edad acorde con la densidad poblacional de cada grupo para la representatividad de la muestra.

Las encuestas en las que se basa este modelo han sido aplicadas en otras ciudades como Sevilla, Osuna y Marchena en España (Benítez *et al.* 2020). El proceso de entrevistas se realizaró entre noviembre y diciembre de 2018, de forma aleatoria entre los ciudadanos.

La primera parte de la encuesta reúne una caracterización social de los encuestados, que permitió conocer aspectos claves de los ciudadanos como la edad, el género, el lugar de origen, ocupación, tiempo de residencia en la ciudad y el nivel de estudios alcanzados, que posteriormente fueron relacionados con los resultados de las preguntas, que contenían las variables sobre la opinión social. La segunda parte de la encuesta [tabla I] permitió al ciudadano evaluar los ítems o afirmaciones para dar cuenta de su opinión sobre aspectos referentes a las problemáticas que sufren los monumentos, como el nivel de conservación, la participación ciudadana e institucional, así como la apropiación y conocimiento sobre el patrimonio edificado de Popayán. En todas las preguntas se puede valorar entre 1 a 5, siendo 1 muy poco importante para el entrevistado, y el valor 5, implica que el concepto es considerado como muy importante por el entrevistado.

Los resultados de aplicación de las encuestas se ponderan mediante la opinión de los encuestados, para evidenciar el valor que representa el patrimonio, traducido en la preocupación de los ciudadanos hacia su conservación y su afectación en la vulnerabilidad del patrimonio de la ciudad.

El porcentaje de respuestas de cada valor (PRv), fue calculado con base al número total de respuestas obtenidas por cada uno de los valores (TRv) y dividida entre el sumatorio total de respuestas obtenidas por el valor correspondiente (∑TRv) [Tabla II].

$$PRv(i) = \frac{TRv(i)}{(\sum TRv)} * 100$$

El promedio ponderado del grado de vulnerabilidad se obtiene, mediante el sumatorio de la multiplicación de cada porcentaje de respuestas de cada valor (PRv) por su Valor de la opinión social (V):

$$\textit{Grado de vulnerabilidad} = \sum [PRv(i) * V(i)]$$

Esta valoración se encuentra en la escala entre 1 y 5, siendo 1 en los casos donde la preocupación social por el patrimonio implicaría un patrimonio menos vulnerable, y 5, en las ciudades en las que no hay preocupación social por el patrimonio, y esto hace que los monumentos sean más vulnerables.

Tabla I.- Resumen de la encuesta

Preguntas	Muy poco importante/ Muy bajo	Poco importante/ Bajo	Algo importante/ Medio	Importante/ Alto	Muy importante/ Muy alto
A. ¿Es importante conservar y mantener los monumentos de mi ciudad?	1	2	3	4	5
B. ¿Considero que los monumentos de mi ciudad son bien conocidos por sus habitantes?	1	2	3	4	5
C. ¿Creo que los políticos de mi ciudad se preocupan por los monumentos?	1	2	3	4	5
D. ¿Realizo visitas frecuentes a museos, monumentos, etc?	1	2	3	4	5
E. ¿Los monumentos tienen un papel importante a la hora de planificar mis viajes?	1	2	3	4	5

Tabla II.- Método para el cálculo de opiniones por escala de valor

Escala de valor de cada pregunta	Valor muy bajo	Valor bajo	Valor medio	Valor alto	Valor muy alto	
Valor de la opinión social (V)	1	2	3	4	5	
Total respuestas de cada valor (TRv)	(TRv)1	(TRv)2	(TRv)3	(TRv)4	(TRv)5	Sumatorio total respuestas (∑TRv)

Resultados y discusión

—*Contexto social de la ciudad de Popayán*

Popayán está ubicada geográficamente en el Valle de Pubenza, entre la cordillera occidental y central al suroeste de Colombia, en el departamento del Cauca [figura 1], zona con alto riesgo sísmico. La vocación del departamento es rural, y esto se ve reflejado en las dinámicas y actividades de la población de composición cultural diversa, convirtiéndose la ciudad, en un centro de comercio donde interactúan los municipios cercanos. Popayán ha sido en las últimas décadas epicentro de migraciones del campo a la ciudad por desplazamientos forzados a causa del conflicto armado en Colombia. El turismo es uno de los motores económicos de la ciudad, que se activa especialmente en el mes de marzo y abril, cuando se celebra la Semana Santa, declarada Patrimonio Cultural inmaterial de la Humanidad.

La estructura productiva de la ciudad no está muy diversificada, y en el contexto social, funciona como un núcleo que acoge a un gran número de estudiantes foráneos al ser una atractiva opción para la realización de estudios superiores en diferentes universidades, por lo que su economía se apoya en actividades relacionadas. No obstante, hay una alta tasa de desempleo respecto a otras ciudades del país, así como los trabajos informales que no están amparados bajo las garantías legales para los trabajadores. El centro histórico de la ciudad actúa como centro político-administrativo, donde funcionan las instituciones gubernamentales, bancarias y sitios de uso comercial. Se trata del centro histórico más grande de Colombia, y pese a los grandes avatares sufridos por los sismos, mantiene su imagen de ciudad colonial, considerado Bien de Interés Cultural de ámbito nacional, por el valor histórico artístico de sus edificaciones [figura 2].

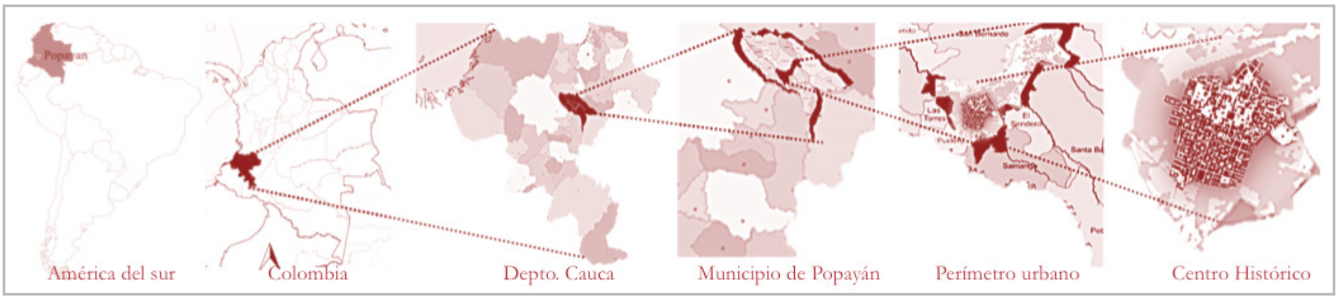


Figura 1.- Ubicación del Centro Histórico de Popayán.

Figura 2.- Vista general de la Parque Caldas en el Sector histórico de la ciudad de Popayán.

Desde el último terremoto de 1983, se han observado en el centro histórico, cambios en el uso de los materiales durante las restauraciones, rehabilitaciones o reparaciones de los monumentos, no siempre compatibles con los mismos, igualmente se ha observado un incremento del uso de los espacios públicos y privados y cambios en los usos del suelo que no son favorables para la conservación o que afectan de manera considerable el paisaje urbano [figura 3] y/o la materialidad de los edificios [figura 4].

—*Caracterización de la población encuestada*

Las 384 encuestas realizadas a residentes permanentes de Popayán fue acorde a la distribución socio-demográfica de la ciudadanía, donde el 58,3% de los encuestados son provenientes del resto del país, un 0,8% son extranjeros, y finalmente un 40,9% corresponde a población nativa. Un 39,6% de los encuestados respondió que su nivel educativo eran estudios secundarios, siendo este el porcentaje más alto,

Figura 3.- Alteración del paisaje urbano en el centro histórico A) Ocupación del espacio público, por uso comercial informal, frente a la iglesia de La Encarnación B) Antigua casa convertida en parqueadero sobre la calle 4 frente a la iglesia de San Francisco C) Alteración del perfil urbano por construcción de nuevas edificaciones, edificio sobre la carrera novena, con calle 4.

Figura 4.- Ejemplo de la morfología de la manzana contigua a la iglesia de San José en Popayán. Se pueden identificar, en esta vista superior de las cubiertas, cambios en los materiales y técnicas constructivas de las cubiertas de tejas de cerámica.

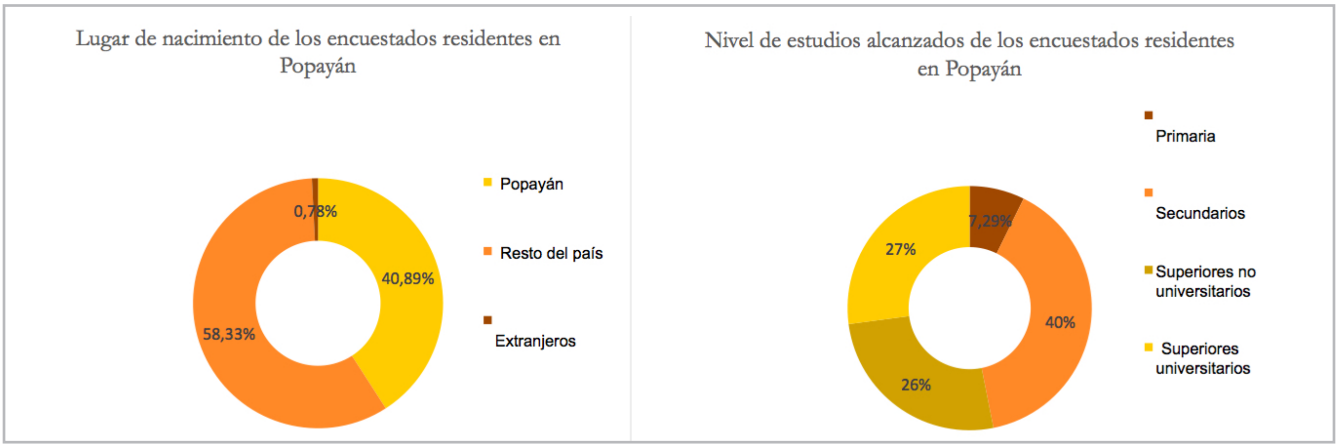


Figura 5.- Caracterización general de la población encuestada

lo que indica que gran parte de la población no ha accedido a la educación superior, universitaria y no universitaria. Para estos casos el 26% dijo tener estudios superiores no universitarios y un 27,1% estudios superiores universitarios. Un 7,3% dijo haber alcanzado sólo estudios de primaria [figura 5].

—*Caracterización de la opinión social*

A continuación, se recogen los resultados de las encuestas a partir de cinco aspectos: a) la importancia de la conservación del patrimonio en la ciudad, b) nivel de conocimiento de los monumentos, c) preocupación de los entes gubernamentales por los monumentos de la ciudad, d) visita a los monumentos de la ciudad y e) importancia de los monumentos para la planificación viajes. Estos resultados se analizan desde los rangos de edad, el nivel de estudios y el sitio de origen de los ciudadanos.

a) Opinión de los habitantes de Popayán sobre la importancia de la conservación del patrimonio de su ciudad.

El 79,2% de los ciudadanos encuestados calificaron en una escala del 1 al 5, que es muy importante la conservación (5); una significativa proporción respecto a las otras opciones, sólo el 0,8% valoró con uno (1), considerando que es muy poco o nada importante la conservación del patrimonio en la ciudad. Estas respuestas en su mayoría positivas aportan en la generalidad la importancia del patrimonio para los habitantes de Popayán, solo existe un porcentaje bajo de ciudadanos, 2,4% entre los niveles bajo (2) y muy bajo (1), que manifiestan que no les interesa, o les interesa muy poco, que sea preservado el patrimonio de la ciudad.

Esta opinión varía considerablemente entre los grupos de edad. El rango de edad que calificó con valores más bajos, corresponde a los jóvenes y adultos de temprana edad (18 a 29 años); los grupos de mayor edad fueron más propensos a calificar con valores más altos este apartado. Lo anterior se puede interpretar a partir de una posición de arraigo, apropiación y sentido de comunidad de las personas mayores, que desde su cotidianidad y a través del tiempo han compartido imaginarios y desarrollado conexiones hacia los valores del patrimonio. Por el contrario, los jóvenes probablemente no se involucran de forma directa por lo que no le dan la misma importancia; además, Popayán concentra a una alta población foránea de estudiantes, que permanece en la ciudad, sin necesariamente establecer vínculos o reconocer los valores de su patrimonio. Este valor hace pensar en la necesidad de mejorar la visión de los más jóvenes del patrimonio histórico, independientemente de su origen, especialmente en países no envejecidos, como es el caso de Latinoamérica.

Según el nivel de estudios de los encuestados se observa que el 98,1% que tienen estudios superiores universitarios le otorgaron una valoración entre 4 y 5, por el contrario, el 17,9% de las personas con un nivel de educación primaria fueron los que otorgaron la valoración más baja (1, 2 y 3). Este resultado revela que el nivel de escolaridad y por tanto, el nivel de conocimiento adquirido indica una preocupación y conciencia mayor por el valor del patrimonio y podría ser la clave para fortalecerlo ante las distintas amenazas. Así mismo, nos lleva a pensar sobre la importancia de incluir el concepto de "conservación del patrimonio histórico" en las escuelas primarias como un aspecto curricular.

Según el lugar de origen, el 84,1% de la población local le otorgó la mayor valoración asignada, al igual que el 75,8% de la población originaria del resto del país. Esto señala que tanto nativos como allegados dan una gran importancia a los monumentos de la ciudad. Este resultado puede evidenciar la apropiación e identificación a causa de los valores sociales que el patrimonio aporta al imaginario colectivo en el transcurso del tiempo; el fenómeno que crea con las personas no locales que residen en la ciudad puede verse influenciado por la participación y el interés por parte de la población nativa.

b) Opinión de los habitantes de Popayán sobre su nivel de conocimiento de los monumentos de la Ciudad:

El 43% de los encuestados contestó que el nivel de conocimiento era regular en una escala del 1 al 5. Sólo un 3,4% consideró que su nivel de conocimiento de los monumentos de la ciudad era muy alto, y en el otro extremo, un 6,8% opinó que era muy bajo. A través de estas respuestas, los ciudadanos expresan que el nivel de conocimiento sobre nuestro patrimonio, no es suficiente, lo que apoya la propuesta sobre la necesidad de incluir el estudio de estos aspectos desde la primaria. Algunos de los entrevistados, no tenían una opinión clara al respecto, favorable o desfavorable, y esto hace mucho más difícil la tarea de conectar de alguna forma los bienes patrimoniales con la sociedad, y mucho más esperar un papel activo de la ciudadanía en cuanto al tema.

En función de los grupos de edad, el que le asignó una mayor calificación (5) a esta pregunta tiene entre 18 y 29 años, y el grupo que dio la valoración más baja (1) tiene más de 60 años. En general las respuestas estuvieron inclinadas a calificarlo como regular (3), siendo los ciudadanos entre los 45 y 59 años los que más insistieron en esta respuesta. Esto indica que el simple hecho de convivir con el patrimonio no es un determinante para conocer el trasfondo detrás de este, y aunque los jóvenes fueron los que expresaron que conocían más el patrimonio, esto no se traduce en que desarrollen un interés particular hacia él, ni un alto grado de apropiación social, lo que se refleja en que no consideran importante su conservación según los resultados recogidos en el apartado anterior.

Según nivel de estudios, todos los grupos educativos concentraron su calificación como regular (3). El grupo con estudios de primaria es el que mejor valoró (5) su nivel de conocimiento, con un 10,7%, tan sólo el 1% de la población con estudios superiores universitarios piensan que su nivel de conocimiento es muy bueno (5). Las respuestas en esta categoría tuvieron una alta variación, pero se puede señalar que para la ciudadanía no es un punto fuerte el conocer su patrimonio a pesar de tenerlo próximo.

Según el lugar de origen de los ciudadanos, las respuestas en esta categoría varían respecto a la calificación asignada. La población proveniente del resto del país es la que le otorga una mayor valoración (5) con un 4%, respecto al 2,5% representado por la población local. Esto podría implicar que los foráneos tienden a percibir que el nivel de conocimiento sobre los monumentos en la ciudad es más alto que lo que consideran los locales. Si bien las diferencias son pequeñas y habría que profundizar en este aspecto.

c) Opinión de los habitantes de Popayán sobre la preocupación de los entes gubernamentales por los monumentos de la ciudad.

El 27,9% de los encuestados consideran que la preocupación de las organizaciones gubernamentales es muy baja (1), el 33,9% lo considera bajo (2) y el 29,7% como regular (3). En contraste, sólo el 0,5% de los encuestados contestó que el nivel de preocupación es muy alto (5). Esto tiene relación directa con el papel de las instituciones gubernamentales en lo concerniente a la gestión del patrimonio en la ciudad, no sólo en términos de conservación, sino en la activación del sector económico y cultural y en la difusión que se hace del trabajo realizado.

Según los grupos de edad, los ciudadanos entre los 45 y 59 años (con un 41,3%) opinan que la preocupación de los entes gubernamentales es regular (3). En el caso de la valoración baja (2), es el rango entre los 30 y 44 quien representa un mayor peso porcentual, con un 38%. En el caso de muy baja preocupación (1), son los ciudadanos de más de 60 años (36,9%) los que consideran el papel de los políticos y gestores como deficiente.

Según el nivel de estudios, el grupo con estudios superiores universitarios considera mayoritariamente (47,1%) como baja la preocupación de los entes gubernamentales por los monumentos. El grupo con estudios de primaria son quienes en mayor proporción calificarían como muy baja (1) la acción de los gestores, seguida de la población estudios superiores no universitarios con un 35,7% y 33,0% respectivamente. Tan solo un 1,7% de los encuestados valora muy positivamente (5) la gestión.

Se evidencia que la opinión generalizada es que existe una deficiente gestión del sector público, tanto de las personas con mayor nivel educativo como de menor nivel educativo, sin embargo, son estas últimas las que peor lo califican, lo que podríamos traducir como una percepción de mayor distanciamiento y exclusión hacia esta población, a la cual probablemente no han llegado las acciones gubernamentales suficientes para involucrarla activamente. Por el contrario, hay que indicar que el centro histórico de Popayán es el más grande conservado en Colombia, su Semana Santa es Patrimonio Inmaterial de la Humanidad y cuenta con un Plan Especial de Manejo y Protección (PEMP) desde el año 2010, por lo que se evidencia la necesidad de medidas de comunicación sociales más efectivas con los diferentes grupos de interés para su participación en los modelos de conservación de la ciudad.

d) Opinión de los habitantes de Popayán sobre visitar los monumentos de su ciudad.

Los encuestados reconocieron en general no visitar los monumentos de la ciudad. El 25.8 % de los encuestados respondieron con un valor 2, lo que indica que el nivel de visitas es bajo; seguido del 24,2% con una valoración regular (3) y un 21,9% con una valoración muy baja (1). Se evidencia que sólo el 9,4% de los ciudadanos encuestados realiza visitas muy frecuentes, esto tiene implicaciones en la conservación del patrimonio, ya que un bien abandonado progresivamente por la sociedad civil, es más propenso a que desde las instituciones no se garanticen los mecanismos necesarios para mantenerlo en uso y en óptimo estado. Las causas son difíciles de analizar, pero podrían estar en el poco interés o tiempo en el esparcimiento cultural, y las pocas o nulas iniciativas desde los gobiernos nacionales y locales para proporcionar y mantener un rol activo del ciudadano hacia su entorno próximo.

Según grupos de edad, el grupo de mayores de 60 años y el de 18 a 29 años manifestaron visitar los monumentos de Popayán con mayor frecuencia (5) con porcentajes del 13,8% y 13,2% respectivamente. Los ciudadanos entre los 45 y 59 años son los que menos visitas realizan, ya que el 27,2% contestó que no realizaba visitas a monumentos y el 31,5% que casi nunca las realizaba.

Según nivel de estudios, los resultados obtenidos muestran que la población con estudios universitarios son los que con mayor frecuencia visitan los monumentos de la ciudad, con un 30,8% y un 13,5% para los valores de 4 y 5 respectivamente. Los ciudadanos que menos concurren a los monumentos pertenecen al nivel de estudios de primaria, representando un 42,9% y 21,4% con respuestas 1 y 2 respectivamente.

Según el lugar de origen, los resultados reflejan que los ciudadanos que nacieron en Popayán son los que manifestaron visitar de forma más regular los monumentos con las valoraciones 3, 4 y 5, con una importante diferencia porcentual respecto a la población foránea. Un 17,2% de los ciudadanos nacidos en Popayán dijeron que la frecuencia de visitas que hacía a los bienes patrimoniales era muy poco frecuente (1), no obstante, la población no local supera esta cifra con 7,9 puntos porcentuales.

e) Opinión de los habitantes de Popayán sobre la importancia de los monumentos para la planificación de sus viajes.

Los ciudadanos en general no consideraron fundamental este aspecto para desarrollar sus actividades de turismo y ocio. Tan solo un 25,5% de los encuestados lo valoró como importante (4) y un 19,3% dijo que era muy importante (5), mientras un 23,7% lo considera con importancia media (3) y un 14,6% manifestó que no era nada importante (1).

Según grupos de edad, los mayores de 60 años y los jóvenes y adultos entre 18 y 29 años son los que manifestaron tener más en cuenta los monumentos para la planificación de sus viajes, con resultados totales de 58,4% y 57,6% respectivamente para valores de 5 y 4. Los ciudadanos entre los 45 a 59 años son los que menos tienen en cuenta este aspecto para planificar sus viajes, representando un 45,7% en total para las valoraciones de 1 y 2.

Con respecto al nivel de estudios, el grupo de ciudadanos con estudios universitarios es el que más tiene en cuenta este aspecto, un 26,0% da la valoración más alta (5) mientras un 33,7% da la valoración (4), lo que significaría que siempre o casi siempre tienen en cuenta los monumentos a la hora de planificar sus actividades de ocio y turismo. Por otro lado, la población que referenció tener solo estudios de primaria, es la que menor valoración le asigna a esta consideración (1 y 2), representando un 42,8% del total, le siguen las personas con estudios secundarios, entre las que un 16,4% da la valoración (1), y con porcentajes similares las personas con estudios superiores no universitarios que calificaron también en un 16% que no es importante (1).

—*Evaluación de la opinión social*

La figura 6 recoge un resumen comparativo de los cinco aspectos evaluados mediante las opiniones de los ciudadanos encuestados en Popayán.

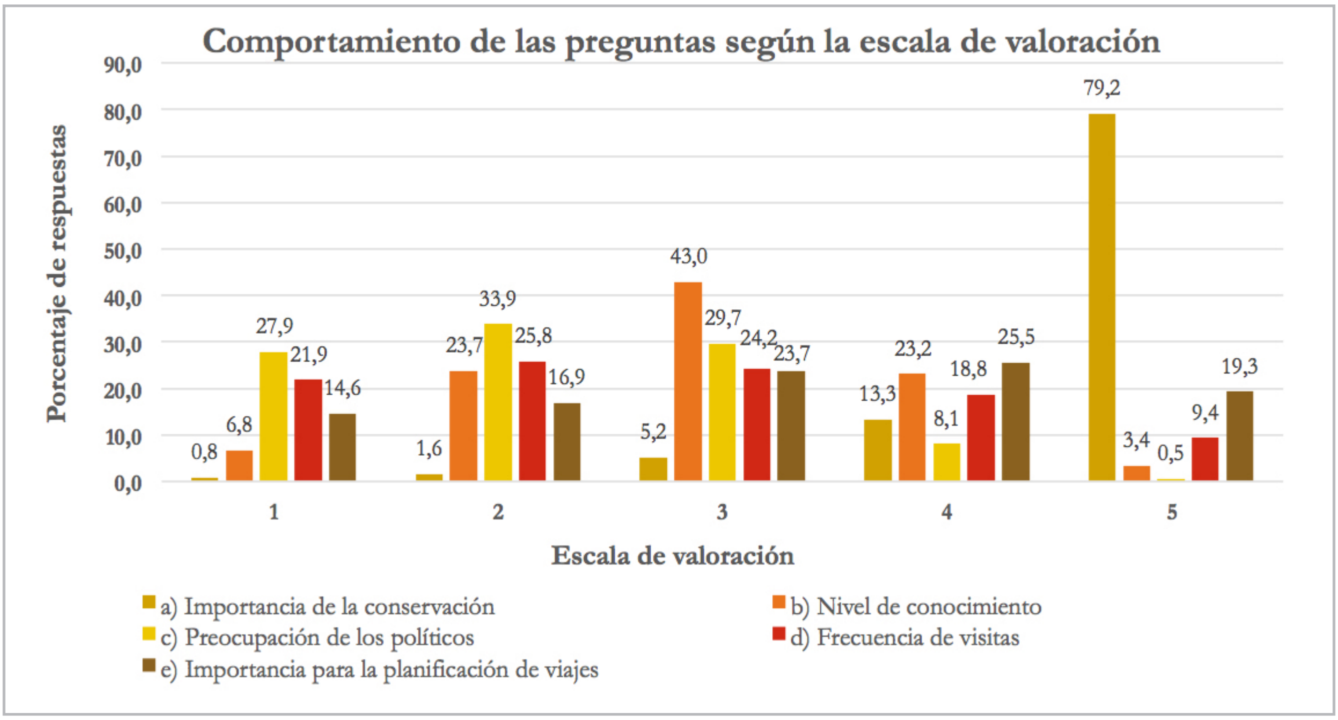


Figura 6.- Opinión social general de los ciudadanos de Popayán (Colombia) recogida en la encuesta sobre el patrimonio

El resultado del cuestionamiento sorprende por la elevada preocupación que expresan los ciudadanos sobre la importancia de la conservación del patrimonio, el 79,2% de los encuestados responde con el valor más alto (5), esto independiente del nivel educativo, edad o lugar de origen de los encuestados.

Este dato parece estar en contradicción con las respuestas a las demás preguntas, ya que, aunque existe un alto nivel de preocupación por la conservación del patrimonio histórico en Popayán, sus ciudadanos opinan que su nivel de conocimiento del patrimonio es regular, la preocupación de sus políticos por el patrimonio es muy baja, y gran parte de la población no visita frecuentemente los monumentos ni tiene en cuenta los bienes patrimoniales de forma significativa a la hora de planear sus viajes de turismo y ocio. Esto se podría explicar a partir del concepto de capital social (The Getty Conservation Institute 2013), que tiene que ver con la asociación identitaria, espiritual, ideológica y hasta de tipo histórico y estética que se puede desarrollar. Podría afirmarse que la importancia evidenciada por la ciudadanía puede ser un factor a favor de la conservación del patrimonio, pero dado el comportamiento de las otras variables no ha sido desarrollado en el territorio.

En cuanto al nivel de conocimiento de los bienes patrimoniales, el panorama no es muy positivo, tan solo el 3,4% lo calificó como muy alto, las respuestas se centraron entre medio y bajo. Esta variable es muy representativa, ya que darle una significación al patrimonio implica conocerlo. La difusión de este tipo de conocimiento no llega a la población en general, entre las posibles causas, encontramos el limitado acceso que tienen al patrimonio, que no motiva a los diferentes grupos de la sociedad, falta de campañas y políticas motivadoras, o la falta de interés de los individuos. Dada la amplia afluencia de personas foráneas en Popayán, es destacable que la población local insista en que el grado de conocimiento no es alto. Es ahí, donde es importante la implementación de estrategias educativas para promover el conocimiento hacia el patrimonio, su uso, su apropiación e incluso su relación como motor del desarrollo social y económico, o de los desarrollos comunitarios. Este estudio deja patente la necesidad de transmitir una visión del patrimonio edificado que vaya más allá de la importancia histórica (García Canclini 1999). Para lograrlo, es imperativo la accesibilidad a los conocimientos, ya que es una condición necesaria para la toma de decisiones, y contribuye a una conservación integrada del patrimonio (Icomos 2015).

En general, la percepción sobre la preocupación de los entes gubernamentales para preservar los monumentos es bastante desalentadora, sólo el 0,5% de los ciudadanos encuestados la calificarían como muy alta; es decir, en opinión de la población, hay una ausencia de interés o voluntad política para llevar a cabo la labor de protección. Lo cierto es que los ciudadanos no perciben los esfuerzos de los gobiernos y líderes políticos, lo cual ofrece una pista acerca del rol histórico y actual de las instituciones frente al patrimonio; que sean las personas de mayor edad las que consideren que estos actores no tienen como una de sus prioridades el cuidado del patrimonio, demuestra una baja confianza en las instituciones, como gestores del mismo, y por tanto una larga tradición de invisibilidad a la sociedad durante generaciones (Garavito Gonzáles 2006; Caraballo Perichi 2008)

El que los ciudadanos en su mayoría no frecuenten los monumentos de la ciudad es un indicador de la baja interacción que tienen con estos, sólo un 9,4% respondió que los visitaba de manera habitual; esto indica que, a pesar de convivir desde la cotidianidad, no se establece un vínculo ni reconocimiento con el entorno patrimonial. Una de las posibles causas son las limitadas iniciativas y actividades, que permitan el disfrute, igualmente la apatía o falta de interés hacia el ámbito cultural. Las visitas y la interacción adecuada con el patrimonio promueven un sentido de apropiación y una preocupación por la salvaguarda. Estas medidas pueden prevenir que se caiga en desuso o uso impropio, condiciones que se pueden dar si los espacios no son reconocidos por los ciudadanos para su aprovechamiento.

Por último, es importante anotar que apenas se tienen en cuenta el patrimonio para planificar viajes, tan sólo un 19,3% aseguró que era muy importante, seguido de un 25,5% que respondió que era altamente importante. No obstante, para la mayoría no representa un factor determinante o imperativo para escoger el destino de su tiempo de ocio y viajes; esto es coherente con las repuestas asignadas a otros aspectos, como el poco conocimiento sobre el patrimonio y la baja frecuencia de visitas. Esto evidencia aún más el desconocimiento de los ciudadanos acerca de los entornos patrimoniales y a su vez denota poco interés y capacidad de divertirse en buena medida por la ausencia de diversificación y difusión del patrimonio.

—*La opinión social como factor agregado en el grado de vulnerabilidad*

El porcentaje de respuestas de cada valor (PRv), calculado con base al número total de respuestas obtenidas para cada uno de los valores (TRv) para la escala de 1 al 5, se representa en la tabla III.

Tabla II.- Método para el cálculo de opiniones por escala de valor

Escala de valor de cada pregunta	Valor muy bajo	Valor bajo	Valor medio	Valor alto	Valor muy alto
Valor de la opinión social (V)	1	2	3	4	5
Total respuestas de cada valor (TRv)	276	391	483	341	429
Porcentaje de respuestas de cada valor (PRv)	14.40%	20.40%	25.20%	17.80%	22.30%

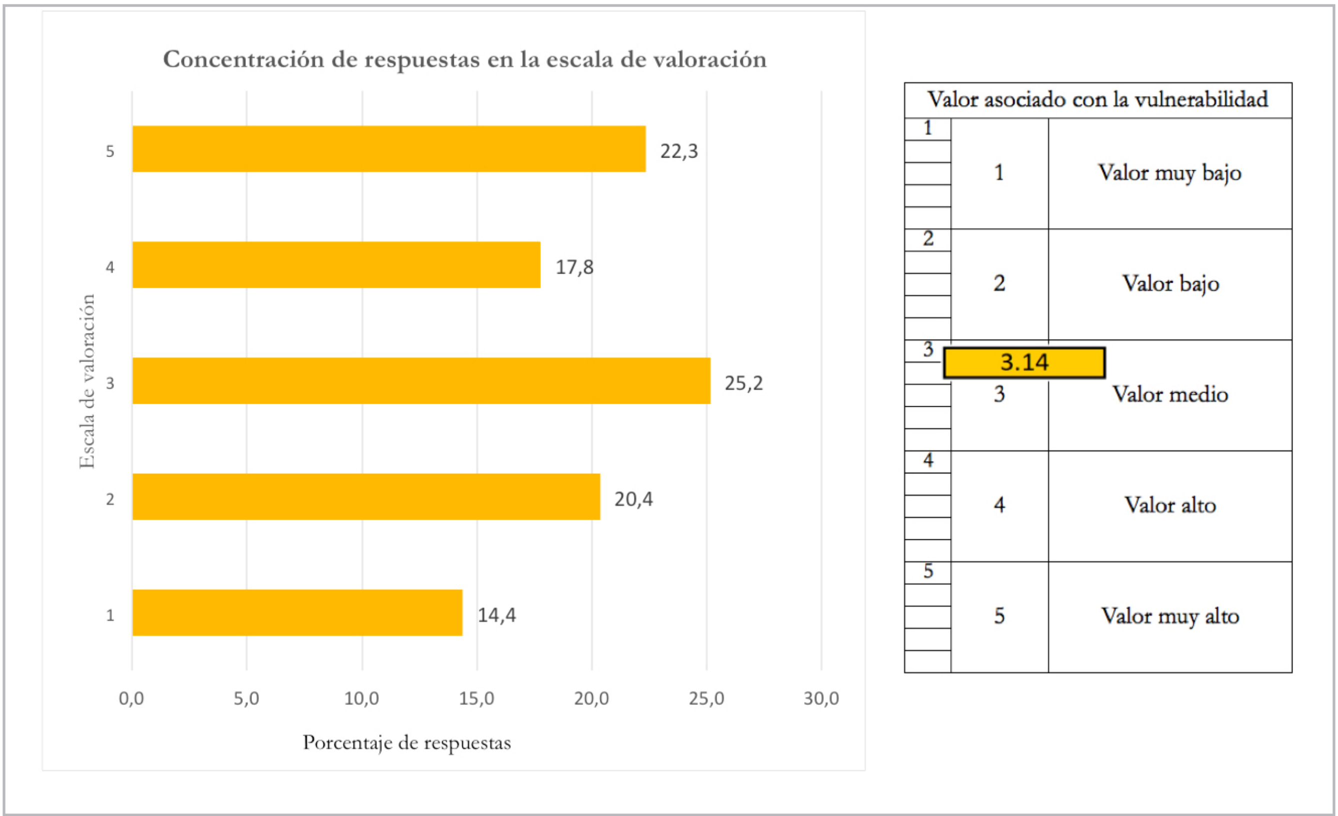


Figura 7.- Grado de vulnerabilidad del patrimonio de Popayán según la opinión social de sus habitantes

A partir de estos datos se ha calculado el grado de vulnerabilidad en función de las opiniones sociales, aplicando la ecuación recogida en la metodología. El grado de vulnerabilidad del patrimonio de Popayán asociada a la opinión de los encuestados, se puede estimar como medio, correspondiente a un valor de 3.14, en una escala de medida de 1 a 5, siendo (1), muy vulnerable y (5) muy poco vulnerable. [figura 7]

En Popayán, como en la mayoría de ciudades hispanoamericanas, están latentes las dinámicas de orden global, que pueden afectar a la opinión de la sociedad frente al patrimonio, como el crecimiento demográfico y aumento de la pobreza, el consumismo, entendido como la visión a corto plazo, la moda global promocionada por los medios de comunicación, la cultura global que discrimina las diversidades culturales, la falta de recursos profesionales para atender técnicamente el patrimonio y la ausencia de conocimiento esencial sobre los monumentos, entre las principales causas enumeradas en el informe de ICOMOS (ICOMOS 2000) sobre monumentos y sitios en peligro. A estas causas, se suman otras de orden nacional o regional que están relacionadas con los problemas de índole colectivo como la fragmentación social, la diversidad en la composición cultural de la población actual, producto de las migraciones y el desplazamiento forzado del campo a las ciudades; además, la falta de alternativas de inversión pública, para suplir la necesidades básicas como la vivienda y la educación, ocasionando cambios socioeconómicos y llevando progresivamente a la pérdida de la identidad cultural.

Las implicaciones sobre los bienes patrimoniales ya se perciben en el centro histórico de Popayán, y pueden estar asociadas a esta baja-media valoración social del patrimonio. Entre esas implicaciones hay actuaciones de la población, que sobrepasan la existencia de la normativa, como son los usos impropios del suelo, la ocupación informal del espacio público con fines lucrativos, o la construcción de edificaciones ilegales afectando el paisaje urbano y la contaminación visual. Estas amenazas al patrimonio histórico pueden tender a incrementarse en el futuro de forma progresiva, en especial por combinación con otros factores, como la presión urbanística, bajo políticas de gestores poco sensibilizados o preocupados por la conservación del Patrimonio. Por otro lado, la falta de conocimiento sobre el valor del patrimonio, puede afectar a proliferación de intervenciones u obras de mantenimiento inadecuadas, que sumada a la carencia de conocimientos técnicos o falta de documentación, puede llevar a actuaciones que desfiguren la materialidad del patrimonio. Además, la ausencia de reconocimiento de los valores tangibles e intangibles del patrimonio puede favorecer el robo, el vandalismo, el abandono o los usos no compatibles; que a la larga ocasionan el debilitamiento físico del monumento, su pérdida de significación cultural, la ruina o incluso su desaparición [figura 8].

Figura 8.- Ejemplos de alteración en la conservación del patrimonio de Popayán. A) Construcción de edificio modificando los perfiles urbanos ubicado en la Carrera 10 con calle 4 en el sector histórico. B) Grafitis como muestra de actos vandálicos afectando el paisaje urbano en la iglesia de El Carmen. C) Contaminación visual y vandalismo por grafiti en la Iglesia de santo Domingo.

Conclusión

La metodología desarrollada en este trabajo puede contribuir a valorar la vulnerabilidad del patrimonio, desde la óptica de las comunidades allegadas. Los resultados ponen de manifiesto la importancia de evaluar el comportamiento social que puede afectar de manera directa al patrimonio, como es el caso de los actos vandálicos o la presión urbanística, o de manera indirecta por las corrientes de orden global y/o conflictos de intereses. En este sentido, estimar la conciencia y principales preocupaciones de los ciudadanos ante la preservación del patrimonio podría medir el nivel de sensibilidad social acerca de la importancia que tiene su conservación, e identificar las necesidades actuales de la población y las medidas para fortalecer la conservación como factor de identidad y desarrollo sostenible.

Los resultados obtenidos en esta investigación son útiles para el planteamiento de estrategias basadas en la colaboración y participación activa de los ciudadanos, donde tengan la posibilidad de comprender, valorar y proteger el patrimonio. El análisis realizado se basa en un componente subjetivo y cualitativo, relacionado con la percepción de los habitantes de Popayán, del patrimonio de su ciudad, y por tanto hay una incertidumbre asociada a la medición y evaluación, que debe ser analizada en futuros estudios. En este sentido, la relación del ciudadano con su patrimonio implica múltiples escalas de percepción basadas en sus necesidades a nivel individual y comunitario, sin embargo, pueden identificarse patrones de valoración discernibles y cuantificables vinculados a causas frecuentes de deterioro o de conservación del patrimonio edificado, por lo que la metodología planteada se puede usar para campañas que impliquen formas de actualización del patrimonio que tengan como fin su conservación.

Este estudio pone de manifiesto la necesitad de la coparticipación de distintos actores gubernamentales y no gubernamentales, que puedan involucrarse en la gestión de los bienes de interés cultural, la estimación e implementación de políticas de actualización del valor del patrimonio para elevar el grado de significación de las comunidades más próximas al él, y a su vez la creación de todo un escenario donde se promuevan los recursos patrimoniales.

Agradecimientos

Esta investigación se basa en la Metodología desarrollada por dos Proyectos: ART-RISK, un proyecto RETOS del Ministerio de Economía y Competitividad y Fondo Europeo de Desarrollo Regional (FEDER), (código: BIA2015-64878-R (MINECO / FEDER, UE)) y el proyecto UPO-03 de la consejería de Fomento, Infraestructura y Ordenación del Territorio de la Junta de Andalucía (España). Pilar Ortiz agradece la beca Salvador Madariaga del Ministerio de Educación, Cultura y Deporte del Gobierno de España (PRX16/00226) para la realización de una estancia en la Universidad de Oxford (UK), durante la cual se trabajó en el diseño de las encuestas utilizadas en esta investigación. Rocío Ortiz agradece su estancia en la Universidad de Lisboa (Portugal), durante la cual se trabajó en el diseño de las encuestas utilizadas en esta investigación.

Referencias

ALCALDÍA DE POPAYÁN. (2015). P*lan de Movilidad para el municipio de Popayán*. Informe 3: diagnóstico parte, 1°ed., Popayán: Movilidad Futura.

BENÍTEZ, J., TIRADO-HERNÁNDEZ, A., ORTIZ, R,. MORENO, M., ORTIZ, P., TURBAY, I., GARRIDO-VIZUETE, MA. (2020). "Social opinion of monuments vulnerability in historical cities". *Science and Digital Technology for Cultural Heritage*, Ortiz, P (coord.) Sevilla: Taylor & Francis Group, 221-224. https://doi.org/10.1201/9780429345470-41

CARABALLO PERICHI, C. (2008). "El patrimonio cultural y los nuevos criterios de intervención. La participación de los actores sociales" *Palapa. Revista de Investigación Científica en Arquitectura/ Journal of Scientific Research in Architecture*, 3:41-49.

DANE (2019). *Resultados Censo Nacional de Población y Vivienda*

2018, 1ªed., Bogotá: DANE

DIAZ FUENTES, D. A. (2017). "Un método simplificado para evaluar el riesgo sísmico y priorizar la atención de los bienes culturales inmuebles: el caso de Chile", *Intervención*, 8:46–62. https://doi.org/10.30763/Intervencion.2017.15.173

GARAVITO GONZÁLES, L. (2006). "El origen del patrimonio como política pública en Colombia, y su relevancia para la interpretación de los vínculos entre cultura y naturaleza". *Opera*, 6:169-187.

GARCÍA CANCLINI, N. (1999). "Los usos sociales del patrimonio cultural", *Patrimonio Etnológico. Nuevas perspectivas de estudio*, 1: 16-33.

GARRÉ, F. (2001). "Patrimonio arquitectónico urbano, preservación y rescate: bases conceptuales e instrumentos de salvaguarda", *Conserva*. 5:5-21.

ICOMOS. (2015). *Documentos de icomos*, 1ª ed., Santiago de Chile: J. de N. Concha, Ed.

ICOMOS. (1999). *Carta de Burra*, 1ª ed., Sidney: ICOMOS Australia.

ICOMOS. "Tendencias, Amenazas Y Riesgos" en Informe Mundial 2000 de ICOMOS sobre monumentos y sitios en peligro. https://www.icomos.org/risk/world_report/2000/trends_spa.htm?fbclid=IwAR2waaCDSNTXRJD1STcIZjRml_b6c1xmhU_mT6ygSi42cMUPmZ1m197dLDY. [consulta: 3/2/2020].

LLULL PEÑALBA, J. (2005). "Evolución del concepto y de la significación social del patrimonio cultural", *Arte, Individuo y Sociedad*, 17:175-204. https://dx.doi.org/10.5209/ARIS

MANZINI, L. (2011). "El significado cultural del patrimonio", *Estudios del Patrimonio Cultural*, 6:27-42.

MINISTERIO DE AMBIENTE VIVIENDA Y DESARROLLO TERRITORIAL. (2006). *Serie Población, Ordenamiento y Desarrollo. Guía metodológica 1: Elementos Poblacionales Basicos para la Planeación*, 1ª ed., Bogotá: Dirección de desarrollo territorial.

ORTIZ, R., ORTIZ, P. (2016). "Vulnerability Index: A New Approach for Preventive Conservation of Monuments", *International Journal of Architectural Heritage*, 10:1078-1100. https://doi.org/10.1080/15583058.2016.1186758

PRIETO, A.J., TURBAY, I., ORTIZ, R., CHÁVEZ, M.J., MACÍAS-BERNAL, J.M., ORTIZ, P. (2020). "A Fuzzy Logic Approach to Preventive Conservation of Cultural Heritage Churches in Popayán, Colombia". *International Journal of Architectural Heritage,* 0:1–20. https://doi.org/10.1080/15583058.2020.1737892

THE GETTY CONSERVATION INSTITUTE. (2013). *Assesing the values of cultural heritage*, 1ª ed., Los Angeles: De la Torre, M

TURBAY I., ORTIZ P., ORTIZ, R. (2019). "Assessment of Vulnerability Index Applied to Churches of 18th Century in the Historic Center of Popayan (Colombia)". En *Resilience and sustainability of cities in hazardous environments*, Dobran, F. (coord.) New York, 26-30.

UNESCO. "Tesauro de la UNESCO" en UNESCO. http://vocabularies.unesco.org/browser/thesaurus/en/. [4/1/2020].

Autor/es

María Isabel Turbay Varona
isaturbay@hotmail.com
Facultad de Arquitectura, Fundación Universitaria de Popayán, Popayán, Colombia

Arquitecta, Master en Diagnóstico del estado de conservación del Patrimonio Histórico, Candidata a Doctora en Historia y estudios Humanísticos, Europa, América, arte y lenguas, en la línea de Tutela, Protección, Gestión y Puesta en Valor del Patrimonio Histórico, de la Universidad Pablo de Olavide de Sevilla. Profesora en la Facultad de Arquitectura de la Fundación Universitaria de Popayán, (Colombia), donde actualmente es Codirectora del grupo de investigación, GREP, Grupo de Estudios del Paisaje. Su experiencia radica en investigación de la vulnerabilidad y riesgos en el Patrimonio arquitectónico, Valoración social del patrimonio y arqueología de la arquitectura. Ha sido docente en la Facultad de Ingeniería Civil de la Universidad del Cauca, en la Facultad de Arte y Diseño del Colegio Mayor del Cauca y en la Facultad de Artes de la Universidad Antonio Nariño, (Colombia). Ha realizado estancias de investigación en instituciones como el Centro de Investigaciones regionales de Mesoamérica CIRMA en La Antigua (Guatemala), en el laboratorio Sanit-ARTE de la Facultad de Ciencias Experimentales de la Universidad Pablo de Olavide de Sevilla y en el Museo Histórico Municipal de Écija (España) y participó en la III Campaña de Excavación Arqueológica en el Palacio de Villa Adriana, Roma (Italia).

Rocío Ortiz
rortcal@upo.es
Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Sevilla, España

Licenciada en Arquitectura en 2001, Máster en Protección del Patrimonio Histórico con un Proyecto enfocado en el estudio de Marchena en 2012. En 2014 Obtuvo el título de Doctora con mención europea en Universidad Pablo de Olavide (Sevilla). Actualmente es profesora en la UPO, donde desarrolla su actividad investigadora en torno a la Conservación Preventiva y el estudio de riesgos y vulnerabilidad del Patrimonio Histórico.

La Dra. Ortiz es directora del Máster de Diagnóstico del Estado de Conservación del Patrimonio Histórico y es responsable del Área de Cristalografía y Mineralogía de la misma universidad. La Dr. Ortiz es experta en el diagnóstico del Patrimonio Histórico, administración, e-learning, y sus investigaciones científicas aparecen publicadas en 30 libros, actas de congresos, y revistas especializadas. Sus proyectos de investigación han sido financiados por la Unión Europea, gobiernos nacional y autonómico, y organizaciones privadas. Los intereses de la Dr. Ortiz se centran en los estudios de riesgo y vulnerabilidad del Patrimonio Cultural, el empleo de información georreferenciada para el estudio del Patrimonio Cultural, materiales de construcción, planes de ordenación urbana y peligros e innovación en las enseñanzas de ciencias con especial énfasis en el diagnóstico del Patrimonio Histórico.

María Arana
mariamonica@unicauca.edu.co
Facultad de Derecho, Ciencias Políticas y Sociales, Universidad del Cauca, Popayán

Estudiante de Ciencia Política de la Universidad del Cauca. Se desempeña como coordinadora general del semillero de investigación Ciudad, Universidad y Juventud, en el cual desarrolla investigaciones en las líneas de comunicación política y ciudad, con particular interés en la cohesión de las instituciones públicas y la sociedad civil en la gestión de las ciudades. Ha publicado textos en la revista universitaria Comarca de la Universidad del Cauca. Realizó un voluntariado en Houston, Texas.

Pilar Ortiz
mportcal@upo.es
Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Sevilla, España

La experiencia investigadora y docente de la Dra. Ortiz se ha enfocado en el diagnóstico, preservación y conservación del Patrimonio Cultural. Para su desarrollo ha colaborado con museos y otras instituciones culturales como el IVCR+i, IAPH, Museo de Cádiz, Museo de Écija, etc. Además, ha desarrollado de actividad en diferentes países: Reino Unido, Bélgica, Italia, Rumanía, Cuba, Colombia, Panamá, etc. Su producción científica puede ser resumida en 38 publicaciones en revistas indexadas; 50 libros y capítulos de libros, participación en más de 25 congresos internacionales, chairman y miembro de comités científicos en numerosos congresos, etc. Ha trabajado como profesora asociada en la Universidad de Amberes (Bélgica), como profesora invitada en la Universidad de Oxford (Reino Unido) y como investigadora invitada en ENEA (Italia). La Dra. Ortiz ha participado en 24 proyectos nacionales e internacionales, contratos y convenios y ha sido la investigadora principal de más de 16 de estos proyectos, destacando un Proyecto de Excelencia de la Junta de Andalucía, un proyecto RETOS del Gobierno de España, un Proyecto de Cooperación Internacional de la Junta de Andalucía y un Proyecto Internacional Erasmus+. Ha iniciado y liderado importantes líneas de investigación como la aplicación de técnicas láser para el diagnóstico in situ de Bienes Culturales, el desarrollo de técnicas no destructivas para el estudio del Patrimonio Histórico, o la aplicación de mapas de riesgos, índices de vulnerabilidad e inteligencia artificial para la preservación del Patrimonio Cultural. La Dra. Ortiz es miembro del Campus de Excelencia Internacional de la Universidad de Jaén en Patrimonio Cultural y Natural, del grupo de trabajo "Cambio" en el Campus Internacional de Excelencia de la universidad Pablo de Olavide (UPO), del Consejo Andaluz de Patrimonio Histórico y decana de la Facultad de Ciencias Experimentales de la UPO.

https://doi.org/10.37558/gec.v17i1.777