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Review

On-site assessment method of air cavities attached to the foundations of historic buildings

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ABSTRACT

Air cavities have quite often been used to reduce underground capillary humidity in buildings of heritage value. The design of these cavities is not supported by objective criteria which ensure they work properly. This study aims to present a method for on-site evaluation so as to understand the workings and evaluate the efficiency of the different kinds of cavities found in the Iberian Peninsula. It is a qualitative and semi-quantitative method, which has been specifically designed, based on the formal, construction and performance aspects of such systems. This process is supported by basic instrumentation and a highly accessible tool for calculation, and has been used on-site in more than eight cavities with satisfactory results. Analysis of the data collected has enabled an approach to the air dynamic in the cavities and the evaporation capacity. On the basis of a classification of types (which did not exist before), the simple method for research proposed here allows the evaluation of the functioning of air cavities on-site. A new and basic instrumentation is used which includes evaporimeters to calculate the cavities' capacity of evaporation.

1. Introduction air cavities

This article describes the on-site methodology specifically developed to discover the air dynamic and functioning of the air cavities. It includes details of the instruments and techniques used for evaluating this system and its efficiency against the problem of capillary humidity in the foundations and base of the walls of buildings of heritage value.

First of all, we documented the different kinds of cavities most often used in the Iberian Peninsula to reduce capillary humidity and its effect on the base of the walls. To this end, there is a description of the formal, construction and functional characteristics.

Based on a wide number of cases (41 types) and the huge number of existing case studies, eight air cavities were selected for on-site study. The most relevant physical parameters of the air were established, whose measurement requires basic instrumentation, and a general plan for monitoring was prepared and adapted to the particularities of each case. Analysis and interpretation of the data collected is based on an accessible tool for calculating and representing the data, Microsoft Excel.

The evaluation process which is the object of this research has proved to be sufficient for a qualitative and semi-quantitative approach to the functioning and efficiency of the air cavities.

There is no known field work on monitoring and studying the functioning of air cavities attached to the foundations of buildings, except the previous, recent research also carried out by the authors of this article [1–3].

However, there are some laboratory studies on air dynamics in active ventilation systems [4]. These incorporate mechanical elements to ensure a specific air speed in drying or stabilising the hygrothermal conditions of the foundations or the wall [5,6]. This system was first used in some buildings such as the church in Vilar de Frades in Portugal [7], and a patent was developed [8].

Other authors have used computer simulation to evaluate: the influence of thermal bridging on evaporation in the perimeter cavities of the foundations [9], ventilation of the crawl space in a typical church in Czech Republic [10] or Slovakia [11], or the different variables (or the cavity's airflow elements) which reduce rising damp in the walls St. Abdon and Sennen in Gemersky Jablonec, Slovakia [12,13].

This research aims to describe and discuss the methodology used by the authors for on-site study of the functioning of passive air cavities for treating capillary humidity in the foundations or base of the walls in historic buildings. Discussing this method-

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STUDY OF DIFFERENT CAVITIES (TIPOLÓGICAL CLASSIFICATION) →	OPERATIONAL ANALYSIS AND CHARACTERIZATION →	CONSTRUCTION CRITERIA
Formal level: project, on-site. **Functional level**: Measured and calculated air physical parameters.	Behaviour of water. **Evaporation rate** in the cavities and the wall.	**Design**: materials and placement. **Sizing**: cross-section of the cavities and aeration or ventilation holes.

Fig. 1. Methodology for on-site evaluation for air cavities.

DATA ADQUISITION →	MONITORING →	ANALYSIS AND INTERPRETATION
Location and description of the building. Boundary and particular conditions of the cavities.	Air physical parameters. Measuring equipment. Measurements.	Graphics. Statistical calculations.

Fig. 2. Monitoring for the analysis of the functioning of air cavities.

ology has allowed us to propose improvements for use in future research.

2. Methodology

The methodology applied at an experimental level on-site (Fig. 1) focuses on the study of real cases, after gathering data on all aspects of each building's context and the formal characteristics of the cavities being studied.

Different kinds of cavities were chosen for analysis and to establish how they work, and then, to define design criteria to use as an aid in construction projects for historical buildings with problems of capillary humidity.

The methodological process suggested and discussed here focuses on documenting the different existing systems of air cavities or ventilation in the Iberian Peninsula and several case studies. Using these examples, we detail the surrounding and specific conditions and measure on-site such physical parameters of the air as are most representative. In field work we use measuring instruments in constant real time, so as to then analyse and interpret the data gathered (Fig. 2). The ultimate objective of these measurements is to evaluate the hygrothermal performance of the cavities, to establish the rate of evaporation in the cavities and wall, and to calculate the evaporation flow in the cavities.

This process is the result of a laboratory simulation of the cavities and the wall (using a methacrylate tube and a test tube with limestone subjected to a constant flow of water) [3] and also of experimental monitoring tests on-site in a pilot cavity [2]. Over the course of the research, this method was refined for implementation in the different cases chosen.

3. Assessment method

Evaluation of the functioning of the air cavities follows the process described at a methodological level and details are given below.

3.1. Documentation

The different systems of air cavities which exist in the Iberian Peninsula were documented and the following sources were consulted: bibliographies, implementation projects, final reports and people involved in project design and construction work.

The most relevant bibliography is limited to a handful of authors (López-Collado [14]; Ortega-Andrade [15]; Jurado-Jiménez [16]; Freitas et al. [5]; Veiga et al. [17]; and González-Fraile [18]), none of whom closely examine the object of our research.

Implementation projects and final construction reports correspond to several developers: national organisations, autonomous communities, archbishoprics and bishoprics, universities and foundations. The archives where the information was found are: Instituto del Patrimonio Cultural de España; Consejería de Cultura y Turismo de la Junta de Castilla y León and their Delegaciones Territoriales; Arzobispado de Madrid; Obispado de Alcalá de Henares and Obispado de Segovia; Fundación del Patrimonio Histórico de Castilla y León (now a part of the Fundación Santa María la Real del Patrimonio Histórico); and the Universidad de Alcalá in Madrid.

Those in charge of the design, works management and supervision of this kind of cavities were interviewed. Some interviewees (project and works managers) were the architects E. Barceló, F. Jurado and P. Lucas. Supervision of such works was carried out by national organisations (C. Jiménez Cuenca), autonomous communities (J. Juste, M. Antonio Garcés, L. Pichel), provincial councils (A. Zaragozá), archbishoprics and bishoprics (J.M. Sacristán, J. L. González Sánchez), universities (J.L. de la Quintana) and foundations (J. García Álvarez).

The construction managers of different building companies have also provided photographic documents of the building execution process. The building companies are: REARASA Restauración de Edificios, Artesonados y Retablos Alonso S.A.; TRYCSA Técnicas para la Restauración y Construcciones S.A.; y Mármoles y Granitos CABANILLAS S.L.

3.2. Selection of cases for study

The cases for study chosen for this research correspond not only to the different kinds identified according to technical performance (Fig. 3) but also to several other aspects, such as their availability for study and the permission of the owners.

For all these cases we obtained the background information and the existing project. In the same way, we obtained permission for access and study. To evaluate each cavity the availability of technical and human resources proved crucial, that is, measuring and monitoring instruments and the labour force to open or to register each cavity.

In each case we followed the same study steps: location and description of the building and the cavities; examination of the building's context (surrounding conditions) and the hygrothermal and construction characteristics of the cavities (specific conditions); monitoring and analysis of specific functioning.

3.3. Boundary and particular conditions

Surrounding conditions are divided into environmental activity and conditions, and into the construction conditions of the ground and the building. As regards environmental activity and conditions, information about the local climate or atmosphere outside is gathered, also physical conditions of the nearby surrounding area like topography or urban water systems, or physical environmental characteristics due to nearby trees or buildings; also, whether there are passive or active ventilation systems present or in use (heating and conditioning) in the inside of the building, next to the cavities. As regards construction aspects, the kind of soil, its permeability, the groundwater level and relative altitude are determined; also, the type of foundations and the construction of the wall and cladding, the degree of wear and tear to the wall and cladding, and rainwater drainage from the roof.

The specific conditions of each cavity refer to hygrothermal activity and construction. Hygrothermal conditions depend on the source of the water: capillary humidity, runoff or rainwater from the roof. Construction elements refer to the floor or pavement, walls, ceiling and complementary elements and the relation between them and the building. There are various kinds of cavity: ditches in the ground, quarter barrel galleries or vertical vaults made of brick, reinforced concrete walls or precast concrete quarter tubes.

Fig. 3. Perimeter cavity on the outside face of the foundations: **a)** Church of convent of Santa Cruz la Real in Segovia, drainage, 2015-01-29; **b)** Parish church of Vall de Almonacid (Castellón), air cavity and rainwater harvesting, 2015-10-23; **c)** Church of San Salvador in Toro (Zamora), rainwater channel parallel to the air cavity, 2016-03-15.

3.4. On-site monitoring

Knowledge obtained from the building allows the planning of monitoring the most relevant physical parameters of the air, using accurate instruments to evaluate the functioning of the cavities.

3.4.1. Measured and calculated parameters

Different physical parameters of the air were measured and calculated depending on the surrounding conditions and the specific conditions as defined for the analysis of the functioning of air cavities.

As for surrounding conditions, we considered the environmental activity or conditions mentioned for the physical parameters of the air in the local climate, the environment outside near the building and the environment inside the building. As regards local weather, we gathered data for temperature, relative humidity, precipitation, barometric pressure, wind speed, prevailing wind direction and evaporation (mm/day) from the Agencia Estatal de Meteorología (AEMet) (State Weather Agency) weather station nearest to the building, without significant changes in the terrain or altitude of both places. Using the data for temperature, relative humidity and barometric pressure we calculated the moisture content in the local weather. As for the outside environment near the building and the cavities, we evaluated the incidence of the building and trees on the sunshine and prevailing wind direction. And for the inside of the building we gathered data for environmental temperature and relative humidity for the area next to the cavities and for the juncture of the flooring and the wall.

The building conditions of the terrain and foundations were also documented, taking into account the relative altitude of the ground outside and inside the building and the depth of the foundations.

For the specific conditions, we studied the construction conditions for each case focussing on the dimensions of the cavity and the ventilation or aeration vents, such as: size of the cavity, evaporation surfaces (wall of foundations and flooring in the cavity) and breathing surfaces in the cavity (size, layout and direction of the vents and vertical elements).

Thus, we recorded the condition of the air in the cavity and on the foundation surface so as to evaluate the functioning or technical performance of the cavity. The physical parameters measured in the air in the cavity to compare with local weather were: temperature, relative humidity, barometric pressure, wind speed and direction, and evaporation (mm/day). And the physical parameters measured in the air at the foundation surface to compare with the environment in the cavity were: temperature and relative humidity (Fig. 4).

This data has allowed us to calculate the moisture content and the rate of evaporation in the cavity and on the foundation surface (Fig. 5). Using the respective values for temperature, relative humidity and barometric pressure, we calculated the moisture content in the cavity and the layer of air on the foundations. The rate of evaporation refers to the difference in the moisture content between two masses of air (in the cavity and environment outside, or layer of air on the foundation evaporation surface and environment inside the cavity) per unit of time.

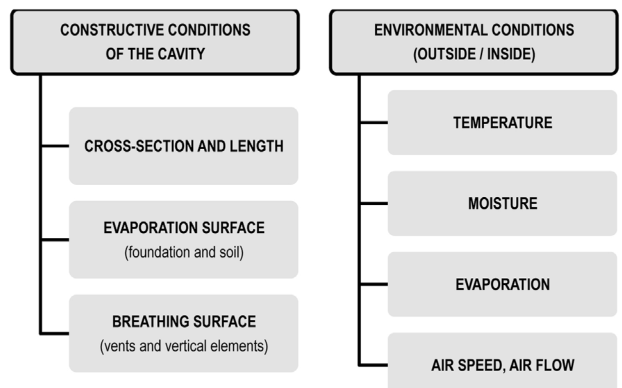

Fig. 4. Data for the cavity and physical parameters of the air measured to evaluate the functioning of air cavities.

In some cases it was possible to calculate the flow of evaporation within the cavity, when the air duct was a closed for its entire length. This is the result of multiplying the m^2 of the cavity's cross-section by the air speed at the geometric centre of the section.

3.4.2. Measuring instruments

The instruments which were used to measure the physical parameters of the air (temperature and relative humidity, air speed and evaporation) were thermo-hygrometers, anemometers and evaporimeters (Fig. 6), all of them economical and easy to find and use. Both the thermo-hygrometers and anemometers work within a range and accuracy which was enough for the purposes of this study (Table 1).

The thermo-hygrometers (Extech MO290, PCE HT-71 and MSR 145 W) were calibrated by comparison, depending on the accuracy of each model, in an AEMet observatory.

The anemometer (TESTO 435-2) was conveniently calibrated to the manufacturer's certificate settings, issued a few days before the instrument was used for our research. We decided on equipment with a resolution of 0.01 m/s, due to the reduced air flow inside the cavities.

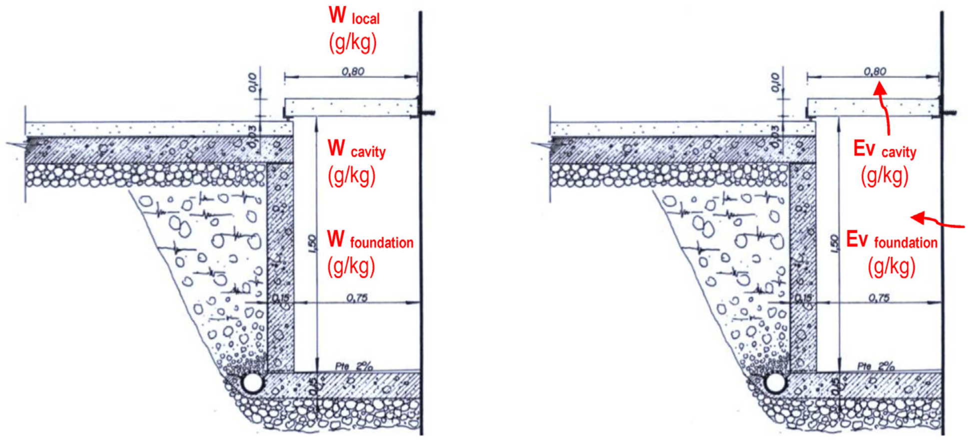

Fig. 5. Physical parameters of the air calculated in an air cavity. Basic plan for the air cavity in the atrium of Zamora Cathedral, section (Casaseca-Beneítez [19], plan 14, with variations in performance): **a)** Moisture content in local weather, cavity and foundations; **b)** Evaporation in cavity and foundations.

Fig. 6. Measuring instruments: **a)** Thermo-hygrometer PCE HT-71; **b)** Thermo-hygrometer MSR 145 W; **c)** Multifunction meter TESTO 435-2 and hot-wire probe; **d)** Piche evaporimeter.

Table 1
Technical specifications for the measuring instruments used.

Instruments	Parameters	Measuring range	Resolution	Accuracy
Thermo-hygrometer Extech MO290	Temperature	−29…+77 °C	–	±2 °C
	Relative humidity	0…100 %RH	–	±2,5 %RH (11…90 %RH), ±3 %RH (0…100 %RH)
Thermo-hygrometer PCE HT-71	Temperature	−35…+80 °C	0,1 °C	±1 °C
	Relative humidity	0…100 %RH	0,5 %RH	±3,5 %RH (20…80 %RH), ±5 %RH (0…100 %RH)
Thermo-hygrometer MSR 145 W	Temperature	−10…+58 °C	–	±0,1 °C (5…45 °C), ±0,2 °C (-10…+58 °C)
	Relative humidity	0…100 %RH (-20…+65 °C)	–	±2 %RH (10…85 %RH, 0…40 °C), ±4 %RH (85…95 % RH, 0…40 °C)
	Barometric pressure	0…2500 mbar	–	±2,5 mbar (750…1100 mbar)
Anemometer TESTO 435-2	Temperature	−20…+70 °C	0,1 °C	±0,3 °C
	Air speed	0…+20 m/s	001 m/s	±003 m/s

The Piche evaporimeter (mm/day) is the model used by the AEMet in its observatories. Its use in this research is groundbreaking as this instrument had not been used in this field of research (pathology of capillary humidity) before. It measures potential evaporation in an atmosphere or its drying action, according to temperature, relative humidity and circulating airflow on a saturated surface (a disc of blotting paper).

Our research was completed with data on the local weather (temperature, relative humidity, barometric pressure, wind speed and direction, rainfall and evaporation) provided by the AEMet according to the location of the different buildings.

In general, variables in temperature, barometric pressure and relative humidity are values registered every hour. Wind speed and direction are the average value for the 10 min before the hour. Rainfall and evaporation are cumulative values per hour or 24 h respectively.

3.4.3. On-site monitoring

First we gathered occasional data to test the air dynamic in the cavity (using probes and independent electronic data loggers and the anemometer), and then we left the equipment installed to measure constantly so as to evaluate the functioning of the system (including cumulative data loggers such as the evaporimeter).

The occasional or approach measurements were carried out in the holes for air interchange and at the mid-point for each section of the cavity, always at the geometric centre of the corresponding sections. These readings were limited to the presence of aeration vents or registration vents in the cavity (sometimes on a human scale).

Constant measuring equipment was placed at the geometric centre of the cross-section: from either end of the cavity (thermo-hygrometers) and from the mid-point of the length of each section (thermo-hygrometer, anemometer and evaporimeter), although access to these areas was not always possible. The equipment placed in the middle was mirrored by others at the same height on the foundation surface and opposite side, or at the juncture of the flooring and the wall (thermo-hygrometer) in the area next to the cavity (usually in use).

At least one thermo-hygrometer, one anemometer and one evaporimeter were set up in each section of the cavity, and, in parallel, two thermo-hygrometers were installed on either side of the foundations or wall (Fig. 7).

In the case of cavities where human access was not possible, which are recordable *via* the vents for interchange of air, the equipment was placed at the mid-point of the cross-section of the cavity next to or below the vents.

The reference values for local weather were taken from the nearest and most reliable weather station (thermo-hygrometer, anemometer, evaporimeter), usually belonging to the AEMet.

The optimum observation period is a whole yearly cycle, but for our research (given our limited resources) the instruments rotated around different cavities for the same climate periods, anti-cyclone (in summer) and depression (autumn or spring), after 9-day observation cycles. Although most data was recorded in dry weather, this being the period of greatest moisture transfer and evaporation in the cavity and foundations.

3.5. Analysis and interpretation

Analysis and interpretation of the data were based on drawing up diagrams and statistical tables using the Microsoft Office Excel computer programme, using the data gathered on-site or recorded by each instrument, subject to validation (stabilisation of probes after installation, checking the measurement periods or abnormal readings due to the equipment being inaccurate).

Different diagrams were used to represent the average values measured and calculated: curve diagrams, bar charts, box plots and psychrometric tables.

The curve diagram shows the (measured or average) parameter for barometric pressure, temperature, relative humidity and moisture content (the latter calculated using the formula from *ASHRAE Fundamentals Handbook* [21], which takes in the three former parameters), air speed or evaporation, all over time. The bar chart shows the cumulative value for rainfall or evaporation over time.

The box plot or Tukey diagram (a diagram using stacked columns) proved to be a very useful tool, as each box shows the quartile values of the same variable (temperature, relative humidity or moisture content), and identifies the highest, lowest and median values (Fig. 8).

In most cases we have grouped the curve diagrams, bar charts and box plots to compare variables for temperature, relative humidity, moisture content, air speed or evaporation, between the cavity and outside it, the wall and the cavity, different sections of the cavity or different seasons.

The psychrometric diagram or ASHRAE shows variables for temperature, relative humidity and moisture content (hourly or daily values, average for hourly data), according to the average barometric pressure (less than normal at higher altitude in the interior of the peninsula, and which adjusts better to reality as the moisture content can vary 1 g/kg if the pressure differs 100 mbar compared with normal barometric pressure at sea level) for the observation period.

Calculated statistical values are the average for temperature (ºC), relative humidity (%), moisture content (g/kg), barometric pressure (mbar), speed (m/s), evaporation (calculated in g/kg in the cavity for the foundation surface or measured in mm/day in the cavity in relation to the local weather) and flow (m^3/s); or accumulated rainfall (mm); also absolute values (maximum and minimum) for temperature, humidity, speed and evaporation.

The different diagrams and statistical values described were interpreted in the analysis of the functioning of the air or ventilation cavities. Basically, it is an analysis by comparing different environments, such as local climate, the cavity and the layer of air on the foundation surface next to the cavity, or the interior space of the building next to the cavity and the interior face of the wall. The environment of the local climate was considered to be a reference value, usually favourable for the stabilisation of the wall's hygrothermal conditions, except during periods of rain and particularly in wet climates.

4. Discussion

The experimental methodology employed in this study of on-site cases has allowed us to evaluate the functioning of passive air and ventilation cavities.

Using the information collected at different levels (bibliographical, projects, on-site or from those involved in the design, execution or supervision of the construction) we have drawn up a classification of the kinds of cavity in the Iberian Peninsula. Although the bibliography is limited and very uncritical, and the projects do not always provide construction details of the cavity (sometimes the project does not even correspond to the construction), and very rarely justify the dimensions or stipulate the systems maintenance needs. From the different people involved in the construction we have gathered information about design criteria for the cavities, their sizing parameters and their opinion of the end result (very rarely checked experimentally).

Therefore, over a hundred construction solutions were studied, which were analysed according to the information available and the opportunity for on-site observation, and were classified in 41 different kinds, most of them on an *ad hoc* basis. Hence the need arises for establishing general application criteria to regulate the design of passive air and ventilation systems as a way of controlling capillary humidity in floors, foundations and wall bases, bearing in mind that each case requires a specific study and solution.

Based on the typological classification, we selected eight case studies with specific environmental conditions, which proved to be enough for this research. As regards specific conditions, we decided to register hygrothermal activity relating to the origin of the water and its appearance in the cavity, such as humidity or water filtration rates depending on the permeability of the cavity's retaining wall.

Several physical parameters of the air were measured (temperature, relative humidity, barometric pressure, air speed and direction and evaporation) in the cavity's surroundings, in the cavity itself, and on the surface of the foundations or of the wall. We also calculated the moisture content, the rate of evaporation (water vapour dissipated per unit of time) or the flow of evaporation. From

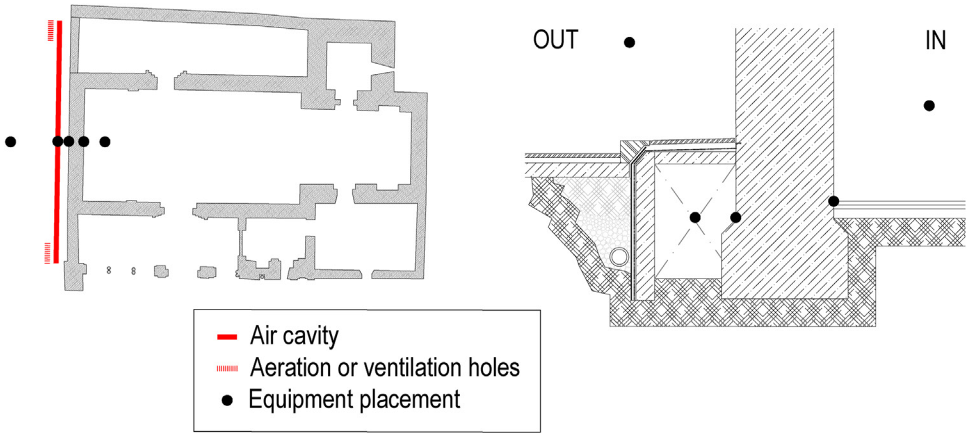

Fig. 7. Floor plan of the location of monitoring equipment at the parish church of Pinarejos, Segovia (Sanz-Bermúdez [20], plan PR-10, floor – restored) and standard section of an air cavity.

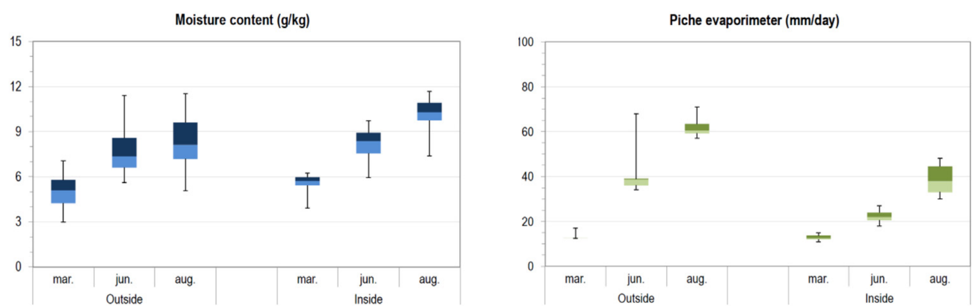

Fig. 8. Air cavity at the church of San Salvador de los Caballeros in Toro (Zamora) at different times of the year: **a)** Moisture content; **b)** Evaporation.

which we conclude that the system is more efficient the greater the rate of evaporation, and the contrary the more it deviates from the maximum possible evaporation of the system, depending on the range of values for the moisture content in the two air masses under consideration.

The measuring instruments used (thermo-hygrometers, anemometers and evaporimeters) were sufficient given their characteristics (range, resolution, and calibration) for an estimate of the behaviour of the air in the cavity. Especially when using the evaporimeter, whose registered data indicate the evaporation experienced by damp dry material when exposed to the environment in the cavity, although such data need adjusting to see the real evaporation from the foundations and floor of the cavity, and thus the real evaporation capacity of the cavity. Another option for measuring the cavity's evaporation rate is to use tracer gases.

The monitoring described, based on accessible and simple equipment, can be extended to a whole yearly cycle, pinpointing the origin of the water (phreatic level, perched water, rainfall, irrigation, urban water supply and sanitation systems); measuring the rate of filtration in the cavity (gauging drainage) or the evolution of the volumetric water content in the ground and foundations (at different heights and depths) using probes like TDR or FDR (whose physical principle is transit time or capacitance respectively). Also, check the evaporation at the base or the degree of change to stone materials (disintegration and efflorescence), before and after building the cavity.

The analysis and interpretation of the measured and calculated data allowed a semi-quantitative evaluation, from which we can establish building recommendations to solve the faults and problems identified in foundations which are exposed to capillary humidity. Such formal aspects as the cavity volume and the surface of the ventilation or aeration vents do influence the rate of evaporation in the cavity: it has been shown that small section cavities with reduced aeration surfaces have a limited rate of evaporation, with high values for relative humidity and humidity content even in the dry season. Likewise, geographical situation or exposure to the surrounding micro-climate also affect the rate of evaporation; for example, in the same cavity sections facing in different directions were found to vary 2 g/Kg. Also the presence of vertical elements which boost the movement of the air, otherwise the flow is produced by differences in vapour pressure or temperature.

5. Conclusion

This research describes an on-site evaluation method applied to different types of air or ventilation cavities next to foundations suffering from capillary humidity in heritage buildings in the Iberian Peninsula. The method is qualitative and semi-quantitative, at a formal and construction level (based on documentation and on-site observation), and at performance level (based on the main physical parameters of the air, both measured and calculated).

We used simple instruments, groundbreaking in the case of the Piche evaporimeter, to obtain an estimate to the evaporation capacity in the cavity. Similarly, we used a readily available calculation tool, Microsoft Excel, to analyse and interpret the data.

Applying this method on-site allows us to know the air dynamic in passive air or ventilation cavities, and to identify criteria which detract from their efficiency.

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