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Integrating thermal and mechanical characteristics of historic masonry categories: development of a Sicilian database

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Abstract. Detailed construction analysis is essential to the compatible energy improvement of historic buildings. In-situ measurements are crucial for energy diagnosis but their use is limited, especially in vernacular architecture. This paper exposes the development of a hygrothermal and mechanical database for Sicilian historic walls. The proposed method, applied to eleven historic centres, is based on the investigation of those masonry construction features, which recur in local contexts. Preliminary results concern the case study of Petralia Sottana, where a first set of laboratory measurements of stone compressive strength and thermal conductivity was conducted, together with in-situ tests of masonry thermal conductance. Focused on stone walls, these results are used to discuss potentialities and limits of the proposed categorisation of traditional masonry as a support to the energy diagnosis of historic buildings.

Keywords – Historic stone wall, masonry, U-value, Masonry Quality Index (MQI), Sicily

1. Introduction

The European Performance of Buildings Directive (2010/31/EU) admits the exemption of “officially protected buildings” from national minimum requirements of energy performance. Extended to the Energy Efficiency Directive (2012/27/EU), this approach is generally confirmed by corresponding national regulations. The main effort, supported by scientific research, is to use this possibility not for a systematic exemption, but to improve the energy performance of historic buildings as far as this is compatible with their aesthetic and construction features. Higher energy efficiency and better indoor climate conditions will promote the use of historic buildings, thus supporting their conservation [1].

The detailed knowledge of the building and its construction features is the basis to assure compatible restoration or refurbishment, also in the field of energy efficiency. This analysis, whose importance is well-established in restoration theories and is evident in the recent standard EN 16883, includes the hygrothermal characteristics of building envelope components. Investigating these features is frequently complicated by the heterogeneity of the historic fabric, above all when masonry is examined. Common uncertainties bear on the materials and their proportion, but also on the stratigraphy used to calculate the thermal transmittance of the wall.

In this sense, in-situ measurements are crucial but multiple tests are necessary to achieve reliable results, especially for buildings subjected to several historic transformations. The practical difficulties of these tests limit sensibly their use, particularly if the construction is not officially protected. But even without emerging artistic elements, non-listed historic buildings are tangible expression of technical culture and are essential to the structure and identity of the built environment. Their energy improvement needs accurate analysis of their current energy performance.

This research is based on the assumption that examining the local features of historic architecture, and developing related data collections, will improve the energy diagnosis of heritage buildings, thus supporting the identification of compatible solutions to improve their energy efficiency.

2. Objective

This study aims to develop a database of hygrothermal and mechanical information for the masonry materials and techniques, which characterise the historic architecture of Sicily.

The purpose is enhancing the technical data which can be obtained through the non-destructive examination of historic walls, in order to develop accurate models to assess the energy performance of the historic building. For this purpose, the hygrothermal analysis of masonry is joint to that of its structural features.

The database is intended to facilitate accurate analysis of the envelope components in vernacular architecture, as the basis to improve the performances of these buildings with respect to the conservation of their cultural value. In monumental buildings, the database may enrich the information of in-situ measurements, in order to assess the reliability of results and fill lacking data.

3. State of the art

Existing technical collections on thermo-physical data do not neglect the traditional materials of historic construction: international standards UNI EN ISO 10456 and UNI EN 1745 provide thermal and hygrometric data for different lithotypes. Regarding Italy, information can be found also in standard UNI 10351, while technical report UNI/TR 11552 - which pertains to envelope components rather than building materials - deals also with stone and brick masonry.

For several stones widely used in historic buildings, discrepancies have been observed if data is taken from different collections [2]. Above all, uncertainties affect the determination of thermal transmittance (U-value) of stonewalls: in terms of calculation, frequently the component cannot be modelled as the sequence of regular layers; in terms of measurement, lack of homogeneity - even within the same wall - adds to the limited accuracy of test results. While a detailed repertory was developed for French heritage in 1980 [3], measurement campaigns have been carried out recently to collect reliable U-values historic stone and brick walls in different European countries [4].

Although early interest on thermal conductivity of Sicilian masonry stone dates back to the end of 19th century [5], characterisation of its masonry materials has focused essentially on physical and mechanical properties [6]. Few specific hygrothermal data is currently available, mainly related to the historic architecture of Palermo [7]: here the most common material for stone units was calcarenite, whose properties vary considerably, given the large number of quarries employed along the centuries for the construction of the local architectural heritage.

4. Methods

4.1. Selection of local contexts

The methodology of this research is based on the analysis of the recurrent construction features of historic architecture in local contexts.

In this study, the local context is an area where homogeneous characteristics are observed in materials and construction techniques of the historic building stock. The local context generally coincides with a single historic centre and the surrounding rural constructions: since the greatest part of Sicily is rich in stones suitable for masonry works, many centres could take advantage of quarries in their vicinity and reduce the costs of transportation. Different local contexts are characterised by the prevalent use of the same lithotype. However, physical properties such as apparent density vary with the quarry, thus influencing the traditional use of that stone in masonry.

The areas of investigation - eleven historic centres - have been selected in order to analyse rocks commonly used in Sicilian historic architecture: calcarenite, hard limestone, quartz sandstone and gypsum. The volcanic rocks widely employed in great part of eastern Sicily are not covered by this study. The set of eleven local contexts aims to include also masonry stones circumscribed to limited areas, but significant because of relevance and size of the corresponding historic building stock: this is

the case of travertine in the architectural heritage of Alcamo. Bricks, frequently the main masonry material in the northern part of eastern Sicily, is analysed only partially; it is present in the traditional architecture of two case studies, but only for specific parts of the fabric. Table 1 summarizes the masonry unit materials examined in each local context.

Table 1. Materials traditionally used for masonry units in the analysed local contexts.

Local context	Calcar- enite	Lime- stone	Quartz sands.	Gypsum	Argil- lite	Congl- omerate	Gneiss	Trav- ertine	Brick
Alcamo	•							•	
Caltabellotta	•	•							
Cammarata		•							
Ciminna				•					
Patti	•						•		•
Petralia Sottana			•			•			•
San Giovanni Gemini		•							
Serradifalco	•			•					
Scicli		•							
Sutera				•					
Tusa			•		•				

4.2. Identification and analysis of local masonry typologies

Masonry typologies have been identified for each local context, based on the observation of all visible outdoor wall surfaces in the historic centre. The visual analysis of their arrangement was integrated by inspecting the corresponding indoor surfaces, when possible, and by examining cross-sections in damaged structures, where available. Attention was focused on the following main features of the bond: size and shape of masonry units, continuity and geometry of horizontal joints, mutual alternation of vertical joints in overlapping courses, presence and frequency of perpend and not-transverse headers (if the stone unit does not extend through the entire width of the wall; onwards “headers”).

Through this preliminary analysis, the recurrent bonds were identified and the categorisation was drafted. This description was verified and detailed by selecting and drawing representative walls for each type. The results of this second step of analysis were reported in sheets.

Each sheet, specific to a masonry typology, includes a drawing of the corresponding bond. This drawing is not the reproduction of a case study but a critical representation, which summarizes the systematic features of arrangement observed in real examples of the same typology. The drawing shows surface and cross-sections (both vertical and horizontal) of a wall, where the dimensions of masonry units and mortar joints are the average of the ranges measured on site. Similarly, position and frequency of perpend, headers and regularization units (used to fill inner macro-voids or to obtain horizontal courses) are drawn according to the features observed. Drawn wall thickness depends on the size measured in the real cases but is rounded, for the sake of generality.

The sheet also provides the range of dimensions for masonry units and mortar joints. It also describes the recurrent geometry of horizontal and vertical joints. Furthermore, the sheet estimates the ratio of stone and mortar in the cross-section, as well as the content of voids (the latter only when reliable information could be achieved from real cross-sections).

In many case studies, more than one rock was observed in the same wall, often because different mechanical properties make each stone suitable for distinct structural functions. Therefore, in each centre, the set of masonry typologies was equipped with the description of materials and solutions used for relevant masonry parts, such as base, corners, cornices and opening surrounds. In case different rocks were observed in the ordinary parts of the same wall type, the sheet points out the prevalent stone and informs about the content of the other ones (expressed as ratio of the wall surface).

Masonry typologies are marked with codes, related to the main features of their bond: from “SM1”, in case of regular masonry units, to “SM3”, for rubble stonewalls. Depending on the local context, a group is not represented or, conversely, is divided in more than one category. Code “BM” is used for brick masonry typologies. Present in two case studies, they are cited but not discussed in this study.

4.3. Mechanical and thermal characterisation of stones

Construction details shown in the sheets, such as stonework cross-section and mortar content, are relevant for structural as well as energy performances of the wall. Therefore, both mechanical and hygrothermal properties of materials are examined, in order to collect data specific to local contexts.

Based on available literature, and archival research if necessary, the main traditional sources of masonry materials - generally local quarries - were identified in order to choose appropriate samples. Masonry units of ruined walls were used as samples for laboratory tests, aimed to determine the apparent density of local stones and measure their compressive strength and thermal conductivity.

Stone cores (diameter 59.5 ± 0.5 mm) were carved from masonry unit samples by means of a coring machine (60-mm cup). Depending on the length of each core, one cylinder or more were obtained through a wet cutting circular saw: 60-mm and 20-mm-high specimens were cut for mechanical and thermal tests, respectively. With regard to thermal conductivity measurements, a disc sander was used to make bases perpendicular to the axis of each cylinder. Consequently, regularisation layers were not added. For each test, a set of three specimens was obtained from the same sample.

Before measurements, the specimens were dried in oven at 105°C until consecutive weighing provided uniform results. Weight of dry specimens was used to calculate apparent density. Destructive tests of compressive strength were carried out according to standard UNI EN 1926, by using the apparatus Controls 50C5642. Non-destructive tests of thermal conductivity were conducted according to standard ISO 8301, by means of FOX 50 heat flow meter.

4.4. Mechanical and thermal characterisation of walls

Structural behaviour of stonewalls was assessed through the Masonry Quality Index [8]. Since the analysis focused on wall types, mortar was considered in good state and not in the current conditions observed in the inspected structures.

In order to identify a range of U-values for each masonry type, in-situ measurements of thermal conductance (Λ -value) are being carried out, according to standard ISO 9869-1:2014. The results of these tests will be used to validate the calculation of Λ -values (in a range of wall thickness) based on the laboratory measurements of thermal conductivity and on the features of each masonry typology. Discrepancy with thermal transmittance calculated through standard λ -values will be estimated.

In Petralia Sottana, where preliminary tests were conducted, the measuring apparatus was made of: data logger Ahlborn Almemo 2690-8, heat flow sensor (plate FQA 119, 250 mm x 250 mm x 1.5 mm, substrate in epoxy resin), four thermocouples (Cu-CuNi). The heat flow sensor was applied to the internal side of the wall through paper adhesive tape and protected by means of a light gauze. Paper tape was used also for thermocouples indoor. Outdoor, sensors were covered with a thin layer of gypsum paste, easy to remove but more reliable than tape on irregular surfaces and in case of rain (tested walls were not protected by overhangs). Before fixing the apparatus, measurement locations were inspected by means of infrared thermography. The recording interval was 150 s. Collected data was analysed according to the average method described by ISO 9869-1.

5. Results: local context of Petralia Sottana

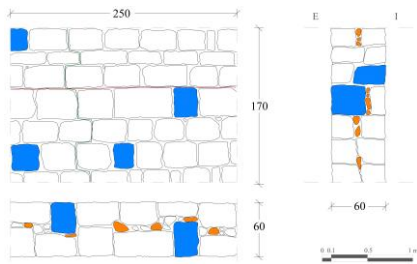

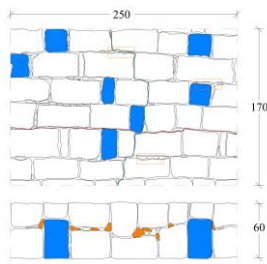
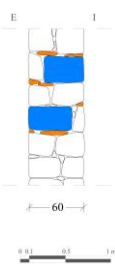
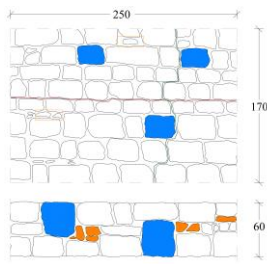
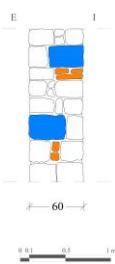
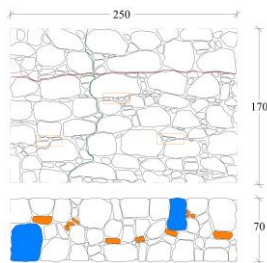
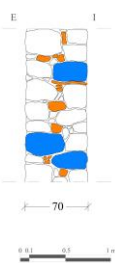
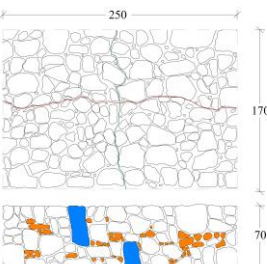
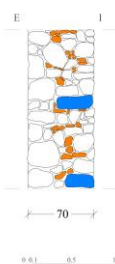
Categorisation of masonry and assessment of MQI have been carried out in all case studies. Laboratory tests of compressive strength and a first set of measurements of thermal conductivity have been conducted on the traditional stones of the analysed centres. In-situ tests of thermal transmittance have been carried out in the case study of Petralia Sottana, northern Sicily. Therefore, the exposition of preliminary results focuses on this local context, with special attention to thermal properties.

5.1. Historic masonry typologies

Two prevalent stones were employed in the historic buildings of Petralia Sottana: hard quartz sandstone and conglomerate. The former was mainly used for the most loaded parts of the wall (quoins, headers, opening surrounds), the latter - generally in form of rubble - for the ordinary parts. Soft limestone was present locally but its use was not common in stonework. Gypsum, widely available in the vicinity of Petralia Sottana, was generally employed as binder. Use of brick was frequent but essentially limited to cornices, arches and vaults, additional storeys.

Seven masonry typologies have been identified. One type is characterised by regular courses of almost cut-edge stone units (SM1). Two recurrent bonds were distinguished in walls with less regular stone units (SM2), mainly differing in continuity and regularity of horizontal joints. Two typologies were identified also about rubble masonry (SM3), especially for the average dimensions of stone units. The two typologies of brickwork (BM) are not examined in this paper. The construction schemes of stonework typologies and the corresponding Masonry Quality Index are shown in table 2.

Table 2. Stone masonry typologies in Petralia Sottana. Orange is used for regularization elements, blue for headers. Red and green lines show the geometry of horizontal and vertical joints, respectively.

	Masonry typology		IQM
SM1			Vertical loading 10 Horiz. in-plane loading 8.5 Horiz. out-of-plane loading 9
SM2.1			Vertical loading 9 Horiz. in-plane loading 8.5 Horiz. out-of-plane loading 7.5
SM2.2			Vertical loading 3.5 Horiz. in-plane loading 3.5 Horiz. out-of-plane loading 3.5
SM3.1			Vertical loading 2.1 Horiz. in-plane loading 2.1 Horiz. out-of-plane loading 2.1
SM3.2			Vertical loading 1.1 Horiz. in-plane loading 1.4 Horiz. out-of-plane loading 1.4

In case of regular masonry units (SM1, SM2.1, SM2.2), the ordinary parts of the wall are generally made of the same stone: the most frequent is conglomerate but quartz sandstone is not rare. Limited presence of quartz sandstone units can be observed in conglomerate stonework.

5.2. Laboratory measurements

Thermal conductivity tests (table 3) were carried out only on quartz sandstone, since the main dimension of clasts typical to conglomerates was comparable to the thickness of the specimens to be used in the measuring apparatus employed in this study. Results of compressive strength measured on quartz sandstone are reported in table 4, together with the corresponding apparent density.

Table 3. Results of thermal conductivity measurements on quartz sandstone.

Sample	Apparent density ρ ($\text{kg}\cdot\text{m}^{-3}$)				Thermal conductivity λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)			
	ρ_{specim1}	ρ_{specim2}	ρ_{specim3}	ρ_{average}	λ_{specim1}	λ_{specim2}	λ_{specim3}	λ_{average}
Quartz sandstone sample 1	2125	2209	2153	2162	0.83	1.52	1.42	1.26

Table 4. Results of apparent density and compressive strength.

Sample	Apparent density ρ ($\text{kg}\cdot\text{m}^{-3}$)				Cylinder compressive strength (MPa)			
	ρ_{specim1}	ρ_{specim2}	ρ_{specim3}	ρ_{average}	$f_{c,\text{specim1}}$	$f_{c,\text{specim2}}$	$f_{c,\text{specim3}}$	$f_{c,\text{average}}$
Quartz sandstone sample 2	2096	2259	2148	2168	28	26	27	26
Quartz sandstone sample 3	2418	2457	2452	2442	64	133	112	103

5.3. In-situ measurements of thermal conductance

Three in-situ measurements of thermal conductance were carried out during winter 2019-2020 in two historic buildings (figures 1-4): a house (measuring point mp1) and a public office (mp2 and mp3).



Figure 1. South-oriented façade with mp1.



Figure 2. West-oriented façade with mp2.



Figure 3. Heat flow meter in mp1.

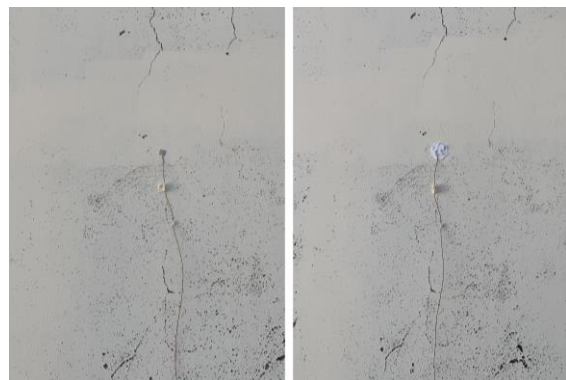


Figure 4. Outdoor thermocouple in mp3, before and after application of gypsum paste.

In the private house, stonewall is made of conglomerate and its type is SM2.1. The North-oriented façade of the building was not suitable for the test, because insulated from the inner side. This condition is frequent in Petralia Sottana and reduces sensibly the choice of measurement points. The test was carried out on a 47-cm-thick wall (plastered only on the inner side), oriented to the South but constantly protected from direct solar radiation by neighbouring constructions. The inner side of the wall faces a living room, regularly heated during the test by means of a radiator.

The main façade of the office building, oriented to the West, is classified as SM3.2 and is a mix of conglomerate (prevalent) and quartz sandstone. The short northern façade is not accessible and shows heavy transformations of masonry arrangement. Since the West-oriented wall is subject to solar radiation, a second measurement was carried out on the opposite façade. Although this is plastered on both sides, it is reasonable that masonry typology is the same of the western façade, according to the information collected about the history of this building. Both tested walls are plastered on their inner side, which faces the following spaces, heated by radiators: a office occupied by a single worker for the 73-cm-thick western wall, a corridor for the 71-cm-thick eastern one. Table 5 reports the duration of each measurement and the resulting thermal conductance.

Table 5. Results of in situ tests of thermal conductance carried out in Petralia Sottana.

Measurement point	Orientation	Wall thickness (cm)	Test duration (h)	Λ -value ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)
mp1	S	47	168	1.78
mp2	W	73	288	1.51
mp3	E	71	336	0.90

6. Discussion

The preliminary results, referred to the case study of Petralia Sottana, include the complete categorisation of local historic masonry but a limited number of laboratory and in-situ tests on stones and walls, currently focused on mechanical and thermal properties but not on the hygrometric ones. Nonetheless, these results are useful to validate the methodology developed for this on-going research.

The construction data for the wall categorisation was collected with homogeneous level of detail in all case studies. On the structural side, this information proved to be sufficient to calculate the Masonry Quality Index for each typology. On the energy side, data collected for each masonry type - and summarized in the corresponding technical sheet - is able to support the accurate thermal modelling of the building envelope in terms of stratigraphy, ratio of mortar, material inhomogeneity. These details have slight influence on thermal conductance of walls, if stone and mortar have similar conductivity (for instance, in the case of soft calcarenite). Conversely, these construction elements require particular attention when hard stones are used as masonry units.

As far as measurements of thermal conductivity are considered, testing small specimens is useful to cover the variety of stones observed in the historic building stock of the eleven case studies. Indeed, especially in the frequent case historical quarries are inactive, existing walls are the main and most reliable source of samples, but stone units may be not appropriate to shape large-size specimens, especially if the material was traditionally used in form of rubble. Nonetheless, the performed tests are not suitable for inhomogeneous rocks with clasts, macro-voids, cracks, inclusions, such as conglomerate and soft calcarenite.

Results of the three tests performed on quartz sandstone from Petralia Sottana are rather uniform, with the average λ -value of $1.26 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. For this rock, $\lambda = 2.6 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ is provided by EN 1745 for quartz sandstone ($\rho = 2600$ to $2800 \text{ kg}\cdot\text{m}^{-3}$). This discrepancy is explained partially by the difference of apparent density, which was $2162 \text{ kg}\cdot\text{m}^{-3}$ as average for the tested specimens, but a corresponding λ -value cannot be derived from the standards. Further measurements will include quartz sandstone samples from the other case studies, in order to obtain λ -values with varying stone density and thus compare measured and standard data.

Regarding the in-situ measurements of thermal conductance, direct comparison with Λ -values based on the performed tests of thermal conductivity is not possible, since conglomerate is prevalent in the inspected walls. Indeed, the campaign carried out in Petralia Sottana showed the difficulty to find a

sufficient set of walls with appropriate and comparable conditions for each typology. On the one side, this confirms the need of a detailed database, in order to overcome the frequent difficulties of energy diagnosis in historic buildings, which are particularly evident in the discrepancy of results between mp2 and mp3. On the other side, this obstacle impedes the determination of ranges of Λ -values related to each masonry type.

Nonetheless, the analysed local contexts show similarities in the bond types, especially if the same lithotype is predominant. This suggests that gaps of specific Λ -values in one case study could be filled by measures carried out on walls of similar typologies in other local contexts, taking into consideration the different thermal conductivity measured on the corresponding stone samples. Therefore, sufficient number of laboratory and in situ tests will be collected by matching the tests performed on the same material - as well as on analogous masonry typologies - in the different case studies.

7. Conclusions and further development

This research proposes the analysis of recurrent construction features, notably the categorisation of masonry, as the methodology to populate a specific database of mechanical and hygrothermal information, aimed to support the detailed diagnosis of historic buildings. This methodology has been applied to Sicilian heritage but can be replicated to other geographical areas.

Since equipped with graphical schemes of masonry typologies, the proposed database is also suitable to the integration with an image recognition system, intended as auxiliary tool for the energy diagnosis of single buildings and for the mapping of energy performance in a historic building stock.

The preliminary results - focused on the case study of Petralia Sottana - show limits to the proposed approach but also suggest possible solutions, especially with regard to the characterisation of Λ -values for each masonry type.

The systematic population of the database for the eleven case studies will be necessary for the research development. In particular, correlation will be investigated between Λ -values and Masonry Quality Index, in order to assess the relevance of wall construction details (inspected for MQI) to the hygrothermal modelling of historic opaque envelope.

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