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# SBE21 Sustainable Built Heritage: renovating historic buildings towards a low-carbon built heritage

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# SBE21 Sustainable Built Heritage: renovating historic buildings towards a low-carbon built heritage

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## Foreword

From small medieval towns to nineteenth-century boulevards or post-modern concrete structures, buildings reflect our culture and should be preserved for our future generations. In Europe, historic buildings account for a quarter of the existing building stock. Renovating these constructions presents many opportunities for reducing carbon emissions and for improving the comfort of the people living and working inside. However, this can be particularly challenging. Each building is unique and needs specific measures to enhance energy efficiency while preserving historic and aesthetic traits. In this sector, the “one-fits-all” approach hardly applies.

From the 14th to the 16th April 2021, the SBE21 Heritage Conference brought together experts working in the fields of energy efficiency and historic building conservation. The conference aimed at fostering multidisciplinary dialogues and finding new affordable and efficient retrofit approaches to save our common heritage and guarantee a sustainable future. Scholars and practitioners worldwide were invited to send their contributions and participate in the debate.

Being the event also the final conference for three research projects at Eurac Research – IEA-SHC Task 59, Interreg Alpine Space ATLAS and HyLAB –, the conference was a great opportunity for these projects to present their findings and achievements, in 34 scientific papers and oral presentations, two workshops on *Balancing heritage preservation, local RES potential and BIPV technology exploitation* (IEA-SHC Task59 and BiPV meets History) and *Historic Buildings Retrofitting 4.0: The Potentials of Simplified Digital Twins in Low Carbon Retrofitting of Historic Buildings* (ATLAS) and organizing the “Research meets Practice day” with seven best practice presentation and a round table discussion. These best practices, along with other examples of energy retrofits of historic buildings, have been thoroughly documented for the www.hiberatlas.com database and can be accessed online. The main outputs of the roundtable were summarised by Franziska Haas, moderator of the discussion and president of the ICOMOS Scientific Committee on Energy and Sustainability, and included in these proceedings.

The conference had to be organised as a virtual event due to the constraints of the global pandemic. However the decision to organize it as “like presence” virtual conference – without recording and the risk to dilute the presence – with as many direct interactions as possible (ranging from limiting parallel sessions to two, having moderated question and answer sections, providing the pre-print of papers to the audience and offering the possibility of virtual coffee breaks to catch up with colleagues and ask directly to speakers), proved to be the right one. We had around 140 registrations, and on average two thirds actively participating in the parallel sessions. More than 30 scientific papers came from complementary projects and research groups, showed that the event was able to attract the research community working on the topic and to give a comprehensive picture of the state of the art of the research on retrofit for historic buildings.

The Sustainable Development Goals, as proposed by the UN, stood at the centre of conference topics. Actually, papers related to two to three SDGs on average: SDG 11 “Sustainable cities and communities” with 33 being the most tagged one, but also SDG 13 “Climate action” with 22 tags and SDG 7 “Affordable and Clean Energy” with 24 tags not being left behind. Furthermore, SDG 3 “Good health & well-being” (15), SDG 9 “Industry, innovation and infrastructure (10), SDG 4 “Quality education” (9) and SDG 12 “Responsible consumption and production” (8) were also mentioned often highlighting the importance of historic building renovations in social implications, the

economic dimension, the need for involving the future generations, or the common responsibility of society.

Themes of the research projects mentioned above led to the three conference's thematic tracks. Firstly, "*Conservation of heritage and resources in the built environment"* collected contributions ranging from climate resilient design solutions to integration of renewables solutions underpinning the hypotheses that conservation of our built heritage and natural resources will go hand in hand in the near future. Secondly, "*Creating favourable framework conditions"* studied the question what is needed to foster renovations of historic buildings, looking at policies and programmes, as well as education experiences and examples of best practice, that can enable a faster implementation towards a low carbon built heritage. And finally, the third track "*Development, analysis, and implementation of technical solutions"* showed that innovation in materials, products and systems will be key in achieving a low carbon built heritage.

After three days full of interesting presentations, motivational keynote lectures, informative workshops and a roundtable that included some of the key actors in the field of energy renovation of historic buildings, it is important to summarise some of the key messages that emerged from the conference.

The importance of dialogue and exchange was a recurring topic across all sessions, starting with the role of *Heritage* in achieving a sustainable built environment. As Dr Ege Yildirim pointed out during her opening keynote lecture, Heritage has been identified as a cross sectional issue in most of the Sustainable Development Goals. However, these references to heritage can only be found implicitly in the text and for those not working in the field it can be easily overlooked. This poses some interesting questions regarding the role of heritage, and more specifically the built heritage, in the European agenda. Why is it only implicitly recognised? How can it be made more explicit? The same way that the heritage significance of a post-war building might not be immediately evident, and the guidance of an expert is sometimes needed, the value and potential of heritage in achieving a better and more sustainable future for all must be highlighted. Now, we, as scholars working in the field, have the opportunity to use the results of our research to shed light on the importance of heritage in our changing climate and society so that new policies can be brought forward.

Reflecting on the significance of heritage is not only important in defining its role in the future agenda, but also in achieving a deeper understanding of what a building might represent and reasons to protect it for the future, and thus informing the adoption of the suitable interventions. Focusing only on an adaptive reuse that is strictly compatible with the elements worth of preservation might hinder potential ideas. If heritage is not seen just as a label but rather as a process, a new possibility to present heritage as a negotiated and re-negotiated cultural asset arises, as the work of Stijn Cools has shown.

The idea of a "negotiation space" has been present in several presentations, especially when it came to unveiling the narratives behind some of the best practice examples of energy renovations presented during the conference. The experiences that Prof. Harald Garrecht shared during his keynote lecture showed that establishing a dialogue around a working table that includes heritage and industry views makes possible what in the beginning of a project might look impossible. Sometimes the development of new prototypes is needed (and possible), but sometimes just giving access to a broader range of solutions might be enough to overcome a barrier that otherwise felt decisive.

The SBE21 Heritage conference brought together a community of researchers, policy makers and practitioners with different backgrounds but working towards a common goal. That is without a doubt a strength in the message we are bound to bring forward.

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The organising committee of the SBE21 Heritage conference, and we as chairs, would like to thank all participants for their involvement and especially of the keynote and roundtable speakers for their valuable contributions.

In Bolzano April 2021

Alexandra Troi
Daniel Herrera

*Conference chairs*

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

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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 $19^{th}$ 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 perpends 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 perpends, 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 ($\Lambda$-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 $\Lambda$-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 $\lambda$-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

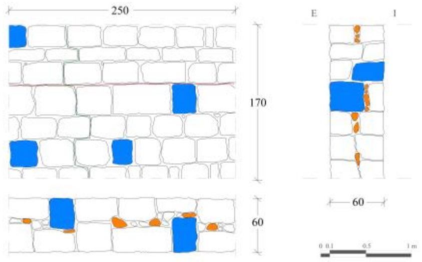
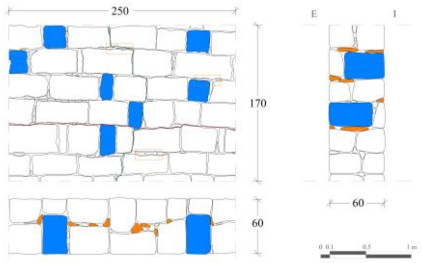
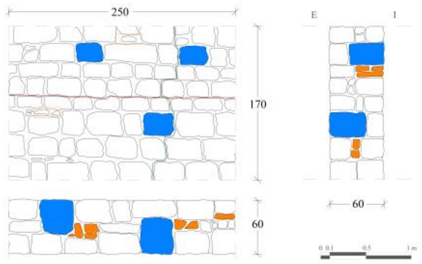
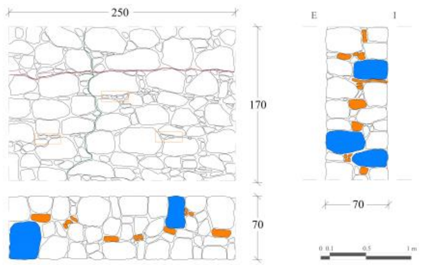
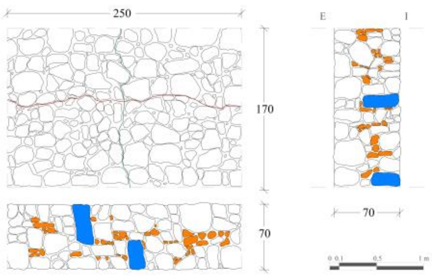
Categorisation of masonry and assessment of MQI have been carried out in all case studies. Laboratory tests of compressive strength and a first set of measurements of thermal conductivity have been conducted on the traditional stones of the analysed centres. In-situ tests of thermal transmittance have 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<br><br>Stone 90%<br>Mortar 10% |  | Vertical loading 10<br>Horiz. in-plane loading 8.5<br>Horiz. out-of-plane loading 9 |
| SM2.1<br><br>Stone 92%<br>Mortar 8% |  | Vertical loading 9<br>Horiz. in-plane loading 8.5<br>Horiz. out-of-plane loading 7.5 |
| SM2.2<br><br>Stone 88%<br>Mortar 12% |  | Vertical loading 3.5<br>Horiz. in-plane loading 3.5<br>Horiz. out-of-plane loading 3.5 |
| SM3.1<br><br>Stone 89%<br>Mortar 11% |  | Vertical loading 2.1<br>Horiz. in-plane loading 2.1<br>Horiz. out-of-plane loading 2.1 |
| SM3.2<br><br>Stone 81%<br>Mortar 19% |  | Vertical loading 1.1<br>Horiz. in-plane loading 1.4<br>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 ($kg \cdot m^{-3}$) | | | | Thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | $\rho_{specim1}$ | $\rho_{specim2}$ | $\rho_{specim3}$ | $\rho_{average}$ | $\lambda_{specim1}$ | $\lambda_{specim2}$ | $\lambda_{specim3}$ | $\lambda_{average}$ |
| 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 ($kg \cdot m^{-3}$) | | | | Cylinder compressive strength (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | $\rho_{specim1}$ | $\rho_{specim2}$ | $\rho_{specim3}$ | $\rho_{average}$ | $f_{c,specim1}$ | $f_{c,specim2}$ | $f_{c,specim3}$ | $f_{c,average}$ |
| 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.

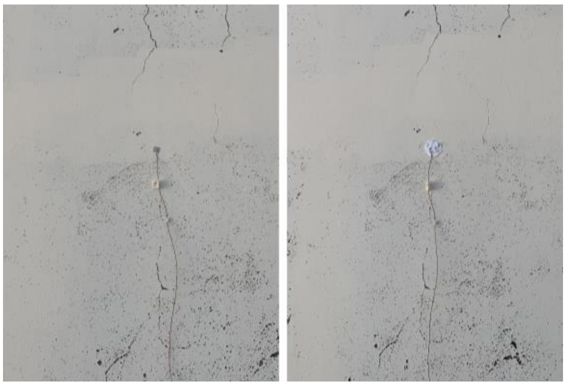


**Figure 4.** Outdoor thermocouple in mp3, before and after application of gypsum paste.

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 ($W \cdot m^{-2} \cdot K^{-1}$) |
|---|---|---|---|---|
| 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 $W \cdot m^{-1} \cdot K^{-1}$. For this rock, $\lambda$ = 2.6 $W \cdot m^{-1} \cdot K^{-1}$ is provided by EN 1745 for quartz sandstone ($\rho$ = 2600 to 2800 $kg \cdot m^{-3}$). This discrepancy is explained partially by the difference of apparent density, which was 2162 $kg \cdot m^{-3}$ 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.

## 8. References

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