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Thermal and hygrometric properties of traditional calcarenite stones in the area of Palermo

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Abstract

The energy improvement of historic buildings requires detailed knowledge of the thermal and hygrometric properties of traditional materials and components. These data should be collected for specific local contexts, where the features of historic constructions are comparable. For the purpose of developing this tool for the architectural heritage of Palermo, this research focuses on calcarenite stones, the material traditionally used in the construction of the local historic masonry, and illustrates the thermal and hygrometric characterization of three calcarenite samples, taken from two historic buildings in the Sicilian city.

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1. Introduction

Detailed literature on the material and construction features of historic buildings, both monumental and vernacular, exists for several geographic areas. However, the availability of few data on the thermal and hygrometric properties of

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traditional materials and components is generally observed [1-4]. This lack of information influences significantly the assessment of the energy performance of both historic building stocks and single constructions. Indeed, several problems impede the accurate diagnosis of historic architecture, especially the scarce homogeneity of the materials and construction techniques used, even in the same building, and the recurring conflict between conservation needs and destructive tests. Therefore, collecting data on the thermal and hygrometric characteristics of traditional materials and building components could support in the detailed energy assessment of the architectural heritage. These collections should refer evidently to local contexts, where the construction features of buildings are comparable.

From this perspective, relevant uncertainties regard masonry both in determining their actual layers and in using existing data collections. Mainly because of transformations and reinforcements, different materials and masonry techniques, generally hidden by plasters and decorations, often coexist in the same building, even in the same wall. Moreover, whereas a comparison with current materials and components is easier in the case of floors and roofs, the wide range of local stones and the variable features of historical bricks further affect the reliability of current data collections, which report a limited list of traditional masonry materials.

This paper describes the results of thermal and hygrometric laboratory tests carried out on calcarenite stones, the most common material in the construction of historic masonry in Palermo. The purpose is contributing to the development of a collection of thermophysical data for the local context of Palermo and Western Sicily, in order to support detailed energy diagnosis and compatible improvements of this architectural heritage.

2. State of the art

The historic walls of Palermo are characterised almost only by the use of calcarenites, stones widespread in the urban territory and in a significant part of Western Sicily. Owing to the large supply of this natural material, easy to be quarried and carved, bricks were limited essentially to light structures and reinforcements.

In the basin of extraction of Palermo three sectors have been distinguished for calcarenites [5]. Along the centuries, they have been exploited through several quarries, first inside the historic town, afterwards in the neighbourhood and finally in farther areas. La Duca [6] provides an extensive list of quarries and for each one he reports the average values of bulk density and compressive strength of calcarenite. For the area of Bagheria, close to Palermo and particularly rich in quarries, a detailed analysis has been carried out by Fricano [7].

The quarry calcarenite was carved from influences considerably its physical and mechanical properties. From this point of view, the traditional practice of selecting calcarenites for specific structural functions, even in the same building, is significant [6, 8]. In the second half of the 19th century, Giovanni Salemi Pace studied the physical and mechanical properties of calcarenites for the most worked quarries, by means of laboratory tests whose results were published in the last two decades of the century [9]. According to the quarry and the depth of extraction, the findings reported in 1890 show ranges of 1,214 ÷ 1,865 $kg \cdot m^{-3}$ for bulk density and 17 ÷ 117 $kg \cdot cm^{-2}$ for compressive strength.

Alaimo et al. [5] investigated the chances to identify at least the sector of extraction, if not the quarry, by means of laboratory tests. Especially for monumental constructions, the origin of the stone may be revealed by archival sources, at least for some phases of the building history. Unknown in the majority of cases, this information is valuable to assess the contribution of masonry to the energy performance of historic constructions. Indeed, the physical and mechanical properties of calcarenite stone influence the thermal ones.

Already in the end of the 19th century, the building materials commonly used in the area of Palermo were examined in their physical and hygiene characteristics. For calcarenites quarried in the main sectors of extraction, measurements provided porosity (36.66 ÷ 47.56 %), capillary saturation (12.51 ÷ 27.19 %) [10] and air permeability [11]. Heat transmission was also investigated for some calcarenite stones [12], but it was expressed through a comparison with local bricks, whose physical and mechanical properties were specified only partially. More recent systematic studies concerning the thermal and hygrometric properties of calcarenite stones have not been found. Some data are available for products currently on the market, which do not include the historical quarries, almost all fallen into disuse within the first half of the 20th century. By analogy with other geographic areas, interesting findings are reported by French studies on tuffs and limestone [13, 14] and particularly by Italian researches on Puglia's calcarenites [15]. Furthermore, the existing collections of thermophysical data for building materials (UNI 10351:2015, UNI EN ISO 10456:2008 and UNI EN 1745:2012) provide a set of data, though limited.

The Italian standard UNI 10351:2015 reports thermal conductivity values for "tuffs", volcanic rocks which calcarenites are traditionally assimilated to, because of similarities in physical and mechanical properties. This standard suggests $\lambda = 0.63$ $W \cdot m^{-1} \cdot K^{-1}$ if $\rho = 1{,}500$ $kg \cdot m^{-3}$ and $\lambda = 1.7$ $W \cdot m^{-1} \cdot K^{-1}$ if $\rho = 2{,}300$ $kg \cdot m^{-3}$. No information is provided about the water vapour permeability. Values specific to sedimentary rocks are included in UNI EN ISO 10456:2008, namely $\lambda = 0.85$ $W \cdot m^{-1} \cdot K^{-1}$ for natural light sedimentary rocks ($\rho = 1{,}500$ $kg \cdot m^{-3}$) and $\lambda = 2.3$ $W \cdot m^{-1} \cdot K^{-1}$ for natural sedimentary rocks ($\rho = 2{,}600$ $kg \cdot m^{-3}$). The water vapour resistance factor ($\mu_{dry} \div \mu_{wet}$) is 30÷20 and 250÷200 respectively. Similarly, UNI EN 1745:2012 reports $\lambda = 0.85$ $W \cdot m^{-1} \cdot K^{-1}$ for very soft limestone ($\rho \leq 1{,}590$ $kg \cdot m^{-3}$) and $\lambda = 1.1$ $W \cdot m^{-1} \cdot K^{-1}$ for soft limestone ($\rho = 1{,}600 \div 1{,}790$ $kg \cdot m^{-3}$). The water vapour resistance factor ($\mu_{dry} \div \mu_{wet}$) is 30÷20 in the first case and 45÷25 in the second. As highlighted in other geographic contexts for both bricks and natural stones [1-4], the differences in the values of thermal conductivity evidently affect the calculation of thermal transmittance. Together with the lack of hygrometric data, they contribute to even significant discrepancies with in situ measurements. Therefore, together with the limited knowledge of the hygrometric features of local masonry, these differences influence sensibly the assessment of the energy performances of historic buildings.

3. Materials and methods

This study was carried out on three calcarenite blocks (named A, B and C), coming from two historic constructions built in Palermo in the second half of the 19th century. Blocks A and B were part of a destroyed rural building located in the neighbourhood of the town, whereas block C has been taken from a residential building close to the historic centre. Archival documents useful to identify the stone quarry have not been found. The macroscopic observation of the stone transverse sections (Fig. 1) shows a substantial difference between block C, where big fossil shells cause macroscopic voids, and blocks A and B, characterised by more homogeneous texture. Each block has been cut in four parallelepiped samples (20 x 20 x 5 cm^3) by means of a wet saw. Bulk and real density, porosity and thermal conductivity have been determined for each stone. The hygrometric characterisation has been carried out on calcarenite A through measurements of water vapour transmission, hygroscopic sorption, water absorption and drying.

Fig. 1. From left to right, transverse sections of calcarenite samples A, B and C.

For each calcarenite block, two samples (20 x 20 x 5 cm^3) were measured and weighted after being dried at 105 °C. The tolerance of the measurement equipment is about ± 0,1 mm for dimensional measurements and ± 0,01 g for weight measurements. The average ratio between weight and volume was assumed as bulk density. True density was measured according to the standard DIN EN 1936, by means of a helium pycnometer (Micrometrics AccuPyc II 1340 V1.05). For each calcarenite block, the sample was made of around 5 cm^3 of fragments, obtained by crushing one of the specimens used for bulk density. Porosity was calculated as [1-(bulk density/real density)].

Thermal conductivity was measured by means of calcarenite specimens (20 x 20 x 5 cm^3) dried at 105 °C (DIN EN 12664). For each specimen, a set of three Pt100 Platine resistance thermometers (accuracy 1/3 DIN B, which means ± 0,1 K) was attached to each 20 x 20 cm^2 surface, assuring the contact by means of a thermal paste. Afterwards, the sample was interposed between two plates at different temperatures (20 °C the upper, 10 °C the lower). The consequent heat flow can be considered unidirectional in the central part of the sample. Closed in a box, the specimen was monitored until the flux became constant, between 21 and 23 hours after the beginning of the test. Since sample geometry and heat flow rate were known, thermal conductivity was determined.

The cup method described in DIN EN ISO 12572 was used to measure the water vapour transmission properties of calcarenite A. Two specimens (20 x 10 x 5 cm^3) were used. For each one the test was performed by following both the wet cup and the dry cup method: in the former the sample was sealed to a glass cup containing an aqueous saturated solution of ammonium hydrogen phosphate, in the latter to a glass cup containing silica gel as desiccant. Paraffin was used to seal the sides of each specimen in order to obtain a unidirectional vapour flow. The sealant covered the edges of the face (20 x 10 cm^2) exposed to the test chamber for around 5 mm. Paper tape was used to connect the sealed specimen to the glass cup and afterwards it was sealed with paraffin. Subsequently, the specimens were placed in a temperature and humidity controlled test chamber (T = 23 °C, R.H. = 50%). They were weighted at the beginning of the test and periodically, until the weight became constant.

The water absorption coefficient of calcarenite A was determined by partial immersion (DIN EN ISO 15148). The test was carried out at 23°C on two specimens (20 x 10 x 5 cm^3), whose sides were sealed with paraffin. The sealant covered the edges to be immersed for around 5 mm, in order to avoid the capillary transport of water through the contact area between stone and paraffin. After being sealed, the dry samples were weighted and immersed in a water tank for a depth of (5 ± 2) mm. Each specimen was weighted 1, 5, 10, 15, 20, 30, 45, 60 minutes and 2, 3, 4, 5, 6 and 24 hours after immersion. The time water spent to emerge on the upper face for each specimen was recorded.

The climatic chamber method described in DIN EN ISO 12571 was used to measure the hygroscopic sorption properties of calcarenite A. By partially crushing a 20 x 20 x 5 cm^3 dry sample, 15 specimens (10 g) were prepared and put in glass cups. Groups of three cups were placed in five climatic chambers with the same temperature (23 °C) and different relative humidity (50 %, 65 %, 80 %, 93 %, 97 %). The test ended when the weight of the specimens became stable, namely after 24 days for R.H. 50 %, 27 days for R.H. 65 %, 19 days for the remaining samples.

The drying curve of calcarenite A was determined by means of two specimens 10 x 20 x 5 cm^3. Weighted after being dried, the samples were saturated by immersion in a water tank for 23 days. Sealed through an aluminium foil with the exception of a 10 x 20 cm^2 face, the specimens were placed in a climatic chamber (T = 23°C, R.H. = 50 %) and weighted until the measurements reached a constant value, evidence that the drying process had been completed.

4. Results and discussion

Contrary to the macroscopic observation, the findings of bulk density, true density and porosity show more relevant differences between samples A and B. As reported in table 1, the former is characterised by the highest bulk density and the lowest porosity, the latter by the opposite, while intermediate values pertain to sample C.

Table 1. Results of bulk density, true density and porosity for the analysed calcarenite samples.

Sample	Bulk density [$kg \cdot m^{-3}$]	True density [$kg \cdot m^{-3}$]	Porosity [%]
A	1,627	2,724.6	40.3
B	1,479	2,705.7	45.3
C	1,558	2,712.9	42.6

The system of big capillaries typical of porous stones, such as calcarenites, causes a quick absorption of water. It is shown by the experiences of water absorption by partial immersion and the shape of the related graphs, plotting the mass difference against the square root of the weighing times (Fig. 2). Indeed, both examined samples are characterised by rapid increase in mass, and water emerged on the upper face after 5 and 15 minutes respectively. Although the lack of three measurement points lying on a straight line, the value 41,41 $kg \cdot m^{-2} \cdot h^{-0,5}$ (average of the two test results 39,90 $kg \cdot m^{-2} \cdot h^{-0,5}$ and 42,91 $kg \cdot m^{-2} \cdot h^{-0,5}$) has been assumed as water absorption coefficient by partial immersion.

The average values of water content in saturated conditions has resulted in 33 mass-%, while the drying curves are shown in Fig. 2. In terms of hygroscopic properties, the equilibrium moisture content for the five climatic conditions (T = 23°C; R.H. = 50 %, 65 %, 80 %, 93 %, 97 %) resulted in 0.84 %, 0.84 %, 1.11 %, 1.13 % and 2.11 % (volume percentages) respectively. These results are consistent with product declarations and laboratory tests regarding tuffs and light sedimentary rocks. However, a comparison with standard values is possible only for the water vapour resistance factor. For the calcarenite samples analysed in this research, it resulted in μ=9.54 and μ=9.88 with the dry-cup and the wet-cup method respectively, lower than the ranges reported by UNI EN 1745 and UNI EN ISO 10456.

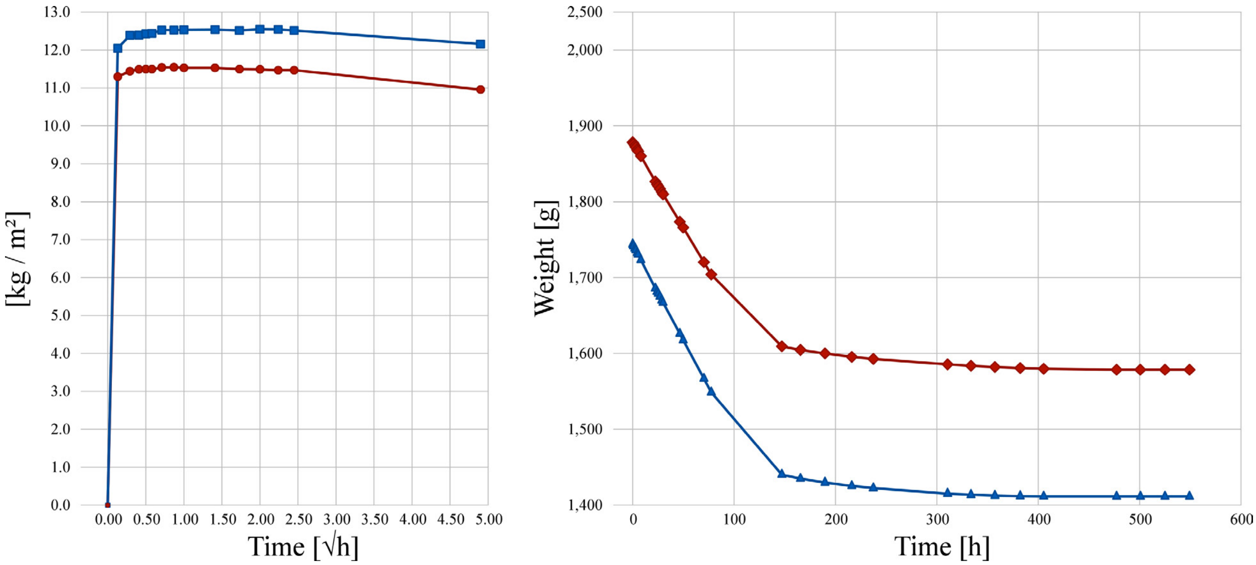

Fig. 2. Graphs of water absorption by partial immersion (on the left) and drying curves (on the right) for specimens of calcarenite A.

A more in-depth parallel is possible for the thermal properties of Palermo's calcarenite stones. As expected, λ-value increases with bulk density. In table 2 the findings of these measurements are compared with λ-values from existing collections. In detail, λ-values of "tuffs" from UNI 10351 are calculated assuming a linear variation of thermal conductivity with bulk density between the values reported by the standard. The same approach was followed for the data of "light sedimentary rocks" taken from UNI EN ISO 10456. Differently, in the case of UNI EN 1745 thermal conductivity was not calculated, since this standard provides the λ-value of "limestone" for ranges of bulk density.

The measured λ-values are in good agreement with "tuffs" from UNI 10351: the discrepancy between measured and calculated values ranges from - 8.3 % for calcarenite B to + 4.2 % for A and is negligible for C. Conversely, λ-values from UNI EN ISO 10456 and UNI EN 1745 overestimate sensibly the thermal conductivity of the analysed calcarenites stone: in the first case the difference ranges from 24.4 % to 31.4 %, in the second one from 12.7 % to 38.4 %.

Table 2. Comparison of λ-values based on measurements and calculations.

Sample	Measurements		UNI 10351:2015		UNI EN ISO 10456:2008		UNI EN 1745:2012	
	ρ [$kg \cdot m^{-3}$]	λ_{mis} [$W \cdot m^{-1} \cdot K^{-1}$]	λ_{10351} [$W \cdot m^{-1} \cdot K^{-1}$]	$(\lambda_{10351}-\lambda_{mis})/\lambda_{mis}$ [$W \cdot m^{-1} \cdot K^{-1}$]	λ_{10456} [$W \cdot m^{-1} \cdot K^{-1}$]	$(\lambda_{10456}-\lambda_{mis})/\lambda_{mis}$ [$W \cdot m^{-1} \cdot K^{-1}$]	λ_{1745} [$W \cdot m^{-1} \cdot K^{-1}$]	$(\lambda_{1745}-\lambda_{mis})/\lambda_{mis}$ [$W \cdot m^{-1} \cdot K^{-1}$]
A	1,648	0.795	0.828	+ 4.2 %	1.045	+ 31.4 %	1.1	+ 38.4 %
B	1,490	0.673	0.617	- 8.3 %	0.837	+ 24.4 %	0.85	+ 26.3 %
C	1,592	0.754	0.753	- 0.1 %	0.971	+ 28.8 %	0.85	+ 12.7 %

These results are consistent with the findings of in situ measurements of thermal conductance, carried out in a monumental building of Palermo, where stone walls date from $15^{th} \div 18^{th}$ century and at least two different calcarenites were investigated. Thermal transmittance values based on these measurements are in good agreement with those calculated through the λ-values of UNI 10351 (- 5 % ÷ + 16 %), while calculations based on UNI EN ISO 10456 tend to overestimate significantly the thermal transmittance of calcarenite stone walls (+ 10 % ÷ + 39 %) [16].

5. Conclusions

The energy performance of the historic architecture is strictly related to the local materials used. However, the existing collections of thermal and hygrometric data are referred to the generality of building materials and contain little information about the traditional ones. Therefore, developing local collections, based on laboratory and in situ measurements, would be beneficial to the knowledge of historic buildings, since it would reduce the uncertainties of energy diagnosis and the discrepancies between calculations and measurements. By focusing on the stone traditionally used for the construction of historic buildings in Palermo, the laboratory tests presented in this paper are intended as a contribution to achieve this purpose for the architectural heritage of Western Sicily. From this point of view, a larger number of calcarenite samples should be investigated in relation to the quarries most worked along the centuries. Nonetheless, the results here discussed provide useful information for the energy diagnosis and modelling of historic buildings in the analysed context.

In terms of hygrometric properties, the capillary, hygroscopic and vapour transmission behaviour of a calcarenite stone has been investigated. However, the possibility to compare the results with existing data is limited by the scarceness of the latter for the analysed stones. Conversely, the results regarding the thermal properties of Palermo's calcarenites show even significant discrepancies with data reported in existing collections. Supported by similar findings obtained by in situ measurements of thermal conductance, the thermal conductivity values here exposed prove to be consistent with those the Italian standard UNI 10351 assigns to "tuffs" (- 8.3 % ÷ + 4.2 %), volcanic rocks which calcarenite is traditionally assimilated to. On the contrary, λ-values reported by ISO 10456 for light sedimentary rocks, which calcarenites belong to, overestimate thermal conductivity in comparison with the laboratory findings discussed in this paper (+ 24.4 % ÷ + 31.4 %). In conclusion, local collections of thermal and hygrometric properties for traditional materials have not to be intended as a simplification. Indeed, the detailed energy diagnosis of each building remains necessary to the study of energy improvements, which must be compatible with the conservation of the cultural value of historic architecture. From this point of view, detailed collections would work as a rigorous support to assess the reliability of current data and to control and complete the results of measurements carried out on single constructions.

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