Congreso Internacional

EFICIENCIA ENERGÉTICA Y EDIFICACIÓN HISTÓRICA

International Conference

ENERGY EFFICIENCY IN HISTORIC BUILDINGS

MADRID
29-30 | 09 | 2014

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Financiado por la Fundación Española para la Ciencia y la Tecnología - Ministerio de Economía y Competitividad

LÓPEZ, M.; YÁÑEZ, A.; GOMES DA COSTA, S.; AVELLÀ, L., (Coord.). ***Actas del Congreso Internacional de Eficiencia Energética y Edificación Histórica / Proceedings of the International Conference on Energy Efficiency and Historic Buildings (Madrid, 29-30 Sep. 2014)***. Madrid: Fundación de Casas Históricas y Singulares y Fundación Ars Civilis, 2014. ISBN: 978-84-617-3440-5

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THE THERMOPHYSICAL CHARACTERIZATION OF TECHNICAL ELEMENTS IN THE HISTORIC ARCHITECTURE: EXPERIENCES IN PALERMO

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ABSTRACT

The improvement of energy and environmental performances in historic buildings has to be achieved respecting their aesthetic, material and construction features. This requires an in-depth knowledge of the thermophysical properties of their materials and technical elements. Nonetheless, several difficulties are related to the availability of few data and to the inhomogeneities typical of historic constructions. This paper focuses on the evaluation of thermal transmittance of historic stone walls in Palermo. As the scientific literature shows, the discrepancy between U-value calculations and measurements can be relevant and the first generally overcome the latter. Therefore, the objectives and methods of a plan of in situ measurements of thermal conductance are presented. It is being carried out on the stone walls of a monumental complex in Palermo. The U-values derived from these measurements are compared to those calculated according to the international standard ISO 6946:2007, for which different thermal conductivity values can be used for stones and mortars. The preliminary findings of this research concern walls made from one of the calcarenites used in the building. Depending on the conductivity value used for stone, they show an overestimation of the measured wall transmittances or a good agreement with them. Notably, the second is reached by U-value calculations referring to the thermal conductivity 0,63 W/(mK), provided for "tufo" (volumetric mass density ρ*=1500 kg/m*^{3}*) by the Italian standard UNI 10351:1994. However, the range of physical properties of calcarenites and the variety of construction features of stone walls in the analysed building highlight the need of further investigation.*

Key words: thermophysical properties, thermal transmittance, historic architecture, energy improvement, stone walls

1. INTRODUCTION

Historic architecture is a relevant part of the European building stock. Therefore, the attention to resource consumption and environmental impact in its restoration and management can contribute significantly to the achievement of the EU sustainability targets: buildings are considered responsible for about 40% of total final energy requirements in Europe (BPIE, 2011) and for 36% of GHG emissions in the atmosphere. The great part of the member Countries has maintained for protected buildings the exemption from minimum energy performance requirements, as set in the directive 2010/31/EU and maintained in the 2012/27/EU. However, it does not concern a relevant part of historic minor architecture. Hence, the latter could be subject to energy refurbishments not respectful to the conservation of their aesthetic and material characters. On the other side, the mentioned exemption makes it possible to improve the energy and environmental performances of historic buildings as far as the predominant need of conservation is respected, following an approach already used for structural strengthening and accessibility. For this purpose, the local dimension of historic architecture has to be considered. Therefore, its materials and construction techniques should be analysed in the light of their thermophysical properties. At the same time, methods and simulation models should be developed in order to represent the peculiarities of each building. Hence, the importance of enriching the knowledge of historic constructions through surveys focused on its energy performance is evident. Technical standards, moreover, require several data to determine the energy demand of buildings for heating and cooling. Nevertheless, in the historic ones the heterogeneity of materials and technical elements adds to the availability of few thermophysical data. This problem is relevant for historic masonry, whose detailed characterization often needs destructive surveys, not always possible. Notably, a necessary parameter to describe the envelope performance is the thermal transmittance of its components: this paper focuses on its evaluation in the case of historic solid walls, referring to the architectural heritage of Palermo.

2. THERMAL TRANSMITTANCE OF HISTORIC MASONRY

The thermal transmittance of technical elements can be calculated according to the method provided by the standard EN ISO 6946:2007. For this purpose, it is possible to refer to product declarations, where thermophysical data such as thermal conductivity are reported, or to tabulated values collected in technical standards. Nevertheless, scientific literature shows for historic walls even significant discrepancies between U-value calculations and the results of the measurement method described in ISO 9869:1994. Following this procedure, Baker (2011) has determined the thermal transmittance of 57 cases of historic walls in Scotland, the most part made from stone. The comparison with calculated values has shown that the latter generally underestimate the performance of historic walls. Furthermore, Baker underlines the relation between the calculation deficiencies and the lack of knowledge of the wall build-up and the thermal properties of traditional materials. Thermal transmittances of historic walls have been measured in England by Rye et al. (2012), referring to a wider variety of construction features. In Italy, measurements has been carried out on brick, stone and mixed walls by Adhikari et al. (2012). Also these researches show that calculated U-values tend to overestimate the results of *in situ* measurements. As Adhikari et al. highlight, further uncertainties are related to the different values of thermal conductivity sometimes attributed to the same material in the available data collections. As a matter of fact, Baker (2013) underlines that the agreement between calculated U-values and measured ones can be higher if thermal conductivity values are known: thus the unreliability of calculations is significantly related to the low quality of input data. Therefore, in addition to *in situ* measurements of thermal transmittance carried out on historic brick walls in England, thermal conductivity laboratory tests have been taken of samples from three historic bricks with different physical properties (Baker, 2013).

The Italian standard UNI/TS 11300-1:2008, referring to UNI EN ISO 13790:2008, describes the evaluation of energy need for space heating and cooling. For existing buildings it allows a simplified evaluation of thermal transmittance of opaque elements, if a more rigorous calculation is not possible. Hence, U-values are provided for five masonry typologies, which refer to wall thicknesses up to 60 cm. Notably, “plastered stone walls” and “brick walls plastered on both sides” are suitable for historic buildings. The use of values reported for “walls made from semisolid bricks or tuff blocks” seems to be forced. However, traditional walls are often thicker than 60 cm even in minor architecture. Furthermore, in the first of the mentioned typologies the wide variety of stones used in Italian historic constructions is not considered. This standard also provides a list of masonry structures containing information about wall stratigraphies and materials for common technical solutions, which is currently being updated. Thermophysical data concerning construction materials, necessary to thermal transmittance calculations according to EN ISO 6946:2007, are provided by specific technical standards. Notably, UNI 10351:1994 collects thermal conductivity values for several stones, mortars and plasters, for the latter also providing vapour permeability. These data are the basis for the standard UNI 10355:1994, reporting thermal resistances for walls and floors: for the first, the values referring to brickworks are suitable for historic buildings, but up to 425 mm; for the latter, on the contrary, only modern technologies are considered. More recent data collections are provided by UNI EN ISO 10456:2008 and UNI EN 1745:2012. They deals respectively with the hygrothermal characteristics of building materials and with the thermal properties of masonry and masonry products.

3. THE HISTORIC STONE WALLS IN PALERMO

The historic solid walls of Palermo are built from shell calcarenite, a sedimentary rock of marine origin, widespread in the town territory and in the neighbouring coastal areas. The use of bricks, on the contrary, was essentially limited to structural repair. The historical calcarenite quarries were numerous, the most ancient inside the town itself (La Duca, 1964). It follows that the physical and mechanical properties of these stones vary significantly. Their first characterization dates at the second half of the XIX century (Fatta, 1993): it was demonstrated that the volumetric mass density of the calcarenites used in Palermo ranged from about 1400 to 1850 kg/m^3, their compressive strength between 3 and 10 N/mm^2. The variety of wall construction features (Campisi et al., 2003), the composition of mortars, but also continuous building transformations have characterized for centuries the historic architecture in Palermo. They add to the widespread, traditional use of plaster, which often hides inhomogeneities related to masonry works.

The first thermophysical characterization of historic building materials in Palermo was carried out in the end of the XIX century. As in other Italian towns and abroad, the hygienic features of the most common construction materials, among which calcarenites, where analysed (De Blasi et al.). Notably, porosity, water absorption and air permeability were determined. For three types of calcarenite the heat transmission, to which the indoor thermal comfort of buildings was mainly related, was examined. The results were expressed in comparison to a local brick, to which unitary value was attributed. The tests showed that, depending on the calcarenite, the difference in heat transmission ranged from about 14% more to 16% less than those of bricks. Furthermore, a test on a plastered specimen highlighted an increasing in the examined property. We have not found recent studies and tests concerning the thermal conductivity of Palermo's calcarenites. This is due to the quarry exhaustion started in the XIX and continued in the following one, when calcarenites from other Sicilian areas spred. The deficiency of data is probably related also to the common practice of identifying the calcarenites as tuffs, denomination peculiar to volcanic rocks with similar physical and mechanical properties. In the technical standard UNI 10351:1994, two thermal conductivity values are provided for "tufo": λ=0.63 W/(mK) and λ=1.7 W/(mK) referring to stone densities ρ=1500 kg/m^3 and ρ=2300 kg/m^3 respectively. For intermediate values linear interpolation can be used. On the other side, the standard UNI EN 10456:2008 attributes λ=0.85 W/(mK) to "natural, light, sedimentary rocks" (1500 kg/m^3) and to "extra soft limestones" (1600 kg/m^3), λ=1.1 W/(mK) to "soft" (1800 kg/m^3) and λ=1.4 W/(mK) to "semi-hard" (1800 kg/m^3) limestones. Similar values for these stones are collected in UNI EN 1745:2012. Therefore, also for calcarenites, the choice of input data can influence significantly the U-value calculation, given the lack of experimental values of thermal conductivity. This uncertainty involves also mortars and plasters. The mentioned list of wall structures refers to "lime and gypsum plaster" (UNI 10351:1994, ρ=1400 kg/m^3, λ=0.7 W/mK) and "mortar of lime or lime and cement" (same standard, ρ=1800 kg/m^3, λ=0.9 W/mK) for internal and external plasters respectively. On the other side, λ-value 0,80 W/(mK) is reported by EN ISO 10456:2008 for a 1600 kg/m^3 lime mortar and UNI EN 1745:2012 attributes 0,66 W/(mK) to a generic mortar of the same density.Although the importance of thermal transmittance to determine the energy performance of building envelope, also other parameters are necessary, such as periodic thermal transmittance, phase shift and attenuation factor, notably to describe the building dynamic behaviour and evaluate the indoor comfort performance of buildings. Recently a laboratory procedure has been proposed to determine the periodic thermal transmittance of technical elements (Arenghi et al. in Galbusera et al., 2010).

4. *IN SITU* MEASUREMENTS OF THERMAL CONDUCTANCE OF HISTORIC WALLS IN A MONUMENTAL COMPLEX IN PALERMO: OBJECTIVES AND METHODS

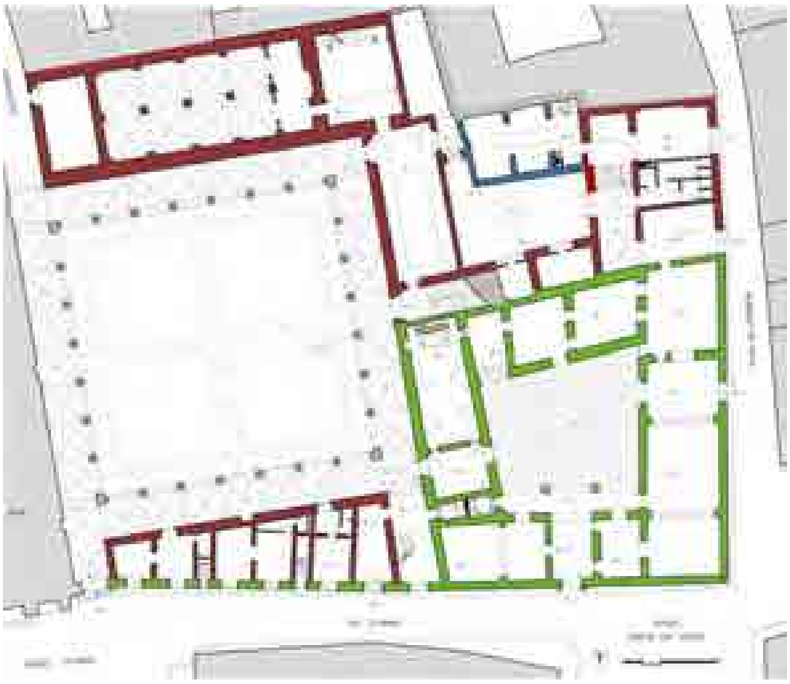

Image 1: Ground floor of the Saint Anne Convent in Palermo. In green: XV-XVI century stone walls. The calcarenites came from intra moenia quarries. In red: XVII-XVIII century structures, where calcarenites from extra moenia urban quarries was used. In blue: mid XIX century masonry, made of calcarenites from coastal areas (Aspra). (On the basis of the project plan: De Angelis Ricciotti, D., Li Castri, M., & Martelli, T., "Progetto di completamento")

In situ measurements of thermal conductance are being carried out on the historic stone walls of an ex convent in Palermo, seat of the town Gallery of Modern Art. Archival researches (Li Castri, 1999), but also the documents concerning the restoration project and works concluded in the last decade, are available for this building. They provide important information about the material and construction features of the analysed walls. The oldest part of the complex is the residence built by the Catalan merchant Gaspare Bonet between the end of the XV and the beginning of the XVI century. In 1618, the Franciscan friars bought the building and its garden. In its turning into a convent, a new storey was added and the indoor spaces radically changed. Furthermore, a monumental cloister, completed in 1648, substituted the garden and was connected to the existing construction through a great staircase. After a new raising in the southern side of the cloister in 1771, significant structural and distribution transformations started in the second half of the XIX century. Aimed at converting the building to public functions, they continued during the following century. Built on alluvial soil, the convent has been seriously damaged by earthquakes: the available archival documents (Li Castri, 1999) provide information about damages and repairs caused by seismic events in 1726, 1751, 1823. The complexity of this architecture, result of centuries of building activities, allows to investigate a significant variety of stone walls: the mentioned restoration documents show the presence of different types of masonry but also the use of calcarenites from at least three different quarries. Moreover, the several structural repairs, carried out in historical period and recently, induce to check the variability of measurement results in different points of the same wall (image 1).

For the *in situ* measurements of thermal conductance, a data logger Ahlborn Almemo 2690-8 is used. A heat flowmeter FQA 119 (250x250x1,5 mm with substrate in epoxy resin), and four thermocouples (Cu-CuNi) to measure the external and internal wall surface temperatures, are wired up to the logger, where data are recorded every 180 seconds. To avoid damaging surface finishings, the sensors are fixed by means of a paper adhesive tape. Its colour, moreover, is similar to that of masonry surfaces. Measurement points are chosen on the base of thermographic inspections, aimed at locating possible, hidden inhomogeneities. It is checked that surface temperature variation does not exceed 2°C in about 60 cm around the analysed points. The heat flowmeter is mounted on the internal surface of the wall, in a location intermediate between openings and corners, floor and ceiling. Temperature sensors are used, one or in couples, both indoor and outdoor. Following the standard ISO 9869:1994, North-facing façades are preferred to reduce the uncertainties related to solar radiation. Otherwise, one of the two external sensors is protected by means of a small shield, made of paper adhesive tape (images 2 and 3). In this way, in some of the tests conducted during summer 2014 (June-September) the difference of external surface temperature between the two sensors has been negligible except for the hours of exposition to solar radiation, when it reached 3 °C.

According to ISO 9869:1994, for heavy elements the analysis has to be carried out over an integer multiple of 24 hours and at least for 72. In Adhikari et al. (2012) measurements last 100-120 hours for masonry from 100 up to 160 cm thick. Baker (2011) underlines the necessity to monitor historic walls for about two weeks or, preferably, for a longer time. In the examined case in Palermo, during winter the average difference between internal and external surface temperatures ranged from 4,0°C to 7,5°C and measurements have lasted 14 days (for walls 56 and 59 cm thick) or 21 days (for measurement point 4 and for walls 96 cm thick). On the opposite during summer, the fluctuations of external temperature are more relevant during the day, but the average difference between internal and external surface temperatures is generally higher. In these measurements, taken of walls around 60 cm thick, the conditions required by the average method have been achieved after a monitoring period of 10 to 12 days.

The mentioned average method, described in ISO 9869, is used to analysed the measured data and determine thermal conductance. From the latter, U-values are derived (table 1) through the conventional resistances provided by UNI EN ISO 6946:2008 (0.04 m^2K/W outdoor and 0.13 m^2K/W indoor in the case of horizontal heat flow). Furthermore, these thermal transmittances are compared with those calculated according to the standard EN ISO 6946 itself. Three hypothetical contents of mortar are supposed for the walls: 10%, 30% and 40%. For calcarenite, two conductivities are considered: 0.63 W/(mK) ("tufo", ρ=1500 kg/m^3, UNI 10351:1994) and 0.85 W/(mK) ("natural, light, sedimentary rock", ρ=1400 kg/m^3, UNI EN ISO 10456:2008). Thermal transmittances of walls are also calculated referring to a masonry conductivity. This is determined, by means of the mentioned λ-values chosen for materials (considered as design values), following the method described in UNI EN 1745:2012 (7.1). The differences in results (table 2) are slight if λ = 0.63 W/(mK) is used, negligible with λ = 0.85 W/(mK). The influence of moisture and voids is not considered: notably, the first hypothesis is supported by the thermographic surveys. The conductivity values used for mortars and plasters are those referred to in the list of masonry structures: "lime and gypsum plaster" (ρ=1400 kg/m^3, λ=0.70 W/mK) for internal plaster, "mortar of lime or lime and cement" (ρ=1800 kg/m^3, λ=0.90 W/mK) for mortar and external rendering.

Images 2, 3: Point of measurement. Measurements taken in summer 2014 of a wall in the ancient Bonet residence. The upper level of the tower is air-conditioned, although not used now for exhibitions

5. PRELIMINARY FINDINGS

Measurements have been taken both in the museum offices and in the exhibition area. The latter occupies the oldest part of the building, whose stone walls are plastered only on the internal side and were built using blocks of grey, fine-grained calcarenite extracted from urban quarries. In these walls, the use of finely cut stones is limited to decorations and quoins. The rest is made of two halves connected by no more than two bonding stones for each square metre of surface: between them, small pieces of calcarenite are bound by a mortar of lime added with pozzolana. Because of the significant percentage of voids and the low mechanical performance of masonry, injections of a mortar of lime-pozzolana were carried out during the restoration. Because of the climatic conditions in the exhibition area, measurements have been taken also during summer (June-September 2014). The values of thermal conductance and transmittance will be compared with those of measurements repeated at the same points during winter. The preliminary findings (Genova et al., 2014) concern the nine measurements conducted during winter 2013-2014 in the office spaces: the southern façade of the cloister, which faces the North, has been examined. The continuous heating of indoor spaces has resulted in the stability of internal temperature, but the average difference between this and the external one ranged from 4,0°C to 7,5°C. The analysed wall is made of squared blocks of calcarenite from extra-urban quarries and is plastered on both sides. In its three levels, thicknesses are 96 cm, 56 cm and 59 cm: two, four and three measurements have been taken respectively. The indoor plaster, substituted during the restoration, is a 2 cm thick render based on lime and its finishing is a stucco (2mm) at the two upper levels, a smooth at the ground floor. The thickness of the external plaster ranges from 3 to 4 cm, but on the upper level it has been increased up to 7 cm during the restoration.

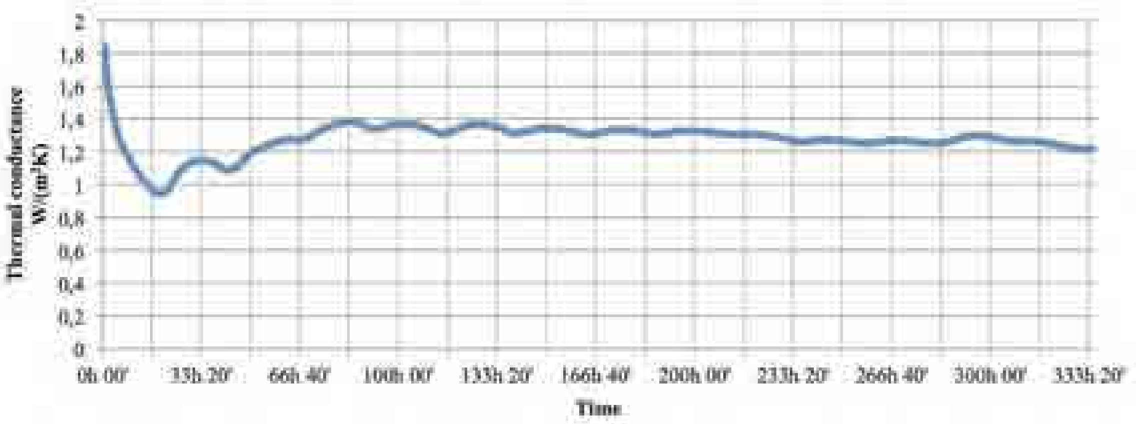

Image 4: Measurement point 6

Table 1: Preliminary results of the *in situ* measurement

Measurement point	**Wall thickness** cm	**$T_{int, av}$** °C	**$T_{ext, av}$** °C	**ΔT_{av}** °C	**Thermal conductance** $W/(m^2K)$	**Thermal transmittance** $W/(m^2K)$
1	96	20.5	15.6	4.5	0.62	0.56
2	96	20.5	15.4	4.4	0.71	0.63
3	56	21.0	14.0	4.8	1.31	1.07
4	56	20.6	14.0	6.1	1.14	0.95
5	56	20.0	14.1	5.9	1.26	1.04
6	56	20.0	14.1	5.9	1.21	1.01
7	59	19.6	12.1	7.5	1.25	1.03
8	59	19.4	14.5	4.0	1.30	1.06
9	59	19.2	14.8	4.2	1.28	1.05

Table 2: Calculated values of thermal transmittance for the three walls analysed

Plaster/ Masonry/ Plaster cm	**Calculated thermal transmittance** $W/(m^2K)$								
	Stone 90% Mortar 10%			Stone 70% Mortar 30%			Stone 60% Mortar 40%		
	"Tufo" ρ=1500 kg/m³		"Natural, light, sedimentary rock"	"Tufo" ρ=1500 kg/m³		"Natural, light, sedimentary rock"	"Tufo" ρ=1500 kg/m³		"Natural, light, sedimentary rock"
		UNI EN 1745			UNI EN 1745			UNI EN 1745	
4/90/2	0.614	0.620	0.772	0.648	0.663	0.779	0.667	0.684	0.783
4/50/2	0.987	0.996	1.208	1.036	1.057	1.218	1.062	1.086	1.223
7/50/2	0.956	0.964	1.161	1.001	1.021	1.170	1.026	1.048	1.175

Although the limited number of tests, the results of thermal conductance and transmittance (tables 1 and 2) are quite homogeneous when referring to the same wall thickness: according to ISO 9869:1994, the total uncertainty can be expected to range from 14% to 28%. For each wall thickness, the average of the three U-values, calculated varying the supposed content of mortar, is compared to the results of measurements (table 3). Notably, the agreement is good if thermal conductivity λ=0.63 W/mK ("tufo", ρ=1500 kg/m³, UNI 10351:1994) is used. On the other side, by referring to "natural, light, sedimentary rock" (λ=0.85 W/mK, ρ=1500 kg/m³, UNI 10456:2008) thermal transmittance is overestimated between 10% and 39% (table 3 and image 5). The slight difference between the thermal conductivities used for calcarenite and mortar, moreover, seems to limit the influence of mortar content and therefore that of the wall construction features. Nevertheless, the different physical properties of calcarenites and the several materials traditionally used together with them in masonry construction, must be taken into account.

Table 3: Percentage variation between U-values calculated and based on measurements

Measurement point	**Wall thickness** cm	**$\Delta U_{tufo\text{-}meas}$**	**$\Delta U_{tufo\text{-}meas}$** (UNI EN 1745)	**$\Delta U_{sedim\text{-}meas}$**
1	96	+14.8%	+17.1%	+38.9%
2	96	+2.1%	+4.1%	+23.5%
3	56	-3.9%	-2.2%	+13.7%
4	56	+8.2%	+10.1%	+28.0%
5	56	-1.1%	+0.6%	+17.0%
6	56	+1.8%	+3.6%	+20.4%
7	59	-3.5%	-1.8%	+13.5%
8	59	-6.2%	-4.6%	+10.2%
9	59	-5.3%	-3.7%	+11.3%

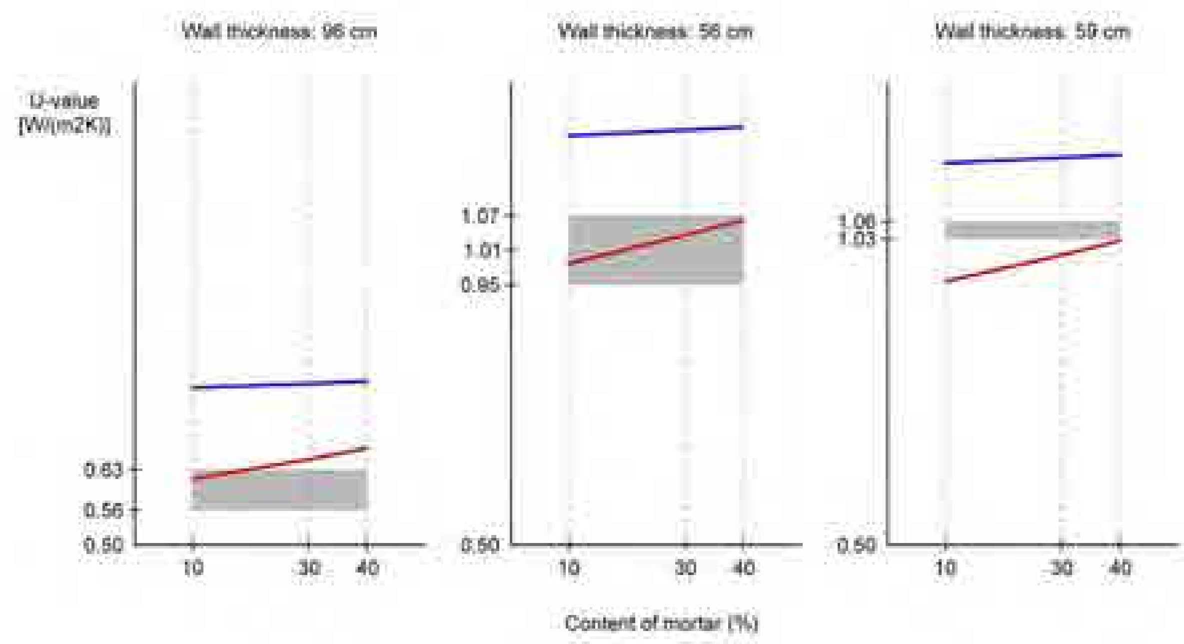

Image 5: Preliminary findings; comparison between measured and calculated values. The grey bands show the range of U-values derived from measurements referring to the same wall thickness. The red lines show the U-values calculated through the thermal conductivity of "tufo" (ρ=1500 kg/m^3, λ=0.63 W/(mK), UNI 10351:1994), while the blue lines represent those related to "natural, light, sedimentary rock" (ρ=1500 kg/m^3, λ=0.85 W/(mK), UNI 10456:2008)

6. CONCLUSIONS

The conservation of the aesthetic, material and construction characters of historic architecture is based on the knowledge of its features and on the peculiarities of each building. In order to improve its energy performance, surveys now essentially used for modern constructions have to be carried out. At the same time, the thermophysical characteristics of materials and technical elements in specific local contexts must be examined: current available data are few and thus several uncertainties influence the calculation of the parameters which describe the envelope performance. In this way, operational directions could be identified, useful both to evaluations on a large scale and to the building restoration. Hence, the objectives and method of a program of *in situ* measurements of thermal conductance in a monumental complex in Palermo have been presented. The preliminary findings concern the nine measurements taken of the walls of a North-facing façade. For each of the three thicknesses examined, they are quite homogeneous according to the range of uncertainty stated in the standard ISO 9869:1994. These results show for the analysed stone walls a good agreement between U-values derived from measurements and those calculations where the thermal conductivity used for stone is 0,63 W/(mK). This value is provided by UNI 10351:1994 for "tufo" (ρ=1500 kg/m^3). Nonetheless, measurement results are strictly related to the construction features of masonry and to the physical properties of calcarenites, which vary according to their origin. Therefore, further tests and in-depth examinations are necessary.

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