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Thermal transmittance of historical stone masonries: A comparison among standard, calculated and measured data

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ABSTRACT

The paper presents the results of an on-site campaign on several historic stone masonries, characterized by different heritage values, historical ages and intended use. Experimental data has been compared with the standard procedures normally used in the Italian legislation framework for assessing the thermal performance of existing masonries. Normally, the standard procedures tend to overestimate their thermal performance for security reasons. Similarly, wrong estimations or excessive simplifications have serious impact on the thermal assessment. For this reason, the paper presents an interdisciplinary assessment methodology for the thermal performance evaluation of the traditional stone walls located in Lombardy Region. The most important challenges are related to the correct definition of the wall morphology and thickness, the thermal properties of stone and the material proportions. The study shows a correspondence between the geology of the territory, the historical ages, the thermal performances and the heritage values of stone masonries. Furthermore, the proportion of materials, as well as the presence of internal air affect greatly the thermal performances.

1. Introduction

The building envelope is the principal responsible for the energy losses through the building. Its amount in existing buildings is commonly quoted in the range from 10% to 45% [74], related to climatic conditions, wall surface area, degree of material degradation and construction technologies. The accurate identification of the thermal performance of a building component is a key requirement for ensuring an appropriate energy assessment [65,66]. Two parameters described this performance: the thermal transmittance (U-value) and the thermal resistance (R-value) that respectively outline the thermal insulation and the thermal resistance of the building element. It depends on: (1) global layout; (2) stratigraphy; (3) characteristics of each material; (4) presence of internal moisture; (5) variation of the climatic parameters; (6) presence of damage and conservative problems; and (7) application techniques. Its evaluation is challenging particularly for historic masonries, where a range of hypotheses is possible for assessing different wall thicknesses, thermal conductivities (λ-value), moisture contents, surface heat transfer coefficients, presence of mixed materials and air cavities. Wrong estimations, simplifications and overcomes can have several consequences on the overall energy balance of the building, producing on overestimation of the energy consumption [1,25,64–66]. Misguided assessments affect also the energy retrofit, promoting substitution or energy improvement of components [1,15,64] without any real benefits for energy-savings and sustainability. The problem is more serious for inhomogeneous masonries, as stone and mixed walls, where the gap in knowledge is related to the identification of the following elements [25,48,52]: (1) traditional morphologies (stratigraphy, layers composition, mortar proportion, . . .); (2) inhomogeneity or geometric discontinuities (thickness variability, air cavities, cracks, materials decay, . . .); (3) physical properties of the materials used along the time (composition, density, thermal performances, . . .); (4) ageing and damage problems; and (5) moisture contents. Furthermore, traditional materials (particularly the range of available λ-value of stones) are hardly represented in available tools, standards and databases [1,65]. These approximations and simplifications cause an overestimation of the real R-value of a historic masonry of (10 ÷ 30%) compared to the *in situ* measurements in 50 ÷ 77% of cases [1,15,34,52,65]. On the contrary, the use of accurate data inputs can improve the agreement with the on-site results [1,64].

To overcome this problem, the thermo-physical characterization of traditional masonries is worthy of continuous research efforts. A detailed review on the methodologies for assessing the thermal performance of historic walls is reported in a previous

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Nomenclature

Nomenclature and abbreviations

R	Thermal resistance (or R-value) (m^2K/W)
U	Thermal transmittance (or U-value) (W/m^2K)
U_t	Tabulated U-value (W/m^2K)
U_a	U-value from abacus of masonry structure (W/m^2K)
U_c	Calculated U-value (W/m^2K)
U_m	Measured U-value (W/m^2K)
C	Thermal conductance (or C-value) (W/m^2K)
λ	Thermal conductivity (or λ-value) (W/mK)
C_p	Specific heat (MJ/m^3K)
α	Thermal diffusivity (mm^2/s)
ρ	Density (kg/m^3)
ε	Emissivity
Φ	Heat flow rate in steady-state conditions (W)
q	Density of heat flow rate (W/m^2)
A	Area (m^2)
T_s	Surface temperature (K or °C)
T_e	Environmental (ambient) temperature (K or °C)
ΔT	Temperature difference (K or °C)
d	Wall thickness (m)
n	Number of hours – monitoring period (h)
MC	Water content (%)
m_W	Water mass (%)
m_O	Weight of dray sample (g)

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j	Individual measurements
m	Total measurements
e	Exterior
i	Interior

paper on brick masonries [55]. Here, the literature review focuses only the on the on-site campaigns of historic masonries. Extensive studies attempted to measure the *in situ* U-values of historic walls in order to study the potential impact of the insulation materials for improving their thermal performance [13,14,19,35,65]. The surveys focused on stone [13,14,65] and brick [19,35] masonries, respectively in Scotland and England. The practice in these countries can give some guidance for the present study. They defined specific procedures for thick solid walls based on the increasing of the standard monitoring period to allow the impact of the thermal mass, the surface temperature and the heat flow fluctuations. They demonstrated that the thermal properties of materials are constant over the range of temperature fluctuations; and the changes of the internal energy are negligible if compared to the amount of heat going through the element. Thus, historical masonries are considered sufficiently homogeneous for using the heat flux meter (HFM) measurements and for applying the standardized surface heat-transfer coefficients [14,19,35,65]. In general, they found measured U-values significantly lower than the standard ones, evidencing the implications of these discrepancies in energy audit and modelling. The problem is more serious for stone masonries. Particularly, Rye and Scott [65] noted that the calculation for traditional stone walls is particularly problematic for the following reasons: (1) lack of knowledge of vernacular materials and construction methods; (2) absence of data on traditional features and potential ambiguity of historic stone walls in the standard procedures; (3) paucity of λ-values data for individual stone types; (4) greater geological diversity of rocks; and (5) use of default assumption. In order to better model the wall build-ups, the following information are required [14,19]: (1) thickness of layers, (2) status of cavities; (3) ratio and types of stone and mortar; and (4) thermal properties of materials used in traditional construction. In addition, Baker [14] established that further research should be carried out to establish a better understanding of the thermal properties of traditional building materials and construction components. Particularly, the standard databases should include more data on the traditional solid stonewalls to allow easier and user-friendly modelling of traditional buildings. Finally, a standardized methodology for the *in situ* measurements of the U-values should be established to ensure that future measurement results are comparable [14]. Mainly due to the extreme complexity of historic stone masonries, the comparison among standard assessment methodologies and databases on thermal performances of traditional masonries lacks. On the contrary, the literature provides several criteria and operative procedures that can be used for the definition of a specific evaluation method for this type of masonries.

2. Research aims

The paper presents a comparative analysis of different standard procedures normally used in Italy for assessing the thermo-physical properties of traditional stone masonries. This research carries on the work on brick masonries, following a similar approach [55] and suggesting specific techniques for stone characterization. The standard procedures defined by the Italian legislation framework [70] ("tabulated design method", "abacus of masonry structures" and "analytical calculation") has been compared with the experimental data collected during an on-site campaign on ten historic buildings in Lombardy Region (30 survey points). These buildings are characterized by different heritage values, ages and intended use to have a wide range of masonries. On purpose, we compared masonries with similar wall morphologies (rubble stone masonries) and types of rock (sedimentary rock), to verify the match between historical ages, heritage values, thicknesses and material percentages. Similarly, we excluded the masonries with damage and moisture problems in order to avoid their influence on the thermal performance. This work permits to: (1) compare different standard procedures for assessing the energy performance of historic stone masonries; (2) characterize better the traditional stone masonries in the northern Italy, (3) enhance the knowledge on traditional materials and construction methods; (4) define a procedure that consider traditional features and potential ambiguity of historic stone walls; and (5) enlarge the existing databases on Italian constructive technologies. The research neither means to be exhaustive or definitive, but simply aims to serve as a guidance for energy auditors and simulators that require simplified data and clear procedures to operate.

3. Research methodology

The research methodology is based on the following steps:

- Selection of traditional stone masonries;
- Masonry characterization using an interdisciplinary assessment method based on preliminary historical researches, geometrical reliefs, visual inspections (VI), infrared thermography (IRT) surveys and gravimetric tests [54,56];
- Thermal performance evaluation of walls, using different procedures suggested by the Italian legislation framework;
- Comparison among the results;
- Final performances assessment.

This methodology has been illustrated below (Fig. 1).