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Experimental measurement of thermal transmittance in reinforced concrete buildings

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***Abstract*— To reduce the incidence of greenhouse gas emissions, radical measures need to be adopted in the most pollutant sectors, among which the building one, where actions can be undertaken, involving both the passive (envelope) and the active (thermal plants) sections.**

In this framework, the aim of this paper was to elaborate and test a suitable procedure to measure one of the characteristic parameters of the envelope, the thermal transmittance of the opaque components. A codified procedure has been exploited, using instruments and experimental techniques able to overcome most of the drawbacks (e.g. long period of measurement) which often have to be dealt with, during field measurement of thermal transmittance of opaque building envelope structures.

The technique was exploited to measure wall thermal transmittance of different buildings located in the city of Reggio Calabria (Italy),

Keywords— NZEB, thermal transmittance measurement, Hotbox method, building envelope, building typology

I. Introduction

Nowadays, the effects of climate changes are unmistakable and strong measures need to be adopted to face their potential catastrophic consequences. According to the International Energy Agency [IEA, 1], CO_2 emissions have reached more than 32.600 Mt, especially due to the use of fossil fuels. More than 40% of these emissions are caused by energy generation processes, linked to the industrial or residential sectors, and to services and transports. At global scale, the industrial sector is the one which requires more energy, followed by the residential sector with a consumption of energy equal to 27%.

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To reduce these percentages, many Directives and Norms have been issued, to support the increase of energy efficiency and the use of renewable sources.

In Italy, in 2017 the National Energetic Strategy [SEN, 2] has been adopted. It envisages the reduction of -3,7 Mtep of consumption in the residential sectors, with actions directed to both building envelope and plants, with a view to reaching the goals proposed by EPBD Directive 2010/31/EU [3] and promoting the concept of Nearly Zero Energy Building.

In order to be effective, such strategies must involve the existing residential stock, which could significantly contribute to reducing the energy consumption, thanks to specific retrofit actions. In this regard, an effective plan requires a deep knowledge of the actual building stock features, which depend on a set of factors, such as age of construction, construction technology, building typology, and which regard both the envelope thermal properties and the configurations of plants and systems.

Many authors have written about retrofit actions on the building stock, for example Aghamolaei and Ghaani [4], who analyse the impact of energy efficiency strategies on comfort indoor; Dall'O and Sarto [5] who focus their attention on a large-scale planning on school buildings; or Ahmed [6] who deals with the financial and practical aspects of converting existing buildings to nZEB.

Referring to specific actions, in particular retrofit actions on the envelope of buildings, other authors have studied aspects linked to thermal transmittance. Desogus and others [7-9] write about in situ measurement of building wall thermal transmittance, comparing different approaches, dealing with the effects of different parameters on measurement results or comparing the various calculation methods. Rasooli [10] and Choi [11] based their researches on the norm ISO 9869, one proposing a slight modification to it and the other analysing the convergence characteristics of the average method. Meng et all. [12] introduce a new simple method to determine thermal transmittance in situ, analysing its adaptability and testing its accuracy in terms of influence of the difference of temperature.

Within this framework, the objective of this paper was to elaborate and test a feasible measurement procedure to determine one of the characteristic parameters of the envelope of building, the thermal transmittance. Starting from codified procedure, experimental instruments and techniques have been used, trying to address the main drawbacks characterizing the conditions usually required for reliable in situ measures [13] (e.g. test long duration, remarkable temperature difference, etc).

Specifically, the aim of the proposed methodology is to define an in situ survey procedure suited to determine the thermal properties of an envelope, in various climatic zones, especially where, because of the climatic conditions, the required measure conditions are difficult to be realised.

In Mediterranean climate, in fact, differences of temperatures major than 10°C between inside and outside environments, which allows the measure error to be minimized [14], can be obtained only in limited period of the year, thereby reducing the chances to do such investigations. Therefore, an experimental apparatus has been ad hoc realised and successively tested performing a preliminary set of measurements.

The procedure was applied to five case studies, selected among the building stock of the city di Reggio Calabria. They all belong to the same construction typology (reinforced concrete buildings), which demonstrated to be one of the more representative categories [15].

II. METHODOLOGY

The realised system is based on the principles of the hot box laboratory method [16] and entails a localised heating of the wall surface where measures are carried out. This enables a proper control of the involved difference of temperature and, after an initial transitory, almost stationary measurement conditions. In particular, the system is made up of:

- a box (Fig 1 a), called hotbox, realised with an insulating material, where a heating plate (Fig 1 b) is put and whose functioning is driven by a thermostat (Fig 1 c) which keeps the temperature almost constant inside it;
- a multifunction instrument/ datalogger, TESTO™ 435-2 which collects and partially analyses the measured data (Fig. 1 e).;
- a heat flow meter for the measurement of the thermal flow and of the temperature on the surface of the wall opposite to the hotbox (Fig. 1 f);
- a temperature sensor to determine the temperature of the surface of the wall facing the Hotbox (Fig. 1 g).

Moreover, to support the instrumentation a rack with an EPS panel (Fig. 1 d) was used, with a view to placing the hotbox at a proper distance from the thermal bridge due to the contact between the wall and the floor.

The main features of the various components of the experimental apparatus are reported in Tables I, II, III, and IV.

Specifically, the hotbox, realised in EPS (R_D= 0,9 m^2K/W; λ_D= 0,032 W/m K, thickness 3 cm), and the heating plate have both the dimensions which, on average, demonstrated to be sufficient to guarantee the presence of a proper one dimension (1-D) heat transfer zone inside the wall, around the measurement point [12].

a) hot box

b) heating plate

c) thermostat

d) supporting rack

e) multifunction instrument

f) heat flow meter

g) temperature sensor (thermocouple)

Fig. 1. Experimental apparatus.

TABLE I. HOTBOX DIMENSIONS

Internal dimensions [mm]	800x800x400
External dimensions [mm]	860x860x430

TABLE II. HEATING PLATE CHARACTERISTICS

Thermal power [W]	300
Dimensions [mm]	605x505x22
Weight [kg]	2,5

TABLE III. HEAT FLOW METER PLATE SENSOR CHARACTERISTICS

Operating temperature [°C]	- 20 ... + 50
Precision heat flow meter	±5%
Precision of the system – U value	±12% of the measured value with a ΔT=15K
Dimensions [mm]	220 x 74 x 46

These dimensions are also suited to address and solve practical issues such as transport difficulties or non-availability of a sufficiently large and homogeneous surface on the investigated wall.

TABLE IV. THERMOCOUPLE CHARACTERISTICS.

Instrument	Field measure	Precision	Resolution
Vertical handle	-50…+1000 C	±(0.7 C +0.3% del v.m.) (-40 ... +900 C) ±(0.9 C +0.5% del v.m.) (remaining field)	0.1 C (-50 ... +199.9 C) 1.0 C (remaining field)
Thermocouple of type K	-50... +400 C	Class 2	//

The experimental technique envisages that the hotbox is installed on the surface of the investigated wall which faces the outdoor environment. The thermostat is set to drive the operation of the heating plate, guaranteeing an air temperature of 35°C. The thermocouple (Fig. 1g) is placed in correspondence of the outdoor side of the wall within the hot box.

The heat flow meter, on the other hand, is placed on the indoor side of the investigated wall.

The advantages of this experimental techniques consist in:

- the possibility of working with a fixed ΔT;
- remarkably reducing the influence of the outdoor air temperature fluctuations;
- limiting the effect due to the direct solar radiation, thanks to the box covering the sensors and the portion of wall object of study;
- protecting the wall from atmospheric events.

All the measurements have been carried out following the steps and the suggestions proposed by the Standard ISO 9869 [13]. All the data were collected with a time step of 10 minutes.

Furthermore, all the measurements have been carried out for 48h. Detected data were processed through the moving average method [13] using the following expression:

$$U = \frac{\sum_j q_j}{\sum_j (t_{i,j} - t_{e,j})} \quad [1]$$

where q_j is thermal flux measured at the jth time step, $t_{i,j}$ is the temperature of the wall surface inside the hot box at jth time step, $t_{e,j}$ is the temperature of the wall surface in correspondence of the indoor environment.

III. CASE STUDY

The measurements have been carried out in 5 buildings, properly selected starting from the information taken from the National Statistics Institute [15] and chosen as case study.

The study has been focused on the residential building stock of the city of Reggio Calabria, located in the Southern area of the Italian peninsula (38°5.7' North Latitude; 15°39.3' East Longitude) and characterized by a Mediterranean climate profile.

In Reggio Calabria, the residential buildings, selected for the analysis, represent 87% of the whole building stock. They have been classified into three categories referring to the constructive typology (load-bearing masonry 25%, reinforced concrete 59%, others different from the previous two 16%).

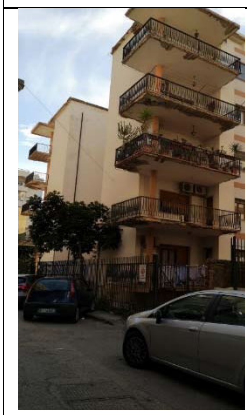
From these data and classifications, it is possible to focus the attention on the most representative cases, in particular buildings built with a structure in reinforced concrete (more than 65% of the total).

In Table V the selected investigated cases and the dates when the measures started are reported. The selection has been obtained also considering some practical aspects, first of all the availability of a suitable wall with a sufficiently large surface, near to a balcony, to enable the installation of the instruments.

For each case study a previous thermographic survey has been conducted, to determine possible inhomogeneities of the wall or thermal bridges. Then, the instruments have been installed as depicted in Fig. 2.

The outdoor air temperature trend during the measure periods [18] is reported in Fig. 3.

TABLE V CASE STUDY

Case study 1	Case study 2	Case study 3	Case study 4	Case study 5
				
Measure starting date: 13/01/2020	Measure starting date: 18/01/2020	Measure starting date: 06/02/2020	Measure starting date: 04/02/2020	Measure starting date: 11/02/2020

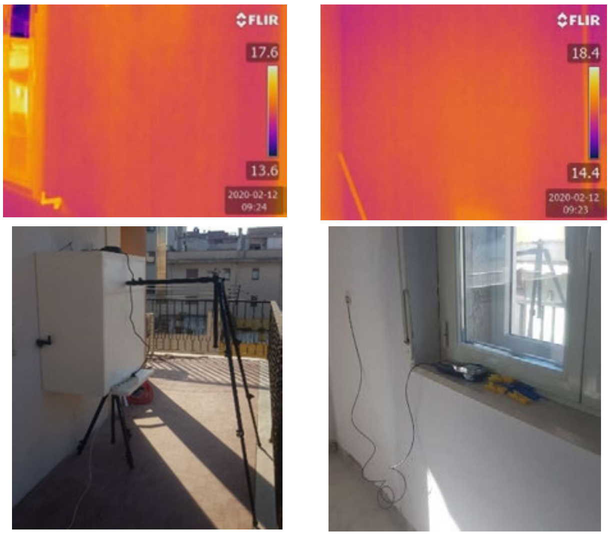


Fig. 2. Thermographic analysis and instruments installed for one of the case studies

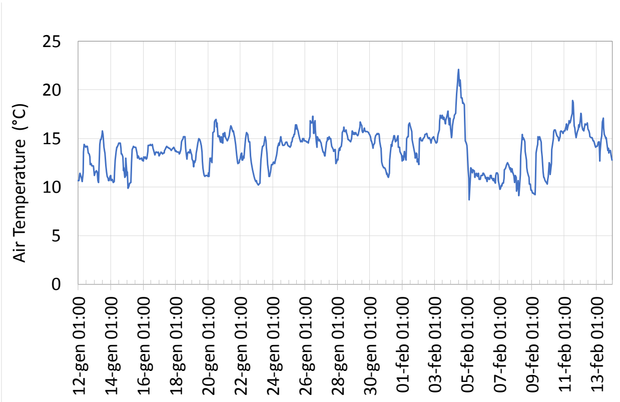


Fig. 3. Outdoor air temperature trend [18].

IV. RESULTS AND DISCUSSIONS

All the measured data have been elaborated as reported in Fig. 3, showing both the indoor and outdoor temperature and the moving average of the thermal transmittance values for the case study 2. The temperatures show a regular trend with light oscillation; the transmittance, instead, after an initial transient behaviour, reaches a final value in the asymptote.

Obviously, this is due to the thermal inertia of the wall, which affects the thermal response of the structure especially during the first part of the measure, whose duration (of about 20 hours, on average) depends on the time constant of the construction.

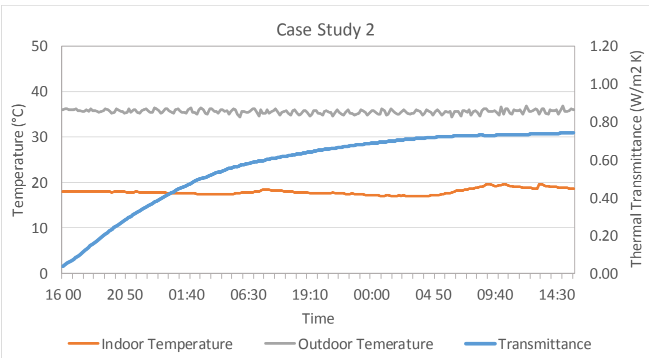


Fig. 4. Data analysis case study 2.

Fig. 4 depicts the trend of the moving average of the measured thermal transmittance values for all the studied cases. It is clear how different are the results with an increase of almost 70% between the two extreme cases.

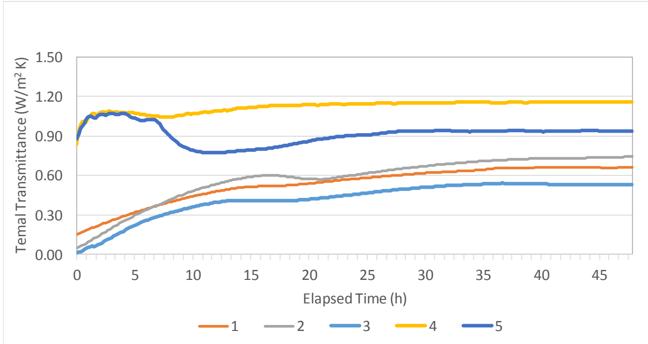


Fig. 5. Thermal transmittance trends for all the case study

In Fig. 5 a comparison of the main results is shown. It can be observed how for the first two case studies the thermal transmittance values are similar (0.71 W/m^2 K e 0.76 W/m^2 K respectively). More performing results are the ones referred to the third case study, where the mean value reaches 0.556 W/m^2 K.

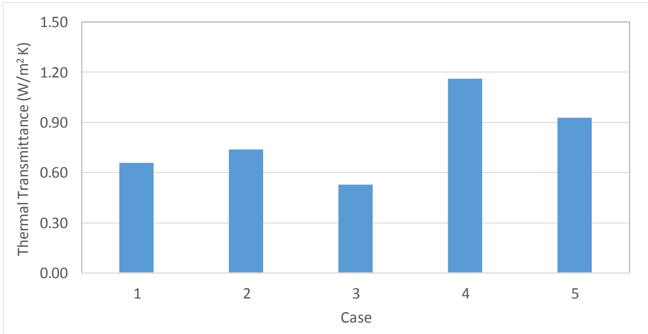


Fig. 6. Comparison among the thermal transmittance of the case study

Higher values have been obtained for case 4. Its thermal transmittance is always close to the unit, with a mean of approximately 1.2 W/m^2 K. Similarities can be found also in case 5, where the transmittance values are anyway higher than the ones of the previous cases.

However, it is worth underlining that the studied cases are to be considered as preliminary measure example to test the procedure and verify its suitability; they do not be considered the typical characteristics of the whole city's building stock.

V. CONCLUSIONS

With the aim of reducing GHG emissions, significant measurements should be taken in the main pollutant sectors, among which the civil and residential one. In this context, the objective of the paper was to elaborate and test a possible procedure of measurement to determine the thermal transmittance, a characteristic parameter of the passive components of buildings.

Therefore, starting from codified measurement procedures, instruments and experimental technique have been used as an attempt to reduce measurement times and determine transmittance values.

The basis of the described experimental technique is the use of a hot box, installed on the external surface of the analysed wall, where a heating plate is placed, so that significant difference of temperatures between indoor and outdoor environments can be reached.

This configuration of the experimental apparatus makes the measurement quite independent of the environmental conditions, allowing the heat flow meter method to be exploited for thermal transmittance measurement also in areas characterized by a warm or mild climate, like Reggio Calabria. For this reason, a ΔT higher than 10°C has been obtained using the hotbox applied on the external wall of buildings.

In addition, stationary conditions were also realized during the measurements, thus guaranteeing the reliability of the results.

The described procedure was tested, performing a set of measurements in various buildings differentiated for the construction period. Specifically, five buildings were singled out and measurements were performed for a period of 48h.

Trasmittance values spanning from 0.7 W/m^2 K to 1.0 W/m^2 K (+43%), were obtained, and the procedures demonstrated to yield reliable results, in relatively short periods (48h).

These measures are to be considered as a preliminary verification of the suitability and reliability of the procedure; the results do not represent the typical characteristics of the whole city's building stock. However, in this direction, the future stages of the analysis are being planning.

Moreover, further developments will be focused on the analysis of the effect of the thermal inertia on the duration of the initial transitory phase, with a view to verifying whether hint regarding the time constant of the structure might be inferred.

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