TEMA

Technologies
Engineering
Materials
Architecture

Journal Director: R. Gulli

e-ISSN 2421-4574

Vol. 7, No. 1 (2021)

Issue edited by Editor in Chief: R. Gulli

Cover illustration: Azulejos, Casa de Pilatos, Seville. © Renato Morganti, 2017

Editorial Assistants: C. Mazzoli, D. Prati

TEMA
Technologies Engineering Materials Architecture

e-ISSN 2421-4574
Vol. 7, No. 1 (2021)
Year 2021 (Issues per year: 2)

Scientific Society Partner:
Ar.Tec. Onlus
c/o DICEA, Università Politecnica delle Marche,
Polo Montedago, Via Brecce Bianche 12
60131 Ancona - Italy
Phone: +39 071 2204587
Email: info@artecweb.org- tema@artecweb.org

Media Partner:
Edicom Edizioni
Via I Maggio 117
34074 Monfalcone (GO) - Italy
Phone: +39 0481 484488

TEMA: Technologies Engineering Materials Architecture
Vol. 7, No. 1 (2021)
e-ISSN 2421-4574

THE EFFECTS OF MORTAR ON THE DYNAMIC THERMAL PERFORMANCES OF STONE MASONRIES

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 7, No. 1 - (2021)

Giuseppe Desogus

DOI: 10.30682/tema0701g

Highlights

The effect of mortar on the dynamic thermal properties of stone masonries is investigated. Twelve samples of different masonry are analysed with Finite Element Modeller. Their stone and mortar basic thermal properties are identified. Periodic thermal transmittance and decrement factor are positively influenced by mortar. Mortar reduces the internal admittance, but absolute values are still relevant.

Abstract

In Italy, an important percentage of historical buildings was built with stone masonry. It is necessary to correctly understand its thermal behaviour in order to evaluate suitable retrofit interventions. Stone masonries can present very complex and variable thermal fields, due to the different geometry of stone blocks, to the various type of stones used and to the presence of mortar. Twelve samples are analysed with a Finite Element Modeller to investigate its effect on dynamic properties. The results show that mortar positively influences periodic thermal transmittance and decrement factor of stone walls.

Keywords

Historical buildings, Stone masonry, Dynamic thermal performance, Thermal finite element modelling.

Giuseppe Desogus
Dipartimento di Ingegneria Civile, Ambientale e Architettura, Università degli Studi di Cagliari, Cagliari (Italy)

** Corresponding author*
E-mail: gdesogus@unica.it

1. INTRODUCTION

The implementation of effective strategies for the decarbonisation of the building sector cannot avoid a severe commitment to the decrease of the energy consumptions of existing buildings anymore [1]. In Italy, a relevant percentage, about 15%, of the residential buildings stock was built before 1918 [2], thus being an essential target for renovation policies. It can be said that it is entirely previous to the massive widespread of reinforced concrete frames, that dates to the second decade of the XX century [3]. It is thus evident that a constant constructive feature in this kind of buildings is the load-bearing masonry. One of the most challenging steps of energy retrofit is reaching enough knowledge of all the constructive features that influence the current energy performance [4].

Between the two most common materials used for bearing elements, i.e. bricks and stones, the latter present a higher degree of complexity. In both cases, masonries are not homogeneous structures, being composed at least by mortar and bearing elements. However, in massive bricks walls the percentage of mortar can always be considered accounting for 20% of the whole volume [5].

Stone walls present, instead, multiple issues that need to be dealt with. Stone is one of the most challenging construction materials to be standardised. The man intervention regards only its geometry, but the other features remain substantially natural. It, therefore, presents a substantial heterogeneity due to its type and the geology of the area of extraction [6]. The stone blocks geometry itself is not easily recognisable. Stone walls are often, wrongly, perceived as being homogenous throughout their thickness. However, they are not uniform constructions, but consist of an outer and inner 'leaf', both made from larger stones with their inside faces left rough. The centre of the wall sometimes is packed with smaller stones and mortar [7]. The quantity of mortar strictly depends on the shape of stone blocks. In masonries with squared blocks, it was generally used only to create small joints between the stones, but when their shape is not regular, the mortar was used to fill the numerous and wide gaps among them. Mortar has different basic thermal properties compared to stone [8, 9] thus affecting the performance of the entire wall.

The aim of the present research is the assessment of mortar's influence both on steady-state and dynamic thermal properties of different kinds of stone masonries.

2. STATE OF THE ART

In literature, different methodologies to calculate the steady-state transmittance can be found. In some cases, the walls are considered as if they are a monolithic slab of stone. It is a very brisk technique but can bring to an overestimation of thermal transmittance [6]. In the case of a rubble wall, if the proportions of mortar and stones are known or assumed from prior knowledge, the wall may be simply modelled as a multi-layer build-up [7]. Some standard considers the masonry leaf as a bridged layer. The joints may be disregarded if the difference in thermal resistance between bridging material (mortar) and the bridged material (stone) is less than 0,1 m²K/W. Otherwise, it can be possible to include the mortar joints with simplified methodologies to assess their fraction [8]. All the described methods are based on the hypothesis that the homogenisation of the section with a fictitious material representing stone and mortar gives reliable results. The use of finite element modelling, however, shows that not every type of historical wall can be modelled using simplified methods [10]. In previous research [11], finite element modelling was used to evaluate the steady-state thermal performance of ten different stone masonries samples coming from various Italian regions. In the present work, the evaluation is repeated adding two new samples and using a different modeller [12], able to evaluate also dynamic properties such as periodic transmittance, time shift, decrement factor and internal admittance [13].

Stone masonry is generally acknowledged with high thermal inertia, because of its thickness and weight. Due to the absence of insulating materials, most of the energy strategies of historical buildings, such as natural ventilation, rely on this property of massive walls [14]. It is, therefore, necessary to achieve a correct estimation of stone masonry dynamic properties. The positive or negative effect of mortar on them has not been investigated so far.

In the following, different samples of stone masonries with varying proportion of mortar will be presented. For each of them, a finite element model has been created and analysed with the use of a modeller [12]. The U-value, the periodic thermal transmittance, the time shift, the decrement factor and the internal admittance of each sample are shown and compared with the ones calculated for a homogeneous section made of the same solid stone of each sample, to assess the influence of mortar on all the thermal parameters.

3. METHODOLOGY

The workflow of the research is shown in Figure 1. The first step is the identification of reliable representations of masonry samples. Nowadays, the necessity to address the seismic upgrade of historical buildings, or simply improve their conservation, is leading to more and more detailed analysis of stone masonry geometries and features. In literature, many case studies can be found.

An exhaustive classification is reported in [15]. The purpose of the present research is to evaluate the influence of mortar on thermal properties of stone masonries. As highlighted in [11], the incidence of mortar on

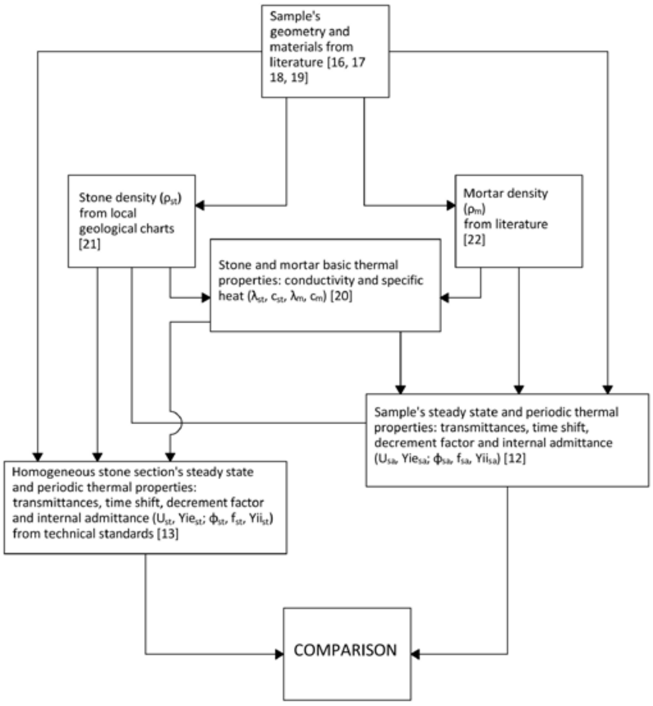


Fig. 1. *Research's workflow.*

steady-state thermal transmittance depends on its quantity and the difference of its thermal conductivity from stones' one. Different samples with different mortar contents and stone types have been selected from four Italian regions to carry out a similar investigation [16–19]. The samples have been chosen to represent five different stones' shaping and bedding. Excluding ashlar masonry, in which the amount of mortar can be neglected, the research focuses on regular coursed rubble masonry, roughly regular coursed rubble masonry, uncoursed random rubble masonry with and without bond stones and three leaf random rubble masonry (with the inner leaf packed with mortar and small stones). The samples are described in Figure 2 and Figure 3.

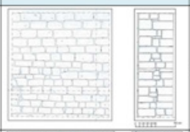
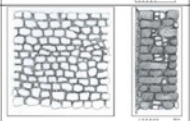
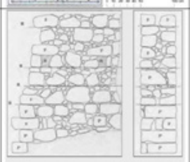
Sample	Elevation and section	Origin	Average thickness (m)	Mortar %	Masonry type	Stone type and colour code	Mortar type
C01		Abruzzo	0,87	13,0%	Regular coursed rubble masonry	Quartz sandstone	Lime mortar with limestone aggregates
C02		Abruzzo	1,20	28,0%	Roughly regular coursed rubble masonry	Compact limestone	Lime mortar with limestone aggregates
C03		Latium	0,77	29,0%	Roughly regular coursed rubble masonry	Limestone	Lime mortar with limestone aggregates
C04		Latium	0,62	15,9%	Uncoursed random rubble masonry	Compact limestone	Lime mortar with limestone aggregates
C05		Latium	0,85	26,0%	Uncoursed random rubble masonry	Limestone	Lime mortar with limestone aggregates
C06		Sicily	0,60	11,9%	Uncoursed random rubble masonry with bond stones	Compact limestone	Lime mortar with limestone aggregates

Fig. 2. *Masonry samples from 1 to 6 with their geometrical and material features.*

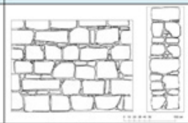
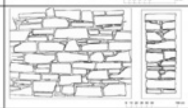
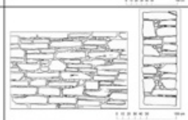
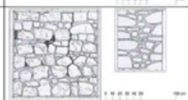
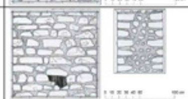
Sample	Elevation and section	Origin	Average thickness (m)	Mortar %	Masonry type	Stone type and colour code	Mortar type
C07		Sardinia	0,58	19,0%	Uncoursed random rubble masonry with bond stones	Trachyte	Lime mortar with limestone aggregates
C08		Sardinia	0,61	10,0%	Uncoursed random rubble masonry with bond stones	Calciferous sandstone	Lime mortar with limestone aggregates
C09		Sardinia	0,57	23,0%	Uncoursed random rubble masonry with bond stones	Limestone	Lime mortar with limestone aggregates
C10		Latium	0,71	34,0%	Three leaf random rubble masonry	Tuff	Pozzolanic mortar
C11		Latium	0,66	47,0%	Three leaf random rubble masonry	Tuff	Pozzolanic mortar
C12		Latium	0,84	23,0%	Three leaf random rubble masonry	Travertine	Lime mortar with limestone aggregates

Fig. 3. *Masonry samples from 7 to 12 with their geometrical and material features.*

Among all the samples identified, four come from Latium, that is the most represented region, three from Sardinia, two from Abruzzo and one from Sicily. Latium samples belong to random rubble and three leaf masonry categories. The mortar percentage in these samples is the highest on average, ranging from a 15,9 % minimum to a 47% maximum. The stones used in Latium are the most various. In random rubble masonry, the limestone is always present, while in three leaf masonry the volcanic tuff or the travertine is used according to the geographical availability. Islands (Sardinia and Sicily's) samples show an extensive adoption of bond stones technique. The presence of big binding elements reduces the necessity of mortar, whose percentages in these samples are the lowest. The samples identified differ mainly from the stone types. Limestone, sandstone and trachyte that have different thermal properties as highlighted in the following are equally used. The samples chosen from Abruzzo are characterised by the highest geometrical regularity of stone elements, that, especially in the first one means a low percentage of mortar. The stones used, both limestone and sandstone, are from the hardest ones, with consequently the highest density and thermal conductivity. In most of the samples, lime mortars with limestone aggregates have been found. The only exceptions are in volcanic tuff masonries where the pozzolanic mortar was used.

The second step is the definition of the basic thermal properties of stones and mortars. The primary reference is [20]. The standard provides thermal conductivity and specific heat of different kind of stones and mortars classified by their density. For the former, the density has been obtained from the geological map edited by ISPRA [21], where every single sheet provides detailed information on local stones. The density of non-hydraulic mortars, instead, depends on its grading of carbonation and aggregates, according to [22].

Once density is known, [20] provides tabulated data of thermal conductivity and specific heat. The values of each sample are shown in Table 1.

The density of all samples' stones ranges from 1500 (tuff) to 2500 kg m^{-3} (quartz sandstone). These also have the lowest and highest thermal conductivity values: 0,90 (tuff) and 2,30 W m^{-1} K^{-1} (quartz sandstone). According to [20], the specific heat is the same for all the stone types. The conductivity of limestone mortar is slightly higher than the pozzolanic one because it is more compact and thus dense. The specific heat is instead the same and equal to the stones' one. Comparing stones and mortars' values, it is evident how the formers are always denser, with only one exception. Finally, the conductivity is always higher for the stones than for the mortars.

Sample	ρ_{st} [kgm^{-3}]	λ_{st} [Wm^{-1}K^{-1}]	c_{st} [jkg^{-1}K^{-1}]	ρ_m [kg/m^{-3}]	λ_m [Wm^{-1}K^{-1}]	c_m [jkg^{-1}K^{-1}]
C01	2500	2,30	1000	1800	0,87	1000
C02	2400	1,80	1000	1800	0,87	1000
C03	1900	1,20	1000	1800	0,87	1000
C04	2100	1,60	1000	1800	0,87	1000
C05	1900	1,20	1000	1800	0,87	1000
C06	2000	1,50	1000	1800	0,87	1000
C07	1700	1,15	1000	1800	0,87	1000
C08	2400	1,90	1000	1800	0,87	1000
C09	2100	1,30	1000	1800	0,87	1000
C10	1500	0,90	1000	1500	0,75	1000
C11	1500	0,90	1000	1500	0,75	1000
C12	2300	2,10	1000	1800	0,87	1000

Tab. 1. *Basic thermal properties of the samples' materials (suffix -st stands for stone, -m stands for mortar).*

The third step is the calculation of steady-state and periodic thermal properties of the samples.

The geometrical and material complexity of stone masonries involves thermal fields that are not unidirectional. Even if the materials themselves can be considered isotropic, the variable geometry of stones and the presence of mortar with different thermal properties, create heat flux vectors that have at least two spatial components. As already said, this situation makes necessary the use of a numerical calculation method based on finite differences or elements [20]. The accepted methods must comply with the requirements of [23]. For the purposes of the present research, a finite element modeller and solver (FEM) [12] conform to [23] has been used. Once the geometry and the raw material properties of each sample are inputted, the solver calculates both its steady-state (transmittance U) and periodic thermal parameters (periodic thermal transmittance Yie, time-shift ϕ, decrement factor f and the internal admittance Yii).

For the first, the solver calculates the thermal coupling coefficient. U-value is then given by (1).

$$U = \frac{L_{2D}}{h}\ [Wm^{-2}k^{-1}]\ (1)$$

Where L_{2D} is the thermal coupling coefficient, and h is the sample height.

The modeller is also able to simulate the thermal field within the sample under 24 hours of periodic forcing conditions. The solver's main result is the complex symmetric matrix Y (2).

$$Y = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix}\ (2)$$

This is linked to the complex heat transfer matrix of the entire sample by equations (3), (4) and (5) [13].

$$Y_{11} = -\frac{Z_{11}}{Z_{12}} \quad (3)$$

$$Y_{22} = -\frac{Z_{22}}{Z_{12}} \quad (4)$$

$$Y_{12} = Y_{21} = -\frac{1}{Z_{12}} \quad (5)$$

From (2), the main thermal parameters can be derived. The periodic thermal transmittance, the time shift, the decrement factor and the internal admittance are given by (6), (7), (8) and (9).

$$Yie = |Y_{12}| \; [Wm^{-2}k^{-1}] \quad (6)$$

$$f = \frac{|Y_{12}|}{U} \quad (7)$$

$$\varphi = \frac{T}{2\pi} \arg(Y_{12}) \; [h] \quad (8)$$

$$Yii = |Y_{11}| \; [Wm^{-2}k^{-1}] \quad (9)$$

Where T is the period (24 hours).

To assess the contribution of mortar to the thermal parameters above listed, the last step of the research is the comparison of them with the corresponding ones calculated for a fictitious homogeneous section of the same thickness of the sample's one but made of only stone. The thermal parameters of the fictitious section have been calculated according to [13].

For each parameter, the comparison is carried out, calculating the percentage difference between the sample's values and the homogeneous section's ones (10).

$$\Delta Q = \frac{Q_{sa}-Q_{st}}{Q_{st}} \; [\%] \quad (10)$$

Where Q is a generic parameter, the suffix -sa refers to the real sample and the suffix -st refers to the fictitious homogeneous stone section. In the following, the results of such a comparison are given.

Sample	U_{sa} [$Wm^{-2}K^{-1}$]	Yie_{sa} [$Wm^{-2}K^{-1}$]	φ_{sa} [h]	f_{sa}	Yii_{sa} [$Wm^{-2}K^{-1}$]
C01	1,59	0,010	23,90	0,007	5,31
C02	0,98	0,002	30,50	0,002	5,14
C03	1,16	0,016	22,85	0,014	4,65
C04	1,72	0,060	17,55	0,035	4,80
C05	0,94	0,008	25,17	0,009	4,50
C06	1,73	0,100	16,26	0,057	5,25
C07	1,34	0,090	16,33	0,067	4,95
C08	2,00	0,080	16,79	0,042	5,45
C09	1,63	0,070	17,80	0,040	5,16
C10	1,01	0,019	21,77	0,019	4,30
C11	1,04	0,021	21,26	0,020	4,11
C12	1,52	0,020	22,58	0,012	5,13

Tab. 2. *Samples steady-state and periodic thermal properties calculated by the Finite Element Modeller.*

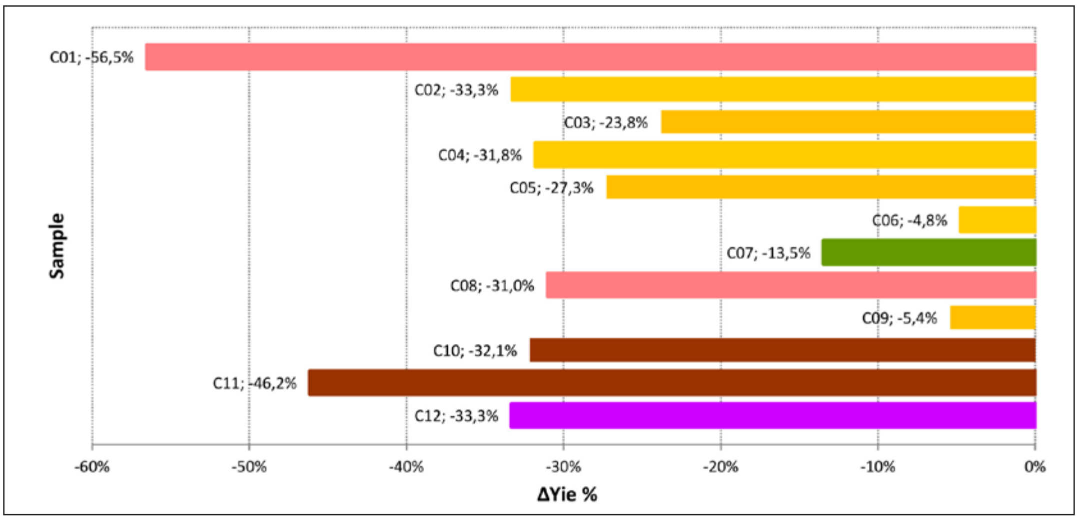


Fig. 4. *Percentage differences between Yie_{sa} and Yie_{st} of each sample (where the suffix -sa stands for the sample and -st stands for homogeneous stone section).*

4. RESULTS

The values calculated by FEM and according to the methodology above described for each sample, are listed in Table 2.

The first thermal parameter analysed is periodic transmittance Yie. The percentage difference calculated is depicted in Figure 4. The difference is always negative. It ranges from -4,8 (C06) to -56,5 % (C01). According to (10) it means that Yie_{sa} is lower than Yie_{st} in each sample.

The periodic thermal transmittance represents the amplitude of the density of heat flow passing through the internal surface divided by the amplitude of outdoor temperature when the indoor one is held constant. Thus, a low value shows the capacity of a wall to protect the indoor environment from external temperature variations, due mainly to solar irradiation. The lower the value, the better the wall performance is. It is evident that mortar contributes to increasing the thermal inertial effect. Despite its lower density than the stone's, the also lower conductivity produces a significant improvement in thermal performance. It is particularly evident in sample C01, where, despite a modest presence of mortar, the highest difference in conductivity than any other sample (due to sandstone's high density) brings to the most noticeable improvement of the periodic transmittance.

The percentage difference in thermal shift is represented in Figure 5.

The differences are restrained within 10%. They range from -0,3 (C06) to 9,4 % (C11). The mortar effect on thermal shift is therefore not so evident as in the previous case. Time-shift is the period between the maximum of the outdoor temperature's amplitude and the maximum of the internal one. Higher values characterise a better performance of the wall. The differences are always positive, except for sample C06. It means that the samples can delay the penetration of heat better than the correspondent homogeneous stone section. The contribution of mortar is again positive.

Decrement factor is the ratio of the internal temperature amplitude to the external one. It is an index of the capability of walls to mitigate the variation of internal surface's temperature. The percentage differences between f_{sa} and f_{st} are illustrated in Figure 6.

Likewise periodic transmittance, the differences are noticeable. They range from 0% of sample C02 to -46,2% of C01. Again, they are negative, highlighting the improvement of thermal performance driven by the mortar. Lower f values mean, in fact, smaller temperature amplitudes on the inner surface of walls.

Finally, internal admittance Yii is defined as the amplitude of the density of heat flow passing through the internal surface divided by the amplitude of indoor temperature when the outdoor one is held constant. It represents the capability of walls to store and release

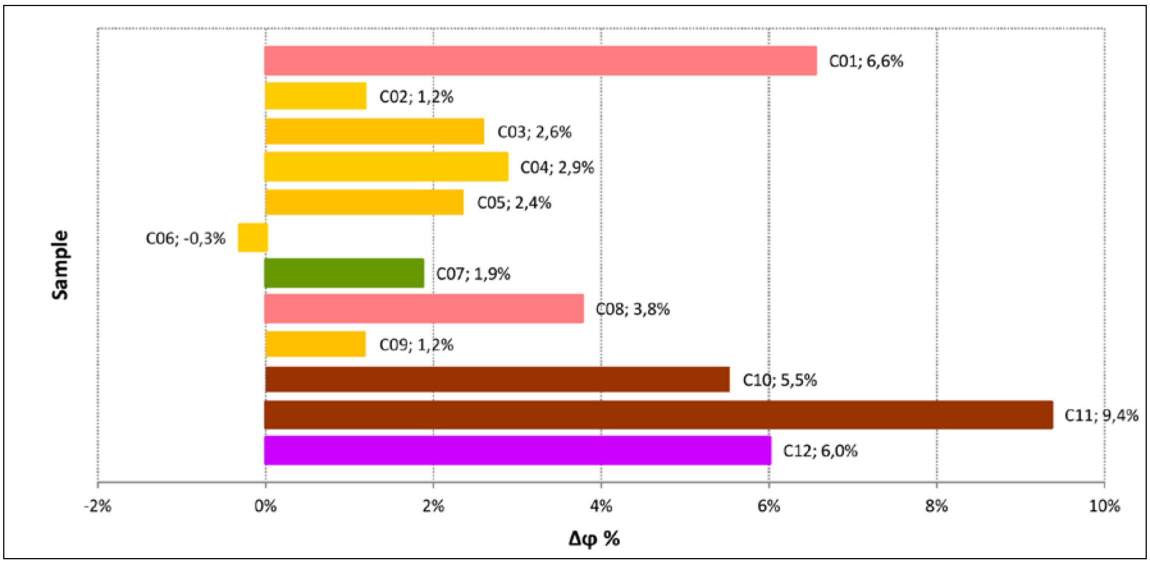


Fig. 5. *Percentage differences between ϕ_{sa} and ϕ_{st} of each sample (where the suffix -sa stands for the sample and -st stands for homogeneous stone section).*

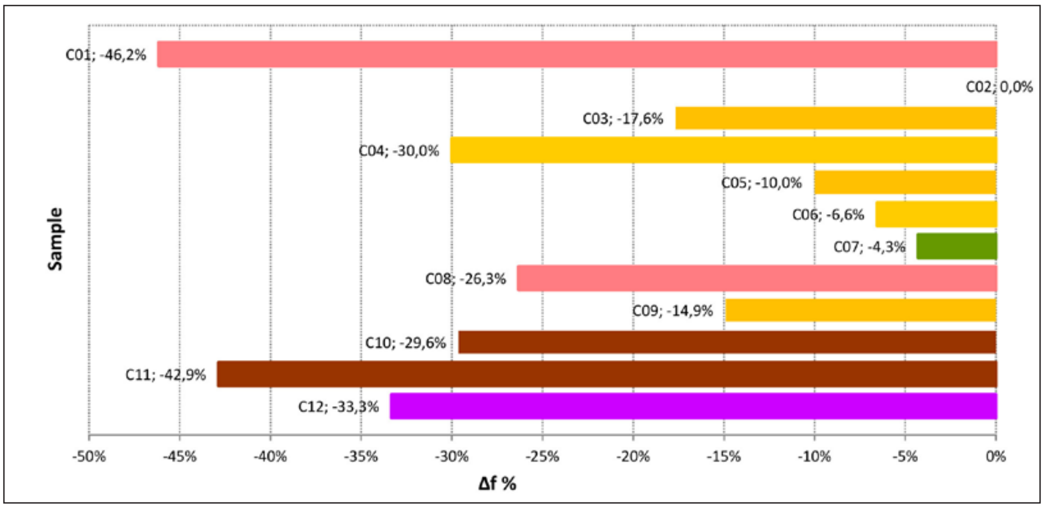


Fig. 6. *Percentage differences between f_{sa} and f_{st} of each sample (where the suffix -sa stands for the sample and -st stands for homogeneous stone section).*

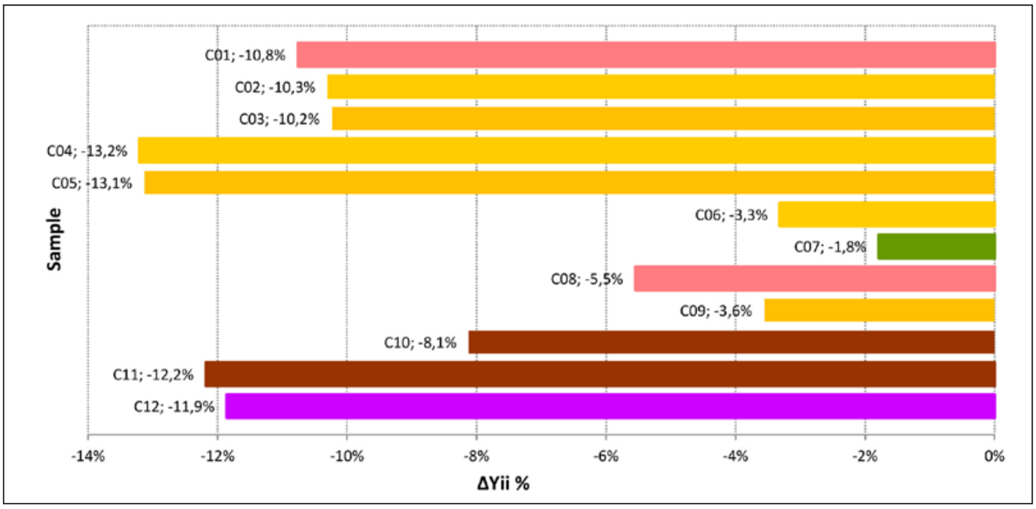


Fig. 7. *Percentage differences between Yii_{sa} and Yii_{st} of each sample (where the suffix -sa stands for the sample and -st stands for homogeneous stone section).*

the heat coming from the indoor environment. The higher the admittance, the better the walls can mitigate thermal variation of the indoor environment due to internal loads. The differences between Yii_{sa} and Yii_{st} are reported in Figure 7.

It is the only parameter that is not positively influenced by mortar. Percentage differences are always negative, and it means that the samples' admittances are lower than the stone homogeneous sections' one. The lower density of mortar reduces the capability of a wall to store and release internal heat. It must be said, however, that differences range only from -1,8 (C07) to -13,2 % (C04).

5. CONCLUSIONS

Historical buildings thermal behaviour mainly relies on the dynamic properties of massive walls, made of bricks or stone. This kind of buildings in most countries, especially in Italy, represents a significant percentage of the whole buildings stock. An improvement of their energy performance cannot avoid an extensive knowledge of their envelope thermal properties anymore.

As shown by the case studies of the research, stones can have very different basic thermal properties. They mainly depend on their density, that in the samples analysed ranges from 1500 (volcanic tuff) to 2500 kg m^{-3} (quartz sandstone). It also reflects on a high variability of thermal conductive values, while specific heat remains constant. In stone masonries, except for the ashlar ones, the presence of mortar is always noticeable. In coursed rubble or random rubble with bond stones masonries, it can represent about 10% of the section area, but in three leaf masonries with a packed inner core, the quantities of mortar and stone become nearly equal. When hard-heavy stones like sandstone or limestone are used, the differences in terms of basic thermal properties between them and mortar grows significantly. For this reason, it is crucial to identify the exact type and geometry of stone blocks, the mortar composition and their proportions.

In this context, the main aim of the paper is the numerical quantification of mortar influence on dynamic thermal parameters of stone masonries. The methodology proposed starts from a precise definition of the walls' sections that allows the use of a finite element modeller, able to evaluate their dynamic thermal properties. The comparison with a fictitious homogeneous stone section highlights how mortar contributes to increase or decrease the main four dynamic parameters: periodic transmittance, time shift, decrement factor and internal admittance. The results are consistent with the hypothesis: mortar effects cannot be neglected. Firstly, it strongly affects periodic transmittance. The differences between samples' and pure homogeneous stone sections' values are important, reaching nearly 60%.

Moreover, it is interesting to point out that it happens in a sample very poor of mortar, but with a very dense stone. Thus, it is not only a matter of proportions but also of basic properties differences. Mortar contributes to decreasing periodic transmittance along with decrement factor and also brings an increase of time shift. Surprisingly, even if it lightens stone walls, due to the minor density, its insulating power improves overall dynamic performance. The only property that is lowered by the presence of mortar is the internal admittance. However, the reduction is not so evident and do not reach the 14%. It must be said that the samples' internal admittances, even considering mortar, are relatively high. Currently, this quantity is not considered by Italian legislation, but some voluntary standard (such as KlimaHaus) suggest a minimum value of 2 $Wm^{-2}K^{-1}$. In all the samples, analysed Yii is more than two times higher.

The results show that an oversimplified methodology based only on the definition of stone properties is strongly limited and unexhaustive, even if it is nowadays still used by technical standards. It is necessary a further effort to enlarge the studies on stone masonries because their thermal behaviour is by far better than the one that can appear by a superficial analysis. It is fundamental because it is a key factor in the definition of the energy performance of historical buildings, that can be wrongly and seriously underestimated. Such a misevaluation can have irreversible consequences on the design of energy retrofit interventions, that can be oversized, causing unjustified and disrespectful modifications on the historical architectural features of these buildings.

Acknowledgments

Sardinia Regional Government financed the present research by Regional Law n. 7/2007. The author wishes to thank Donatella Corda and Giampaolo Mugheddu, whose master and degree thesis contributed to the collection of the masonry case studies.

6. REFERENCES

[1] European Parliament (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2010.153.01.0013.01.ENG&toc=OJ:L:2010:153:TOC

[2] ISTAT Istituto Nazionale di Statistica (2011) 15° Censimento della popolazione e delle abitazioni. http://dati-censimentopopolazione.istat.it/Index.aspx

[3] Iori T (2001) Il cemento armato in Italia: dalle origini alla seconda guerra mondiale. Edilstampa, Roma

[4] Lucchi E, Pracchi V (2013) Efficienza energetica e patrimonio costruito: La sfida del miglioramento delle prestazioni nell'edilizia storica. Maggioli, Rimini

[5] Lucchi E (2017) Thermal transmittance of historical brick masonries: A comparison among standard data, analytical calculation procedures, and in situ heat flow meter measurements. Energy and Buildings 134:71–184

[6] Rye C, Scott C (2012) The SPAB research report 1: U-value report. Society for the Protection of Ancient Buildings, London

[7] Baker P (2015) U-values and traditional buildings. In situ measurements and their comparisons to calculated values, Technical Paper 10. Glasgow Caledonian University, Glasgow

[8] Anderson B (2006) Conventions for U-value calculations 2006 edition. BRE, Watford

[9] Lucchi E (2017) Thermal transmittance of historical stone masonries: A comparison among standard, calculated and measured data. Energy and Buildings 151: 393–405

[10] Mad J, Ko J (2013) A complex finite-element model for the investigation of historical masonry. WIT Transactions on the Built Environment 131:221–231

[11] Desogus G (2019) The assessment of the thermal transmittance of historical stone masonries through finite element modelling. In: Colloqui. AT. e 2019. Ingegno e costruzione nell'epoca della complessità. Torino

[12] Kornicki TP, AnTherm. http://www.antherm.at/antherm/EN/.

[13] CEN - European Committee for Standardization (2017) EN ISO 13786:2017 Thermal performance of building components - Dynamic thermal characteristics - Calculation methods. CEN

[14] Evola G, Marletta L, Natarajan S, Patanè EM (2017) Thermal inertia of heavyweight traditional buildings: Experimental measurements and simulated scenarios. Energy Procedia 133:42–52

[15] Ministero per i Beni e le Attività Culturali. ICCD - Istituto Centrale per il Catalogo e la Documentazione, Criteri di descrizione delle tecniche murarie per la predisposizione di moduli schedografici codificati. Ricognizione bibliografica

[16] Zordan L, Bellicoso A, De Berardinis P, Di Giovanni G, Morganti RT (2002) Le tradizioni del costruire della casa in pietra: materiali, tecniche, modelli e sperimentazioni. Amazon, Seattle

[17] Carocci C, Ceradini V, De Benedictis R, Felice G, Pugliano A, Zampilli M (2006) Sicurezza e conservazione dei centri storici. Il caso Ortigia. Laterza, Bari

[18] Fiorani D (1996) Tecniche costruttive murarie medievali: il Lazio meridionale (Vol. 1). L'Erma di Bretschneider, Roma

[19] Sanna A, Cuboni F (2008) I Manuali del Recupero dei Centri Storici della Sardegna. Architettura in pietra delle Barbagie, dell'Ogliastra, del Nuorese e delle Baronie. DEI, Roma

[20] CEN - European Committee for Standardization (2012) EN ISO 1745:2012 Masonry and masonry products - Methods for determining thermal properties. CEN

[21] ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale, Geological Map at a scale 1 to 50000. https://www.isprambiente.gov.it/en/services/cartography/geological-and-geothematic-maps/geological-map-at-a-scale-1-to-50000

[22] Arizzi A, Cultrone G (2013) The influence of aggregate texture, morphology and grading on the carbonation of non-hydraulic (aerial) lime-based mortars. Quarterly Journal of Engineering Geology and Hydrogeology 46(4): 507–520

[23] CEN - European Committee for Standardization (2017) EN ISO 10211:2017 Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations. CEN