HIGH TEMPERATURES INFLUENCE ON STRESS-STRAIN CURVES FOR MASONRY MATERIALS

M. Andreini[1], A. De Falco[2] and M. Sassu[3]
[1] Msc, University of Pisa, DESTEC - Department of Energy, Systems, Territory and Constructions Engineering, Largo Lucio Lazzarino 1, 56126 Pisa, Italy, marco.andreini@dic.unipi.it
[2] PhD, Lecturer, University of Pisa, DESTEC - Department of Energy, Systems, Territory and Constructions Engineering, Largo Lucio Lazzarino 1, 56126 Pisa, Italy, a.defalco@ing.unipi.it
[3] PhD, Associate Professor, University of Pisa, DESTEC - Department of Energy, Systems, Territory and Constructions Engineering, Largo Lucio Lazzarino 1, 56126 Pisa, Italy, m.sassu@unipi.it

ABSTRACT
An experimental test procedure on specimens of masonry material (clay, lightweight concrete, aerate autoclaved concrete, mortar) is performed. The aim is to detect the influence of high temperatures on the mechanical properties of different materials. On the basis of the results, the free thermal strain, the load-induced strain and the variation of axial strength are determined; the secant modulus of elasticity is expressed as a function of temperature and some proposals for the stress-strain curves are shown in comparison to those of EN 1996-1-2. The constitutive model obtained by non linear regressions is validated using statistical methods: it can provide a mechanical model for masonry walls subjected to fire actions.

KEYWORDS: fire action, high-temperatures, masonry walls, mechanical model

INTRODUCTION
The mechanical behaviour of masonry walls subjected to high temperatures is of relevant interest for structural design of loadbearing walls or compartment panels with fire resistant properties.
Although the response to fire of masonry walls has been the subject of several past studies, experimental results have been just recently compared with numerical models. Nadjai et al. in [1] and [2] report numerical studies on the behaviour of walls in presence of one-side fire. They assumed two preset curves compression strength - temperature proposed by Abrams [3] and Thelanderson [4] and two possible curves crushing strain-temperature proposed by Terro [5] and Anderberg and Thelanderson [6]. Al Nahhas et al. [7] address the experimental tests of walls made of double-cavity and the subsequent analytical modelling. The distribution of the isotherms was determined through an energy balance approach by measuring the proportions of convection, conduction and radiation: the temperature-time curves were determined in various points throughout the wall thickness. The influence of changes in the mechanical strength with varying temperature were however not modelled. In order to check the experimental results reported by Shields et al. [8], Dhanasekar et al. [9] carried out numerical analysis in a thermal field to determine the bowing of panels exposed to fire.
With regard to regulations, the recent Eurocodes on structures, in particular the adjustments to EN 1996-1-2 [10], lead to the application of new methods for experimental or analytical tabular design of bearing masonry walls, partially based on the results of a series of experimental trials conducted by Hahn et al. [11]. The analytical methods prescribed in the Eurocodes depend upon the knowledge of the ultimate strain and compression resistance as functions of temperature, as

well as the main thermal parameters (conductivity, specific heat and density). It should however be noted that some such parameters are significantly influenced by brick humidity, as reported by Nguyen et al. in [12], so caution should be exercised when applying standard diagrams in the design process.
The aim of the present paper is to give experimental data on the main materials used for blocks and mortar joints, measuring the variation of compression resistance and deformation properties depending on the temperature. The tests were managed on cylindrical specimen (diameter 100 mm, height 200 mm), on a set of temperatures between 20°C and 700°C. The compressive strength, the ultimate strain (in absence of preload), the free thermal strain and the equivalent Young modulus were measured for each test, in comparison with results obtained from tests in cold conditions. A proposal for the stress-strain curves in function of temperature was presented in comparison to those of EN 1996-1-2 [10].

MATERIALS AND METHODS

The four main phases of the test procedure, called Hot Mechanics Characterization (HMC) which allowed the determination of the dependence of various material properties from temperature, are summarized in Figure 1.

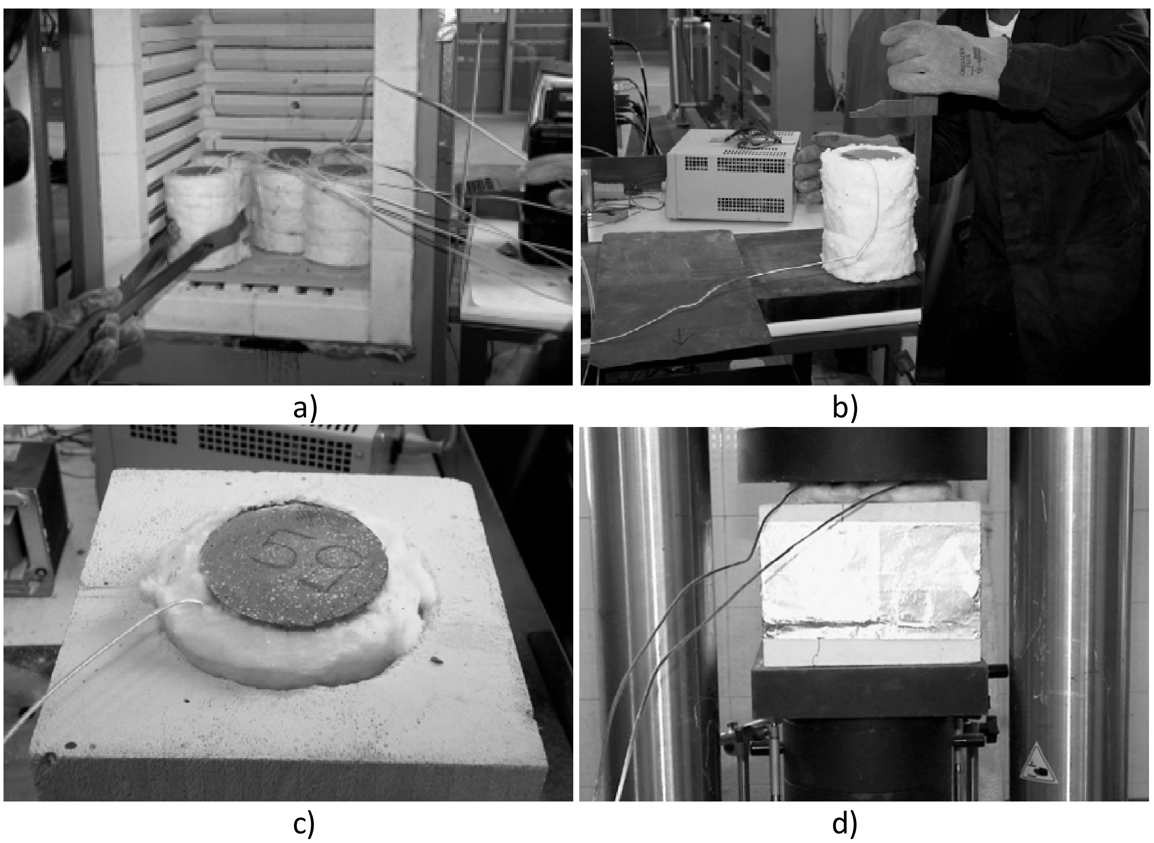

Figure 1: Main phases of the HMC testing procedure: a) extraction of the specimen from the furnace; b) height measurement with centesimal gauge; c) inserting in an AAC thermos pre –heated at a temperature of 200°C; d) compression test execution.

The experimental campaign concerned about two hundred cylindrical specimens of the following typologies: clay (CLAY), aerated autoclaved concrete (AAC), lightweight concrete (LWC),

façade lightweight concrete (LWC-FV), lightweight concrete with voulcanic gravel (LWC-LAP), hydraulic lime mortar, classes M5 and M10 (EN 1996-1-1 classification). The storage conditions of the specimens and the details of the HMC are described in Andreini et al. (2012).
The experimental data furnished, for each sample, the free thermal strain ε_{th}, the coefficient of linear expansion α_{th}, the compressive strength f_c and the ultimate strain ε_{cu0}, in absence of preload. The apparent modulus of elasticity E_b (blocks) and the tangent-secant E_m (mortar) were also determined for values corresponding to about 40% of the strength f_c for each specimen. Further details are in Andreini et al.[13].

TEST RESULTS AND ANALYTICAL EVALUATIONS

As described in Andreini et al. [14], the average values of mechanical properties allowed us to draw many continuous functions of the temperature. In reference to what is proposed by Terro [5] for the concrete, it was chosen to take the third order polynomial functions, namely:

$$\hat{X}\left(\theta\right) = A_0 + A_1\theta + A_2\theta^2 + A_3\theta^3 \,, \tag{1}$$

where X represents the generic mechanical property depending on temperature θ.
The constants A_i have been determined through polynomial regressions performed on average values of variables measured at different temperatures. According to the criteria of Eurocodes for the compression strength f_c, together with the average value f_{cm}, it has been determined the characteristic value f_{ck}, corresponding to a probability of not exceeding of 5% on a log-normal distribution with the standard deviation obtained at each temperature.
For example, we report in Figures 2, 3 and 4 the expression (1) for the compressive strength, for the ultimate strain and for the apparent modulus of elasticity, related to LWC, LWC-LAP and LWC-FV materials, corresponding to three different mix designs. The LWC specimens showed a maximum reduction of about 30% in terms of compressive strength in the absence of preload in the temperature range 500 to 600°C (Figure 2a), while in terms of ultimate strain, shortening was observed in that range two times larger than those obtained with the compression test in cold condition (Figure 2b). This resulted from the fact that the apparent modulus of elasticity decreases almost linearly with a negative trend of about 7.40°C^{-1}MPa, as shown in Figure 2c.
The lightweight concrete with voulcanic gravel, showed a maximum reduction of about 35% in terms of compressive strength in the absence of preload near the maximum temperature tested of 600°C (Figure 3a). With regard to the ultimate strain in the absence of preload, the maximum increase observed was 100% compared to the value obtained from the compression test in cold condition (Figure 3b), thus resulting in substantial decreases in the apparent modulus of elasticity with increasing temperature (Figure 3c).
Samples of lightweight concrete for façades, unlike type previously examined, showed ability to maintain the compressive strength with increasing temperature (Figure 4a). However, the deformation behaviour was very similar to that shown by LWC-LAP samples (Figure 4b). The apparent modulus of elasticity showed reductions of about 50% at the maximum temperature tested of 600°C (Figure 4c).

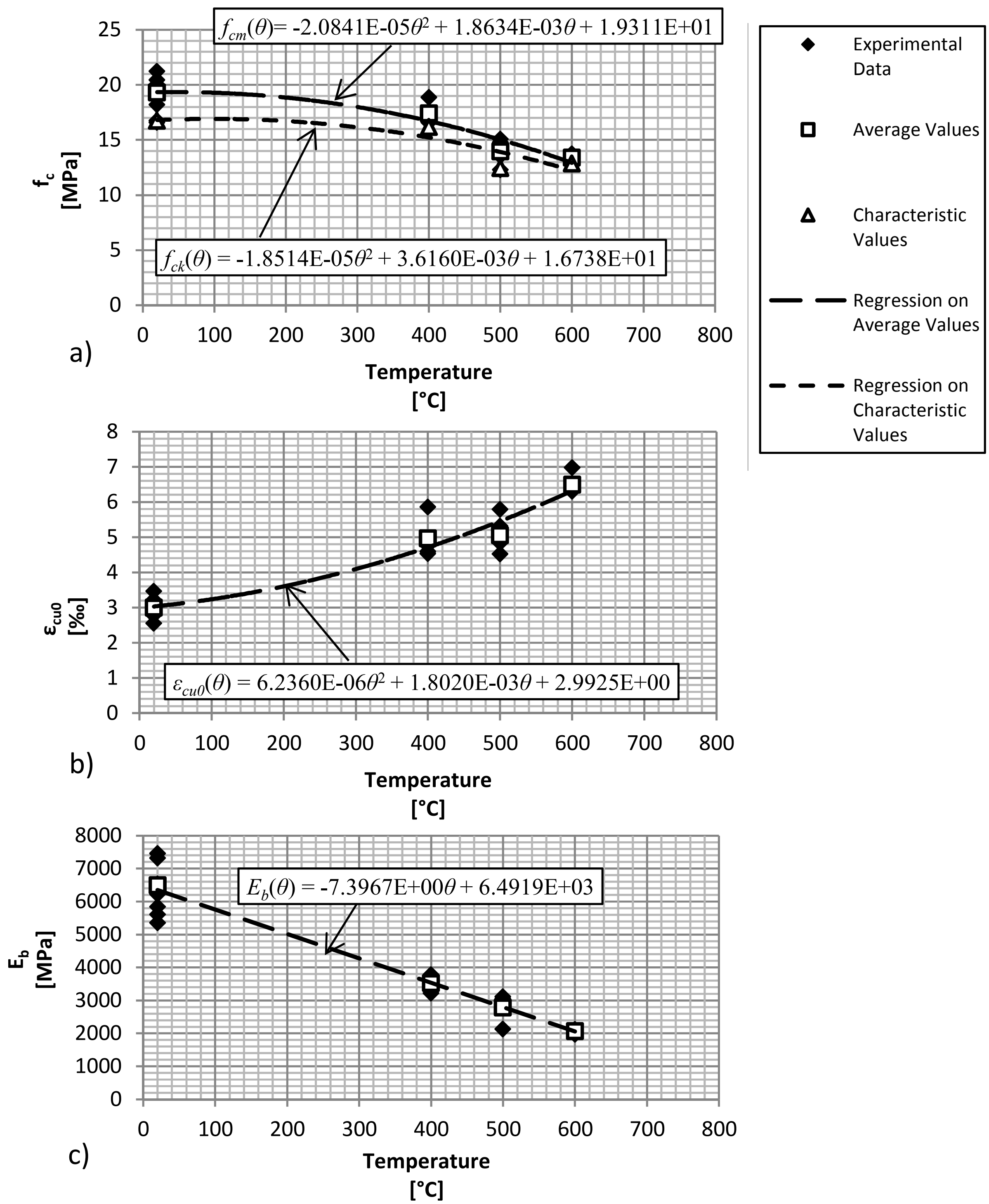

Figure 2: LWC: a) Compressive strength (f_c). b) Ultimate strain (ε_{cu0}). c) Young Modulus of Elasticity (E_b).

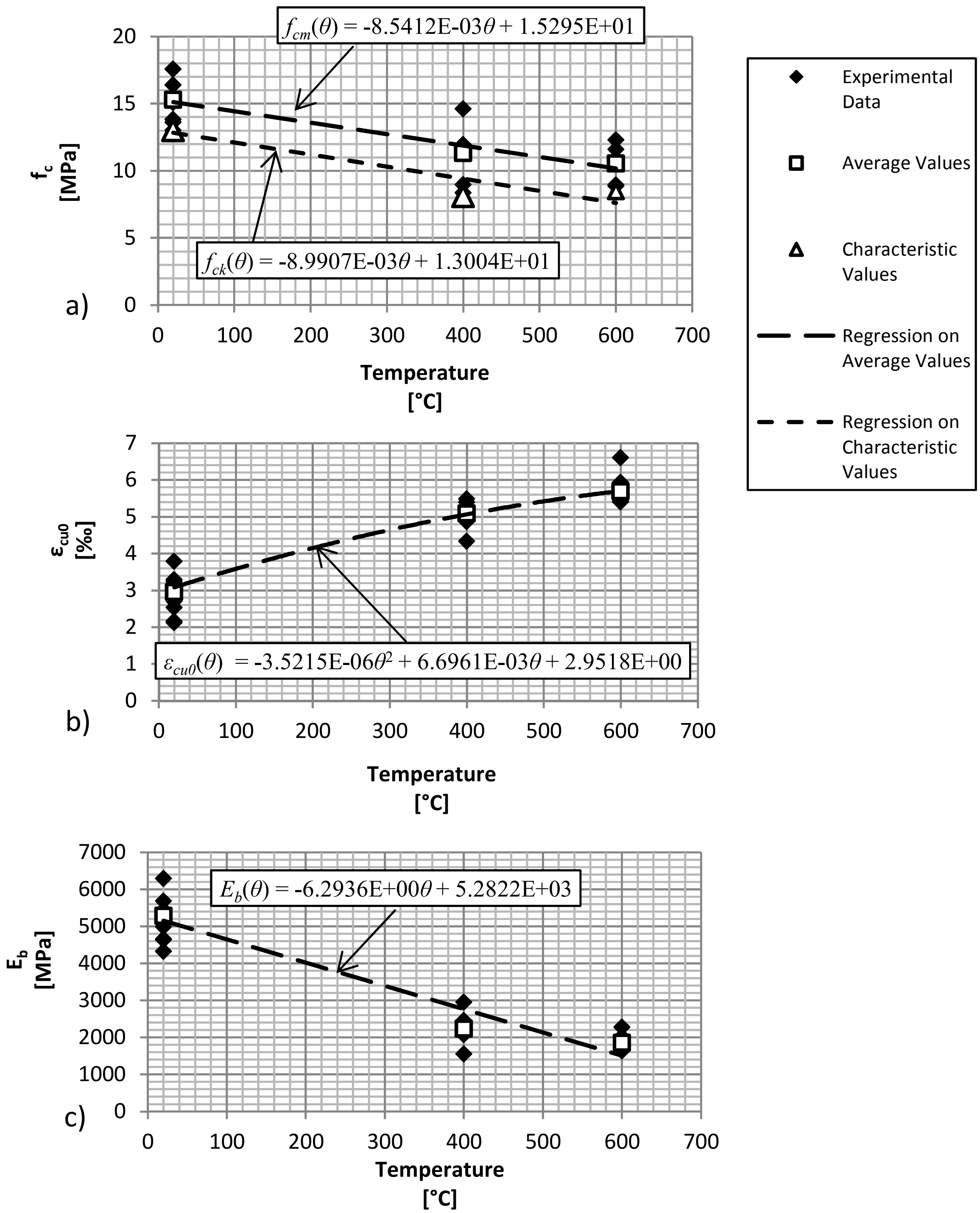

Figure 3: LWC-LAP: a) Compressive strength (f_c). b) Ultimate strain (ε_{cu0}). c) Young Modulus of Elasticity (E_b).

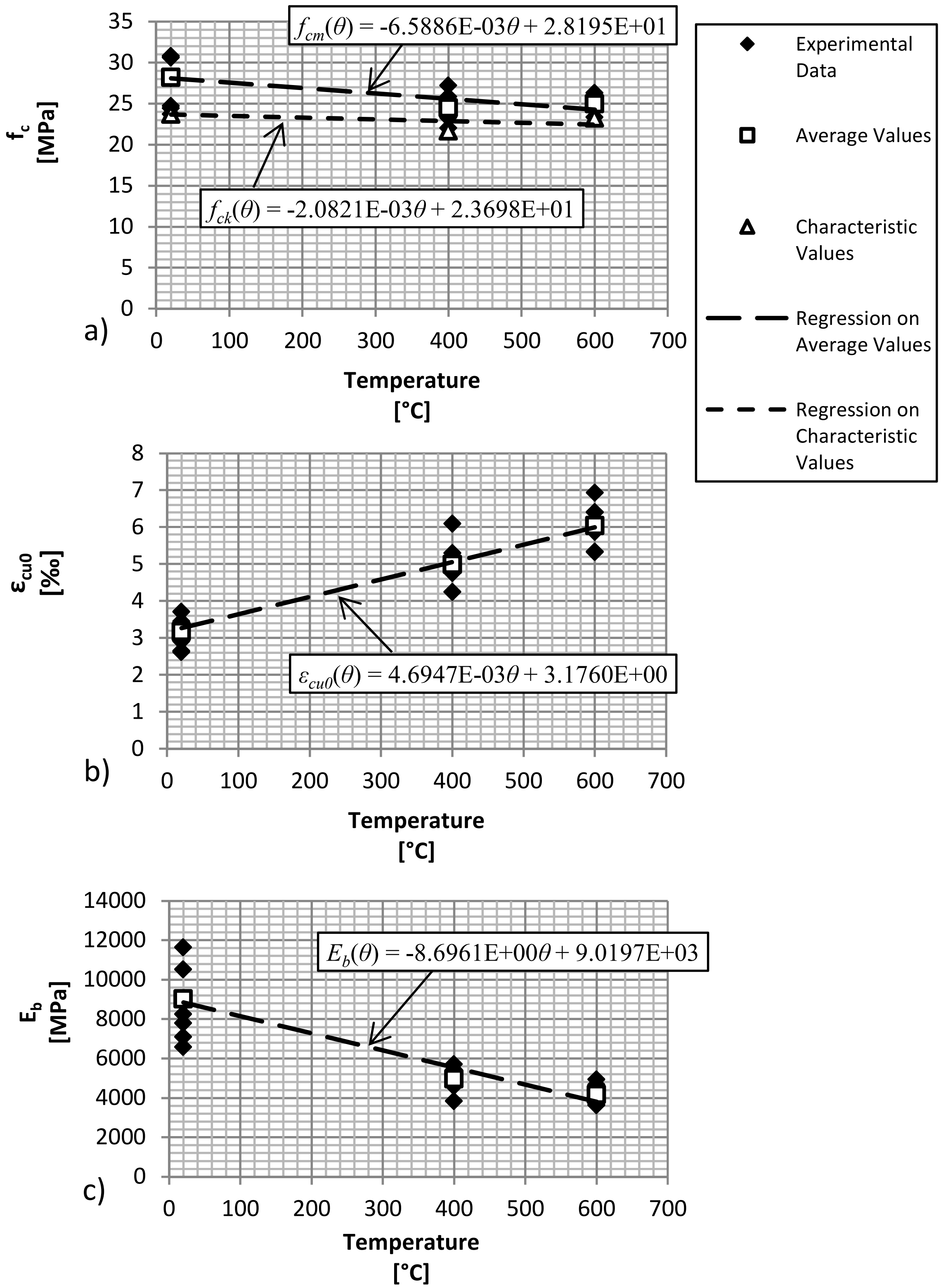

Figure 4: LWC-FV: a) Compressive strength (f_c). b) Ultimate strain (ε_{cu0}). c) Young Modulus of Elasticity (E_b).

It was chosen to consider the following Popovič model for properties and the guarantees offered in the post-critical behaviour, as described in [15]. As in EN 1992-1-2 [16] for concrete, this model was adapted to the variation of the mechanical properties with high temperatures, assuming the following form:

$$\hat{\sigma}\left(\varepsilon,\theta\right)=f_c\left(\theta\right)\frac{\varepsilon}{\varepsilon_{cu0}\left(\theta\right)}\frac{n}{n-1+\left(\dfrac{\varepsilon}{\varepsilon_{cu0}\left(\theta\right)}\right)^n}, \tag{2}$$

where the n parameter characterizes each type of material, regardless of the temperature. The determination of this parameter has been carried out considering the full pairs of dimensionless values $[\sigma/f_c(\theta);\ \varepsilon/\varepsilon_{cu0}(\theta)]$ (both belonging to the range [0; 1]) recorded during the execution of the tests on each specimen. The total number of these pairs of values for each material had an order of $10^4 \div 10^5$ (e.g. for CLAY material was about 1.61×10^5, while for AAC was 4.00×10^4).
The value of n that minimizes the mean squared error (MSE) has been determined by applying the non-linear regression algorithm of Levenberg–Marquardt (LMA), based on the method of least squares, to these pairs of values on the Popovič model. The n parameter with the functions (2) for each material are shown in Figure 4, where a high value for CLAY is apparent. As n tends to $+\infty$, the expression (2) tends to the linear form for $\varepsilon/\varepsilon_{cu0}(\theta) \in [0; 1]$, so for CLAY material a linear constitutive model is proposed according to the Annex D of EN 1996-1-2 [10] as in the following expression (3).

$$\hat{\sigma}\left(\varepsilon,\theta\right)=f_c\left(\theta\right)\frac{\varepsilon}{\varepsilon_{cu0}\left(\theta\right)}. \tag{3}$$

For AAC material the constitutive law (2) assumes the expression (4) that follows:

$$\hat{\sigma}\left(\varepsilon,\theta\right)=f_c\left(\theta\right)\frac{\varepsilon}{\varepsilon_{cu0}\left(\theta\right)}\frac{7.9}{6.9+\left(\dfrac{\varepsilon}{\varepsilon_{cu0}\left(\theta\right)}\right)^{7.9}}. \tag{4}$$

It is important to point out the independence of n from the temperature. It has been proven through the application of an adapted k-fold cross-validation procedure to the regressions done. In fact, in this case k represented the number of temperatures at which the tests were conducted and the k-folds were the number of sets of all stress-strain readings taken at the same temperature for the various materials.

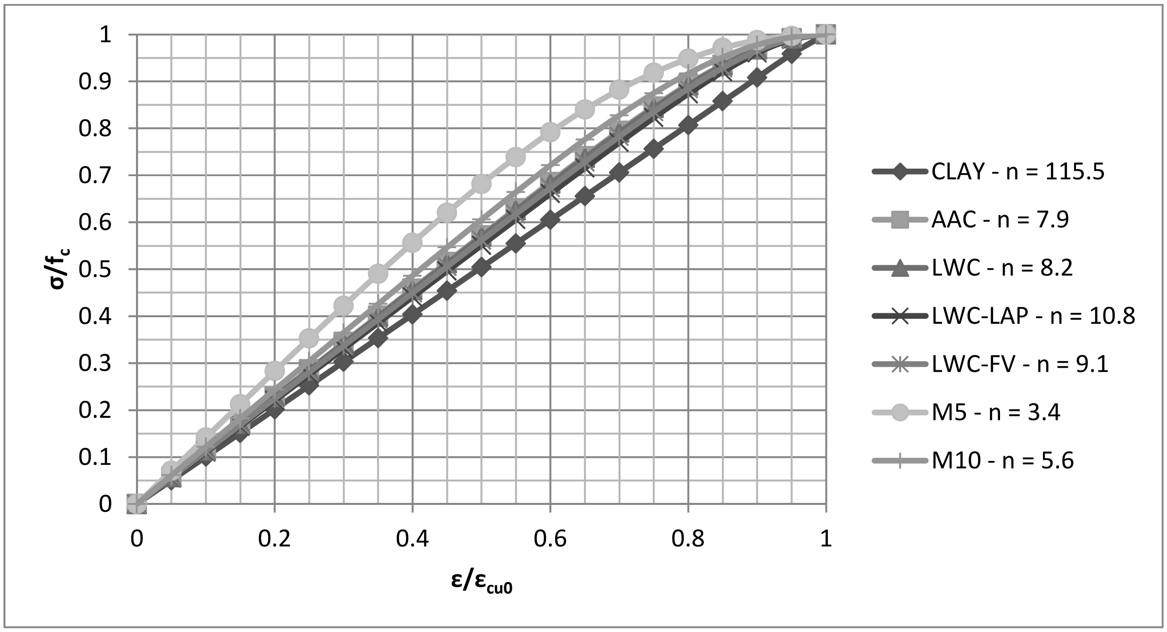

Figure 4: Stress-strain models for tested materials with "n" parameter related values.

A single subsample, among the *k* ones, was used as validation data for the model testing, while the remaining *k*−1 subsamples were used as training data. The cross-validation process has been then repeated *k* times (the folds), and each of the *k* subsamples was used exactly once as validation data. The *k* results from the folds then can be averaged to produce a single estimation. The advantage of this validation method is that all observations were used for both training and validation, at the same time, and each observation was used for validation exactly once.

In this specific case, the LMA has been reapplied *k* times for the determination of the *n* value on all the stress-strain readings belonging to the union of the *k*-1 sets (training data), and then the MSE of that one related to the generic *k* set has been calculated.

In this way, the independence of *n* from the temperature could be proved. Indeed the average value of this parameter deduced from the training sets is close to that obtained over the whole sample of the readings, and that the value of the MSE determined on validation subsets maintains a steady value. More details are reported in [17].

Finally, it is relevant to compare the proposed model and parametric curves defined in Annex D of EN 1996-1-2 [10]. The Figures 5 and 6 show the overlapping graphs of the expression (2), the constitutive law proposed by this Eurocode and the experimental curves relating to materials AAC and CLAY. It is easy to observe that in both cases the constitutive law suggested by Eurocode does not follow the trend of the experimental curves. This aspect is much more marked in AAC where for temperatures higher than 400°C such bond diverges greatly from the experimental data. However in the cases of AAC and CLAY the proposed model reduces the mean square error percentage, from experimental results, of about six times in respect to those provided by the Annex D of EN 1996-1-2 [10].

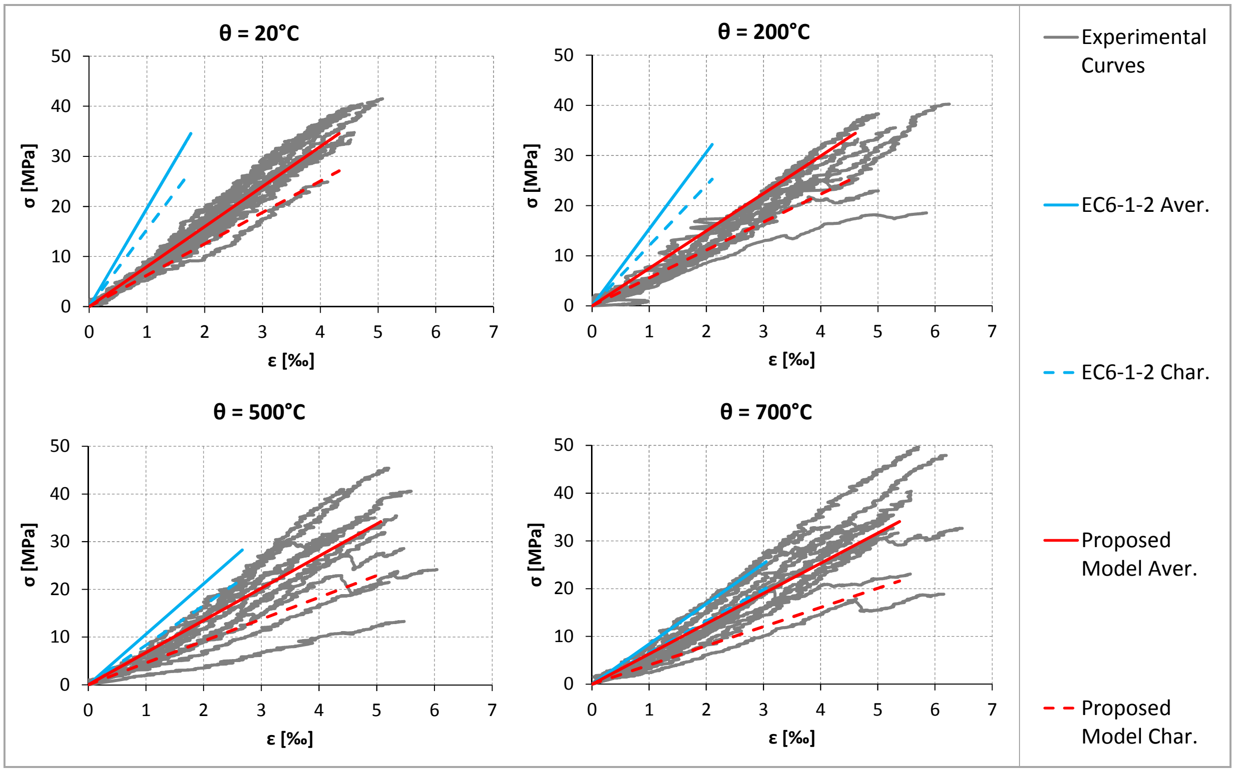

Figure 6: Proposed Constitutive Law for CLAY in comparison with EN 1996-1-2 Annex D.

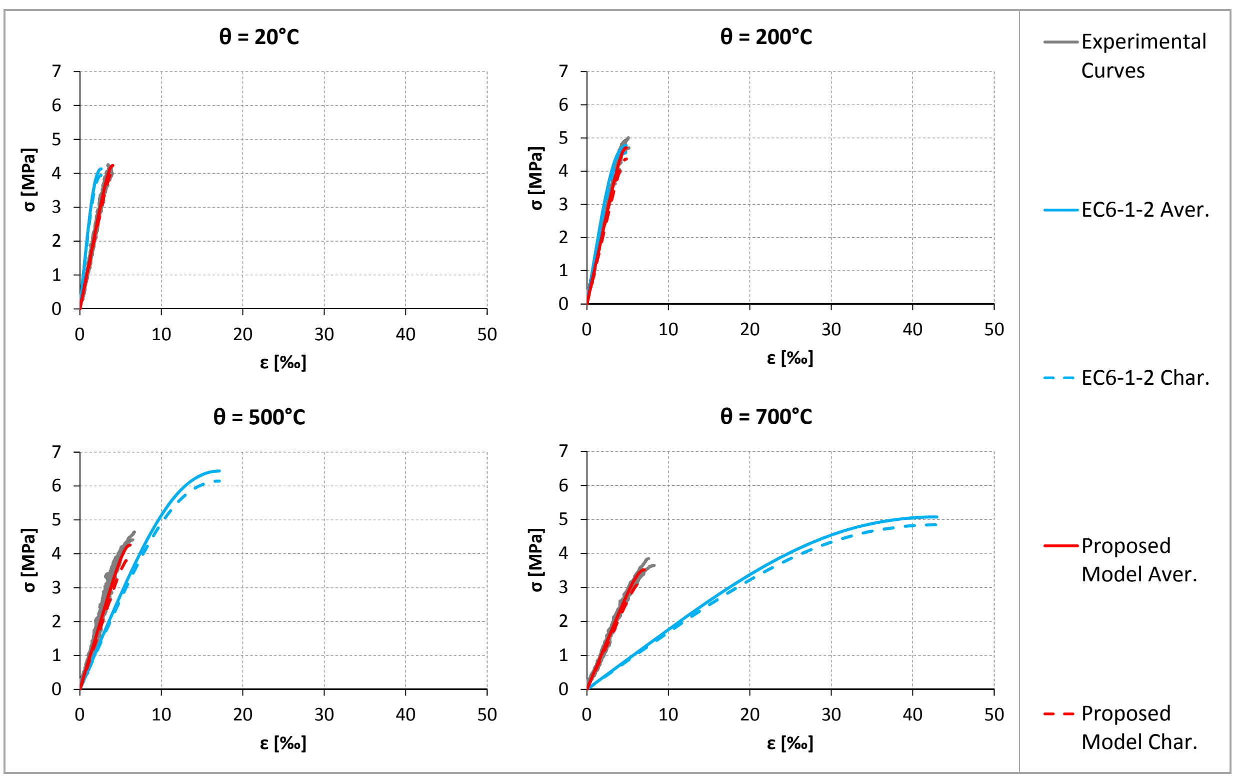

Figure 7: Constitutive Law for AAC in comparison with EN 1996-1-2 Annex D.

CONCLUSIONS

The described tests allowed to appreciate the variation of the constitutive law of materials for masonry walls at different temperatures: the parametric stress-strain curves can provide a basis for modelling of masonry walls subjected to fire action.

The mechanical behaviour at high temperatures, deduced only by experiments on materials, makes it necessary to take into account mechanical interaction between mortar and blocks together with geometry, texture, dimensions and restrains of panels. It is necessary to validate the procedure with a set of experiments on full scale masonry panels. Moreover a certain dispersion on the experimental results has been found, due to production processes variability of clay specimens, which would require further experimental tests on portions of wall panels.

Nevertheless, the trend of resistance and axial deformation in dependence on the temperature for different materials can provide useful information for design in case of compressive stress. In case of eccentric compressive actions, it can be also referred to the procedure proposed by Andreini & Sassu in [18] and [19], using M–N (out-of-plane bending moment – axial force) or N–e (axial force – out-of-plane eccentricity) crushing domain for masonry panels, depending from the time of exposure to “one-side” at the nominal fire load condition.

ACKNOLEDGEMENTS

The authors wish to thank ANDIL Assolaterizi, Fornaci Giuliane S.p.A., RDB Hebel S.p.A., LecaSistemi S.p.A., Assobeton, UNIBLOC S.r.l. and the National Fire Corp (Central Direction for Prevention and Technical Safety) for their assistance and support.

REFERENCES

1. Nadjai, A., Laverty, D., O’Garra, M. (2001)“Behaviour of compartment masonry walls in fire situation”. Civil and Structural Engineering Computing. B. H. V. Topping (Editor).
2. Nadjai, A., O’Garra, M., Ali, F. (2003)“Finite element modelling of compartment masonry walls in fire”. Computers & Structures 2003; 81(18-19): 1923-1930. DOI:10.1016/S0045-7949(03)00212-8.
3. Abrams, M.S. (1971) “Compression strength of concrete at temperatures to 1600 F. Effect of temperature on concrete”. Portland Cement Association Research and Development.
4. Thelandersson, S. (1971) “Effect of high temperature on tensile strength of concrete”. Division of Structural Mechanics and Concrete Construction. Institute of Technology, Neostyled.
5. Terro, M.J. (1988) “Numerical modeling of the behaviour of concrete structures in fire”. ACI Structural Journal 1998; 95(2): 183-193.
6. Anderberg, Y., Thelandersson, S. (1976)“Stress deformation characteristics of concrete at high temperatures”. Division of Structural Mechanics and Concrete Construction. Institute of Technology. Bulletin 54.
7. Al Nahhas, F., Ami Saada, R., Bonnet, G., Delmotte P. (2006) “Resistance to fire of walls constituted by hollow blocks: Experiments and thermal modelling”. Applied Thermal Engineering 2006; 27(1): 258-267. DOI:10.1016/j.applthermaleng.2006.04.017.
8. Shiels, T.J., O’Connor, D.J., Silcock, G.W.H., Donegan, H.A. (1988) “Thermal bowing of a model brickwork panel”. Proc. 8th International Brick/Block Masonry Conference,. Dublin, Ireland, 1, 846-856.

9. Dhanasekar, M., Chandrasekaran, V., Grubits, S.J. (1994) “A numerical model for thermal bowing of masonry walls”. Proc. 10th International Brick/Block Masonry Conference, Calgari, Canada.
10. EN 1996-1-2:2005, Eurocode 6: Design of masonry structures – Part 1-2: General – Structural fire design.
11. Hahn, C., Hosser, D., Richter, E. (1998) “Development of a detection method for determining of the fire behaviour of masonry”. Fraunhofer IRB Verlag, Stuttgart. (in German).
12. Nguyen, T.D., Fekri, M., Chammas, R., Mebarki, A. (2009) “The behaviour of masonry walls subjected to fire: Modelling and parametrical studies in the case of hollow burnt-clay bricks”. Fire Safety Journal 2009; 44(4): 629-641. DOI:10.1016/j.firesaf .2008.12.006.
13. Andreini, M., Caciolai, M., La Mendola, S., Mazziotti, L., Sassu, M. (2011) “Mechanical behaviour of masonry materials at high temperatures”. Submitted manuscript.
14. Andreini, M., De Falco, A., Sassu, M. (2012) “Experiences and Analysis on Masonry Materials subjected to High-Temperature”. Proceedings of 15th International Brick and Block Masonry Conference, 3-6 June 2012, Florianópolis, Santa Catarina, Brazil. ISBN 978-85-63273-09-3.
15. Popovič, S. (1973) “A numerical approach to the complete stress-strain curve of concrete”. Cement and Concrete Research 1973; 3(5): 583–599. DOI:10.1016/0008-8846(73)90096-3.
16. EN 1992-1-2:2005, Eurocode 2: Design of concrete structures – Part 1-2: General – Structural fire design.
17. Andreini, M. (2013) “Mechanical behaviour of masonry walls subjected to fire action”. Ph D. dissertation, under revision by scientific committee.
18. Andreini, M., Sassu, M. (2010) “Behaviour of Masonry walls subjected to fire: Experimental tests and analytical model”. Proc. of SEMC 2010, 6-8 Sept. 2010, Cape Town, South Africa. In Advances and Trends in Structural Engineering, Mechanics and Computation. A. Zingoni (Ed.).
19. Andreini, M., Sassu, M. (2011) “Mechanical behaviour of full unit masonry panels under fire action”. Fire Safety Journal, 2011; 46(7): 440-450. DOI: 10.1016/j.firesaf.2011.07.004.