

CILASCI

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**5º CONGRESSO IBERO-LATINO-AMERICANO
EM SEGURANÇA CONTRA INCÊNDIOS**

***5th IBERIAN-LATIN-AMERICAN CONGRESS
ON FIRE SAFETY***

15-17 /07/ 2019 - Porto, Portugal

**Atas dos Artigos
Proceedings (full papers)**

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PUBLISHER:

ALBRASCI - Associação Luso-Brasileira para a Segurança Contra Incêndio

ALBRASCI - Luso Brazilian Association for Fire Safety

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BOOK COVER DESIGN:

Soraia Maduro – Instituto Politécnico de Bragança

INTERNET WEB PAGE:

Pedro Oliveira – Instituto Politécnico de Bragança

EDITION:

1ª, Julho de 2019

ISBN:

978-989-97210-3-6

IMPRINT:

Tipografia Artegráfica Brigantina

NOTE:

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PREFACE

The Iberian-Latin American Congress on Fire Safety (CILASCI) is held once every two years, with the aim of disseminating scientific and technical knowledge in the field of fire safety, integrating different players involved in this area of knowledge. The first edition of the Iberian-Latin American Congress on Fire Safety (CILASCI 1), was held in Natal (Brazil) between 10-12 March 2011. The second congress (CILASCI 2) was held in Coimbra (Portugal), between May 29 and June 1, 2013. The 3rd and 4th editions took place on the South American continent. The third congress (CILASCI 3) was held in Porto Alegre (Brazil) from November 3 to 6, 2015, while the fourth congress (CILASCI 4) was held in Recife (Brazil) from 9 to 11 October 2017. The CILASCI 5 will take place in the city of Porto (Portugal) from 15 to 17 July 2019, and presents 5 invited lectures and 78 manuscripts (full papers) from researchers around the world (Algeria, Australia, Belgium, Brazil, China, Czech Republic, France, Hong Kong, Italy, Mozambique, Portugal, Spain, United Kingdom and United States).

the 5th Iberian-Latin-American congress on fire safety reflects the new developments achieved on active and passive fire protection, on evacuation and human behaviour under fire, on computational modelling of structures and materials under fire, on explosion and risk management, on architectural issues for fire safety in buildings, on fire dynamics, on the experimental analysis of materials and structures under fire, on fires in special buildings and spaces, on fire-fighting operations and equipments, and on the behaviour of structures and materials under fire.

The Fire Safety is reaching new developments as a result of new research, development and innovation around the world, based on the excellence level of the research, the support of new skilled professionals and due to the existence of advanced training programmes in fire science technology. This development will increase the safety level of people, buildings, and products, but also is going to produce an impact in the economy of each country, with a positive impact on society.

The organizing committee believe that this congress will address to our delegates a wide forum of discussion about the recent developments in Fire Safety, promoting the exchange of ideas and international cooperation.

The organizing Committee would like to thanks to all authors and delegates.

On the behalf of the Organizing Committe
Paulo A. G. Piloto

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**FIRE BEHAVIOUR OF ECOLOGICAL SOIL-CEMENT BLOCKS WITH
WASTE INCORPORATION – EXPERIMENTAL AND NUMERICAL
ANALYSIS**

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1. INTRODUCTION

The increasing interest on earth construction as a sustainable building solution (low CO₂ emissions and capacity to return the earthen materials back to nature after their life-cycle), led to the development of modern earth construction techniques, and particularly of masonry made of compressed earth blocks (CEBs). Soil is an abundant raw material, recyclable and reusable, non-combustible, non-toxic, with significant thermal behaviour and without too expensive transformation processes, which allows selecting this material as a major possibility for sustainable construction. In fact, earth construction can constitute a feasible solution for a more sustainable construction industry in developed countries. However, the major drawback is that traditional earthen materials are typically considered as non-standard. The great variability and heterogeneity of the properties of the available soils as well as the lack of quality control in the manufacturing of the earthen materials and in the construction process can be pointed out as the main reasons behind this situation.

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Traditional earth construction has been successively subjected to improvement of earthen materials and building techniques in order to overcome the aforementioned limitations. Masonry built with CEBs is probably the most relevant case of improvement introduced in the earth construction technology, as these blocks can be seen as an upgrade of the adobes.

CEBs are manufactured resorting to specific presses, where the moistened earth is statically compacted in a mould to form the block, which is immediately demoulded and put to dry [1]. Nowadays, hydraulic presses can be used instead allowing higher compaction pressure and thus increasing mechanical properties [2]. The chemical stabilisation of the soils by addition of components (binders) as cement and lime is often used in the manufacturing of CEBs to increase the mechanical properties of the CEBs and decrease their susceptibility to variations of moisture. An advantage of soil-cement blocks is the possibility of adding other materials to the mix, especially disposable material, which is an important factor for sustainable construction.

The main goal of the present study is to assess the behaviour of soil-cement blocks with incorporation of organic wastes. The problem of waste accumulation exists worldwide and has become a concern for today's society, leading to enormous environmental damage. One of the possibilities for reducing their environmental impact is the reuse of these wastes in new materials. However, incorporating wastes changes mechanical, physical and thermal properties of the new material. In order to evaluate the potential use of the wastes in blocks composition, laboratory tests were conducted and results were analysed [3].

This paper presents the fire behaviour of ecological soil-cement blocks with waste incorporation. At high temperatures, physical and mechanical changes were evaluated in the tested elements. Therefore, an experimental program was performed using sample of wall panel with soil-cement blocks. Previously, thermomechanical behaviour on cylindrical samples at different temperature ranges have been studied [4]. The highest temperature tested was 600 °C. The wall specimen under fire conditions was also analysed by a non-linear transient finite element numerical model, in time and temperature domains, and the numerical and experimental temperature fields were compared.

2. COMPRESSED EARTH BLOCKS WITH WASTE INCORPORATION

2.1 Materials

The compressed earth blocks with incorporation of wastes were manufactured with an artificial soil (mixing 70% of sand and 30% of kaolin), cement (10% of dry soil mass), water and the organic compound (20% of compound in replacement of dry sand volume), provided by the company "Resíduos do Nordeste". The option for an artificial soil instead of a natural soil was due to the fact of attempting to minimize the factors that can influence the final results, since natural soils are very heterogeneous [4].

In order to ascertain the suitability of the soil to stabilization with cement, particle size analysis and determination of consistency limits are required. Once the soil was selected, compaction test

were performed for composition to be studied, in order to assess the compaction control values, since the soil-cement is the product resulting from the mixture of soil, cement, water and waste, that compacted in the optimum humidity ($w = 9,7\%$) and under the maximum density ($\gamma_d = 2,1 \text{ g/cm}^3$), acquire resistance and durability through the hydration reactions of the cement.

2.2 Manufacturing of CEBs

The blocks were moulded individually and the process started by drying first the sand, kaolin, cement and waste in amounts previously determined. After dry, the elements of composition were mixed, the water added and mechanical mix continued until the final material shown homogeneity. Figure 1a) shows the equipment used to mould the CEBs. The manufacturing conditions were maintained for all blocks, Figure 1b). After moulding the blocks, the curing period has proceeded in a humid chamber where they were maintained at a substantially constant 95% humidity and at a temperature of $\pm 20 \text{ }^\circ\text{C}$, see Figure 1c).

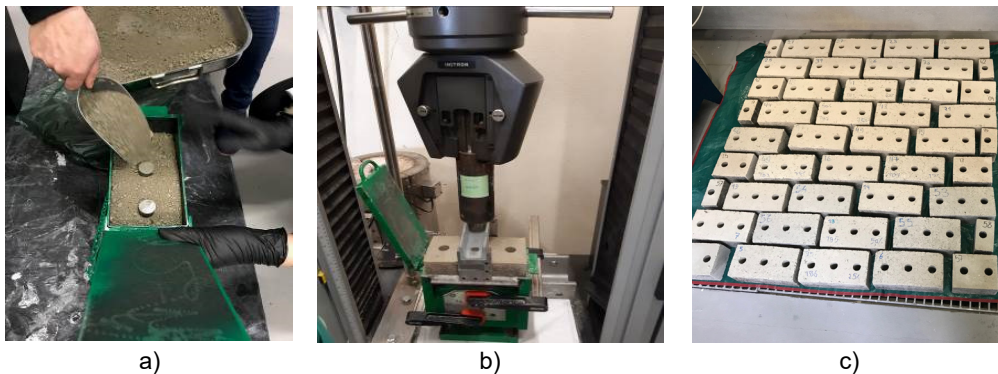


Figure 1: a) Moulding equipment; b) Fabrication of CEBs; c) CEBs in humid chamber.

2.3 CEBs panel and construction details

The wall panel had $1 \times 1 \text{ m}^2$, tested in a fire resistance furnace according to EN 1364-1 [5] applied for non-loadbearing elements. Fire resistance is a measure of the ability of a building element to resist a fire, usually the time for which the element can meet appropriate criteria during exposure to a standard fire resistance test. Two performance criteria were verified which are the integrity and the insulation.

The CEBs panels studied were composed of 11 alternating strands organized in three different ways, Figure 2. The geometry of the blocks that form the panel consists in a hollow block with dimensions $220 \times 110 \times 80 \text{ mm}^3$ (width \times thickness \times height), as can be seen in Figure 3. The geometry of the CEBs and the respective building system was based on an output from a previous partnership between the University of Minho and the University of Trás-os-Montes e Alto Douro [6, 7].



Figure 2: CEBs wall panel.

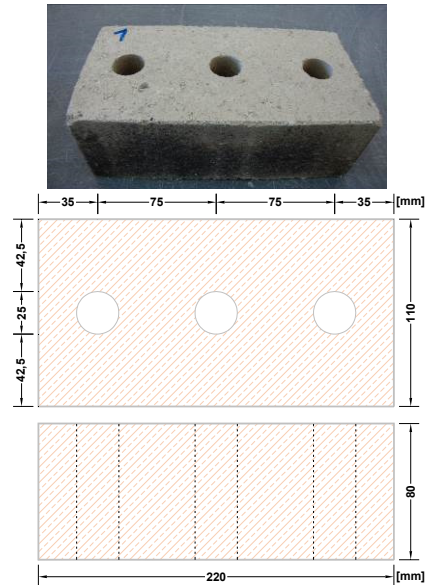


Figure 3: Dimensions of the CEBs blocks.

2.4 CEBs panel instrumentation

The thermal behaviour of CEBs panel exposed to the fire was evaluated using several thermocouples for measuring both internal and external temperatures of the wall. The entire procedure is based on European standard for the general requirements for fire testing [8] and the specific requirements for the fire testing of non-loadbearing walls (testing conditions, specimen preparation, specimen fixation, conditioning and instrumentation) [5]. According to these standards, two performance criteria should be evaluated through all tests: the insulation and integrity criteria. The insulation criterion is the time, in completed minutes, for which the test specimen continues to maintain its separating function during the test without developing temperatures on its unexposed side which increase the average temperature above the initial average temperature: i) by more than 140 °C (fire insulation criterion 1), ii) or increase more than 180 °C at any location of the unexposed side above the initial average temperature (fire insulation criterion 2). The integrity is the ability to prevent the fire and the smoke transmission through the element. The integrity criterion was verified throughout the experiments by employing a cotton wool pad saturated in ethyl alcohol.

Different types of thermocouples were installed to verify the evolution of the CEBs panel' temperature during the test. Simple type K thermocouples have been placed at different depths from the unexposed surface (27,5 mm, 55,0 mm and 82,5 mm) in order to obtain temperature records: inside the block (TB), Figure 4a), in the mortar (TM), Figure 4b), and inside the blocks holes (TH), Figure 4c). The unexposed surface was also instrumented using type K thermocouples welded on copper discs protected by plasterboard (TD), Figure 4d), used for

measuring temperatures at specific panel points in order to assess and to verify the insulation criterion. The thermocouples were placed according to Figure 5.

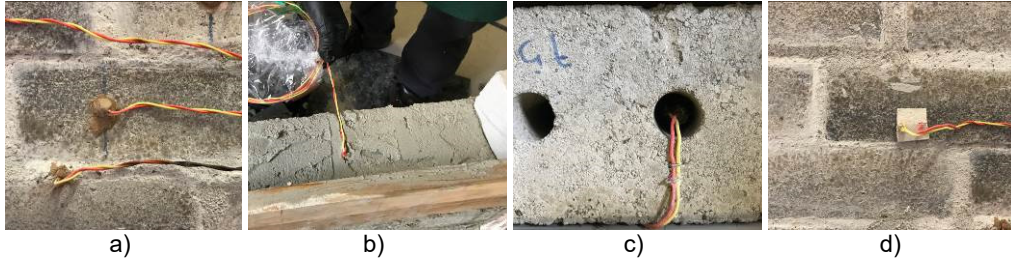


Figure 4: Type K thermocouples-

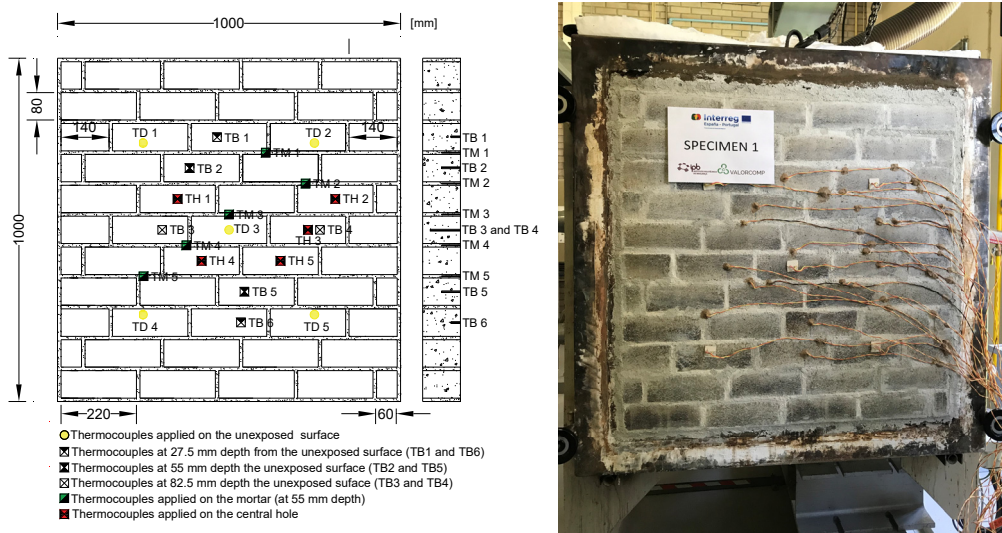


Figure 5: Thermocouples location.

3. EXPERIMENTAL TEST

Fire test was performed in a resistance furnace prepared to work with the standard fire curve ISO 834 [9]. At the beginning of the tests, the CEBs wall panel was at the ambient laboratory temperature of about 20 °C and air humidity around 65%. The ambient air temperature shall be monitored at a distance of between 1 m and 3 m horizontally away from the unexposed face under conditions such that the sensor is not affected by thermal radiation and the ambient air temperature shall be 20 °C ± 10 °C, Figure 6. During the test, the integrity of the wall and the insulation of the panel were evaluated by assessing the unexposed surface temperature according to European standard [8].

The test was performed over a period of time of 90 min corresponding to a maximum real temperature in the furnace of 1000 °C. It can be observed that the CEBs did not suffer damage

nor crack, Figure 7, but small cracks appeared in the mortar which allowed smoke released from the burning of the blocks and the compound volatilization. When the wall was disassembled it was possible to observe the change of colour of the blocks due to its exposure to fire, as can be seen in Figure 8.

The integrity criterion was also verified because there was no flame or ignitions of the cotton. At the same time, the insulation criterion was as well verified taking into account that the higher value of temperature measured in thermocouple TD2 was of 92 °C.



Figure 6: Ambient air temperature monitored.



Figure 7: Integrity of the CEBs panel.



Figure 8: CEBs after expose to the fire.

4. NUMERICAL ANALYSIS

The wall was analysed numerically using a nonlinear transient heat transfer analysis by the finite element method, using the software Ansys® [10]. The complete wall, CEBs and mortar, was modelled by 3D Solid90 finite elements. This element is a high order element with 20 nodes and with temperatures as a single degree of freedom. The temperature field is determined accordingly to the energy equation, see equation (1), considering the solid material thermal capacitance and the conduction heat flux.

$$\frac{d}{dt}(\rho(T) \cdot c_p(T) \cdot T) = \frac{d}{dx}\left(k(T) \cdot \frac{dT}{dx}\right) + \frac{d}{dy}\left(k(T) \cdot \frac{dT}{dy}\right) + \frac{d}{dz}\left(k(T) \cdot \frac{dT}{dz}\right) \quad (1)$$

Convection and radiation were considered in the exposed and unexposed surfaces, taking into account the boundary condition represented in equation (2):

$$k(T) \frac{dT}{dn} = h_c \cdot (T_s - T_\infty) + \varepsilon \cdot \sigma_{sb} \cdot (T_s^4 - T_\infty^4) \quad (2)$$

where $k(T)$, $\rho(T)$ and $c_p(T)$, are the thermal conductivity, the specific mass and the specific heat for CEBs and mortar. h_c is the convection heat transfer coefficient, considered as 25 W/m²K for the exposed surface and 4 W/m²K for the unexposed outside surface. Radiation is also added to both surfaces, and defined by an emissivity equal to 0.85 to CEBs and mortar, and the Stefan-

Boltzmann constant σ_{sb} . T_{∞} represents the air temperature in contact to the surface, at temperature T_s , being defined by the standard fire curve ISO834 and the ambient temperature, for the exposed and unexposed faces, respectively.

CEBs are made from compressed earth and are consequently porous. The heat transfer inside the block occurs in different ways, namely conduction in the solid, liquid and gas fractions, convection and radiation in the porous fraction. Additionally, endothermic and exothermic reactions are present due to water and cement presence. An equivalent thermal conductivity should consider all these heat mechanisms, but for CEBs there is a lack of information of thermal properties varying with temperature.

The model considers the solid specific mass temperature variation from the equation defined in the Eurocode EN 1992-1-2, [11], for concrete mortar, considering the measured values at ambient temperature. This Eurocode was also used to establish the specific heat and thermal conductivity temperature variation, according to the moisture of mortar. For the CEBs the Eurocode was also used, but to allow for the heat consumed during water evaporation, a specific heat peak was calculated from the measured moisture content and water latent heat of vaporisation (2260 kJ/kg), assuming that water vaporization occur between 100 °C and 200 °C, giving a peak value at 150 °C equal to $1170 + 3977,6 = 5147,6$ J/kg.K.

Thermal conductivity of CEBs is influenced by several factors, being the most relevant the compaction pressure, block porosity, moisture and cement contents [12, 13]. The work of Zhang *et al* [13] showed that thermal conductivity is much more influenced by the bulk density rather than cement content. This occurs due to the decrease in porosity when the compaction pressure increases gives a higher bulk density. SEM images from Zhang's work show that for a bulk density around 2,0 g/cm³ the CEBs have porous close to 100 µm diameter. This porous size can be expected to increase when CEBs are exposed to elevated temperature causing the water content to evaporate. Mansour *et al* [12] work to study the influence of compaction pressure and porosity on thermal conductivity give a porosity equal 26,5% to CEBs of bulk density equal to 2,06 g/cm³, and for a moisture content of 3,23% a thermal conductivity equal to 1,12 W/mK.

Considering the unknown variation of thermal conductivity with temperature, an effective thermal conductivity was used, considering the average porosity from the Russell model [14]. This model consider the average porosity (φ) as well as solid (k_s) and gas (k_g) thermal conductivities.

$$k_{eff} = k_s \frac{\varphi^{2/3} + \left(\frac{k_s}{k_g}\right)(1 - \varphi^{2/3})}{(\varphi^{2/3} - \varphi) + \left(\frac{k_s}{k_g}\right)(1 - \varphi^{2/3} + \varphi)} \quad (3)$$

The gas thermal conductivity includes the conductive term given by the air conduction heat transfer coefficient, presented in equation (4) [15], and by an irradiative component.

$$k_g = -1,881 \times 10^{-8}T^2 + 8,38 \times 10^{-5}T + 0,002244 \quad (4)$$

Radiation inside porous material was modelled as a series of parallel opaque planes with separation equal to the cell size, giving a irradiative contribution to the total effective conductivity defined in [16] by equation (5):

$$k_r = 4 \frac{\epsilon}{2 - \epsilon} \sigma d T^3 \quad (5)$$

where ϵ is the wall emissivity, taken as 0,85, σ is the Stefan-Boltzmann constant and d the pore diameter, considered equal to 160 μm . Russell model was applied after water dehydration due the increased importance of porosity. In order to approximate experimental and numerical results, an increase variation between 50 °C and 100 °C was used. Figure 9 presents these properties in function of temperature.

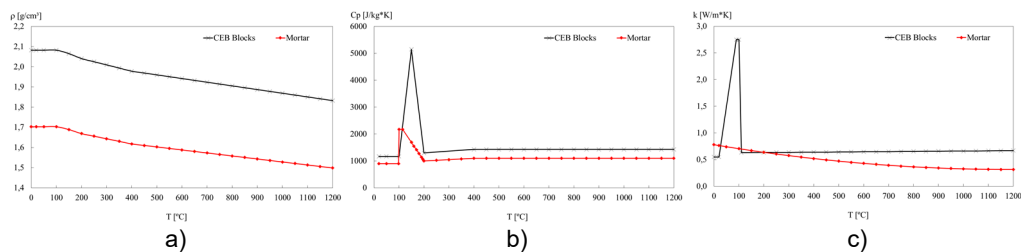


Figure 9: CEB Blocks and mortar physical and thermal properties: a) Specific mass, b) Specific heat, c) Thermal conductivity.

5. EXPERIMENTAL AND NUMERICAL RESULTS

The following figures (Figure 10 to Figure 12) show the experimental time-temperature evolution of the fire exposed surface (T_e) and the corresponding numerical results (T_n) of the CEBs wall panel related to the thermocouples located on the CEBs (TB), on the CEBs holes (TH) and on the mortar (TM). Figure 13 shows the temperatures recorded by the thermocouples applied in the unexposed surface of the CEBs wall panel.

5.1 Experimental results

From Figure 10 it can be seen that thermocouples TB3 and TB4 (which are placed in the block at 82 mm depth from the unexposed fire surface) recorded the highest temperatures of approximately 400 °C. Concerning the thermocouples located near the unexposed surface (27,5 mm deep), the temperature was 115 °C. The thermocouples placed inside the block hole recorded temperatures between 270 °C and 320 °C, it was noticed that thermocouples positioned on the left side recorded lower temperatures than thermocouples positioned on the right side, Figure 11. The thermocouples placed in the mortar recorded temperatures between 225 °C and 325 °C, the thermocouples positioned in the centre of the panel recorded the higher values, see Figure 12.

From Figure 13 it is noticed that the temperatures of the unexposed surface reached 90 °C in all thermocouples. According to EN 1363-1 [8], the insulation criterion was then verified.

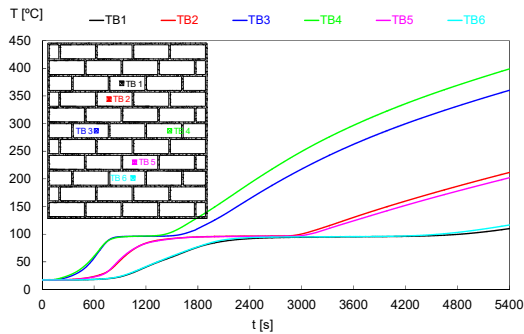


Figure 10: Time-temperature evolution inside the block (TB).

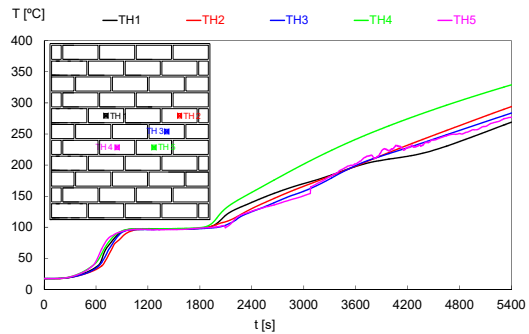


Figure 11: Time-temperature evolution inside the blocks holes (TH).

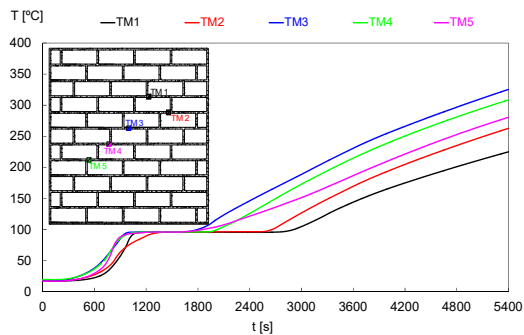


Figure 12: Time-temperature evolution in the mortar (TM).

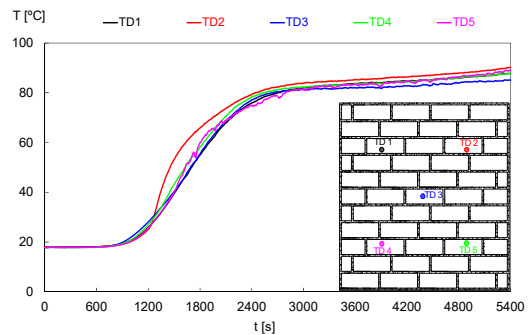


Figure 13: Time-temperature evolution in the unexposed surface (TD).

Comparing Figures 10, 11 and 12 it is noticed that there is a plateau around the temperature of 100 °C. This is due to the moisture content in the panel. Afterwards, the temperatures on the thermocouples began to increase. In this process, the materials accumulate energy in an endothermic process. When the water evaporation ended, the measured temperatures increased again, following the same evolution slope than the initial behaviour.

5.2 Numerical results

The 3D wall model exposed to the ISO 834 standard fire curve is shown in Figure 14. All images are shown with the exposed face towards. The temperature gradient across the wall is similar for the CEBs and for the mortar elements. This is mainly due to the assumed perfect thermal contact between both materials, neglecting any thermal conductance between both surfaces. Additionally, CEBs holes were modelled as cavities, living radiation between surfaces possible. However, due to the temperature levels, no temperature gradient around the holes was found in comparison to the solid CEBs section.

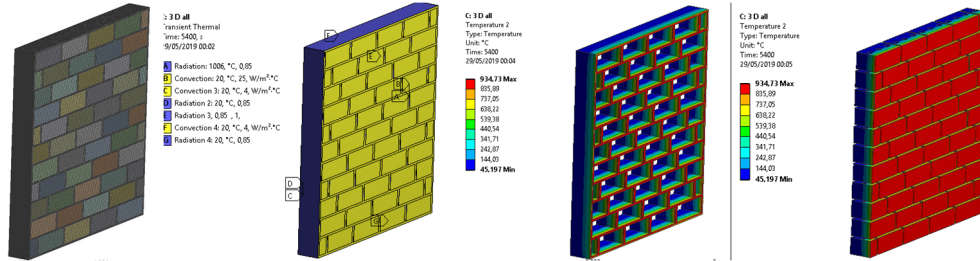


Figure 14: Finite element wall model with CEBs and mortar temperature fields.

Although convection and radiation heat losses were modelled in the contour wall faces, the major heat flux is through the wall thickness. This is evident in Figure 15, where the experimental and numerical results are compared. This Figure shows the temperature variation in three different points, corresponding to the depths of TB1, TB2 and TB3, defined in Figure 5.

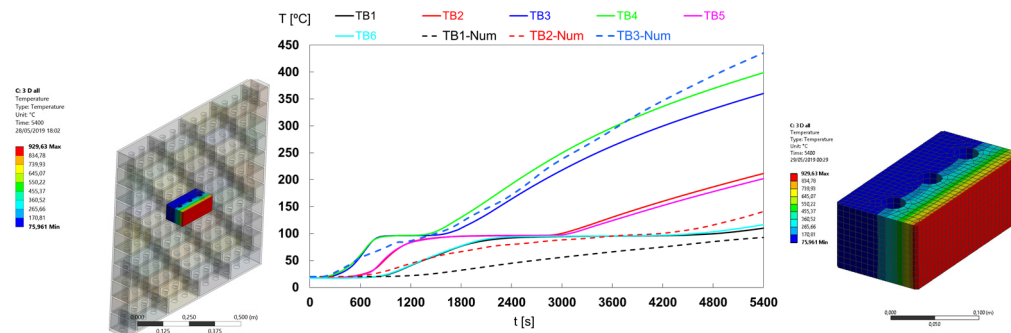


Figure 15: CEBs temperature distribution and comparison between experimental and numerical results.

The difference between numerical and experimental temperatures increase from the exposed to the unexposed wall face. Being noticed a higher difference for the TB1 position, which numerically stays below the 100 °C. Even the dehydration experimental plateau is remarkably higher than the numerical, giving some evidence to a better definition of the thermal conductivity and specific heat.

5.3 Infrared (IR) thermography

In the following figures one can see the infrared (IR) thermography diagrams at different testing stages. The results of the IR thermography complement the above ones since the surface temperatures of the entire unexposed surface of the panel can be assessed. In contrast, thermocouples measured temperatures locally. This field measurement is of great importance to define the position of thermocouples used to find maximum temperature events in future tests. Figure 16 shows the evolution of temperatures of the outer face of CEBs wall panel. According to the IR thermography, the increasing of temperature was noticed after 30 min and ranged to a maximum of 90 °C. Comparing the respective time temperature evolution obtained by the

thermocouples placed unexposed surface and using infrared thermography, comparing these two data acquisition procedures, it is possible to figure out that there is an adequate accordance.

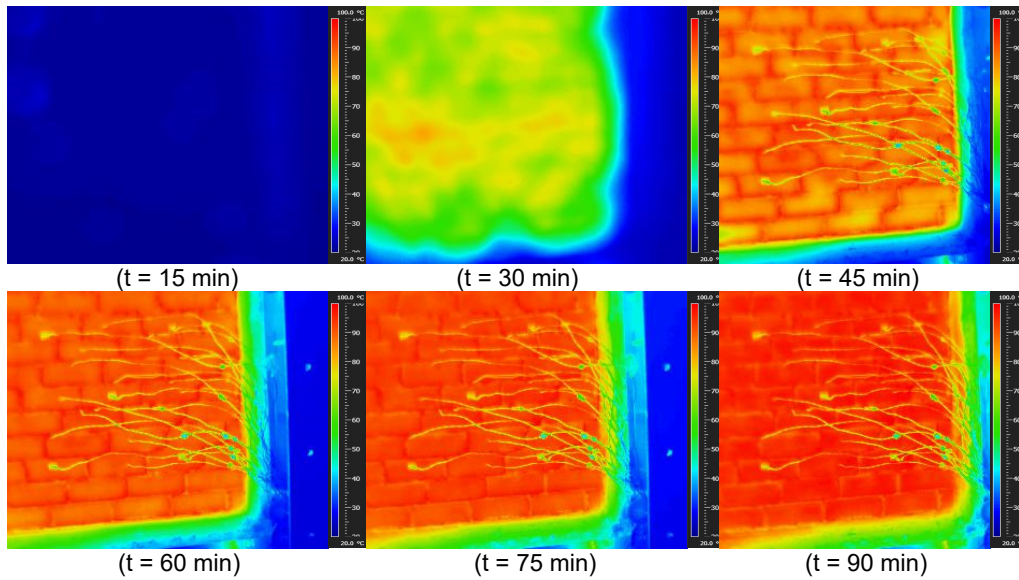


Figure 16: Infrared thermograph diagrams of CEBs wall panel.

6. CONCLUSIONS

The incorporation of wastes into the soil-cement mixtures allows another use for the compound, while saving the amount of soil and cement to be used. This paper presents an experimental program related to fire behaviour of CEBs walls, concerning its fire resistance. The CEBs panel, with the incorporation of wastes, was manufactured in laboratory. The CEBs panel represents a portion of a real-scale wall, and all the dimensions are real ones, like the one can be met in real buildings. Experimental results allowed the authors to verify that both criteria (insulation and integrity) defined in the European standard for fire resistance tests [5, 8]. Suitability is related to the material's ability to remain intact for a given period of time and under adverse temperature conditions, thus ensuring insulation integrity conditions.

The insulation criterion verification was conducted according to the relation between the average temperature increase and the average initial temperature, which was not higher than 140 °C. Moreover, the maximum temperature at any point of the unexposed surface of the CEBs panel did not exceed the final temperature of 180 °C. The integrity criterion was observed throughout the experiments, no flame has been identified. However, a smoke release from burning CEBs was noticed since middle of the test.

The temperatures evolutions were linear up to 100 °C, and then a plateau corresponding to evaporation of the humidity of the blocks was noticed. After the moisture content in the panel had evaporated the temperatures increase again with a similar slope as in the beginning.

It can be seen that the highest temperatures were recorded near to the exposed surface, as it was expected.

The comparison between the numerical and experimental temperature results gives a higher difference on the unexposed wall side. It is evident the need to define clearly the CEBs' thermal properties temperature variation.

7. ACKNOWLEDGMENTS

The VALORCOMP project, supported by the FEDER through the INTERREG Program V-A Spain-Portugal (POCTEP) 2014-2020 is acknowledged.

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