The influence of thermal gradients on the fire behavior of raw earth and cement stabilized bricks at various water contents

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RESUME : Le but de cette étude est d'examiner l'effet des gradients thermiques sur le comportement global au feu des matériaux en terre crue avoir été exposés au feu à une vitesse de chauffage rapide. Des briques de terre crue compactées à 50 MPa et des briques stabilisées au ciment (3,5 % de ciment) compactées au niveau de la charge Proctor ont été fabriquées. Les deux matériaux partageaient une propriété initiale de résistance à la compression similaire. Avant l'essai au feu, les briques ont été soumises à quatre conditions de conservation différentes afin d'obtenir quatre teneurs en eau différentes. Les conditions de cure sont : séchage à l'étuve à 80 °C et trois autres conditions humides avec 50, 75 et 100 % d'humidité relative à température ambiante. Des thermocouples ont été intégrés dans les briques, qui ont ensuite été soumises à la courbe de feu ISO 834-1. La mesure des gradients thermiques a permis de mieux comprendre l'occurrence d'instabilités au cours du chauffage de type feu.

Mots-clefs : Terre crue, Comportement au feu, Teneur en eau, Gradients thermiques.

I. INTRODUCTION

Earthen materials have recently resurfaced in the race of construction material use. Its environmentally friendly characteristics, such as being an abundant recyclable material that requires less energy implementation, drew the attention of many studies focusing on reducing the world's current economic and environmental challenges. This material has been extensively studied in terms of its thermo-hygromechanical behavior; however, there is some knowledge gap regarding the fire resistance behavior that these studies have overlooked. A behavior that is an important characteristic of the material if it is to be used in residential dwellings that are susceptible to serious high temperature or fire risks.

There has been little research into the fire behavior of earthen materials. In their study of heating earthen samples with radiant panels of 30 and 50 $kW.m^{-2}$, Apte et al. (2008) discovered that earthen materials can act as a barrier to oxygen transmission. Préneron et al. (2017) conducted another study that demonstrated the insulation criteria of earthen materials after exposing earthen blocks to a high heating temperature of 800°C in an oven. They also demonstrated that these materials could not ignite themselves after being heated with a radiant heat source and then subjected to ignition time and extinguishability tests. Beckett et al. (2019) concluded that rammed earthen materials can remain intact during and after heating after carrying out tests with unidirectional heat fluxes of 20, 35, and 50 kW.m^{-2}. Abdallah et al. (2022) conducted a study about earthen materials under fire after exposing raw earth and cement stabilized bricks with varying water contents (by varying the surrounding equalizing conditions) to fire at a very fast heating rate while following the ISO 834-1 fire curve (International standard, 1999). They discovered that both water content and cement stabilization can have a substantial impact on the thermal stability/instability of earthen materials. A characteristic that could have an implication on the utility of those materials in dwellings if they exhibit some thermal instability caused by the breaking of their surface layers.

At the wall scale level, Byrne (1982) demonstrated that a wall made of compressed earth blocks could prove to have an insulation property after subjecting this wall to ISO fire for four hours, with a maximum central deflection of only 24 mm at the end of the test. Buson et al. (2013) observed that earthen walls with kraft papers might prevent the passage of flames, smokes and hot gases after being exposed to ISO fire for two hours. An ISO fire test on compressed cement stabilized earth blocks confirmed the insulation and integrity criteria of earthen material in another study on the wall scale performed by Ferreira et al. (2019).

This paper is a continuation of the previous study of Abdallah et al. (2022) in order to investigate the reason behind the obtained fire behavior of those materials. The same materials with varying water contents (equalizing conditions) will be exposed to the same ISO 834-1 fire at the same very fast heating rate, but with thermocouples embedded inside the bricks to inspect if the evolution of the formed thermal gradient inside the materials (due to heating) could be a reason for the observed behavior or not.

II. MATERIAL AND METHODS

A. Materials used

Nagen Brickwork Factory (Toulouse, France) provided the soil for the current experimental work. The used soil is a typical soil for the manufacture of standard fired bricks. This soil has previously been characterized and classified (Bruno, 2016; Bruno et al., 2019) as a silty-clayey soil with medium plasticity, consisting of 16.3 % clay (0.002 mm), 42.9 % silt (0.002-0.063 mm), 40.4 % sand (0.063-2 mm) and 0.4 % gravel (>2 mm).

CEM III/A 52.5 L CE cement was used to produce cement stabilized earthen bricks. It is a cement blended with blast furnace slag delivered by EQIOM Group (Héming-France) and manufactured in accordance with NF EN 197-1. Its low clinker content (35%) aided in the production of environmentally friendly cement stabilized earthen materials.

The microstructure of two different materials was to be studied: compacted raw earth and cement stabilized earthen materials. It was noted that the mechanical strength of the material could influence the overall fire behavior (Abdallah et al., 2022). As a result, the strength of the two tested materials was chosen to be equivalent. To match the strength of hollow fired bricks used in construction units, a strength of 5 MPa was targeted (Abdul Kadir and Mohajerani, 2013). As a result, compacted raw earth specimens at 50 MPa compaction load (SW50) and cement stabilized specimens with 3.5 % cement compacted at the standard Proctor load (SWC3.5) were produced.

B. Specimen preparation and equalization

For raw earth SW50 specimens, oven dried soil was mixed with the required amount of water (percentage of dry weight of soil) to achieve the desired 50 MPa compaction load level (Bruno, 2016). Cement stabilized SWC3.5 specimens, on the other hand, were formed by incorporating dry soil with a pre-blended cement paste. SWC3.5 had a total water content of 12.5 % of the dry weight of soil (optimum Proctor water content) plus 30 % cement weight (complete cement hydration).

Double compacted bricks of 20 x 10 x 5 cm³ were manufactured for the two materials in order to have dimensions similar to those of standard fired clay bricks (21.5 x 10.25 x 6.5 cm³) used in the United Kingdom (BS 3921, 1985). Double compaction was performed in order to achieve stress uniformity inside the sample (Bruno, 2016).

Bricks were then sealed inside plastic bags for 28 days to ensure a proper distribution of water content for SW50 specimens and to ensure the complete cement hydration reaction for SWC3.5 specimens. To investigate the influence of initial water content, specimens were then equalized to four different conditions by targeting four different water contents that were themselves varying for both materials. Oven dried state by drying specimens in an oven at 80°C for a minimum period of 3-4 days until having a mass variation of 0.1% between two consecutive daily measurements. Other conditions were humid ones of 50 %, 75 % and 100 % relative humidity (RH) by using either a controlled humidity chamber (case of 50 % RH) or sealed containers with either saturated sodium chloride solution or only water and sponges at their bottom (case of 75 % and 100 % RH respectively). Humidity equalization was found sufficient after a period of 15-16 days after achieving a 0.1 % mass difference between two consecutive daily measurements. Same 0.1 % mass difference was found for oven dried samples after 4 days in the 80°C oven.

C. Fire test

Before test, thermocouples were embedded inside the bricks for tracking the evolution of the generated thermal gradients with temperature rise at each instant during the fire test. K-type thermocouples, covered by glass fibers, were employed in this process. These thermocouples were placed at 0.5, 1 and 2 cm away from the heated face exposed to fire. They were placed inside three, manually formed, thin holes having the required distance of 0.5, 1 and 2 cm from the heated face between the two tested bricks and particularly, inside the core of the bottom brick from its upper 20 x 5 cm² surface. A thin raw earth joint was then added above the thermocouples and between the bricks to cover the thermocouples tips first and then to ensure a proper bonding of the two superposed bricks. A scheme for thermocouples, to be embedded, is illustrated in Figure 1. In this figure, the hatched zone corresponds to the exposed face of the two superposed bricks to fire from the furnace.

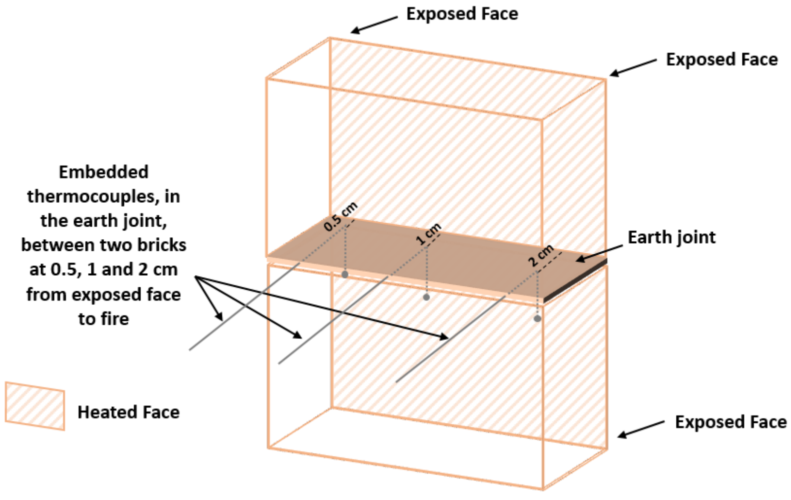
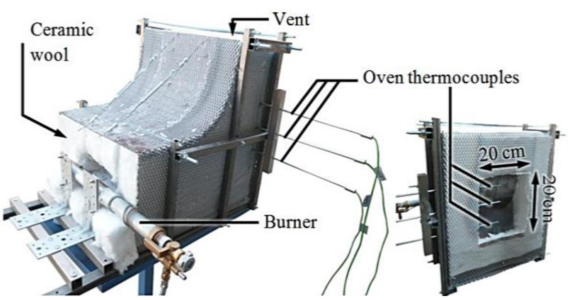
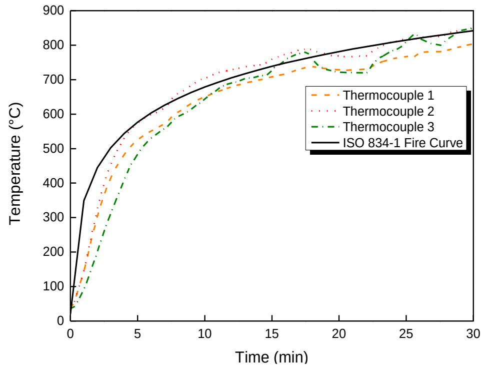


Figure 1. Scheme of the embedded thermocouples

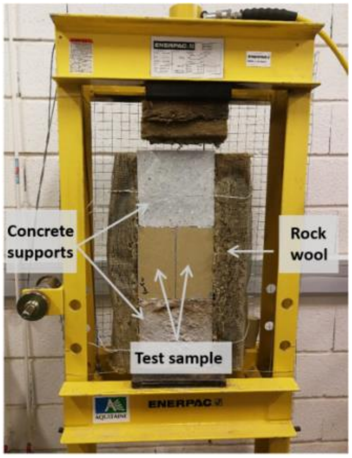
Following that, bricks were laterally wrapped with an aluminum foil in order to block the moisture escape from specimens during the fire test. These fire tests were carried out on SW50 and SWC3.5 specimens by means of a mobile gas furnace provided with a linear gas burner and butane gas (Figure 2a). To record temperatures of the air inside the furnace, three K-type jacketed thermocouples were placed at 4, 10 and 16 cm from the bottom of the furnace opening (20 x 20 cm^2) and 1 cm from the heated face of the tested bricks. During the test, the gas pressure was manually adjusted so that the thermocouple's temperature reading was made sure to follow the standard ISO 834-1 fire curve (Figure 2b). For the procedure of fire test itself, and in order to cope with the 20 x 20 cm^2 furnace opening, two bricks of the same configuration were installed next to each other (Figure 3a) between two concrete blocks per a single fire test. The whole set up was then laterally wrapped by a 12 cm rockwool insulation to ensure having a unidirectional flow of heat (Figure 3a). In the normal cases, the test run for 30 minutes. The full test setup (Figure 3b) with its procedure can be found in the study of Abdallah et al. (2022).

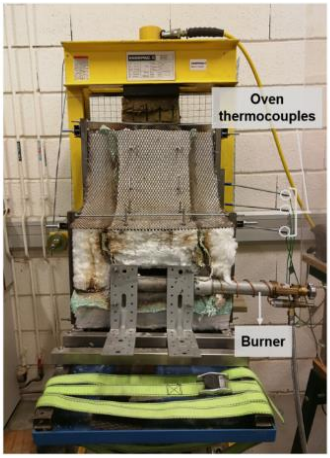




(a) (b)

Figure 2. (a) Mobile gas furnace (b) Example of fire curve of a tested specimen: ISO 834-1 curve and recorded temperatures of thermocouples





(a) (b)

Figure 3. (a) Setup before fire test: two bricks placed together per single test with lateral sides wrapped with rock wool (b) Setup during fire test

III. Results and discussion

Following the results obtained by Abdallah et al. (2022), it was shown that the influence of the material's water content played a major role in the occurrence of thermal stabilities / instabilities.

Thermal instabilities were only found with the compacted raw earth SW50 bricks equalized at only 50 % and 75 % RH. These thermal instabilities resulted in a few pieces detaching from the heated surface of those tested bricks. This is similar to what happens in concrete when it is tested under fire; it is known as spalling (Miah, 2017). Thermal stabilities, on the other hand, were found in compacted raw earth SW50 specimens equalized at oven dry condition (0 % RH) and 100 % RH and also with SWC3.5 cement stabilized earth specimens at all four tested equalizing conditions. To investigate the effect of this fire test result, the evolution of thermal gradients in both materials was assessed.

The thermal gradient (ΔT/Δd) was calculated by dividing the difference of thermocouple temperature readings (ΔT) between two separate locations by the exact distance (Δd) between these two locations at a given time. Δd was calculated as the difference between the thermocouple's accurate positions. These accurate positions were determined after scanning the 20 x 5 cm^2 surface of the brick (the surface where thermocouples were embedded) after the end of the fire test and then precisely calculated using ImageJ software. Figure 4 displays the obtained evolution of thermal gradient with respect to water content of both SW50 and SWC3.5 at a specific time and duration of the test that were taken to be 10 minutes between 0.5 cm and 2 cm. The time period of 10 minutes was chosen because the majority of thermal instabilities, during fire test, occurred at this period.

The values of thermal gradient (ΔT/Δd) for 0% water content (oven dried condition) for SWC3.5 have been omitted from the figure due to a technical problem encountered in the thermocouple's tip which affected the reading of the thermocouple.

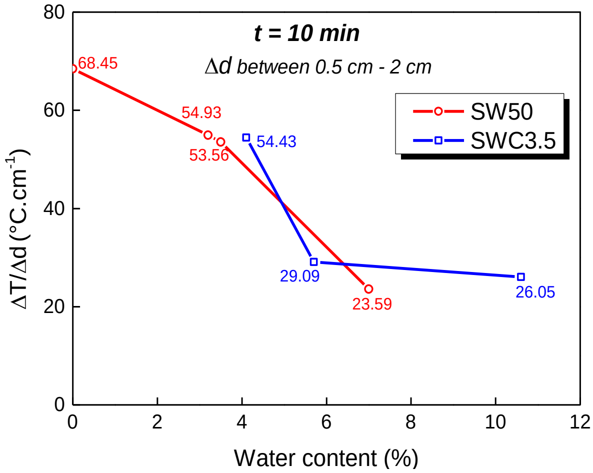


Figure 4. Evolution of thermal gradient of SW50 and SWC3.5 after 10 min of fire with respect to water content

The increase in water content was discovered to contribute to the material's energy consumption, during heating and water evaporation, and thus decreases its thermal gradient and consequent thermal stresses, which could normally contribute to a lower risk of instability. Both materials had similar thermal gradients, with some variations in some cases. After equalization to 50% RH (water content ranging between 3.2-4.1 %), SW50 and SWC3.5 had nearly identical thermal gradient values of 54.93 $°C.cm^{-1}$ and 54.4 3$°C.cm^{-1}$, respectively. SW50 overtook SWC3.5 after increasing to 75% RH equalization (water content ranging between 3.5-5.7 %), with a much higher thermal gradient value of 53.56 $°C.cm^{-1}$ compared to 29.09 $°C.cm^{-1}$. When the thermal gradient values reached the highest water content of 7-10.6 % (corresponding to 100 % RH equalization), SWC3.5 appeared to have a slightly higher value of 26.05 $°C.cm^{-1}$ than the value of 23.59 $°C.cm^{-1}$ for SW50.

As previously stated, both materials demonstrated a stable behavior at dry condition even though the data obtained from Figure 4 showed a very high thermal gradient value (68.45 °C.cm^{-1} for SW50) which normally could lead to high thermal stress, increasing the risk of instability. The fire resistance of those materials at those conditions is thought to be due to the material's high mechanical properties after heating (Bruno et al., 2020) which could assisted in reducing the impact of the high thermal stresses on the material and thus exhibited a thermal stable behavior.

Lower thermal gradients were observed as water content increased, implying that lower consecutive thermal stresses would have formed. SW50, on the other hand, exhibited instable behavior at lower water contents of 3.2-3.5 %, corresponding to an equalization of 50-75 % RH (Abdallah et al., 2022). The high evaporation of water is viewed as an evidence of this result after increasing the heating temperature. The water vapor evaporation presumably went partly to the heated face and escaped, and partly to the colder face. This second phenomenon could have caused a local increase in water content, as well as condensation of water. This has previously been demonstrated to occur in concrete materials exposed to fire in the presence of moisture clog formation (McNamee, 2013; Miah, 2017; Sultangaliyeva, 2020; Zeiml et al., 2006). This increase in water content, at the local level of the heated face and particularly at some deeper colder regions, could have been accompanied also by a lower decrease in mechanical properties.

Both SW50 and SWC3.5 were reported to exhibit thermal stability despite their expected decrease in mechanical properties with the highest increase in water content corresponding to a 100 % RH equalization. This is due to their proximity to extreme low thermal gradients and, as a result, extreme low thermal stresses, which could have overcome the effect of the material's decrease in strength and handed the material its resistance to fire.

Furthermore, the SWC3.5 cement stabilized specimen is claimed to have a higher fire resistance propensity due to its likely low sensitivity to the increase in water content and the high mechanical properties that could have been gained by heating the material.

Therefore, it is postulated that a thermo-hydro-mechanical coupling existed in the earthen materials during fire test and contributed to the obtained result. This postulate could be better described and recognized from the scheme in Figure 5 which explain the occurring behavior inside earthen materials exposed to fire.

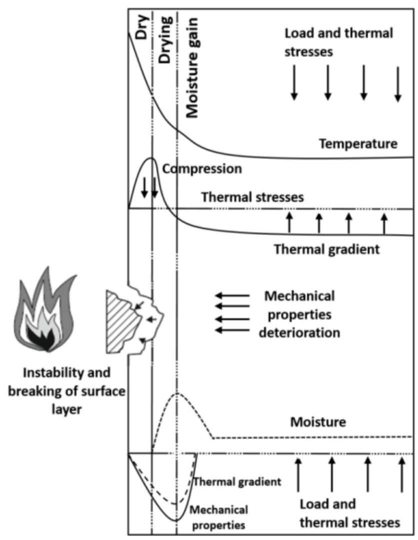


Figure 5. Gradients of temperature, thermal gradients (thermal stresses) and mechanical properties in earthen materials section during heating from a single unsealed surface (inspired from Khoury, 2008)

IV. Conclusion

In this study, the reason behind the thermal stability/instability of raw earth SW50 and cement stabilized SWC3.5 specimens, acquiring various water contents, after being subjected to a very fast heating rate was investigated. Thermocouples were embedded inside SW50 and SWC3.5 bricks before their fire test. This was performed to check the evolution of the created thermal gradients (due to heating) on the overall fire behavior.

Following the obtained results, a coupling of thermo-hydro-mechanical phenomenon could have been responsible for the obtained fire behavior of SW50 and SWC3.5. This was postulated after discovering the following conclusions:

1. The increase in water content resulted in a decrease in the thermal gradient of the materials after 10 minutes of testing between 0.5 and 2 cm from the heated face. This was attributed to the energy consumption by water during evaporation after heating.
2. Both SW50 and SWC3.5 shared almost similar thermal gradient values with slight variations in some cases.
3. Oven drying the specimens could have given the materials a very high mechanical property to stand against fire. A high property that could exceed in its impact the influence of the their very high thermal gradients and consecutively their very high thermal stresses.
4. For the cases of SW50 and SWC3.5 with higher water content, the migration of water vapor (due to evaporation) to some colder deeper regions inside the brick, followed by their condensation, could have led to a deterioration in the mechanical properties of the material and thus led to an instability. This influence may have outweighed the effect of having lower thermal gradients, which should result in lower thermal stresses on the material. Additionally, the extreme low thermal gradient associated with the highest water content provided the materials with the necessary requirements to be fire resistant while also having the lowest mechanical properties.
5. The hypersensitivity of compacted raw earth materials to water content, which is thought to have resulted in deterioration of their mechanical properties and thermal gradients, could be the reason for the thermal stability criteria of the cement stabilized material (SWC3.5) compared to the compacted raw earth material (SW50).

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