Effect of the level of compaction on the risk of thermal instability of compressed earth bricks

Rafik Abdallah[1], **Hélène Carré**[1], **Fionn McGregor**[1]

[1] *Université de Pau et des Pays de l'Adour, E2S UPPA, SIAME, Anglet, France*

RESUME : Les matériaux en terre, une ancienne technique de construction, font à nouveau la une des journaux en raison de leur capacité à relever les défis environnementaux et économiques. De nombreuses études ont été menées sur les propriétés thermo-hygro-mécaniques mais leur résistance au feu reste peu étudiée. Le travail présenté s'intéresse au comportement au feu des briques de terre crue compressées. Différentes briques ont été fabriquées à partir d'un mélange de terre et d'eau avec différents niveaux de compactage. Les briques sont conservées à température ambiante et à 75 % H.R. jusqu'à stabilisation. Cette ambiance correspond à une configuration défavorable vis-à-vis du risque d'instabilité thermique. Cela a été montré par des travaux antérieurs.

Deux essais au feu ont été réalisés pour chaque configuration à la petite échelle : deux briques testées à chaque essai. Ils ont montré que le risque d'instabilité est plus élevé pour des niveaux de compactage plus élevés. Une compacité plus élevée conduit à des évènements d'écaillage plus nombreux et une perte de matière plus importante.

Mots-clefs : terre crue, brique de terre compressée, niveau de compactage, haute température, feu, instabilité thermique

I. INTRODUCTION

In order to contend with the current climate change, new construction materials had to be developed and used in the construction sector. Earthen construction materials were revealed a good solution in such circumstances. Their significance in this sense stems from their nature as materials with low environmental impact, abundance in nature, and ease of recyclability. This material has been studied in almost all of its hygro-mechanical aspects in order to meet the recommendations for its use in buildings. However, one of its behaviors, high temperature and fire behavior, has been given little attention. This latter behavior is important to consider when designing a building because it concerns the material's load bearing capacity in the event of a high temperature rise and a fire inside the building. The high temperature behavior of fired earth bricks and clays, that is, bricks exposed to temperatures greater than 1200°C for extended periods of time, has been known and mastered since ancient times. However, the high temperature heating associated with a fire that occurs at a very rapid rate on wet bricks is rarely reported. This can lead to the appearance of an instability risk that is still not well known.

There is very little existing research that discusses the fire behavior of earthen materials at the small scale level of bricks. Apte et al. (2008) observed that earthen materials can act positively as a barrier to oxygen transmission in their study of heating earthen samples with radiant panels rated at 30 and 50 $kW.m^{-2}$. Préneron et al. (2017) carried out another experiment that displayed the insulation criteria of earthen materials after exposing earthen blocks to a high heating temperature of 800°C in an oven. They also revealed that these materials could not ignite themselves after being heated with a radiant heat source and then subjected to ignition time and extinguishability tests. Moreover, Beckett et al. (2019) deduced that rammed earthen materials can remain intact during and after heating after conducting tests with unidirectional heat fluxes of 20, 35, and 50 $kW.m^{-2}$. Furthermore, the most recent studies on earthen materials under fire were conducted by Abdallah et al. (2022). They exposed raw earth and cement stabilized bricks with varying water contents to fire at a very fast heating rate following the ISO 834-1 fire curve (International standard, 1999). They discovered that both water content and cement stabilization could have huge impact on earthen material thermal stability. A feature that could affect the functionality of those materials in dwellings if they exhibit some thermal instability caused by the peeling of their surface layers. Abdallah (2022) continued and conducted a deeper analysis of this test, in which further profound tests were performed on compacted raw earth and cement stabilized bricks to check the influence of water and cement content on the thermal gradient evolution in those bricks subjected to fire. The obtained results of thermal stability and instability of the tested bricks under fire suggested that a coupling of thermo-hydro-mechanical phenomena could be behind the obtained behavior.

Much fewer tests were carried out at the wall scale testing level. Byrne (1982) tested a compressed earth block wall exposed to an ISO fire for four hours and demonstrated that it had an insulation property with a maximum central deflection of only 24 mm at the end of the test. After being exposed to ISO fire for two hours, Buson et al. (2013) discovered that earthen walls containing kraft paper could prevent the passage of flames, smokes, and hot gases. Another ISO fire test on compressed cement stabilized earth blocks confirmed the insulation and integrity criteria of earthen material in Ferreira et al. (2019) wall 's scale study .

This paper discusses the effect of compaction levels on the thermal instability risk of raw earth bricks. Fire tests were conducted, on compacted raw earth bricks at compaction levels of 5, 15, 30 and 50 MPa applied during their fabrication process. An ISO 834-1 fire was used to test the bricks. Some bricks exhibited thermal stability, while others exhibited an instability that intensified with increasing compaction pressures. It was presumed that the increased pore pressure in compacted raw earth bricks caused by higher compaction pressures contributed in the reported occurred thermal instabilities.

II. Material and methods

A. Materials used

The soil for the current experiment was supplied from Nagen Brickwork Factory in Toulouse, France. The soil used is typical for the production of standard fired bricks. This soil has been earlier characterized and classified (Bruno, 2016; Bruno et al., 2019) as a silty-clay 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) with an optimum Proctor density of 1948 $kg.m^{-3}$.

B. Sample fabrication and equalization

Raw earth samples were produced by mixing soil and water. The soil was oven dried for 3-4 days at 80°C until there was a 0.1% mass difference between the two consecutive mass daily measurements taken. To achieve different compaction levels in the samples, each raw earth sample was mixed with its required optimum amount of water content (percentage of dry weight of soil) to achieve its targeted optimum density and compaction level (Bruno, 2016).

Water and soil were mixed for a period of 10 minutes in a planetary mixer to obtain a homogenous phase. After that, bricks were double compacted in a mold to have a dimension of 20x10x5 cm^3. A dimension recommended as to be close to the ones of the standard fired clay bricks (21.5x10.25x6.5 cm^3) used in the United kingdom (BS 3921, 1985). Double compaction was followed to ensure having a uniform stress in the sample (Bruno, 2016). Compaction levels of 5, 15, 30, and 50 MPa were set as targets. As a result, the samples were given the notations **SW5**, **SW15**, **SW30** and **SW50.** Note that to attain desired compaction levels in each of the fabricated samples, soil was mixed with the optimum amount of water content (percentage of dry weight of soil) to attain the desired optimum density and thus the intended compaction level (Bruno, 2016).

The bricks were then sealed inside plastic bags for 28 days. A period determined to be necessary to ensure a uniform distribution of water content throughout the sample, allowing for stronger bonding between soil particles. Following that, samples were set for an equalization period of 15-16 days in a climatic chamber at a relative humidity of 75 %. This equalization stage was necessary to eliminate the potential influence of different hygroscopic conditions on the measured mechanical properties of the material (Bruno, 2016; Bui et al., 2014). This time period was also found sufficient to ensure a 0.1% difference in mass between the two consecutive daily measurements (Bruno, 2016). Besides that, the previous research of Abdallah (2022) and Abdallah et al. (2022) found that the RH level of 75 % corresponds to an unfavorable configuration in regard to the risk of thermal instability of compressed earth bricks, which is why it was chosen.

The table below (Table 1) lists some of the properties of the fabricated samples. Where the humid density value represents the density of the sample after 75 % RH equalization, which is taken at the time of testing. The density value is the average of two samples' densities. As for water content, it is expressed as a percentage of dry mass (dried at 80°C) on a single sample following the equalization period.

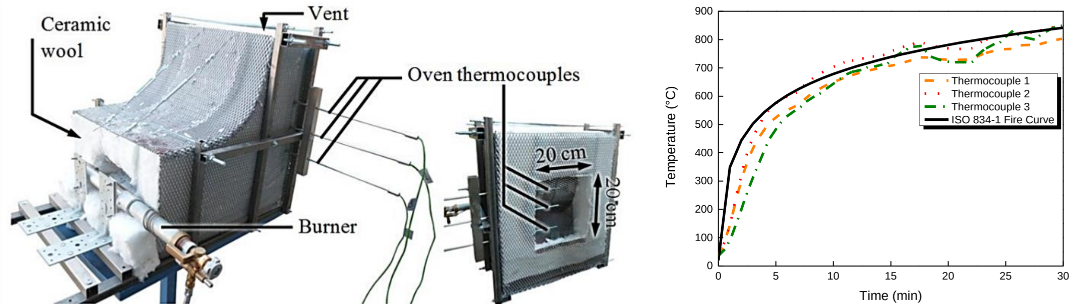
Table 1. Properties of the fabricated samples

Property	SW5	SW15	SW30	SW50
Humid density (kg/m^3)	2090	2246	2297	2399
Water content (%)	3.65	3.53	3.48	3.46

C. Fire test setup

Before beginning the fire test, the bricks were laterally wrapped by an aluminum foil with a high temperature resistant glue that could withstand a maximum temperature of 800°C to prevent moisture from escaping from the edges of the bricks during the fire test. The fire test was carried out on the bricks with the help of a mobile gas furnace outfitted with a linear gas burner (Figure 1a) backed by butane gas. To record the temperature, three K-type 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 samples. During the test, the gas pressure was manually adjusted so that the temperature measured with the three thermocouples close to the heated surface follows the ISO 834-1 standard fire curve (Figure 1b).



(a) (b)

Figure 1. (a) Mobile gas furnace (b) Fire curves of a tested sample (ISO 834-1 and recorded temperature of thermocouples)

For the fire test procedure, and to adjust the 20 x 20 cm^2 furnace opening, two bricks of the same composition were installed next to each other without any joint in between (Figure 2a). Bricks were placed between two fiber reinforced concrete blocks acting as a support. The bricks were placed vertically as a small-scale representation testing for the tests that can be applied on larger wall scale tests. An upcoming experimental program will test additional orientations and methods of brick fabrication. This is to see if the orientations of the bricks and their anisotropy (given the method of fabrication) contribute to the overall fire behavior. The entire setup was then laterally insulated by a 12 cm rockwool to ensure unidirectional heat flow (Figure 2b). The test will last 30 minutes except if the instabilities led to the collapse of the bricks. The complete test setup and procedure can be found in the study of Abdallah et al. (2022). Two fire tests were performed for each of SW5, SW15, SW30 and SW50 samples without the application of any extra load. Only two tests were performed because previous research of Abdallah et al. (2022) proven that the fire behavior of earth bricks can follow a reproducible pattern with only two tests.

(a) (b)

Figure 2. (a) Setup before fire test: two bricks placed together per single test with lateral sides insulated with rock wool (b) Setup during fire test

III. Results

An analysis criterion was established, which would be followed by analyzing the behavior of the bricks during and after the fire test (Abdallah et al., 2022). As a result, the process of analyzing the fire behavior of the tested samples began the moment the test started. Some samples showed thermal instabilities corresponding to surface layer detachment in the form of broken pieces (Figure 3), falling away from the setup. Concrete samples have been observed to exhibit this type of behavior when they are exposed to fire and it is known as spalling (Miah, 2017). These instabilities are accompanied by a sound which shows us the occurrence of this thermal instability. The number and time of instabilities that occurred for both performed tests of each sample type were tracked throughout the fire test and are presented in **Table 2**.


(a) SW15 (b) SW30 (c) SW50

Figure 3. Thermal instable samples (a) SW15 (b) SW30 (c) SW50

Table 2. Number of occurring instability events and their respective occurrence time

Sample name	Equalizing condition (% RH)	Number of events	Time of instability event (min)	End of test (min)	
SW5	75	0	--no instability--	30	30
		0		30	
SW15		2	13/14	30	22
		2	13/14	14	
SW30		4	7/ 9 / 11 / 12	13	12.5
		4	7/ 10 / 11 / 12	12	
SW50		6	7 / 8 / 10 / 11 / 13/ 15	15	15
		10	5/ 6/ 6 / 9 / 10 /11/ 13 /13/14/15	15	

Following the end of the test, both thermal stable and non-stable samples were quantified. Water mass loss was calculated for the stable ones. In the case of non-stable ones, the number of broken pieces, mass loss due to these broken pieces and water loss are calculated. The quantifications are presented in Table 3. More details about the calculations of these mass losses can be seen from Abdallah et al. (2022).

Table 3. **Quantification of thermal stability and instability of tested bricks**

Sample name	Equalizing condition	Average number of broken pieces (retained by a 10 mm sieving)	Average percentage mass (%) of broken pieces	Average total mass loss (%) (broken pieces + water loss)
SW5	75 % RH	0	0	4.73
SW15		7	33.31	38.06
SW30		53.5	27.27	32.56
SW50		264	28.51	36.81

IV. Discussion

During a fire test, the material is normally subjected to thermal stresses caused by the generated thermal gradients. Along with these thermal stresses, the water within the material begins to evaporate, and the temperature evolution of the material is disrupted as a result of the energy absorption. When the water evaporation process begins, some of the water vapor migrates outside of the sample from its heated face, while the remaining portion migrates to the deep inner colder regions within the sample's core material. Condensation of the water could occur at this level, forming a tight layer (called a moisture clog for concrete) and limiting the vapor from being released (Consolazio et al., 1998, 1997; Schneider and Horvath, 2002; Zeiml et al., 2006). This can later contribute in a buildup of pore pressure inside the sample, which can put a lot of stress on the capillary pores inducing a high level of unbearable stresses along with the already existing thermal stresses from thermal gradients during the increase in temperature from fire. These factors could lead to breaking and peeling of the surface layers; a condition known as thermal instabilities. As a result, a coupled thermo-hydro-chemo-mechanical phenomenon could occur in such a behavior. This is typically the case in concrete samples; however, due to their porous mineral structure, a parallel can be drawn between soil and concrete. As a result, this was presumed to happen inside the earthen materials exposed to fire (Abdallah, 2022; Abdallah et al., 2022).

The results of the fire tests, according to Table 2, Table 3 and Figure 3 display that thermal instabilities were observed in SW15, SW30, and SW50, whereas SW5 was the only sample that happened to exhibit a thermal stability during this high heating rate test. SW5 demonstrated zero instability events in both tests and an average duration of 30 minutes, which is the entire duration of the test. It also revealed a 4.73% average mass loss corresponding to only water evaporation of the sample during its fire testing (Table 3). However, higher compacted samples all showed instabilities that varied with compaction level. SW15 presented two instability events per test, with seven broken pieces and a mass loss of 38.06%. As a normal result of the instability events, the mean test duration decreased to 22 minutes. With the SW30 samples, the number of events increased to an average of 4 events per test, with 54.5 average broken pieces and a relative mass loss of 32.56%. The mean test duration decreased as the number of thermal instability events increased, eventually reaching 12.5 minutes. Lastly, the SW50 sample had the highest propensity for instability, with an average test duration of 15 minutes per test. This was demonstrated by the high number of instability events, which averaged 7.5 per test. The average mass loss of broken pieces and total mass loss were slightly higher than SW30 but lower than SW15. However, the number of broken SW50 pieces increased significantly to an average of 264 pieces (Figure 3), indicating that the highest energy of instability was exerted in this SW50 sample.

According to the proposed theory of a thermo-hydro-chemo-mechanical coupling occurring inside earthen materials and the experimental results, it is anticipated that the pore pressure build-up has played a significant role in the overall fire behavior of the tested samples. This point supports the previously raised point in the study of Abdallah et al. (2022). More compacted material is more particularly prone to thermal instabilities owing to its more compacted microstructure. This can be seen from the density values in Table 1 which showed higher density values (accompanied by lower water contents) with higher compaction levels, and a probable lower permeability, which can lead to a higher risk of pore pressure build up on the formed moisture clog inside the earthen material. This is demonstrated by the fact that the least compacted material (SW5) revealed a thermal stability tendency. Meanwhile, as compaction stresses rise from 15 to 50 MPa (SW15, SW30, and SW50), thermal instabilities started to appear. And, among the thermally unstable samples, SW50 had more thermal instabilities than SW30, and SW30 had more than SW15. This was explained by the quantification of the tracked number of instability events and the corresponding mass loss of the spalled pieces.

IV. Conclusion and perspectives

The current study attempted to shed light on the effect of increasing compaction pressure on the fire behavior of compacted raw earth samples. Fire tests were carried out on four different materials, each corresponding to a different compaction pressure. A rapid heating ISO 834-1 fire was applied to test compacted raw earth samples of 5, 15, 30, and 50 MPa, with the respective nomenclature of SW5, SW15, SW30, and SW50. Thermal stability of the least compacted sample with 5 MPa (SW5) and thermal instabilities with SW15, SW30, and SW50 were revealed.

The increase in compaction pressure resulted in more thermal instabilities, more instability events, and more broken pieces, resulting in a relative increase in mass loss and a clear normal outcome decrease in test duration. Higher compaction pressure is believed to have permitted for a substantial rise in pore pressure buildup inside the material, which made it more prone to thermal instabilities by inhibiting the release of formed pore pressure from water evaporation.

Further tests can be performed to acquire a better understanding of the material's porosity and residual permeability as a function of temperature in order to develop a stronger hypothesis and even attempt to prove the interference of pore pressure build up and its influence on earthen materials exposed to fire.

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