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AN EXPERIMENTAL ANALYSIS ON THE THERMAL PERFORMANCE OF RAMMED EARTH WALLS

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ABSTRACT

Earth has been used as a building material since the beginning of civilizations and its utilization was widespread to most regions of the world, promoted by the high availability, easy access and low cost of the material. As result of the generalised use of raw earth as building material, many earthen building techniques were developed through time, where adobe masonry, rammed earth and wattle-and-daub are among the most important. Currently, it is estimated that one quarter of the world's population lives in buildings made of earth. However, during the last century, earthen materials fell into disuse in several developed countries with the popularization of concrete, steel and fire bricks. Nevertheless, earthen architecture has been receiving increasing attention in the last few decades, driven by its green building potential and by other features of earthen materials, which includes, among others, unique aesthetics and hygrothermal regulation capacity.

Several studies have been developed to characterize earthen solutions concerning physical and mechanical properties. However, regarding the thermal behaviour, it is known that the thermal conductivity of rammed earth is a parameter that depends on the characteristics of the soil (particle size distribution, mineralogy, etc.) and moisture content. Thus, given the soils variability, it becomes clear that further investigation should be addressed to characterize the thermal performance of rammed earth solutions, contributing to define more accurate thermal conductivity values for the design of rammed earth buildings. On this regard, this paper presents an experimental study that aims to characterize the thermal behaviour of rammed earth built with different soils and with different thicknesses. A continuous measurement allowed to obtain heat fluxes, inner surface temperatures and the thermal transmission coefficient of the tested rammed earth walls solutions. The results obtained so far confirmed that the type of soil and thickness significantly influences the thermal behaviour of the earthen material. It was also observed that the thermal transmission coefficient of a 50 cm thick wall is about 30% lower than the one verified for the wall with 35 cm, built with the same soil.

KEYWORDS: Sustainability; Earth construction; Rammed earth; Thermal performance.

1. INTRODUCTION

Raw earth has been used as a building material for millennia, as evidenced by the earth bricks dating back to Mesopotamia around 10 000 BC [1]. Furthermore, its use was widespread to most regions of the world, promoted by the high availability, easy access and low cost of the material. As result of the generalised use of raw earth as building material, many earthen building techniques were developed through time, where adobe masonry, rammed earth and wattle-and-daub are among the most important [2]. Nowadays, building with raw earth is still popular in many developing countries, such as India, Peru, Brazil and Columbia [3]. On the other hand, in developed countries the use of earthen materials became marginal during the last century, as they were rapidly substituted by more modern building materials, such as concrete, steel and fired bricks [4][5]. Nevertheless, earthen architecture has been receiving increasing attention in the last few decades, driven by its green building potential and by other features of earthen materials, which includes, among others, unique aesthetics and hygrothermal regulation capacity [6][7]. Despite the sustainable value of rammed earth [8], the dissemination of this building material in developed countries is hindered by several barriers related with steering mechanisms, processes, economics, client understanding and underpinning knowledge [9]. Furthermore, Portugal does not present any specific standard or document supporting rammed earth construction, while the current building regulations complicate the licensing of new projects, especially with respect to energy performance compliance. In addition, several variables influence the thermal performance of this type of solutions. The fact is that the thermal conductivity of rammed earth is a parameter that depends on other different factors, such as the characteristics of the soil (particle size distribution, mineralogy, among others) and moisture content [10][11]. Thus, it becomes clear that further investigation should be addressed to characterize the thermal performance of rammed earth solutions contributing to define more accurate thermal conductivity values for designing rammed earth buildings. On this regard, this paper presents an experimental study that aims to characterize the thermal behaviour of rammed earth walls built with different soils from Portuguese regions. The influence of the wall thickness will also be discussed.

2. MATERIALS AND METHODS

2.1. Soil Characterization

Two different soils (*S1* and *S2*) were considered as a raw material to produce rammed earth walls solutions, and their thermal properties were experimentally evaluated. The two soils were originated from two completely different Portuguese regions. Soil *S1* was collected in Guimarães, located in the Northern region of Portugal, while soil *S2* was from a further south region, Santiago do Cácem. Both soils have been locally used in earth construction, namely in compressed earth blocks manufacturing, indicating the possibility of being applied as rammed earth raw materials. Some experimental tests were performed to characterize both soils, such as mineral composition, particle-size distribution (ASTM D6913-04 (ASTM, 2017) and ASTM D7928 (ASTM, 2021)), organic matter content (OMC) (ASTM D2974-20e1 (ASTM, 2020)), density (ASTM D7263-21), sand equivalent value (EA) (ASTM D2419-14 (ASTM, 2016)), and Atterberg limits (liquid limit (LL), plastic limit (PL) and plasticity index (IP)) (ASTM D4318-00 (ASTM, 2003)), whose results are presented in Tables 1 and 2. A graphical representation of both soils was also performed using the Feret´s triangle, Figure 1.

Table 1: Mineral composition of soil *S1* and soil *S2*.

Soil	**Mineral Composition [%]**			
	Clay (<0,002m)	**Silt (0,002-0,05mm)**	**Sand (0,05-2mm)**	**Gravel (2-50mm)**
S1	12	13.5	25.9	48.6
S2	17	26.6	21.7	34.7

Table 2: Main Properties of soil *S1* and soil *S2*.

Soil	**Particle-Size Distribution**	**OMC [%]**	**Density [g/cm^3]**	**EA**	**LL [%]**	**PL [%]**	**PI [%]**
S1	20% (0.001–0.01 mm) 21% (0.01–1.0 mm) 41% (1.0–10.0 mm) 18% (10–20.0 mm)	1.93	2.58	9.8	33.0	21.0	12
S2	34% (0.001–0.01 mm) 25% (0.01–1.0 mm) 20% (1.0–10.0 mm) 21% (10–50.0 mm)	1.99	2.83	4.2	43.8	24.8	19

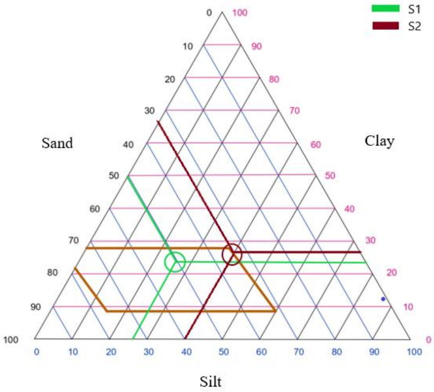

Figure 1: Representation of soil *S1* and soil *S2* in Feret´s triangle.

The obtained results showed that, according to ASTM D-2487 (ASTM, 2020), both soils are classified as clayey gravel with sand (GC). However, clearly differences can be identified by simple observation concerning texture and colour when the characterization tests were performed, as it was verified in the case of the limit liquid (LL) determination, Figure 2 a) and b). The same was observed after the production of the rammed earth samples, as shown in Figure 2 c) and d).

Figure 2: Liquid limit (LL) test: a) Soil *S1* and b) Soil *S2*; Manufacturing process: c) Soil *S1* and d) Soil *S2*.

The results also revealed the suitability of soil *S1* for rammed earth construction, given its location the Feret´s triangle. Furthermore, soil *S1* presented a particle size distribution and a PI recommend for this type of applications. On the contrary, in the case of soil *S2*, the compliance with these parameters was not verified for all the situations, being in some cases outside the recommended range or very close to the limit values. However, soil *S2* has been widely used by construction companies for earth solutions purposes. Thus, soil *S2* was also under investigation. Compaction tests were performed through the Proctor test (ASTM D-55821), revealing that both soils comply with the standard requirements related to the optimum moisture content range for compaction purposes, being suitable for rammed construction.

2.2. Thermal Performance Assessment

Experimental tests were performed to characterize de thermal performance of the different solutions of rammed earth walls according to ISO 9869 (1994), Pereira (2011) [12] and Leitão et al [13]. After the manufacturing of the earth rammed earth samples using soils *S1* and *S2*, they were placed on the north façade of a controlled-temperature test room with dimensions of 4.00 m × 3.00 m × 2.54 m (length × width × height) located in the laboratory of civil engineering at the University of Trás-os-Montes e Alto Douro campus. All the samples were surrounded by extruded polystyrene and polyurethane foam to avoid thermal bridges and lateral flows, whose occurrence could compromise the feasibility of the experiments and the veracity of the results (Figure 3). A heating device was used to guarantee the stability of the temperature inside the text room, allowing the required temperature differential between the interior and the exterior environment, and the heat flow occurrence from inside to the outside of the room. Two measurement periods were considered allowing to compare the two types of soils and the influence of the thickness on the thermal behaviour of the rammed solutions. A first period of measurements was carried out for rammed earth samples produced with soil *S1* and thicknesses of 35 cm and 50 cm were considered. A second period allowed to compared soils *S1* and *S2* for 35 cm of thickness. Each sample was instrumented for the continuous measurement of the heat flux and inner surface temperatures (Figure 3 b) and Figure 4). Heat flux sensors *HF1* and *HF2* allowed to obtained the values of *Q(1)* and *Q(2)*, respectively. *Tsi11*, *Tsi12*, *Tsi21* and *Tsi22* were registered using inner surface temperature sensors. Temperature probes were also used to continuously measure the temperature of the interior (*Ti*) and exterior (*Te*) environments. Values acquisition was made with 10 min intervals during the two measurement periods.

Figure 3: Experimental procedure for the 2nd measurement period: a) placement of sample *S2*; b) instrumentation of *S1* and *S2*.

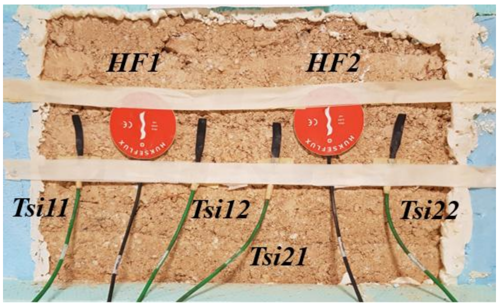

Figure 4: Placement of the sensors in the case of Soil *S2*: heat flux sensors *HF1* and *HF2* and inner surface temperature thermocouples *Tsi11*, *Tsi12*, *Tsi21* and *Tsi22*.

After collecting all the acquired data, the value of the thermal transmission coefficient (*U*) was estimated for each rammed earth sample, based on the heat flux and the temperature differential between the interior and the exterior environments. For each sample, two values of *U* were calculated, and a mean value was achieved. Values of the thermal conductivity (l) were also obtained.

3. RESULTS AND DISCUSSION

The instrumentation and the monitoring of the rammed earth samples allowed to characterize their thermal behaviour under continuous measurements. Heat flux, inner surface temperatures, thermal transmission coefficient, and thermal conductivity values were analysed. A comparison between the different samples were performed. The influence of the type of soil and thickness on the thermal performance was discussed. Figures 5 and 6 present the results obtained during the 1st measurement period, corresponding to soil *S1*, whose rammed earth samples with 35 cm and 50 cm were subjected to experimental tests. In Figure 5, it is possible to observe the heat flux curves development for each sample. Indoor and outdoor temperatures variation is also presented, showing that the required conditions concerning the stabilization of the interior temperature was guaranteed, being higher that the exterior one during the measurement period. The minimum and the maximum values of *Ti* were 28.5 ºC and 39.6 ºC, respectively, and a mean value of 37.0 ºC was achieved. Although the temperature values were lower at the beginning of the test, the use of the heating device allowed the temperatures to stabilize in the remaining periods. It is also important to note that some of the fluctuations are related with the impossibility of controlling the outdoor environment conditions, which is characterized by significant thermal amplitudes during the day and night periods, as it can be observed in Figure 5. In this case, *Te* presented a minimum value of -2.3 ºC and a maximum of 12.3 ºC. A temperature differential leads to heat flow occurrence through the samples, showing the impact of the thickness on the heat transfer between the interior of the test room and the exterior environment. The results demonstrate, as expected, that the heat flux has lower values and less oscillations in the case of the 50 cm thick rammed earth sample. The curves of $Q(1)_{S1\_50}$ and $Q(2)_{S1\_50}$ are practically coincident, while in the case of the sample with 35 cm, a differential in the curves $Q(1)_{S1\_35}$ and $Q(2)_{S1\_35}$ was verified. This could be justified by some soil heterogeneities in the areas were the sensors *HF1* and *HF2* were fixed. A slight delay in the curve pattern is verified for the 50 cm thickness solution comparing with the 35 cm solution, which may be related with an increase of the thermal inertia, in the first case, and a consequent delay of heat release.

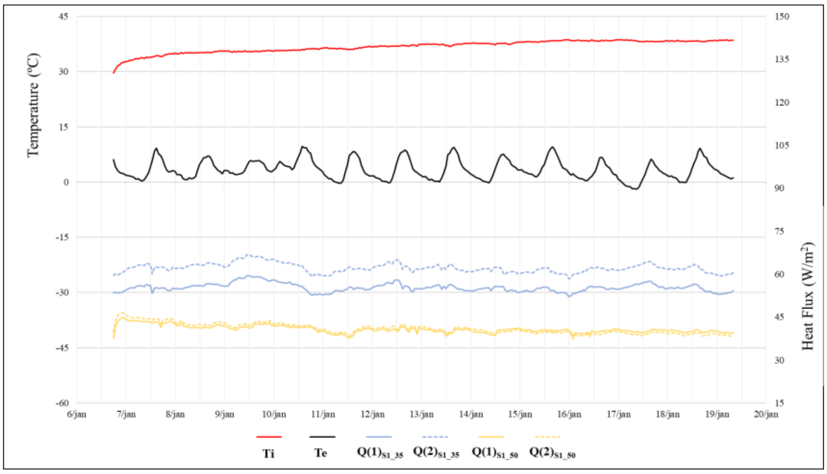

Figure 5: Heat flux variation during the 1st measurement period, corresponding to soil *S1* with 35 cm and 50 cm of thickness.

A corroboration of these results is verified with the ones obtained for the inner surface temperatures. Figure 6 presents the development of the curves corresponding to *Tsi1* and *Tsi2* for both samples. Given that the values of *Tsi11* and *Tsi12* were quite similar, it was decided to present the ones corresponding to *Tsi11*, which is *Tsi1* in Figure 6. For the same reason, the same procedure was taken for *Tsi12* and

Tsi22, whose values represented in Figure 6 refer to *Tsi12*, in this case defined as *Tsi2*. As previously observed, heterogeneity of the soil may me related with the differential verified in the values of *Tsi1* and *Tsi2* concerning the rammed earth sample with 35 cm. An approximation of the curves is visible for the 50 cm sample as it was previously verified for heat flux variation. In this case, a delay of the curve's development is also observed compared to the ones of the 35 cm sample.

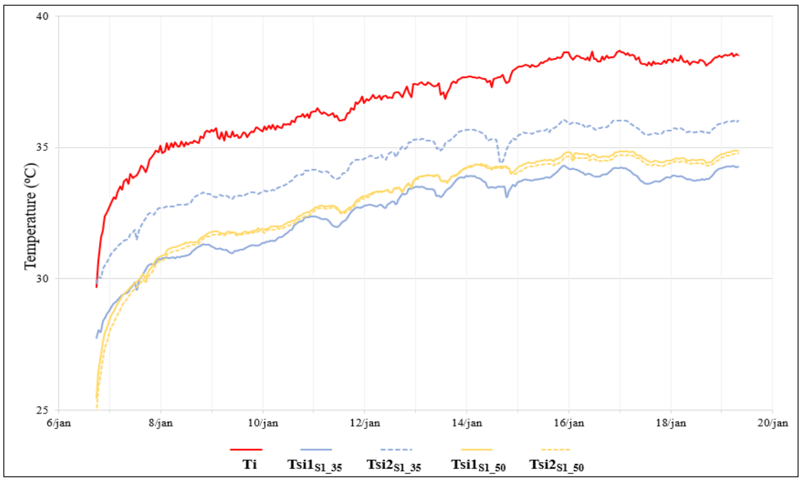

Figure 6: Inner surface temperatures variation during the 1st measurement period, corresponding to soil *S1* with 35 cm and 50 cm of thickness.

Similar analysis was carried out for the 2nd experimental period. In this case, soil *S1* was compared to soil *S2*, considering the thickness of 35 cm, whose results are represented in Figures 7 and 8. The required conditions to guarantee the feasibility and reliability of the experiments were verified. The temperature inside the test room was higher than the outside during all the periods, Figure 7. The minimum and the maximum values of *Ti* were 32.3 ºC and 36.1 ºC, respectively, and a mean value of 34.6 ºC was achieved. Regarding *Te* values, the minimum and maximum values were 2.0 ºC and 17.8 ºC, respectively. In what concerns to the heat flux variation, soil *S1* presented lower values and a significant differential is observed comparing with soil *S2*, revealing that, for the same thickness, a better thermal performance is verified for soil *S1*, which is characterized by lower density and higher particle size distribution than soil *S2*. In this case, a better thermal stabilization was achieved, evidenced by the reduced oscillation of the heat flux curves. These results were corroborated by the ones presented in Figure 8 regarding inner surface temperatures, showing higher values for the earthen material composed by soil *S1*. In both cases, *Tsi1* and *Tsi2* values were lower that *Ti*.

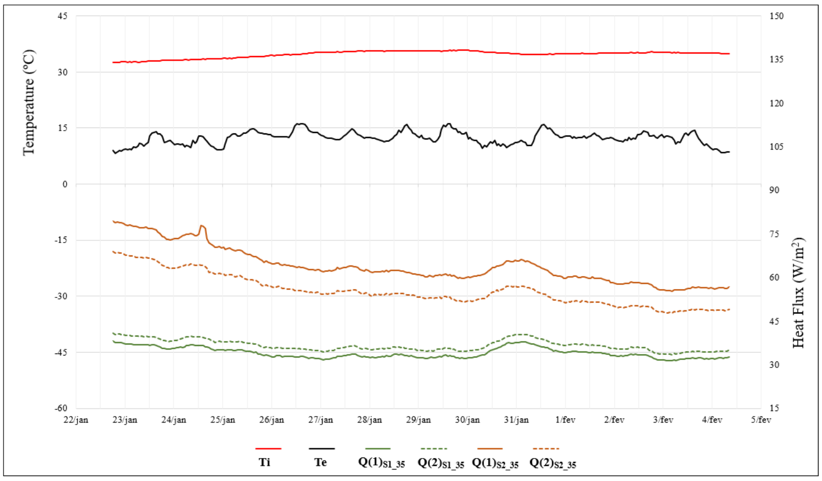

Figure 7: Heat flux variation during the 2nd measurement period, corresponding to soils *S1* and *S2* with 35 cm of thickness.

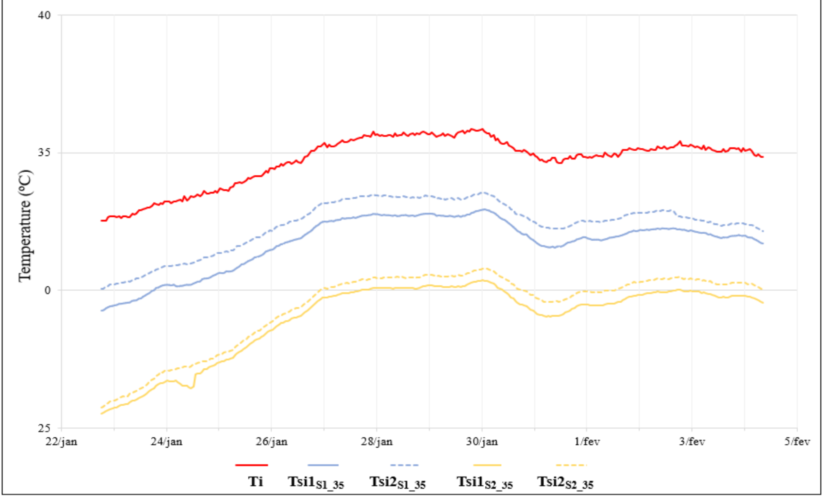

Figure 8: Inner surface temperatures variation during the 2nd measurement period, corresponding to soils *S1* and *S2* with 35 cm of thickness.

The continuous measurement of *Q(1)*, *Q(2)*, *Ti* and *Te* allowed to estimate the thermal transmission coefficient values for soils *S1* and *S2*. The results obtained during the first measurement led to mean values of *U* of 1.67 W/m^{2}ºC and 1.14 W/m^{2}ºC for soil *S1* with 35 cm and 50 cm, respectively, showing that an increase of the wall thickness results in an improvement in thermal performance by approximately 30 %. Values of 1.43 W/m^{2}ºC and 2.15 W/m^{2}ºC were estimated for the second measurement period concerning soils *S1* and *S2* with 35 cm of thickness, respectively. Comparing these results with the ones of the previous period, a decrease of *U* value is verified for the rammed earth sample made from 35 cm of soil *S1*, which may be related to the reduction in soil moisture resulting from the compaction process and subsequent drying. Comparing the values obtained for soils *S1* and *S2*, a better performance was observed when soil *S1* is used for rammed earth walls, achieving a reduction of around 34% in the thermal transmission coefficient. Values of the thermal conductivity (λ) were also estimated. A mean value of 0.72 W/mºC was obtained for soil *S1* and 1.17 W/mºC for soil *S2*.

4. CONCLUSIONS

Earth construction has been receiving increasing attention in the last few decades, driven by its green building potential and by other features of earthen materials. This construction solution encompasses different techniques such as: wattle and daub, cob, rammed earth, earth bricks and compressed earth blocks. The investigation that has been carried out in this field show several interesting characteristics of such construction technique related to carbon emissions, thermal performance and efficient alternatives to load bearing walls. However, several gaps were also found referring to their thermal performance. It is already known that the characteristics of the soil decisively influences the thermal properties of earth solutions, justifying further studies. In this context, the aim of this research was to analyse the influence of two different soils in the thermal performance of rammed earth solutions for walls. The obtained results allowed to corroborate that thermal performance is clearly influenced by soil properties, such as mineralogical composition, density, particle size distribution, and moisture content. In this study, these specificities of the considered soils allowed to achieve a reduction of around 34% in the thermal transmission coefficient. It was also observed that, for the same soil, the thermal transmission coefficient of a 50 cm thick wall is about 30% lower than the one verified for 35 cm of thickness.

5. ACKNOWLEDGEMENTS/FUNDING

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