41st IAHS WORLD CONGRESS
Sustainability and Innovation for the Future
13-16th September 2016
Albufeira, Algarve, Portugal

THERMAL AND ACOUSTIC PERFORMANCE OF INTERLOCKING COMPRESSED EARTH BLOCKS MASONRY

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Keywords: Thermal Performance; Acoustic Performance; Earth Construction; ICEB

Abstract: *The earth construction is an ancient building technique that, with the emergence of new materials and technologies, has received less attention during the last decades. Nevertheless, the new concerns in terms of environmental protection and sustainable construction have recently led to its revalorization. The masonry construction with interlocking compressed earth blocks (ICEB) is one of the earth construction techniques that features several advantages and has received the most developments in the last years. This type of masonry is currently being used worldwide, especially in developing countries, although the suspicions about its performance remain very wide. Another problem is the lack of standards and documents that can support designers in projects development. This research aims to contribute in this direction, creating bases to help designers in their work and contribute to the knowledge about this type of construction. Furthermore, there has been an increase in the standard requirements related to the comfort inside the building, namely at the thermal and acoustic level. So, the knowledge of the thermal and acoustic performance of the ICEB masonry is essential to define and optimize the constructive solutions at the design stage. Experimental studies were carried out in order to characterize these properties. The results are presented and discussed. It is expected that the results obtained serve as design support for this type of construction.*

1. INTRODUCTION

Today's society is showing a growing level of concern about the environmental issues and their consequences, emphasizing the environmental dimension as a conditioning for the economic growth and the use of natural resources [1].

The construction industry is one of the oldest and most important human activities that has contributed to the development of the planet, suffering a high advance in the last few years. This sector is one of the largest and most active throughout Europe [1]. This is demonstrated by the 750 million euros in annual turnover, as well as the share of industrial production, which amounts to 25%. This sector is also considered the world's largest exporter with values that achieve 50% of share [2]. Nevertheless, more recent studies have highlighted the increased of the environmental concerns in the construction industry, especially with regard to issues related to over-exploitation of non-renewable resources and environmental unsustainability due to the construction of new buildings [3]. In industrialized countries, such as Portugal, about 30 to 40% of natural resources are directed to the construction industry, reaching a value near 3000 million tonnes per year which is responsible for around 30% of $CO2$ global emissions. In addition, approximately 40% of the total energy produced is consumed by construction processes and building maintenance [4].

Thus, in order to minimize the negative impact that the construction industry has in the environment, it is urgent to adopt more sustainable and "environmentally friendly" materials [5] and techniques. In this field, earth construction has a prominent role worldwide. Earth construction is often defined as a construction technique that uses local raw, environmentally friendly, abundant, affordable, economic, reusable, non-combustible and with good thermal properties materials. This type of construction can also be easily adaptable to the various requirements that characterize the construction sites [6]. Although this technique has fallen into disuse due to the technological development and the emergence of new materials, it is observed that the stakeholders are increasing their knowledge in this area in order to revitalize this traditional technique.

In this context, masonry construction with interlocking compressed earth blocks (ICEB'S) has been applied. The construction technique using compressed earth blocks (CEB'S) appeared in Europe in the early nineteenth century by the hand of François Cointeraux. The wet earth was compressed with the feet in a wooden mould. This technique has earned its global expression with the creation of the first metal press, in Colombia, in the mid-twentieth century, called CINVA-ram. This is one of the earth construction techniques with the highest use nowadays [7][8].

However, the lack of social and institutional acceptance is a constraining for the use of this type of construction. Besides this type of construction is associated with poor communities, there is also a gap in the knowledge of its characteristics and how it can comply with the various requirements, particularly those related to the comfort in the internal spaces of earth buildings. Thus, in this research work it is intended to contribute to the knowledge of ICEB'S technique, through the analysis of its thermal and acoustic performance.

2. MATERIALS AND METHODS

In this section, the materials used to manufacture the ICEBs applied in this research work are described and characterized. The ICEBs units and masonry characterization, as well as the methodology used to perform the thermal and acoustic assessments, are also described.

2.1. Materials

Generally, earth and water are the main materials used in earth construction. These materials are mixed until obtain a mixture as homogeneous as possible. Thus, when the material is compressed to the maximum dry density of the soil (γ_d) and to the optimum water content (OWC), its maximum strength can be achieved. Taking this into account, geotechnical characterization of the soil is often necessary in order to evaluate its suitability to be used in earth construction.

The soil used to obtain the ICEBs for this study was collected in Guimarães, a city located in the Northern Region of Portugal. This soil is usually known as Granitic Residual Soil (GRS) and it is very common in this Region. Its characterization was done in what concerns to its particle size distribution (PSD) [9], Proctor compaction parameters [10], Atterberg limits [11] and particle density [12]. The results obtained for this characterization can be observed in Table 1.

Table 1. GRS geotechnical characterization.

Test	Fraction	Content (%)	Type	Feature	Result
PSD	Clay	4			
	Silt	14			
	Sand	60			
	Gravel	22			
Atterberg limits				Liquid limit (LL)	28%
				Plastic limit (PL)	-
Particle density test (g/cm^3)					2.62
Proctor compaction parameters			Standard	Maximum dry density (g/cm^3)	1.71
				OWC (%)	12.1
			Modified	Maximum dry density (g/cm^3)	1.85
				OWC (%)	12.3

The results obtained for the Atterberg limits allow to classify the GRS as non-plastic. With regard to the PSD, considering the results presented in Table 1 and also in **Erro! A origem da referência não foi encontrada.**, it can be concluded that the clay fraction content is low regarding the intended application, presenting only 4% of clay. Some international standards, such as HB 195 [13], ARS 680 [14], UNE 41410 [15] e NC 103 [16], present the minimum value of clay content to consider the soil suitable for CEB production, which are 5%, 10%, 10% and 8%, respectively.

Rigassi [17], Norton [18] and the Auroville Earth Institute [19] indicate clay content values of 8%, 10% e 20%, respectively. Taking those values into consideration, it can be concluded that the GRS collected is not a suitable soil to produce ICEBs with the desired quality. Therefore, its improvement is needed.

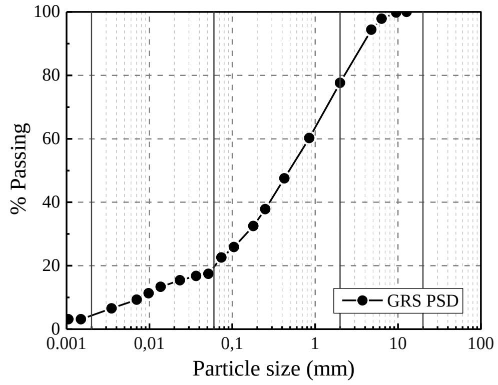

Figure 1. Particle size distribution of GRS.

An alternative cementation technique, known as alkaline activation (AA), was used to improve the soil properties. This technique appeared in the first half of the 20th century and its potential in soils improvement has been studied [12, 13, 14]. Its use to improve CEBs has also been analysed. Research work in this field shows that very promising results in the mechanical performance can be achieved using this technique [15, 16, 17].

Alkali activated Class F fly ash, with no commercial value, was used in the mixture to produce CEBs with enhanced mechanical performance. The Class F classification is due to the low calcium content in fly ash, which is generally less than 10%. Its characterization was performed in terms of grain size and chemical composition obtained by Energy Dispersive X-ray Spectroscopy (EDS), as can be seen in Table 2. An average of 10.64µm was obtained for the grain size. The quantity of material used in the activation process was approximately 75%, corresponding to the aluminium, silicium and calcium present.

Table 2 - Chemical composition obtained by EDS.

Element	Si	Al	Na	Ca	Fe	Mg	P	S	K	Ti
Quantity (%)	48.81	21.77	1.31	3.85	14.74	1.56	0.58	1.17	4.42	1.79

The fly ash with the alkali activator forms a gel that involves and bind the soil particles. A cementation agent, which can be defined as alkali activated binder (AAB), was created. The alkali activator used was obtained using a mixture of sodium hydroxide and sodium silicate. The sodium hydroxide was obtained in solid form (flakes) with 98% purity. It was dissolved in tap water 24 hours before its use in order to obtain a sodium hydroxide solution with the desired concentration. The sodium silicate used for the activator was obtained in the solution form, containing sodium oxide (Na_2O) and silicon dioxide (SiO_2) in a 1:2 mass ratio and presenting a density of 1.464±0.021 g/cm^3.

2.2. ICEBs

The GRS used in the production of the ICEBs was previously air dried and de-flocculated by hand. The mixture, presented in Table 3, was selected based on previous studies [15, 16, 17, 18].

Table 3. ICEBs mixture composition.

Solid Phase (%)		Liquid Phase (%)		Solid/Liquid (Phases) (%)	Concentration $NaOH_2$ (m)
Fly Ash	Soil	$NaOH_2$	Na_2SiO_2		
15	85	66.7	33.3	13.7	12.5

In order to produce the blocks, the materials were weighted and the mixture was prepared in two steps. The first step was defined as dry phase homogenization, composed by fly ash and GRS. In the second step, the liquid phase (alkaline activator) was added, producing the final mixture (Figure 2a). After the homogenization process, the mixture used to produce each block was weighted and placed properly in the press (Figure 2b). The manual press used in the ICEBs manufacture was a Terstaram®, which allows the application of a compression stress up to 4MPa. After production, the blocks were left indoor, for air-curing, during 28 days (Figure 2c). An average temperature and relative humidity of 18ºC and 55%, respectively, were guaranteed, according with NP EN772-1.

(a) (b) (c)

Figure 2. ICEBs manufacture: (a) mixture production; (b) blocks production; (c) air curing.

The geometry proposed by the HiLoTec project [26] was used in the blocks production. This geometry consists in a vertical hollow interlocking block system, which allows the reduction of unit weight and the material consumption in the production of each block. The hollow interlocking system admits the structural building reinforcement, as well as the installation of the hydraulic and electrical systems, without damaging the structural masonry integrity. The thermal and acoustic performance assessment was executed in blocks with 28 days curing. At this stage, its average density was 1800kg/m3 (approximately 6.7kg per block) and the average compressive strength was 3MPa [23].
The structural masonry walls built with the ICEBs produced for this study presents a mechanical interlocking system, which dispenses the use of bed joint mortar. Due to its geometric features it is possible to construct single-leaf and double-leaf walls, being the walls construction simpler, fast and inexpensive.

2.3. Methodology

A single-leaf dry-stack wall with the interior dimensions of 2.5×4.0 (m2) was built in the mobile frame of the test cell (Figure 3). This test cell, with about 2.5×2.5×4.0(m^3) of interior dimensions, presents a high thermal and acoustic insulation. To reduce the thermal and the acoustic transmission in the wall/test cell interface, the wall was pressed into a very compressible material with high density in order to minimize the influence of this interface in the measurements.

(a) (b) (c)

Figure 3. Tests preparation: (a) test cell; (b) construction of the single-leaf wall; (c) tested wall.

The ICEBs masonry thermal performance assessment was performed according to the standard ASTM C1046 [27], using experimental procedure. Five test point were selected to place the measurement sensors as indicated in Figure 4a: (i) vertical joint (test point 1); (ii) horizontal joint (test point 2); (iii) joint intersection (test point 3); (iv) hollow zone of the block (test point 4); and (v) solid zone of the block (test point 5).

An air conditioning Daykin FTXS50G2V1B was used inside the test cell to control and maintain a constant temperature. This equipment allows to obtain the required temperature range between the interior and the exterior of the test cell, which was important to guarantee that the heat flux through the element occurred always in the same direction. The sensors were installed in three steps. Firstly, it was installed the type T thermocouples sensors of copper/constantan (Figure 4b) on both sides of the wall in order to measure the masonry surface temperature during the tests. This step was proceeded with the installation of the Hukseflux HFP01SC with self-calibrating heat flux sensor^{tm} (Figure 4c). These sensors were used to measure the heat flux across the masonry wall and were placed in the outer face of the wall over the thermocouples. Toothpaste was used as the thermal contact material to place the sensors, as requested by the standard. In the final step was installed the Rotronic Instruments Hygroclip HC2-S sensors (Figure 4d) to measure the temperature and the relative humidity. These sensors were also used in the calibration of the masonry surface temperature.

After the sensors installation, the air conditioning was switched on. The first 24 hours were considered the necessary period to stabilize the interior temperature of the test cell at 18ºC. So, the data collected during this period was not considered for the analysis. Thus, it was possible to obtain a suitable temperature gradient between the interior and the exterior wall faces, achieving more representative heat flux measurements. In order to control, acquire and store the test data it was used a Campbell Scientific® CR10X datalogger. All the data was stored in a personal computer for further analysis.

(a) (b) (c) (d)

Figure 4. Thermal performance assessment: (a) test points; (b) type T thermocouples; (c) Hukseflux HFP01SC heat flux sensor; (iv) Hygroclip HC2-S sensor.

The data analyses was performed according to the procedures described in ASTM C1155 [28]. Being the tests performed in a laboratory environment and considering the point 5 of the referred standard, it was assumed that the quality of the materials and construction processes are homogeneous throughout whole wall area., The heat flux was always perpendicular to the wall plane at the selected measurement points due to the test cell format and the thermal conditions of the test cell were approximately constant during the experimental period. The measurements were performed in 5 minutes intervals and the values obtained represent the physical quantities average over that time. The test should be carried out in at least one 24-hour cycle. However, considering the controlled environment where the tests were performed, it was possible to obtain stable values in a shorter time period. In order to obtain the proper data convergence, it was selected a minimum of 12-hours cycle. The convergence is obtained when the convergence factor (CR_n) value is below 10% for 3 consecutive time periods.
The thermal performance of the ICEBs masonry was estimate determining the thermal resistance. The parameter was obtain applying (1, which includes the heat flow and the surface temperature range values during the considered period.

$$R_e = \frac{\sum_{k=1}^{M} \Delta T_k}{\sum_{k=1}^{M} q_k} \tag{1}$$

Where the masonry thermal resistance (R_e) is related with the temperature difference between the interior and the exterior surfaces of the wall in a particular period of time (ΔT_k) and the heat flux in the same period (q_k). The data validation was computed using the test of variance, $V(R_e)$, and only was considered when the convergence was achieved for at least three independent intervals. As happens in the majority of the constructive elements, all the tested points have different thermal behavior, given its heterogeneous constitution. So, in order to achieve a representative value for the masonry thermal resistance, it was necessary to use the Equation (2), which gives the weighted average values.

$$R_m = \frac{\left[\sum_{j=1}^{N} A_j\right]}{\left[\sum_{j=1}^{N} \frac{A_j}{R_{ej}}\right]} \tag{2}$$

Being R_m the masonry thermal resistance average and R_{ej} the thermal resistance in a region of a constructive element with an area A_j where the thermal conditions are similar. Computed the masonry thermal resistance, the heat transfer coefficient (U) can be obtained using Equation (3):

$$U = \frac{1}{[R_m]} \tag{3}$$

The ICEBs masonry acoustic performance assessment was carried out according to the standards ISO 354 [29], ISO 140-4 [30] and ISO 717-1[31]. The measurement of the sound pressure was obtained using a sound level meter Tektronix® CEL INSTRUMENTS

CEL573.C1 with accuracy class 1 (Figure 5a), placed inside the test cell (Figure 5b). An acoustic calibrator Tektronix® CEL INSTRUMENTS CEL284/2 was used to assure its calibration and valid data acquisition. The noise was produced with the help of a noise generator. In this sense, it was used a CEL INSTRUMENTS CEL513 noise generator. A sound source B&K type 4224 was used to produce sound. These equipment's were placed together in the outside of the test cell (Figure 5c).

(a) (b) (c)

Figure 5. Acoustic performance assessment: (a) sound level meter; (b) sound level meter placed inside the test cell; (c) Noise generator and sound source.

The ICEBs masonry acoustic performance was performed considering the analysis of four parameters: (i) reverberation time (T); (ii) average sound pressure level in the source room (L_1); (iii) average sound pressure level in the receiving room (L_2); (iv) background noise level (L_b). The T value was achieved using the test procedure in accordance with the described in ISO 354 [29] and it is determined through the decay curve obtained after the noise interruption. Regarding the described in the standards, the two sound level meters sensors were placed at a distance of 50cm from each other. The measurement of L1 and L2 was carried out according to the standards ISO 140-4 [30] and ISO 717-1[31]. The sound pressure measurements were performed in the range of central frequency bands, between 100 Hz and 3150 Hz. The background noise level (Lb) must be measured in order to ensure that the results are not influenced by disturbing noises. Considering the results obtained for this parameter, L2 must be revised in accordance with the Table 4.

Table 4. Conditions for L_2 revision.

Condition	L to consider
L_2-L_b $\geq$ 10 dB	$L_{2\ revised} = L_2$ dB
6 dB $\leq$ L_2-L_b < 10 dB	$L_{2\ revised} = 10\ Log(10^{L2/10} - 10^{Lb/10})$ dB
L_2-L_b < 6 dB	$L_{2\ revised} = L_{2\ revised}$ -1.3 dB

The weighted standardized level difference, $D_{nT,w}$, and the weighted sound reduction index, R_w, values were determined using the procedure described in ISO 717-1 for the frequency of 500Hz. In order to obtain $D_{nT,w}$ it is necessary to previously compute the standardized level difference, D_{nT}, which is calculated by the difference between L1 and L2 and with the correction of the reverberation conditions influence in the receiving room (Equation (4)).

$$D_{nT} = L_1 - L_2 + 10 \log \frac{T}{T_0} \quad (4)$$

Where T_0 is the reference reverberation time (0.5 seconds for dwellings). The $D_{nT,w}$ value is determined by the comparison of the reference and the test curves, with variations of 1dB, and is satisfied when the sum of the negative deviations is as high as possible but less or equal to 32dB.

R_w was determined by the comparison of the reference curve and the R'_w curve, obtained with the test measurements and applying Equation(5), taking into account the volume of the reverberation chamber (V) and the area of the tested element (A).

$$R'_w = D_{nT} - 10\log\frac{0.16V}{0.5A} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. Thermal Performance

The analyses of the exterior ambient temperature and the exterior and interior thermocouples curves, represented in Figure 6, allows to conclude that the temperature is stable with no major oscillations and with values convergence in the considered time period. Thus, it is possible to proceed with the thermal resistance (R_{ej}) calculation for the block unit. It was achieved a values of 0.13m^2·ºC/W and 0.12m^2·ºC/W for the test points 1 and 2, respectively. In the case of the test points 3, 4 and 5, the thermal resistance value obtained was 0.19m^2·ºC/W. The masonry thermal resistance average is 0.16 m^2·ºC/W. As an example, the heat flux curve for test point 1 is presented in Figure 6. All data acquired during the experimental program was computed according to the same analysis parameters.

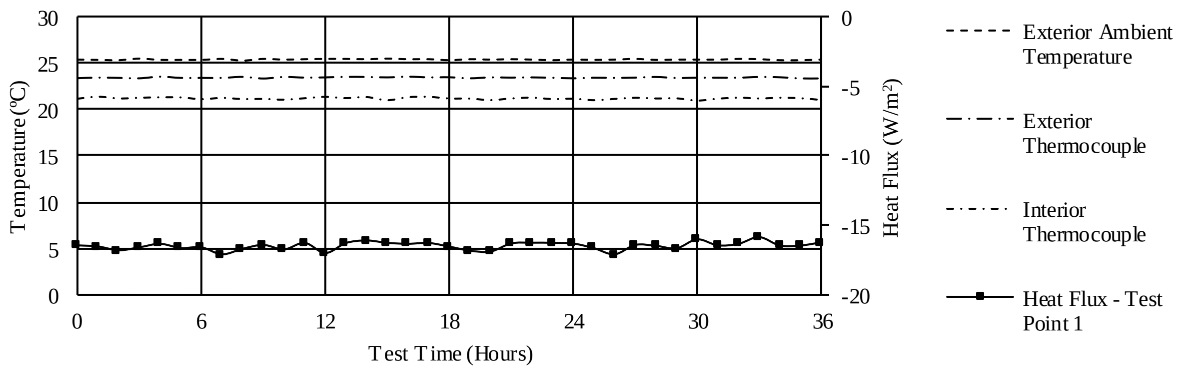

Figure 6. Test point 1 thermal behaviour assessment curves.

In order to obtain a representative thermal resistance of the ICEBs masonry, it was necessary to compute the weighted average area (A_{eq}) for the tested points. The thermal resistance (R_T) was obtained adding the surface thermal resistances values. The thermal resistance of interior (R_{si}) and exterior (R_{se}) surfaces is 0.13m2·ºC/W [32]. Acquired the RT value, it is possible to obtain the heat transfer coefficient (U) using the Equation (3). All the relevant results to estimate the thermal performance are presented in Table 5.

Table 5. Values for thermal resistance and heat transfer coefficient.

Test Point	R_{ej} (m²·ºC/W)	A_{eq} (m²)	R_m (m²·ºC/W)	R_T (m²·ºC/W)	U (W/m²·ºC)
1	0.13	0.21	0.16	0.42	2.38
2	0.12	0.72			
3	0.19	0.18			
4	0.19	1.26			
5	0.19	0.43			

3.2. Acoustic Performance

Two different measurements were performed in order to determine the ICEBs masonry acoustic performance. The first measurement was carried out in the morning and the second in the afternoon. Equation (4) was applied and it was possible to obtain the curves represented in Figure 7.

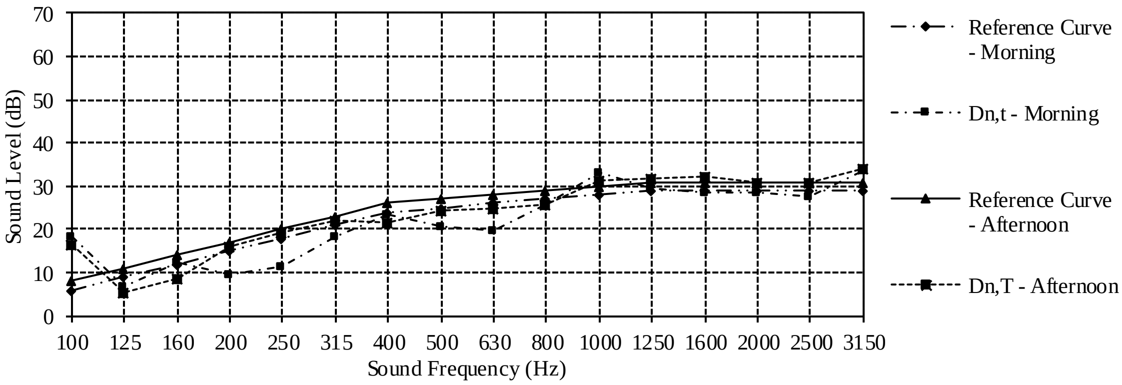

Figure 7. Acoustic performance assessment curves.

The analysis of Figure 7 lead to the conclusion that the weighted standardized level difference, $D_{nT,w}$, takes the values of 25dB and 27dB, in the morning and the afternoon periods, respectively.

Complying with the described before, the values obtained for the first and the second measurements were 31.5dB and 28.2dB, respectively. The results obtained in this test are presented in Table 6.

Table 6. $D_{nT,w}$ assessment from negative deviations analysis.

Sound Frequency (Hz)	Reference Curve - Morning (dB)	D_{nT} - Morning (dB)	Negative Deviations - Morning (dB)	Reference Curve - Afternoon (dB)	D_{nT} - Afternoon (dB)	Negative Deviations - Afternoon (dB)
100	6	18,27	0,00	8	16,43	0,00
125	9	6,84	2,16	11	5,45	5,55
160	12	12,49	0,00	14	8,52	5,48
200	15	9,58	5,42	17	15,94	1,06
250	18	11,32	6,68	20	19,24	0,76
315	21	18,54	2,46	23	21,92	1,08
400	24	23,34	0,66	26	21,46	4,54

500	25	20,79	4,21	27	24,34	2,66
630	26	19,70	6,30	28	24,87	3,13
800	27	25,57	1,43	29	25,57	3,43
1000	28	33,11	0,00	30	31,13	0,00
1250	29	29,32	0,00	31	31,51	0,00
1600	29	28,59	0,41	31	32,23	0,00
2000	29	28,53	0,47	31	30,79	0,21
2500	29	27,69	1,31	31	30,69	0,31
3150	29	33,63	0,00	31	34,17	0,00
	Negative Deviations Sum		31,50			28,20

4. CONCLUSIONS

The experimental work presented in this paper aims to contribute to the characterization of the thermal and the acoustic performance of the ICEBs masonry. It is also important to note that the soil is a multiphase material, which is especially important in the context of this work. The blocks used in this study were idealized taking special emphasis in the environmental impacts inherent to the construction processes. Thus, in the manufacture of the blocks it was used soil, which is a natural material that does not require processing procedures, and allows the incorporation of industrial by-products in the creation of the soil binder material. With respect to the thermal performance assessment it can be concluded that the ICEB's presents a heat transfer coefficient (U) of 2.38W/m2·ºC. This represents a contradiction of the general accepted idea that earth buildings presents a good thermal behavior. However, when compared with the reference value indicated in the Portuguese Standard, ITE50 [32], which is 3.37W/m^2·ºC, clearly this type of buildings offers better performance. It is possible to conclude that this type of constructions can be recommended for regions with temperate climates, such as southern Europe. However, in Portugal, a layer of an insulation material should be added to the wall to comply the thermal requirements.
In what concerns to the acoustic performance it is possible to conclude that the results are in line with the thermal properties. An average value of DnT,w of 26dB does not comply with the RRAE [33] requirements, given that the minimum value must be equal or higher to 33dB. However, despite the ICEBs masonry does not meet the requirements for thermal and acoustic levels, it is important to note that the obtained values are similar to others obtained for commonly used solutions which not include thermal and acoustic insulation materials. Therefore, it is considered that this research study fills a gap in the knowledge of these properties and that further studies should be conducted to their improvement.

ACKNOWLEDGEMENTS

This work is financed by FEDER funds through the Competitivity Factors Operational Programme - COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633. The authors wish to express their gratitude to Helena de Araújo and Liliana Simões for the support in the experimental work, to Eng. Jorge Henriques, on behalf of the company PEGOP – Energia

Eléctrica SA, for providing the fly ash, and to Miguel Rodrigues, on behalf of the company CJR GROUP, for providing the soil.

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