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The Effect of Mussel Shell Additions on the Mechanical and Thermal Properties of Compressed Earth Blocks

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ABSTRACT

Since their appearance in the 1950s, compressed earth blocks, a modern form of adobe brick have increasingly been studied for their many advantages compared to earlier forms of earthen materials. Their mechanical and thermal improvement is one of the main interests of many researchers. This study investigates the mechanical and thermal behavior of compressed earth blocks (CEB) loaded with crushed mussel shells (CMS) and stabilized with Portland cement. Two series of mixtures were prepared for CEB manufacturing using various CMS contents (0%, 5%, 10% and 15%), then compacted with a static load. Series 1 CEB without cement; Series 2 CEB with cement. Using X-ray diffraction, the mineralogical composition of soil and CMS was established. A scanning electron microscopy (SEM) examination of the mussel shell's morphology was performed too. The compressive and tensile strengths for both series were assessed after two different curing times (14, 28 days). The thermal conductivity of manufactured blocks was evaluated using the hot-disk method. The findings revealed that the increase in CMS content (from 0% to 15%) led to a reduction of the compressive strength by 35% for non-stabilized CEB and by 53% for stabilized CEB. However, the obtained compressive strengths remain above the minimum required compressive strength ($\sigma c > 1\ MPa$). In contrast, the thermal performances of both series were significantly enhanced. When increasing the CMS content (from 0% to 15%), the thermal conductivity decreases by 13% for non-stabilized CEB and decreases by 17% for stabilized blocks. The findings presented in this paper suggest that mussel shell aggregates are a feasible option to improve thermal behavior of compressed earth blocks.

1. INTRODUCTION

Earth construction has existed since the first agricultural communities, which, according to current knowledge, occurred between 12000 and 7000 BCE [1]. Currently, about 30% of the global population resides in earthen constructions [2].

In recent years, earthen construction has had a renaissance, primarily due to environmental concerns regarding the high global warming potential and high embodied energy of burnt bricks and cement-based products [3]. Earth material is available in nearly all climates, to nearly all civilizations across the globe in numerous forms, such as adobe, wattle and daub, cob, rammed earth, and compressed earth blocks [1-4]. It is one of the most tempting possibilities since it is inexpensive, readily accessible, and extracted and processed on the construction site with minimal production energy. In addition, the earth is recyclable, non-exhaustible, and, when used appropriately, provides good resistance, excellent hygro-thermal properties, and low embodied energy at reasonable pricing [5]. Compressed earth blocks (CEB) are one of the most used forms of earthen materials that have gained popularity in many countries since the invention of the famous CINVA-RAM press in the 50s. It is a modern evolution of the adobe brick. The compressed earth blocks consist in compacting moist earth inside a parallelepiped mold to a density that allows the blocks to be used as masonry units. The compaction is done by means of hydraulic or mechanical presses which allow to the material to be stronger and more stable compared to earlier forms of earthen materials. Despite the strength improvement achieved through the compaction process of these blocks, they are still less resilient compared to conventional materials. Several investigations on earth stabilization using chemical, physical, and mechanical mechanisms have been conducted to address this issue [6]. Stabilization is a time-honored procedure, particularly with clay plasters and stuccos [7]. It consists of altering the soil characteristics to enhance its physical or mechanical properties [1]. Soil densification by compaction and gradation, fiber reinforcement (natural and synthetic), and chemical treatment (such as and cement, lime...) are the most well-known and widely used techniques. Cement and lime are widely employed to improve the characteristics of the compressed earth blocks, but they considerably increase the embodied carbon and energy of materials and can inhibit passive humidity regulation [6]. These factors have sparked a renewed interest in natural stabilizers, additives and wastes with minimal environmental impact. Natural additives like as

Arabic gum, natural bitumen, tree resins, opuntia cactus juice, agave juice, cowpats, and casein from milk, etc., have been used by traditional builders throughout the world [7] and have recently regained popularity. Wastes and residues such as carpet waste fibers [8], tomato and beetroot residue [9], shredded waste plastic [10] were also examined to determine their viability as stabilizers.

Seashell wastes are among the wastes whose efficacy was widely studied by many researchers in different composites.

Seashell wastes management is a concern in several nations. These vast wastes thrown into public waters and/or landfills generate many environmental difficulties, including contamination of coastal fisheries, management of public water surfaces, odor, harm to natural landscapes, and health/sanitation issues [11]. As the production and processing of bivalves have expanded, the efficient utilization of their shells has become crucial to maximize financial return and handle waste disposal issues due to their sluggish natural decomposition rate. Several studies investigated the viability of incorporating seashell wastes such as periwinkle [12], oyster [13-15], cockle [16], mussel [17-19] and scallop shells [20] into various composites, such as concrete, cement mortar, air lime and bricks. These experiments concluded that when the percentage of seashells in concrete increases, its compressive strength, workability, and density decrease. In addition, they established that incorporating seashells impacts the water permeability, drying shrinkage of concrete, tensile splitting strength and modulus of elasticity. The incorporation of these seashell wastes, however, has produced favorable results in terms of thermal insulation.

Although the performances of seashell wastes have been extensively studied in numerous composites, their use in earthen materials was studied once. The only investigation that exists in the literature concerns the use of powdered green mussel shell in combination with pig hair fibers in compressed earth blocks. The study has been limited to the mechanical strength's assessment of the manufactured blocks. The authors concluded that the compressive strength of CEB made with ground green mussel shells as partial binder and 5% cement as stabilizer decreased, however it increased slightly when pig hair fibers were added to the mix combinations.

The present research aims at investigating the effect of crushed mussel shells on the mechanical and thermal properties of compressed earth blocks (CEB). Mussel shell wastes were chosen to be assessed in this investigation as additives in CEB mixtures since these mollusks are the most available marine wastes in Souss Massa region (Agadir). However, the most significant difference between this study and the aforementioned study, is the size of mussel shell aggregates, the mineralogical and structural analysis of these mollusks and the thermal conductivity analysis of manufactured blocks. Mussel shells collected from Cap Ghire site (Agadir) were heat treated to remove impurities, then crushed and sifted at 5mm. After that, their physical, mineralogical and structural properties were determined. The soil used in this investigation was selected according to the AFNOR standard criteria for compressed earth blocks after a series of tests done in the laboratory. After that, two series of compressed earth blocks were prepared using various CMS contents (0%, 5%, 10% and 15%). Series 1 non-stabilized CEB; Series 2 stabilized CEB, then conserved at room temperature (20°C) and 40%-50% of relative humidity. The optimum water content used in CEB manufacturing was determined by applying the static compaction in accordance with CDE method.

The CEB properties analyzed were compressive and flexural tensile strength and thermal conductivity.

2. MATERIALS AND METHODS

2.1 Materials

This investigation employed soil and mussel shell aggregates as the main matrix and cement as the stabilizer for compressed earth block production.

2.1.1 Soil

The soil was sourced from a site in Agadir (Morocco). First, the soil was sieved to remove all particles up to 20 mm [21]; then, the soil's geotechnical properties were determined through a set of tests, which included the particle-size distribution by sieving [22] and sedimentation [23], the Atterberg limits [24], the methylene blue value [25] and the absolute density by the pycnometer method [26]. The grain-size distribution is depicted in Figure 1 and the remaining soil characteristics are listed in Table 1. The soil has a plastic limit of 17%, a liquid limit of 29%, and a plasticity index of 12%, as shown in Table 1; thus, it is classified as A2 according to the French [27] and Moroccan [28] guides of road earthworks classification. The obtained grain-size distribution curve and Atterberg limits were compared with the AFNOR standard criteria of suitable soils for CEB manufacturing [21]. As illustrated in Figure 1 the particle-size distribution curve of the examined soil is within the CEB grain-size range recommended and the soil liquid limit and plasticity index fall within the recommended plasticity criteria (Figure 2), therefore the soil under study is suitable for CEB manufacturing. A Bruker D8 Advance Twin diffractometer equipped with a copper anticathode (Cu K = 1.5418, 40KV) was employed to establish the mineralogical composition of soil. XRD patterns were acquired with a 0.02° step from 5 to 80°. The software X'Pert High Score Plus was used to analyze the resulting patterns. As shown in Figure 3, the soil consists mainly of quartz, calcite and traces of kaolinite, muscovite, clinochlore and albite. Figure 4 is a scanning electron micrograph (SEM) of the examined soil, which reveals dispersed and non-oriented structures with visible pores. Figure 5 indicates significant contents of oxygen, silica and aluminum in soil composition.

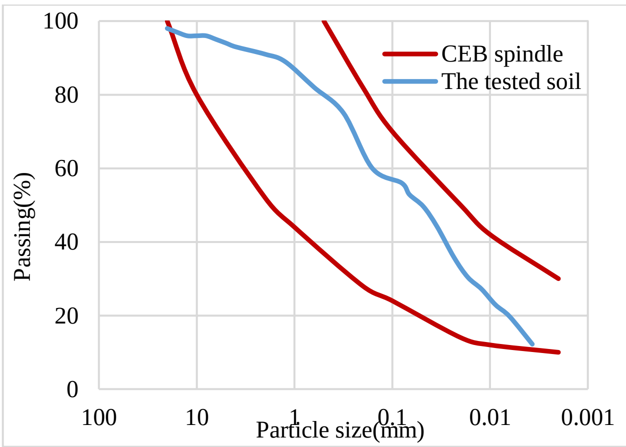

Figure 1. Particle-size distribution of the soil

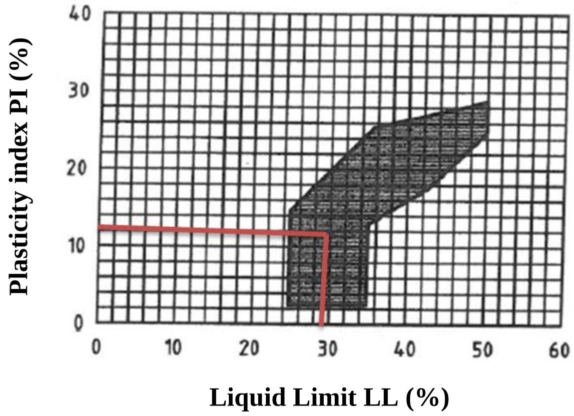

Figure 2. Atterberg limits of the soil

Table 1. Soil physical properties

Liquid limit (%)	29
Plastic limit (%)	17
Plasticity index (%)	12
Apparent density (Kg/m^3)	1430
Absolute density (Kg/m^3)	2650
Methylene Blue Value	1.2
Classification of soil	A2

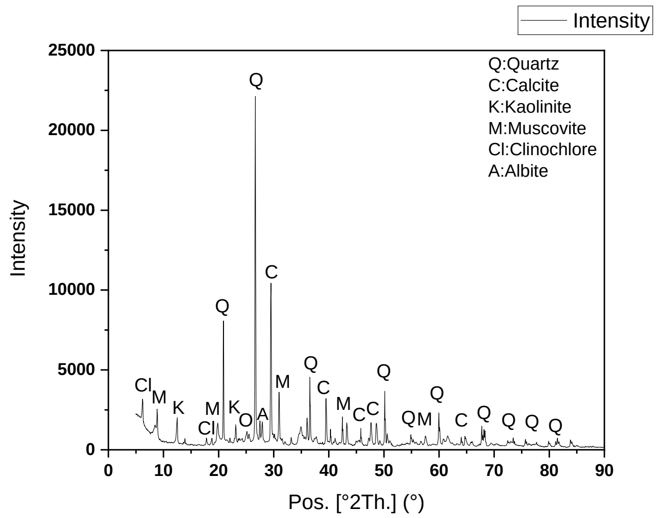

Figure 3. X-Ray diffractogram of the soil

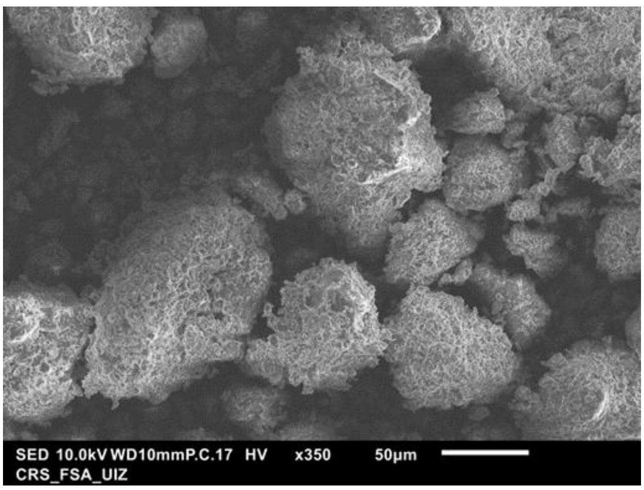

Figure 4. SEM micrographs of the tested soil

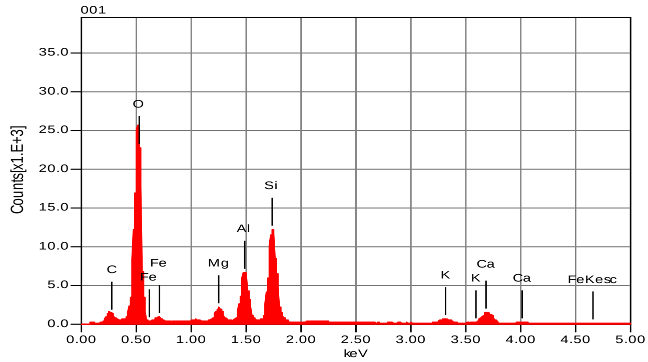

Figure 5. Energy-dispersive X-ray spectroscopy (EDX) of the soil

2.1.2 Cement

The cement was added to some CEB mixtures to improve their durability and compressive strength [29]. We chose the minimum recommended dose for CEB, which was 5%.

The cement employed in this study is CPJ 45 from Ciments du Maroc subsidiary of the German Group HeidelbergCement; it satisfies the NM 10.1.004 standard criteria [30].

2.1.3 Crushed mussel shells (CMS)

The mussel shells used in this research were collected from the CAP GHIR site in Agadir (Morocco) Figure 6 (a). After washing Figure 6 (b), the shells were heat-treated at 135°C for 32 minutes according to the European regulation [31] Figure 6 (c) then crushed using a jaw crusher Figure 6 (d) and sifted at 5 mm to obtain a homogeneous distribution. The new aggregates were analyzed through a set of tests which include the particle-size distribution [32] (Figure 7), natural water content, absolute and apparent density, absorption coefficient [33] and sand equivalent test. The physical properties of mussel shell aggregates are listed in Table 2. X-ray diffraction was used for determining the mineralogy of CMS (Figure 8). It was concluded that the mussel shell consists primarily of calcite and aragonite. This composition was also confirmed by other authors [17, 34, 35].

Figure 6. Preparation of mussel shell aggregates (a) Cap Ghire site, (b) mussel shell washing, (c) mussel shell drying, (d) jaw crusher

Shell morphology was observed with a SEM analyzer (JEOL JSM-IT100) coupled with a detector of emission of X-rays of type EDXS (Energy Dispersive X-Rays Spectroscopy) which makes it possible, by analysis of the characteristic emissions of the elements, to determine the local quantitative elemental composition of a sample. It presents a maximum resolution of 100 nm. Mussels, like other bivalves, consist of two shells formed by biomineralization of $CaCO_3$ held together with an organic matrix composite of polysaccharides (chitin), proteins and glycoproteins [34], each shell is composed of three parts: the outer layer, periostracum, the middle layer (prismatic layer) and the inner layer (nacre layer) Figure 9. The periostracum which function is to shield the prismatic layer from dissolution by acids and abrasion is unmineralized and composed mainly of protein [35], the prismatic layer consists of parallel calcite prisms [34] and the inner layer (Nacre layer) which could be classified as a biomineralized composite [35] is composed of laminar aragonite [34]. The detailed SEM microphotography of the mussel shell is illustrated in Figure 9.

Table 2. Mussel shell physical characteristics

Natural moisture content (%)	1.8
Absolute density (t/m^3)	2.66
Apparent density (t/m^3)	1.23
Absorption after 24h under water (%)	0.06
Sand equivalent	By piston test (%): 96.4 By sight (%): 97.9

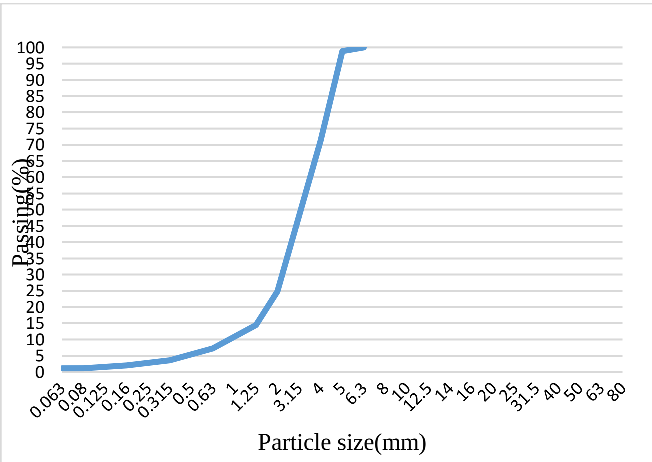

Figure 7. Particle-size distribution of CMS

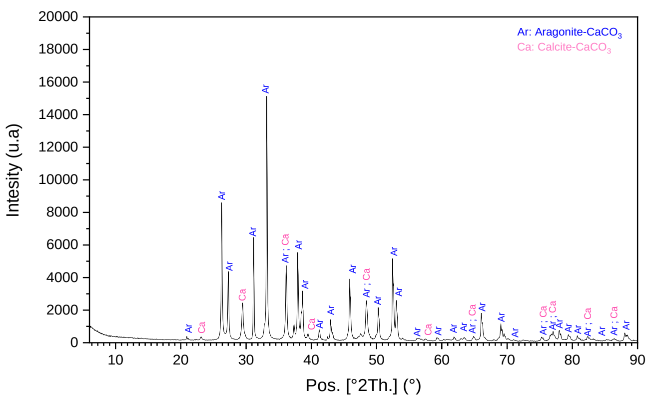

Figure 8. X-Ray diffraction curve of CMS

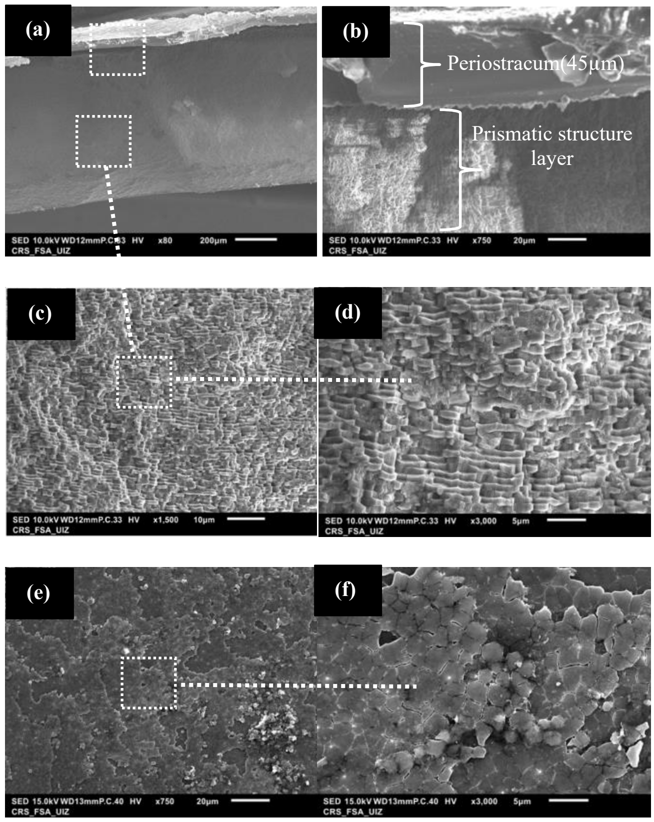

Figure 9. SEM morphology of cross section of mussel shell: (a) whole cross section of the outer part of the mussel shell; (b) the periostracum and the prismatic layer; (c) and (d) prismatic structure layer; (e) and (f) top view of the inner part of the mussel shell

2.2 Specimens manufacturing

A total of two series of mixtures were prepared for CEB manufacturing using several CMS contents (0%, 5%, 10% and 15%). Series 1 CEB without cement; series 2 CEB with cement. The details of these two series are summarized in Table 3. Mixtures were compacted by a hand press which allows to obtain samples in a one dimension (14*29.5*9.5 cm) (Figure 10). It generates a compaction pressure of approximately 2 MPa [36]. The optimum water content W_{omc} (%) and dry density ρ_s (Kg/m^3) of each mixture were determined by applying the static compaction in accordance with CDE (Centre for the Development of Enterprise) method [37]. Values obtained are presented in Figure 11.

The soil used for processing CEB was first sieved to remove all the particles up to 20 mm, then dried in an oven at 105°C for 24 h to remove any excess of moisture. The soil was mixed with mussel shell aggregates and cement (0% / 5%) manually thereafter, the optimum water content was added to the mixture. Mixing continued until obtaining a homogeneous mix. The Mixtures were then placed into the mold and compacted immediately. After compaction, both series were stored in the laboratory (20±2°C, 40-50% RH). CEB without cement were left to cure for 14 days and stabilized CEB were covered with a plastic sheet for the first 14 days to prevent quick drying out (Figure 12).

Before subjecting the specimens to the mechanical and thermal tests, they were dried in an oven at 40±5°C until reaching a constant mass to remove any moisture excess (Figure 13).

Figure 10. Compressed earth blocks manufacturing

Table 3. Mixture proportions of CEB

	Mix Code	CMS (%)	Cement (%)	Retaining Period
Series 1	CMS0%-CEM0%	0%	0%	14 days
	CMS5%-CEM0%	5%	0%	14 days
	CMS10%-CEM0%	10%	0%	14 days
	CMS15%-CEM0%	15%	0%	14 days
Series 2	CMS0%-CEM5%	0%	5%	28 days
	CMS5%-CEM5%	5%	5%	28 days
	CMS10%-CEM5%	10%	5%	28 days
	CMS15%-CEM5%	15%	5%	28 days

CMS: Crushed mussel shells

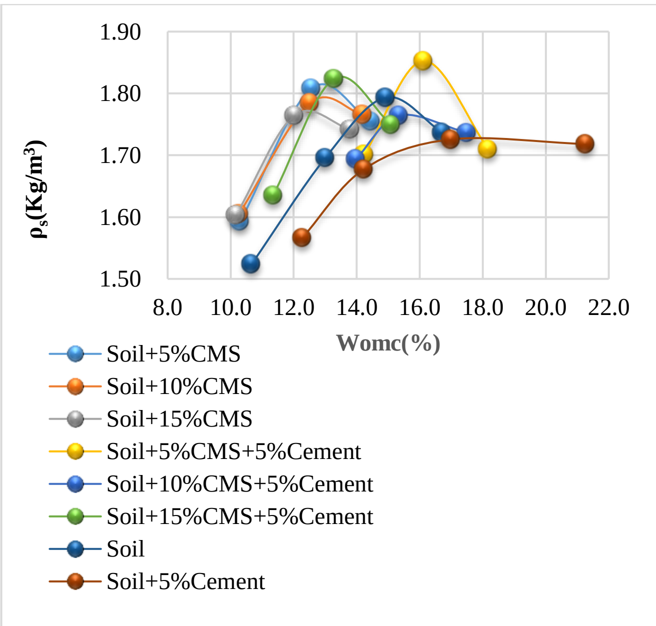

Figure 11. Optimum water content of soil and different mix combinations

Figure 12. Storage and curing of (a) non-stabilized blocks, (b) cement stabilized blocks

Figure 13. Drying of manufactured blocks

2.3 Tests conducted

2.3.1 Dry compressive strength

The dry compressive strength test was done according to the procedure adopted in XP P 13-901 standard [21]. The dried blocks were halved Figure 14 (a) and stacked bonded using earth mortar for non-stabilized blocks and cement mortar for stabilized blocks, then kept in the laboratory for mortar hardening Figure 14 (b). A cardboard sheet was positioned between the platen and the blocks to minimize friction; the test set-up is shown in Figure 14 (c). The dry compressive strength of CEB was then calculated using the following formula [21]:

$$R = \frac{F*10}{S} \quad (1)$$

in which:

R: Compressive strength (MPa)

F: Maximum load applied to the specimen (KN)

S: Average area of bed faces (cm^2)

Figure 14. Dry compressive strength test; (a) cutting the block into two half-blocks, (b) superposition of the two half-blocks, (c) set up used for dry compressive strength

2.3.2 Splitting tensile strength test

The splitting tensile test, also referred to as Brazilian test was conducted in accordance with the method outlined by Olivier et al. [38]. The test involves subjecting the block to compression along two rigid wood strips placed on both sides of the block, resulting in a tensile stress along a vertical facet passing between these strips Figure 15 (a). Using the following formula [38], the splitting tensile strength of CEB was determined

$$Rt = 0.9 * 10 * \frac{2*F}{\pi*l*h} \tag{2}$$

in which:
Rt: Tensile strength (MPa)
F: The maximum load supported by the specimen (KN)
L: The width of the specimen (cm)
H: The thickness of the specimen (cm)

Figure 15. Splitting tensile strength test

2.3.3 Thermal tests

The thermal properties of soil, CMS and CEB were determined by the TPS 1500. The TPS is a Hot Disk thermal constant analyzer designed to measure the thermal transport properties according to ISO 22007-2 [39]. The Hot Disk analyser consists of a nickel double spirale sandwiched between two thin insulating sheets (Kapton, Mica, etc.). It acts as a heat source as well as a dynamic temperature sensor by passing a sufficient electrical current to raise the sensor's temperature while simultaneously recording the temperature increase as a function of time. The thermal conductivity measurement of CMS Figure 16 (a) and soil Figure 16 (b) was performed by inserting the Hot Disk sensor within the material. Each test was performed three times, and the average values are summarized in Table 4.

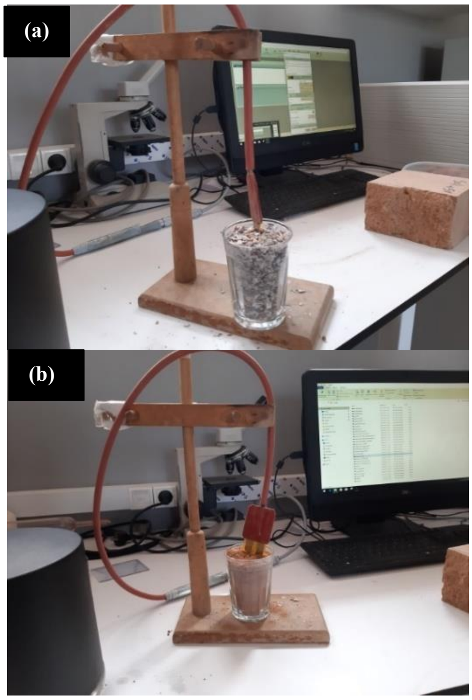

Figure 16. Thermal conductivity measurement of CMS (a) and soil (b) using the Hot Disk Thermal Constants Analyzer

Table 4. Average values of thermal conductivities of CMS and soil

Thermal Conductivity of Soil (W/m.K)	Thermal Conductivity of CMS (W/m.K)
0.3634	0.3048

Figure 17. Thermal conductivity measurement of CEB using the Hot Disk Thermal Constants analyzer

The thermal conductivities of manufactured blocks were determined by fitting a Hot Disk sensor between two half-blocks (Figure 17).

3. RESULTS AND DISCUSSION

3.1 Dry compressive strength

Figure 18 displays the evolution of compressive strength of CEB according to CMS content. As the CMS percentage increases, the dry compressive strength of non-stabilized CEB decreases significantly while still exceeding the minimum recommended compressive strength of 1 MPa [40]. It decreases from 1.87 MPa at 0% of CMS to 1.21 MPa at 15% of CMS; a decrease of 35%. Whereas, the compressive strength exceeds the target strength for stabilized blocks but it still decreases according to CMS content. It goes from 4.47 MPa at 0% of CMS to 2.09 MPa at 15% of CMS; a decrease of 53%. This enhancement is due to the creation of rigid links resulting from the hydration reactions of cement. This study's findings corroborate those of Lejano et al. [41]. They find out that the compressive strength of CEB made with ground green mussel shells as partial binder and 5% cement as stabilizer decreased, but increased slightly when pig hair fibers were added to the mix combinations. These findings are also consistent with those of Martinez et al. [17, 18] for different composites, such as concrete and cement mortar. They concluded that an increase in mussel shell aggregates content led to a rise in porosity due to their flat and flaky shape and organic composition, which reduce cement paste-aggregate bonds, resulting in a reduction in compressive strength. The cement percentage has a substantial impact on the compressive strength as well. According to Taallah et al. [42], for a 5% cement content, the decrease in compressive strength is attributable to the predominance of fibers, as the amount of hydration products becomes insufficient to fill the pores created in the mix. The mortar joint between the blocks may also impact the results. As reported by Walker et al. [29], the mortar is weaker and less rigid than the blocks as a result of its higher water content and lack of compaction.

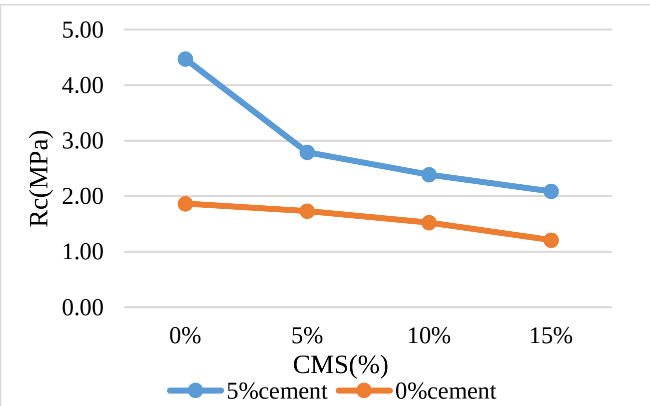

Figure 18. Variation of the dry compressive strength as a function of the CMS content

3.2 Splitting tensile strength test

Figure 19 depicts the evolution of CEB splitting tensile strength as a function of CMS content. The tensile strength of non-stabilized CEB increases to an optimal value of 0.49 MPa at 5% load content, then decreases for higher load contents, reaching 0.24 MPa at 15% load content (Figure 19); a decrease of 25%. For stabilized CEB, the tensile strength decreases with increasing CMS content. It decreases from 0.44 MPa to 0.22 MPa for CMS contents between 0% and 15%; a decrease of 50%. This can be explained again by the flat and flaky form of mussel shell aggregates, the presence of organic substances in their composition and the low cement content used.

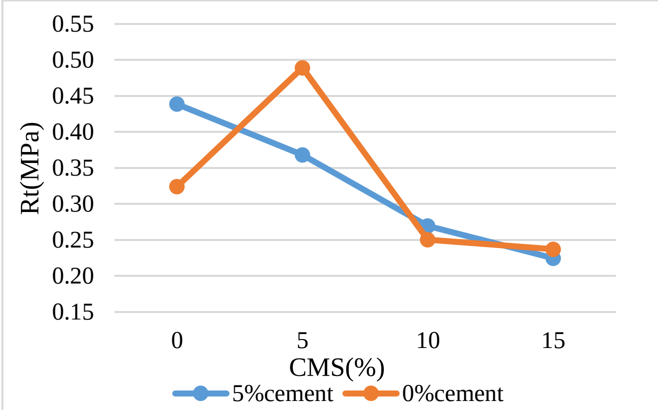

Figure 19. Evolution of the splitting tensile strength as a function of the CMS content

3.3 Thermal conductivity

Figure 20 displays thermal conductivity for both stabilized and non-stabilized CEB according to the CMS content. As can be seen, the greater is the CMS content, the lower is the thermal conductivity. For non-stabilized CEB, it decreases by 13% from 0.774 W/m.K at 0% of CMS to 0.673 W/m.K at 15% of CMS, while it decreases by 17% for stabilized CEB, from 0.721 W/m.K at 0% of CMS to 0.592 W/m.K at 15% of CMS for stabilized CEB, this is primarily attributable to the increase in porosity of CEB [43]. In fact, the irregular and flat form of mussel shell aggregates introduces pores in CEB mixtures, these pores contain air which represents an insulating medium for transfer of heat between grains.

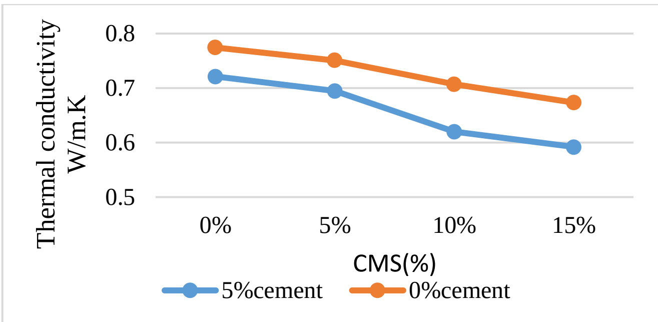

Figure 20. Variation of the thermal conductivity as a function of the CMS content

These findings are in agreement with those of Ez-zaki et al. [44], they find out that using mussel shell as a partial sand replacement is an effective method for enhancing thermal insulation by decreasing the thermal conductivity of mortars. In fact, the thermal conductivity of mortar decreased by 34% at a substitution rate of 60%. These outcomes are also consistent with those of Lertwattanaruk et al. [45], they found that the thermal conductivity of mortars formulated with ground seashells decreased by 1% to 45% for a substitution rates ranging from 5% to 20% by weight of binder, and that the lowest thermal conductivity is found in mortars containing ground mussel shells. This is due to the porosity created in elaborated mortars which makes them less dense than standard mortar [45].

4. CONCLUSIONS

This study aimed to assess the effect of mussel shell aggregates on the dry compressive and tensile strengths and thermal conductivity of compressed earth blocks. From the obtained values, the following inferences can be drawn:

1. The mechanical strengths and thermal conductivity of CEB do not evolve in a similar manner. An improvement of thermal performances of manufactured blocks is accompanied by a reduction in their mechanical performances.
2. The compressive and flexural strengths of manufactured blocks decrease as the CMS content increase. The compressive strength of non-stabilized CEB decreased by 35%, while it decreased by 53% for stabilized blocks. However, obtained compressive strengths are above the minimum required strength ($\sigma c > 1\ MPa$). The flexural strength of non-stabilized CEB decreased by 25% for non-stabilized CEB, while it decreased by 50% for stabilized CEB.
3. The stabilized CEB show greater strengths compared to non-stabilized CEB due to the formation of calcium hydroxide during the hydration of cement particles.
4. The main mussel shell characteristics that affected the mechanical performances of manufactured CEB are their flat and flaky shape as well as the presence of organic matter in their composition.
5. The thermal conductivity of CEB decreases as the content of CMS increases. The thermal conductivities of non-stabilized CEB were decreased by 13%, while it decreased by 17% for stabilized CEB. This is mainly attributed to the porosity created by the flat and flaky shape of CMS.

In general, it may be said that the incorporation of mussel shell aggregates is a viable method for enhancing thermal insulation in building construction.

The following issues must be addressed in future research: (i) incorporation of a higher cement percentage, (ii) the shape of mussel shell aggregates, and (iii) increasing the compaction pressure (>2MPa) or using a hydraulic press to maximize the contact surface area between grains, thereby reducing porosity.

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