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ORIGINAL

Effect of Compaction Pressure on a Stabilized Rammed Earth Behavior

Efecto de la presión de compactación en el comportamiento de una tierra apisonada estabilizada

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ABSTRACT

The current work addresses the effect of compaction pressure on durability against water ingress, compression behavior, and thermal conductivity of rammed earth specimens stabilized with fly ash geopolymer. These properties were investigated for specimens made from 25 % fly ash and proportions of sand, silt, and clay. The fly ash was activated with 2M sodium hydroxide solution, and the specimens were compacted statically to 5, 10, or 25 MPa. Reference mixtures containing the raw material (i.e., sand, silt, and clay) were also prepared for comparison. The results of the durability test on stabilized specimens indicated excellent resistance to deterioration caused by water ingress, unlike those made from raw materials which almost failed completely. The materials elastic stiffness and compressive strength were both improved substantially with the inclusion of fly ash geopolymer and with compaction pressure increase. The inclusion of geopolymer resulted in 6 to 10 folds improvement in the compressive strength. For instance, the stabilized specimens provided a compressive strength of 2,7 MPa when compacted to 5 MPa, compared to only 0,3 MPa provided by the unstabilized specimen. Likewise, an increase in compaction pressure from 5 to 25 MPa, resulted in an increase of 56 % in the compressive strength. The thermal conductivity of the stabilized material was in the order of 0,4-0,5 W/ (m.K) and was considered relatively low comparing to that of other competitors such as normal concrete and even lower than that of the raw material by about 18 %. The thermal conductivity increased by about 20 % with compaction pressure increase from 5 to 25 MPa. It seems that the increase in the stiffness and strength with compaction pressure increase can compensate the small undesirable increase in the thermal conductivity.

Keywords: Rammed Earth; Compressive Strength; Thermal Conductivity; Durability.

RESUMEN

El presente trabajo aborda el efecto de la presión de compactación sobre la durabilidad frente a la entrada de agua, el comportamiento a compresión y la conductividad térmica de especímenes de tierra apisonada estabilizados con geopolímero de cenizas volantes. Estas propiedades se investigaron para especímenes fabricados con un 25 % de cenizas volantes y proporciones de arena, limo y arcilla. Las cenizas volantes se activaron con una solución de hidróxido sódico 2M y las probetas se compactaron estáticamente a 5, 10 ó 25 MPa. También se prepararon mezclas de referencia que contenían la materia prima (es decir, arena, limo y arcilla) para su comparación. Los resultados del ensayo de durabilidad de los especímenes estabilizados indicaron una excelente resistencia al deterioro causado por la entrada de agua, a diferencia de los fabricados con materias primas que casi fallaron por completo. La rigidez elástica y la resistencia a la compresión de los materiales mejoraron sustancialmente con la inclusión del geopolímero de cenizas volantes y con el aumento de la presión de compactación. La inclusión del geopolímero produjo una mejora de 6 a 10 veces en la resistencia a la compresión. Por ejemplo, los especímenes estabilizados proporcionaron una resistencia a la compresión de 2,7 MPa cuando se compactaron a 5 MPa, en comparación con sólo 0,3 MPa proporcionados por el espécimen no estabilizado. Del mismo modo, un aumento de la presión de compactación de 5 a 25 MPa, dio lugar a un aumento del 56 % en la resistencia a la compresión. La conductividad térmica del material estabilizado fue del orden de 0,4-0,5 W/(m.K) y se consideró relativamente baja comparada con la de otros competidores como el hormigón normal e incluso inferior a la del material bruto en aproximadamente un 18 %. La conductividad térmica aumentó alrededor de un 20 % con el aumento de la presión de compactación de 5 a 25 MPa. Parece que el aumento de la rigidez y la resistencia con el aumento de la presión de compactación puede compensar el pequeño aumento indeseable de la conductividad térmica.

Palabras clave: Tierra Apisonada; Resistencia a la Compresión; Conductividad Térmica; Durabilidad.

INTRODUCTION

Rammed earth is a technique mainly used to construct walls from raw earth-based materials of different constituents of gravel, sand, silt and clay. The employment of earthen materials in construction is on the rise, mostly because they are less expensive and have a lower embodied energy than common wall materials like fired bricks and concrete masonry units.(1,2,3) In order to overcome some of these issues, compressed stabilized soil blocks which are stronger and more dimensionally stable than standard adobe blocks are being alternatively investigated.(4) Currently, research is being conducted to enhance the characteristics of soil blocks because of perceived limitations in strength and durability.(5) Soil blocks stabilized with ordinary Portland cement have characteristics common to cementitious materials, such as quasi-brittleness and low strain and tensile capabilities. A workable way to improve the functionality of these matrices is to add different kinds of fibers to increase their ductility, strength, toughness, and resistance to impact loads.(7,6)

Growing public awareness of sustainable living, improved understanding of the earth's thermal advantages, safety, durability, and the reduced energy inputs of earthen buildings are among the factors promoting the use of stabilized rammed earth.(8,9,10,11) Despite its importance in the built environment, rammed earth is one of the most underappreciated materials in society.(12) Earth buildings have emerged as the most promising materials in recent years due to their minimal influence on the environment and their high energy performance.(13,14)

To encourage their usage and integrate them into the specifications of the existing rules, many studies have been performed on their structural behavior, durability, and water absorption tenacity. Likewise, many recent studies have been conducted to thermally characterizing compressed earth blocks, stabilized rammed earth materials, and rammed earth blocks (15) and brick walls.(16,17)

Nevertheless, local soils can contain contaminants that can affect building projects. In addition, inadequate engineering processes can result in unstable and weak structures, which increase the cost of building projects that use local soil. The main objective is to increase the mechanical properties and durability of soil, while reducing its susceptibility to swelling and shrinking. To address these issues, researchers have explored the use of different stabilizers to improve the quality of local soil.(18,19)

The current work explores the effect of compaction pressure on a number of rammed earth properties, i.e., durability, compression, and thermal conductivity of geopolymer-stabilized earthen materials. In practice, lowering compaction pressure to as low as 5 MPa, has several advantages, including, for example, lower production costs and better thermal insulation.

Experimental Work and Procedures

Soils. To form a rammed earth, appropriate fine and coarse soils had to be sited. Such soils (figure 1) were found available in quarries near Ramadi. Sufficient amount of each soil was collected in plastic bags, brought to the soil lab, dried in the oven at 110oC, pulverized, then samples were taken for classification. The result of grain size distribution is shown in figure 1 and a list of the classification test results is given in Table 1. As can be noticed, Soil 1 was classified as poorly graded sand while Soil 2 was classified as fat clay.

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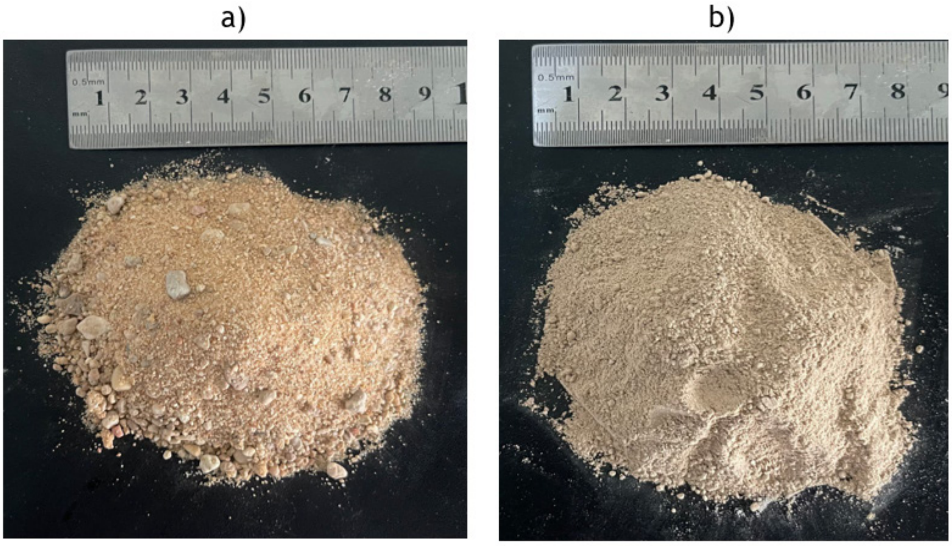

Figure 1. Images of: a) Soil 1, b) Soil 2

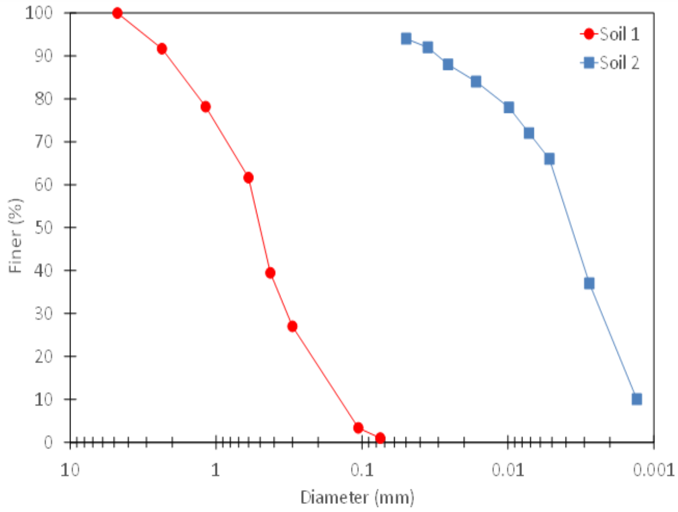

Figure 2. Particle size distribution of Soils 1 and 2

Table 1. Soil 1 and Soil 2 classification

Specification	Soil 1	Siol 2	Property	
ASTM D422-2007[20]	0	0	Gravel (>4,75 mm, %)	Gradation
	100	0	Sand (4,75-0,075 mm, %)	
	0	35	Silt (0,075-0,005 mm, %)	
		65	Clay (<0,005 mm, %)	
		66	Liquid limit (%)	
ASTM D4318-1[21]	Non-plastic	27	Plastic limit (%)	Plasticity
		39	Plasticity index (%)	
ASTM D2487-1[22]	D60 D30 D10		Effective diameters (mm)	Soil classification (USCS)
	0,60 0,35 0,15			
	1,4		Coefficient of curvature, Cc	
	4,0		Coefficient of uniformity, Cu	
	SP	CH	USCS class	
ASTM D854-2014[23]	2,67	2,70	Specific gravity	

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Fly Ash Geopolymer. Yahya and Al-Sharrad[24]preformed an in-depth investigation of the use of fly ash geopolymer rammed earth stabilization. Several trial soil-geopolymer mixtures were prepared from different NaOH molarities and fly ash contents and test specimens were fabricated by static compaction to 25 MPa. They concluded that geopolymer mixtures prepared with (2-4) M NaOH and (20-25)% by weight fly ash to soil yielded satisfactory results in terms water erodibility resistance and strength, among other properties. Following the recommendation of Yahya and Al-Sharrad[24], the NaOH was prepared at 2M and was added to 25 % fly ash to form the geopolymer paste. These two materials were provided by a local vendor. The NaOH is used as the activator for the synthesis of geopolymers because it is more alkaline compared to other activators, e.g., KOH, and is readily available with reasonable purity (≈98 %) as a by-product. The NaOH solution was achieved by dissolving a certain mass of NaOH flakes in a predetermined volume of distilled water. Because the dissolution reaction generates heat, the solution was allowed to cool to ambient temperature on the bench for approximately two hours before being kept for the night before use.

Table 2. Mineralogical composition of the fly ash

Other oxides	K2O	Na2O	P2O5	MgO	SO3	TiO2	Fe2O3	CaO	Al2O3	SiO2	Elemental oxides
0,70	0,69	0,73	0,81	1,25	1,41	2,28	4,13	9,84	28,56	46,97	Concentration %

The Compaction Characteristics of the Mixtures

In this work, the specimens were prepared with a static pressure to 5, 10, 25 MPa, using the compaction rig shown in figure 4. The use of these pressures is justified by the fact that hardened geopolymer serves as a cementitious material which provides additional strength in such a way it counterweighs the decrease in materials density with decreasing compaction pressure. A mold made of stainless steel was manufactured with; an inner diameter of 50 mm, wall thickness of 25 mm, and a height of 170 mm. The diameter of the shafts was 49 mm and the height is 220 mm. Perforated steel discs 49mm in diameter and 20mm high to allow water to drain. To characterize the material's water-unit weight relationship at various compaction pressures, compaction trials were performed at each pressure on fly ash-soil mixtures prepared at various water content values. To ease the compaction test, water was the only liquid used, however in a real specimen preparation, NaOH solution substituted the water at a ratio of 1:1.

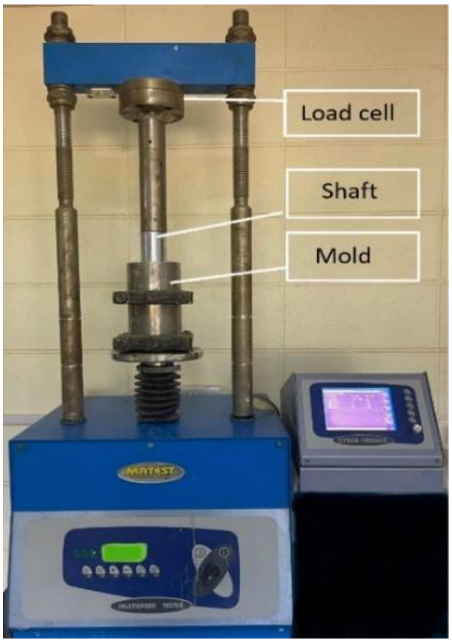

Figure 3. Compaction equipment

Production of Raw and Stabilized Rammed Earth Specimens

Six mixtures were investigated in this work, three of which were for raw material (i.e., Mix 1 to Mix 3) while the other three were for geopolymer-soil material (i.e., Mix 4 to Mix 6), see table 3. To prepare specimens, oven-dried proportions of Soil 1 and Soil 2 are prepared and mixed at the ratio of 30:70. For the mixes 1 to 3, a predetermined amount of water corresponding to the optimum moisture content was added, whereas for the mixes 4 to 6, the NaOH solution was thoroughly mixed with the fly ash proportion of the mix, the paste was then added to the soils. The NaOH solution content of the three mixture was fixed at 10 % for all the stabilized

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mixtures, regardless the optimum values. This decision was made on the basis that a 10 % activator content was found sufficient (as will be shown later) to activate most of the fly ash, and producing enough binder to stabilize the material against deterioration by water ingress. This also has the implication that production cost is reduced with reducing the amount of sodium hydroxide.

The specimens (50 mm in diameter and 100 mm in height) were compressed by pouring one-third of the material into the mold at a time then applying a constant displacement of 12 mm/min until the target compressive pressure 5, 10 or 25 MPa was attained. After unloading and extrusion, the specimen's weight and dimensions were recorded and it was placed in a plastic bag to maintain a high humidity level. The specimens were cured for 7 days in an oven under a constant temperature of 35 °C.

Table 3. Mix design of the work

	Mix No.	1	2	3	4	5	6
	Mix code	**Raw-5MPa**	**Raw-10MPa**	**Raw-25MPa**	**Stabilized-5MPa**	**Stabilized-10MPa**	**Stabilized-25MPa**
	Compaction pressure (MPa)	5	10	25	5	10	25
	Fly ash (%)	0	0	0	25	25	25
Soil 1	Sand (%)	70	70	70	52,5	52,5	52,5
Soil 2	Silt (%)	9	9	9	7,9	7,9	7,9
	Clay (%)	21	21	21	14,6	14,6	14,6

Testing of Raw and Stabilized Rammed Earth Specimens

Durability Test. Inspection of materials durability against erosion caused by water immersion was performed according to the German Normative DIN 18945. Figure 6 shows how this test is configured. The cylindrical specimen was secured, lowered, and immersed in water for 10 minutes to a depth of 5 cm. Once the immersion was completed, the sample was carefully removed from the water bath, and the remaining material in the beaker was filtered, dried, and stored at 40°C and 50 % relative humidity until a constant mass was achieved. Once two consecutive weighing attempts separated by a 24-hour period did not deviate by more than 0,2 % from the least measured mass, this mass was recorded. The mass loss by immersion was calculated as the percentage of the mass of the remaining material from three identical specimens with respect to the initial total mass of these specimens.

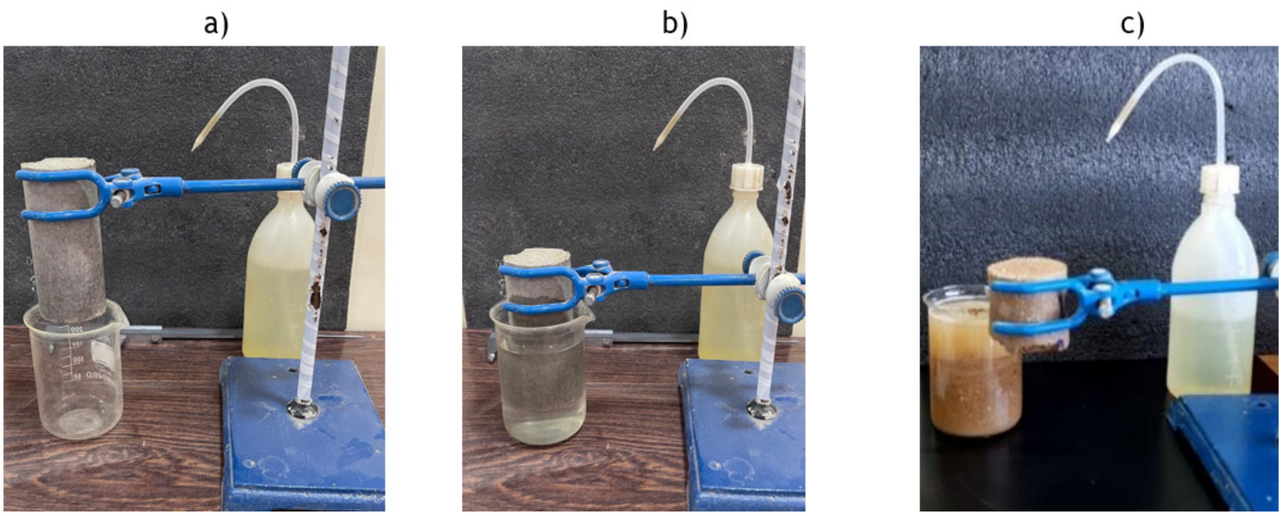

Figure 4. Dip test: a) test configuration, b) specimen passing the test, c) specimen failing the test

Unconfined Compression Test

The unconfined compression test was performed in accordance with the ASTM D2166-16.[25] Two specimens of each mixture were tested by compressing the specimens under a constant rate of displacement of 1 mm/ min. Values of load and displacement were frequently recorded and the test continued until the specimen attained failure state. Test results were analyzed for elastic modulus and the compressive strength. The former was taken as the slope of the line best-fitting the straight portion of the stress-strain curve (ASTM D7012-14).[26] The latter was taken as the highest compressive stress attained by the specimen before failure.

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Thermal Conductivity Test

This test was performed by the technical staff of the Iraqi National Center for Construction Laboratories (NCCL) on various raw and stabilized specimens following the transient hot wire method (ASTM C1113-2013).[27] Prismatic test specimens were prepared with 100*100*50 mm3 inside a specially manufactured mold. These specimens were compacted to 5, 10, or 25 MPa.

RESULTS AND DISCUSSION

This section provides a summary of the fundamental findings about the material's compaction, durability, and response of compression.

Compaction Characteristics. Figures 5 and 6 show the variation of dry unit weight with water content for the raw and the stabilized materials, respectively. For both materials, the maximum dry unit weight expectedly increases whereas optimum water content decreases with increasing static compaction pressure. For comparison, the values of maximum dry unit weight and the optimum water content are summarized in Table 4. Because the used fly ash had lower specific gravity of 2,26 compared to the soils (2,67-2,7), as in Table 1, the stabilized mixtures showed lower maximum dry unit weight values than the corresponding unstabilized ones. Also, because the fly ash is mainly fined-grained (≈85 % finer than 0,075 mm), it showed higher affinity to water compared to the soils, thereby yielding higher optimum water content.

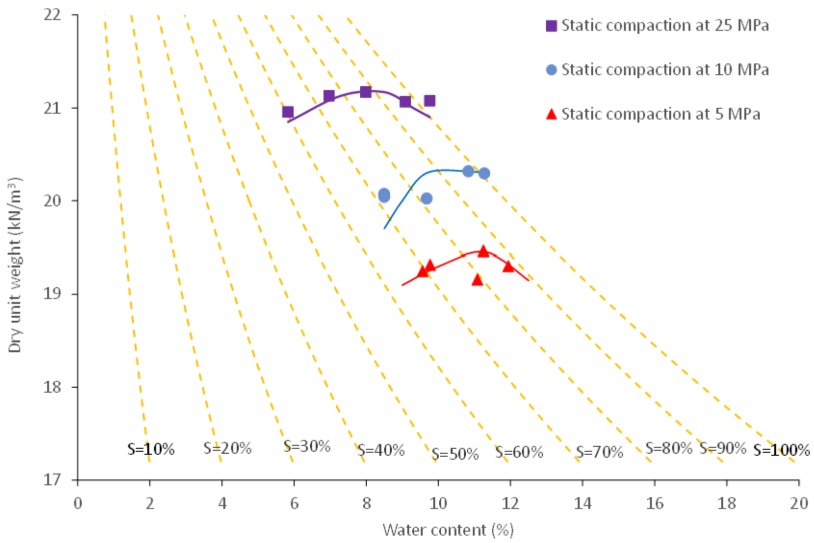

Figure 5. Compaction characteristics of the raw material

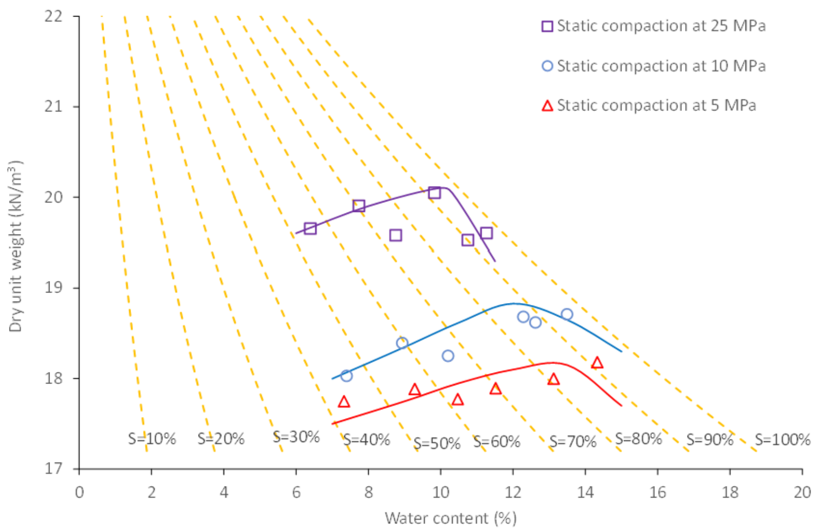

Figure 6. Compaction characteristics of the stabilized material

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Table 4. Maximum dry unit weight and optimum water content values

Optimum water content (%)	Maximum dry unit weight (kN/m3)	Compaction pressure (MPa)	Mix code	Type
11,3	19,45	5	Raw-5MPa	Raw material
10,2	20,35	10	Raw-10MPa	
8,0	21,17	25	Raw-25MPa	
13,5	18,15	5	Stabilized-5MPa	Stabilized material
12,0	18,83	10	Stabilized-10MPa	
10,0	20,10	25	Stabilized-25MPa	

Dip Test

Table 5 shows the mass loss values which were obtained from the dip test, together with the maximum limits provided by the DIN 18945 (2013).[28] The raw material essentially failed the test with 70 % mass loss, unlike the stabilized materials which, regardless the compaction pressure, showed almost no mass loss. This assures that geopolymer is an effective binder which can provide sufficient protection against water ingress.

Table 5. Results of dip test on various mixtures

Scope of application	Mass loss criterion according to DIN 18945	Mass loss (%)	Mixture
Ia: Plastered, weather-exposed exterior masonry of exposed half-timbered walls	≤ 5 % for Class Ia and Class Ib	70-100	Raw-5MPa
Ib: Consistently plastered exterior masonry exposed to weathering			Raw-10 MPa
	≤ 15 % for Class II		Raw-25 MPa
II: Clad or otherwise constructively weather-protected exterior masonry, interior masonry		0,002	Stabilized-5 MPa
		0,0	Stabilized-10 MPa
		0,0	Stabilized-25 MPa

Unconfined Compression. A typical stress-strain response of the raw and stabilized specimens compacted to 5, 10, or 25 MPa is presented in figure 7. In comparison, shear failure occurred in the stabilized specimens at relatively lower strains compared to the specimens made from the raw material. For instance, failure occurred at strains of 1,3-1,5 % in the stabilized specimens, whereas it occurred at strains of 2-3,5 % in the raw materials. This brittle behavior is attributed to the fact that compression and shear resistance of the material is mainly provided by the geopolymer which has much higher stiffer than the soil. Figures 8 and 9 further illustrate the effect of compaction pressure on the elastic modulus and compressive strength, respectively. The elastic stiffness of the compacted raw material (figure 8) is very small and did not appear to be affected by the pressure level. In contrast, the elastic stiffness of the stabilized compacted stabilized materials is extensively higher than those of the raw material and clearly increased with increasing compaction pressure. This is, again, highlights the role of geopolymer in stabilizing material's fabric. The compressive strength (figure 9) for both materials expectedly increased with increasing compaction pressure, which is anticipated as the number of contacts between material's particles increased with increasing density (see also Table 4). The inclusion of geopolymer has resulted in substantial increase in the strength of six to ten folds in the stabilized specimens, compared to the raw material.

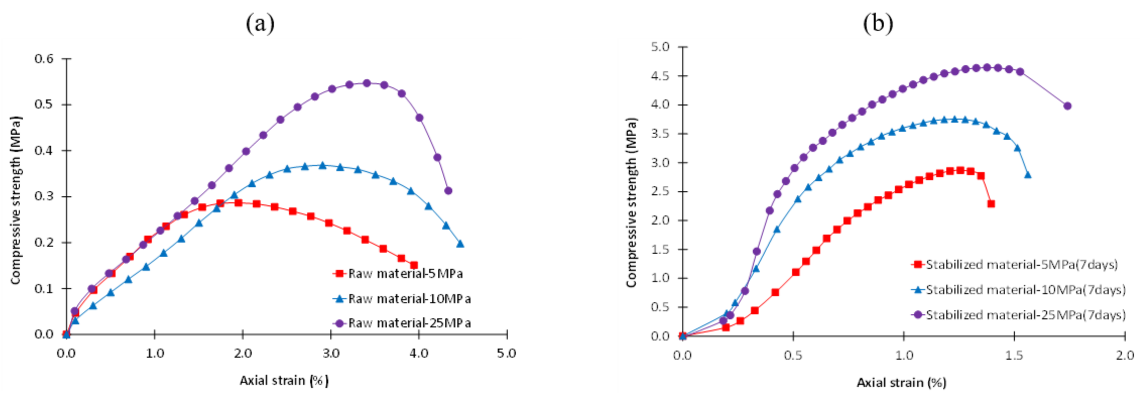

Figure 7. Typical stress-strain curves of the: a) raw material b) stabilized material (after 7 days curing)

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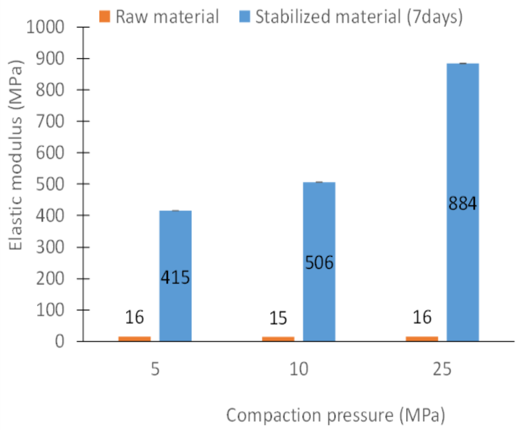

Figure 8. Variation of the elastic modulus with compaction pressure

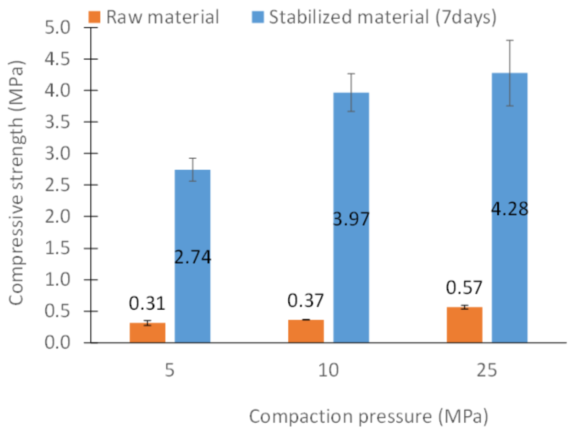

Figure 9. Variation of the compressive strength with compaction pressure

Thermal Conductivity. The variation of transient coefficient of thermal conductivity with compaction pressure is illustrated in figure 10. Interestingly, the stabilized material appears to have lower thermal conductivity values than the raw material due to the lower conductivity of the fly ash geopolymer. Thermal conductivity of the stabilized material moderately increased in response to increase of the unit weigh, i.e., with increasing compaction pressure. For instance, the thermal conductivity coefficient increased from 0,41 W/(m.K) by 20 % with compaction pressure increase from 5 to 25 MPa.

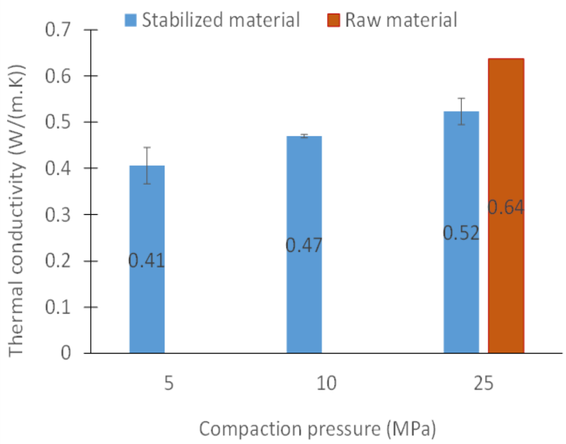

Figure 10. Variation of thermal conductivity with compaction pressure

CONCLUSIONS

The work presented in this article studied the influence of compaction pressure on three of the most important aspects of rammed earth behavior; durability, compression and thermal conductivity. Several specimens made of raw compressed earth materials stabilized with fly ash geopolymer was tested and compared against those made from the same materials but without geopolymer stabilization. The results of the dip test indicated that material durability against water ingress was promising regardless of the compaction pressure. The stabilized specimens showed excellent performance with respect to elastic stiffness and strength, where both significantly increased with geopolymer stabilization and with increasing compaction pressure. A minimum compressive strength of 2,7 MPa was obtained at 5 MPa compaction pressure, which is notably higher than that expected for conventional rammed earth. Likewise, the stabilized material exhibited a relatively small thermal conductivity of about 0,4-0,5 W/(m.K), which is much smaller than that of rival construction materials such as normal concrete which averages between 1,5-3,5 W/(m.K). The thermal conductivity increased with increasing materials unit weight where, as the particles become closer and more air is pushed out, heat effectively transfers through materials fabric

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