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Original Article

Improving the properties of clay soils in foundations through compaction and the integration of fibres and cement

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Abstract: Clay soils present significant challenges in engineering applications, particularly in the design and construction of foundations, due to their susceptibility to swelling and shrinkage. This research investigates the enhancement of clay soils through the incorporation of fibres, compaction, and cement, based on a comprehensive series of tests conducted at the Public Works Laboratory in Adrar, southern Algeria. The tests adhered strictly to technical standards in soil mechanics, examining the physical, mechanical, and thermal properties of the clay soil. The results demonstrated that applying a compressive strength of 2.5 MPa and incorporating palm and glass fibres in proportions ranging from 0% to 0.3% reduced bulk density by 0.95% to 7%. The capillary water absorption rate increased by 10.61% to 12.63%, while compressive strength improved by 11.4% to 34.37%. Furthermore, thermal conductivity decreased by 0.71% to 11.9%. These findings provide valuable insights into the properties of clay soils and the observed improvements. It can be concluded that soil enhancement through various materials and fibres is viable and yields positive outcomes in geotechnical applications.

Keywords: compact earth block, compressive strength, fibres, physical and mechanical properties, thermal properties

1. Introduction

The effective construction of civil infrastructure projects often necessitates geotechnical engineering services to evaluate site characteristics [1], which include conducting appropriate field and laboratory tests on soil materials. Clay soils are particularly challenging as they create difficult building conditions, often requiring costly remedial measures to adjust their geotechnical properties before construction [2]. Soils are commonly classified based on their composition, such as "cohesive" or "granular" soils, or by their physical state, such as "saturated" or "dry" soils. The mechanical behaviour of clay soils is complex due to the interplay of several factors, including natural loading from building construction, inherent cohesion resulting from increased stresses, and mechanical deformations that cause pore pressure dissipation and changes in saturation levels. Additionally, environmental influences such as temperature and salinity can lead to pressure redistribution and changes in physical conditions. These processes often occur simultaneously or sequentially, making it challenging to predict the performance of clay soils [3].

In civil engineering, professionals focus on the design and construction of buildings, infrastructure, and other projects [4]. Geotechnics involves the study of the soil on which civil structures are built [5]. Engineers in this field examine the quality and composition of soils to understand their physical, mechanical, and thermal behaviour [6], enabling them to predict how soils will respond to applied loads. The geotechnical analysis of soils aims to anticipate and detect hazards that may threaten structural stability, particularly in clay soils prone to swelling and shrinkage caused by water [7]. This issue has become increasingly prevalent in construction. Soil stabilisation is one of the methods used to address the engineering challenges associated with clay soils. This technique involves incorporating various inert substances into the soil to enhance its chemical, physical, and mechanical properties. Consequently, soil stabilisation is widely employed in infrastructure construction.

Several previous studies have investigated this field. Louafi et al. conducted experimental research to explore the effects of slurry treatment using lime, employing ultrasonic and pressure testing techniques [8]. In another study, soil mechanical behaviour was improved using additives such as cement, with tests including Atterberg limits, standard compaction, and unconfined compressive strength performed on the samples [9]. Fibre reinforcement has also gained significant attention as a technique for strengthening clay soils, being recognised as an effective method for addressing soil instability. Previous research explored the addition of nylon fibres to improve clay soils [10]. Another study examined the mechanical performance of clay soils reinforced with carbon fibres, focusing on the effects of fibre length and content on shear strength and stress behaviour [11]. Butt et al. investigated the use of natural fibres, such as human hair, to enhance the shear and bearing capacity of clay soils [12].

Many construction projects are developed on clayey soils, necessitating precautionary measures to mitigate the risks associated with hydric conditions. Various soil stabilisation methods are available, including the use of natural materials, chemicals, or industrially produced additives. However, some industrial additives may compromise the performance and durability of subgrades. Chemical treatment with cement remains one of the most widely used and tested methods. Nevertheless, when clay soils are treated solely with cement, they tend to exhibit brittle behaviour, which can lead to cracking. To address this issue, the addition of fibres is recommended. Cement has been employed in numerous previous studies to enhance clay soils [13].

In this research, clay soils are treated using both mechanical and chemical methods. Cement and fibres are added to improve the soil's compressive strength, while soil compaction techniques are employed to increase the cohesion of granules [14]. This approach is utilised in various countries, such as China [15], Kenya (as a low-cost construction method) [16], and Portugal, where it has been analysed in the context of life cycle assessments of compressed blocks [17]. In the city of Adrar (Algeria), cement is added to the soil to further enhance granule cohesion, as cement is a highly effective stabilising material that improves shear strength and reduces the swelling coefficient [18]. Additionally, two types of fibres are used in this study: vegetable fibre (palm fibre) and synthetic fibre (glass fibre), in varying proportions (0%, 0.05%, 0.1%, 0.15%, 0.2%, 0.25%, and 0.3%). The research examines changes in bulk density, water permeability, compressive strength, and thermal conductivity. The materials used in the experiments and the preparation of laboratory samples are meticulously defined.

The research is divided between two teams. The first team investigates the effect of pressure and fibres on bulk density and water permeability, while the second team focuses on the impact of compression and fibre content on the mechanical and thermal properties of the samples. The results are subsequently analysed and reviewed, with comparisons made using ANSYS simulation software to model heat transfer. The findings provide a new reference for the treatment of clay soils using fibre and compaction in this context. The value of this research lies in combining multiple variables to enhance the properties of soils for construction purposes.

2. Materials and methods

2.1. Clay

When excavating to a depth of 3 metres at a site designated for the construction of residential buildings, a layer of clay was encountered. Clay soil samples were collected, crushed, and sifted through a 5 mm sieve. Each specimen weighed 300 grams and was mixed with 100 cL of water (30%), then placed in a metal mould. The resulting brick measured 10 × 5 × 2.5 cm^3 and was left to dry naturally for 28 days.

Figure 1 shows the excavation site allocated for the construction of the architectural facility, while Fig. 2 illustrates the soil after crushing and sifting. Following the drying process, the hardness of the samples was tested, revealing that they could withstand pressures between 0.65 MPa and 0.7 MPa. The samples could be reassembled by adding water. The apparent density of the samples was measured at 2.6 g/cm^3.

The samples were subsequently taken to the laboratory for analysis of their chemical and geotechnical properties. The results of the laboratory analysis of the clay are presented in Table 1. It was concluded that the soil is clayey with a high water absorption capacity. It absorbs water slowly and retains it effectively.

A granular analysis of the clay soils was also performed, with Fig. 3 showing the granular distribution of the clay soils.

The behaviour of plastic soils depends on several factors, including particle size distribution, physico-chemical characteristics, and the presence of additional chemical compounds in the soil. The coefficient provides insights into the degree of soil homogeneity, distinguishing between cohesive and non-cohesive soils. However, it does not provide sufficient information for comprehensive geotechnical soil classification. In a broader context, plasticity refers to the soil's ability to undergo plastic deformation [19].

The Atterberg Limits test is used to classify the fine-grained portion of soils based on their plasticity characteristics. This test determines the liquid limit (LL), plastic limit (PL), and plasticity index (PI). The Proctor Compaction test is also conducted to identify the soil's maximum dry density and optimum moisture content [20].

Fig. 1. Drilling site

Fig. 2. Clay samples

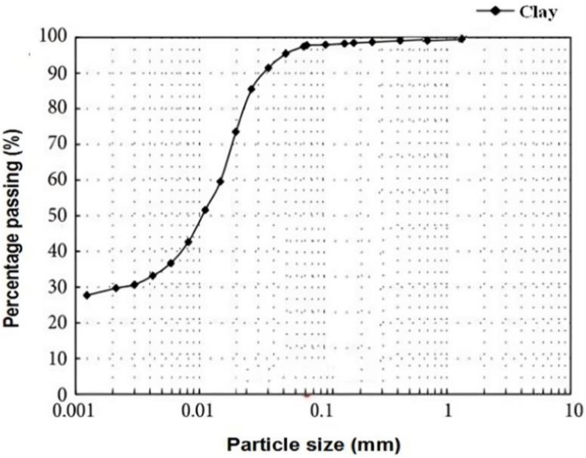

Fig. 3. Particle size distribution

Granular soil analysis is essential for various engineering applications. The most common types of granular soils are sand and gravel. Well-graded granular soils are widely utilised in construction due to their ability to drain water efficiently and consolidate within a short timeframe. Consequently, their performance is predictable and can be readily calculated for both short- and long-term scenarios. Determining the physical properties of granular soils is a critical step before their use in construction or agricultural projects [21].

The Proctor compaction test is a widely used laboratory procedure designed to establish the optimum moisture content and maximum dry density of granular soils. This test evaluates the effect of varying moisture content on the soil's compaction characteristics, a fundamental property influencing its performance as a construction material in earthworks and embankments [22].

Table 1. Properties of clay used

Geotechnical characteristics [23]		Chemical composition [23]	
Silt (0.02-0.002 mm)	48%	SiO2	58.98%
Clay (<0.002 mm)	30%	Al_2O_3	17.31%
Sand (> 0.02 mm)	22%	Fe_2O_3	7.08%
Plasticity limit PL	26%	K_2O	4.68%
Liquidity limit LL	49.9%	MgO	2.39%
Plasticity index PI	23.9%	TiO_2	0.93%
Methylene blue value	6.5	CaO	0.63%
Specific weight γ s	2.61 g/cm^3	SO_2	0.35%
		Na_2O	0.28%
		P_2O_3	0.07%
		Cl^-	0.055%
		Loss on fire	7.29%

The plasticity index (PI) is a crucial measure of soil plasticity. Soils with a very low plasticity index (PI < 4) are typically well-graded based on grain size. Conversely, soils with a high plasticity index (PI > 20), such as clayey soils, may either remain dry and brittle or become wet and viscous, both of which are undesirable for engineering applications.

The plasticity index is a fundamental criterion for classifying cohesive or fine-grained soils, as it reflects the soil's plasticity characteristics. Plastic soils behave differently under loads compared to non-plastic soils, requiring greater attention in engineering projects. The plasticity index is critical for understanding key soil properties, including shear strength, compressibility, permeability, shrinkage, swelling, and drillability [24].

From the analysis of Table 1, the plasticity index is determined to be 23.9%, classifying the soil as highly plastic according to the ASTM D4943 standard.

2.2. Cement

The cement used in this study is Portland cement (CEM II/B, class 42.5), which is readily available in northern Algeria. It is characterised by its high calcium oxide content. The chemical composition of this cement is provided in Table 2.

Soil stabilisation involves improving soil properties to meet specific project requirements. The objectives of stabilisation include reducing plasticity, minimising shrinkage and swelling potential, decreasing permeability, enhancing compaction, and improving the soil's durability and stability. Effective stabilisation ensures that the soil can bear construction loads and remain stable throughout the structure's service life [25]. Stabilising clay soils presents particular challenges due to the cation exchange capacity of clay particles, which impedes the transition from a plastic to a solid state. The interaction between external forces and the microstructural properties of clay fixes the pore geometry in the "cement + water-soil" mixture. This process mitigates shrinkage and swelling risks, ensuring long-term soil stability.

Cement has been extensively used for soil stabilisation in various applications, including roads, sidewalks, earthen embankments, and soil fill supports for buildings, due to its numerous benefits. It enhances strength and stiffness, forms impermeable barriers when compacted into the soil, and prevents water movement through the soil [26]. The use of cement for soil stabilisation is a well-established civil engineering technique. Mechanical mixing of cement with clay soil is an effective and cost-efficient method for strengthening plastic soils.

Table 2. Chemical composition of cement used [27]

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	K_2O	Na_2O	PF
%	21.45	4.31	4.56	61.43	1.24	2.28	0.018	0.61	0.39	2.19

2.3. Palm fibres (PF)

Untreated palm fibre, sourced from a common plant in southern Algeria, is used in this study. Its composition includes 27% cellulose, 37% hemicellulose, and 28% lignin. The fibres selected for this research are obtained from the areas surrounding the trunk and leaves of the palm tree.

2.4. Glass fibres (GF)

E-glass fibres are utilised in this study. These fibres consist of very thin strands and are characterised by their hardness, lightweight nature, and resistance to burning, stretching, and rust. They are commonly used in the installation of optical fibres for internet connectivity.

Table 3 presents the physical, mechanical, and chemical properties of the fibres used (glass fibres and palm fibres). Both types of fibres were cut to a length of 10 cm.

2.5. Sample preparation

Clay soil was treated using two techniques: fibre reinforcement and cement stabilisation. Several samples were prepared to study the effects of fibre type and concentration. Laboratory investigations were conducted to examine the basic characteristics of the soil, including tests for grain size and Atterberg limits to classify the soil. Preliminary tests were carried out with varying proportions of glass and palm fibres to determine the optimal values for fibre and cement stabilisation.

The results showed that both cement and fibre improve the performance of clay soils. Due to its ability to enhance engineering properties, soil reinforcement using short fibres has gained significant attention within the geotechnical engineering community. Fibre reinforcement is widely applied in construction projects to enhance soil properties.

The clay was crushed and sifted through a sieve with a diameter of 5 mm. The Proctor test, a crucial step in this process, was performed to determine the optimal water and cement ratios, following ASTM D1557 standards. This test calculates the percentage of water based on bulk density, identifying the optimal water ratio as the value corresponding to the highest bulk density.

The percentage of cement varied between 6%, 8%, 10%, 12%, and 14%, influencing the percentage of water accordingly. Figure 4 illustrates the results of this test. Based on the analysis of Fig. 4, the optimal water content was found to be 14%, corresponding to a cement percentage of 12%.

Table 3. Properties of palm fibres and glass fibres

Palm Fibres [28]			Glass Fibres [29]		
Chemical properties	Cellulose (%)	27	Physical and mechanical properties	Density (g/cm^3)	2.57
	Hemicellulose (%)	37		Filament diameter (mm)	12
	Lignin (%)	28		Diameter (µm)	19
	Fats (%)	7		Tensile strength (MPa)	3500
Mechanical properties	Tensile strength	170-275 MPa		Lengthen at break (%)	4.8
	Young's modulus	5-12 GPa		Modulus of elasticity (Mpa)	73500
	Elongation	5-10%			

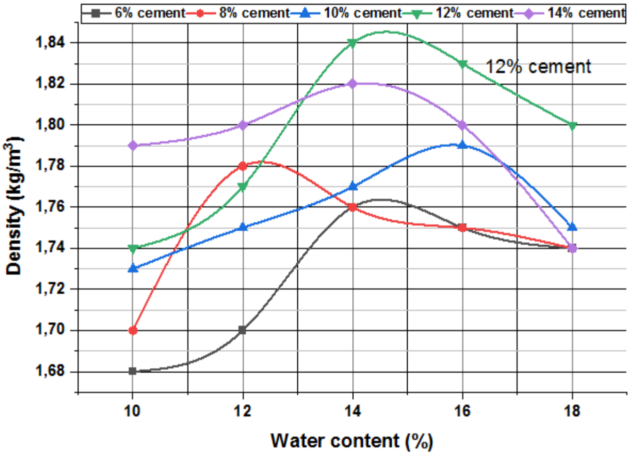

Fig. 4. Optimum water content

Cement stabilisation has been widely used to improve clayey soils. The enhanced strength and stability of soil structures achieved using cement as a stabiliser are attributed to oxidation reactions that produce compounds such as calcium silicate hydrates, calcium aluminate hydrates, and alkali aluminosilicates, which bond soil and cement particles [30].

The wet weight of the mixture is measured at 2000 grams. Fibre is added, and the mixture is blended for 2 minutes using an electric mixer. Water is then introduced, and mixing continues for an additional 2 minutes. The resulting mixture is placed into a metal mould, where a force of 2.5 MPa is applied over an area of 20 × 10 cm, equivalent to a pressure of 250 N/cm². Table 4 outlines the sample preparation procedure. The samples are left to dry for 28 days, with six samples prepared for each percentage of glass and palm fibres.

Table 4. Sample preparation

Clay (%)	Cement (%)	Water (%)	Palm fibres (%)	Glass fibres (%)	Samples
74	12	14	0	0	GPF0
			0.05	0	PF1
			0.1	0	PF2
			0.15	0	PF3
			0.2	0	PF4
			0.25	0	PF5
			0.3	0	PF6
			0	0	GPF0
			0	0.05	GF1
			0	0.1	GF2
			0	0.15	GF3
			0	0.2	GF4
			0	0.25	GF5
			0	0.3	GF6

After drying the samples for 28 days, their physical, mechanical, and thermal properties are analysed.

2.6. Measuring the change in density

The dimensions of the samples are measured, and their weights are recorded. The bulk density is calculated using the following formula:

$$\rho = \frac{m}{v} \tag{1}$$

When calculating density, it is essential to ensure that the samples are thoroughly dried and free from moisture. The density of clay soils is closely related to the size of the grains and the pores between them, a relationship that is fundamental in soil mechanics and construction.

Figure 4 illustrates the variation in density as the ratios of cement and water are adjusted. According to the modified Proctor Standard ASTM D1557 [31], the highest dry density corresponds to the optimal water content. The optimal water content was determined to be 14%, which corresponds to a composition of 12% cement and 74% clay. Figure 7 depicts the changes in bulk density with the addition of glass and palm fibres in varying proportions.

2.7. Measuring the change in water absorption rate

The rate of water absorption in the samples is determined by calculating the difference in weight before and after immersion in water for a specified period. The ASTM D570 standard is applied to evaluate the percentage of weight gain during the experiment [32]. The capillary coefficient is used to calculate the absorption rate using the following equation:

$$C = \frac{(m2 - m1) \times 100}{A \times \sqrt{t}} \tag{2}$$

where: C is the water absorption by capillarity coefficient (g/cm^2·min$^{0.5}$); m2 is the weight of the block after immersion in water (g); m1 is the weight of the block before immersion in water (g); A is the immersed area (cm^2); t is the immersion time (min).

The rate of water absorption is influenced by porosity and moisture content.

Equation 3 illustrates the relationship between these factors:

$$\varphi = 1 - \frac{\gamma d}{\gamma s} \tag{3}$$

where: γd is the dry bulk density; γs is the soil particle density.

The rate of water absorption can be determined using relation 4:

$$m(\%) = \frac{m\,2 - m1}{m2} \tag{4}$$

where: m2 is the wet mass after immersion in water; m1 is the dry mass before immersion in water.

To determine m1, the samples are first weighed. Then, the samples are immersed in water for 120 minutes, as shown in Fig. 5. After immersion, m2 is calculated. The results of these experiments are presented in Fig. 8.

Fig. 5. Capillary water absorption experiment

m1 PF12: The dry mass of samples containing palm fibres with 12% cement.
m2 PF12: The wet mass of samples containing palm fibres with12% cement.
m1 GF12: The dry mass of samples containing glass fibres with 12% cement.
m2 GF12: The wet mass of samples containing glass fibres with12% cement.

2.8. Change in compressive strength

To calculate the pressure force applied to the samples, a hydraulic pressure machine with a capacity of 300 kN is used. This pressure testing machine is designed to determine the compressive strength of materials such as rocks. Tensile testing is conducted on a sample area measuring 20 × 10 cm.

The value of stress is determined using Relation 5:

$$\rho = \frac{F}{A} \tag{5}$$

Figure 6 shows a simulation of samples subjected to a compressive force F applied vertically over an area A = 20×10 cm^2. The results of the experiments are presented in Fig. 9.

2.9. Change in thermal conductivity

Thermal conductivity is measured in accordance with ASTM standard D5334 [33]. The test involves puncturing the soil samples and inserting a thermal needle. The temperature inside the samples is recorded at five-minute intervals. The results of this experiment are shown in Fig. 10.

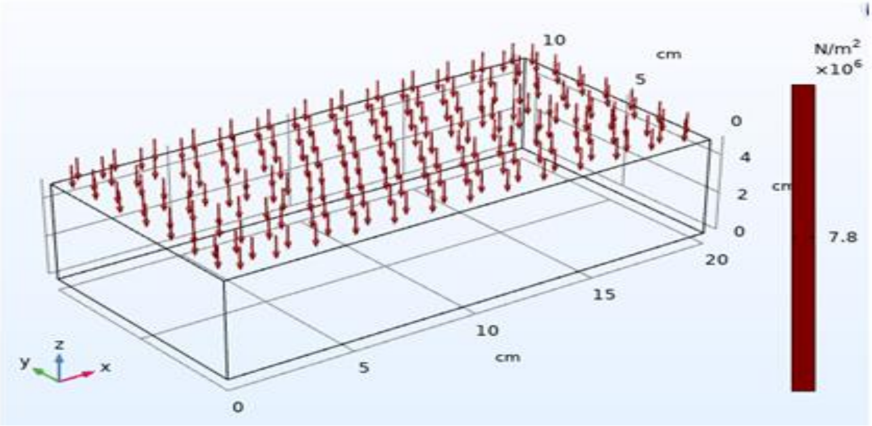

Fig. 6. Simulation of applying a compressive force to samples

The ANSYS program, widely used for engineering applications, is employed to create models using finite element analysis [34]. A numerical simulation of heat flow is conducted on fibre-free samples over an area of 20 × 10 cm. The purpose of this simulation is to predict heat transfer in samples with the same composition. Figure 11 depicts the simulation of heat flow within the samples.

3. Results and discussion

Table 5 presents the results of measurements, including bulk density, changes in the water absorption rate, the compressive strength required to break the samples, and thermal conductivity.

PF: Samples containing palm fibres.

GP: Samples containing glass fibres.

3.1. Bulk density

Figure 7 illustrates the change in bulk density of the samples with the addition of fibres. A decrease in density is observed as the percentage of fibres increases. Compared to the fibre-free sample (GF0), the bulk density decreases by 0.95% to 6.82%. The addition of glass fibres results in a density reduction of 1.18% to 7%, while palm fibres produce a similar decrease.

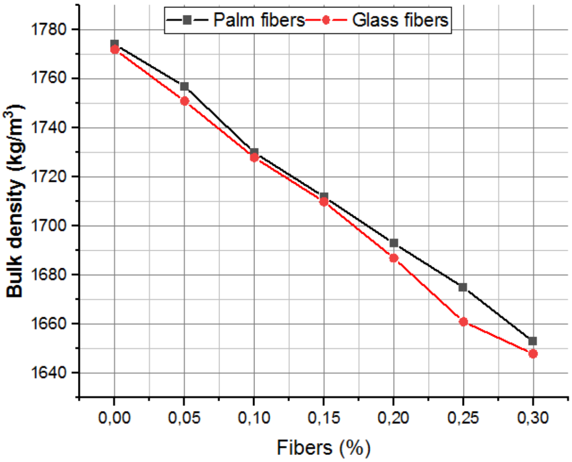

Fig. 7. Change in bulk density

The reduction in bulk density is attributed to the increased number of voids within the clay soil matrix as fibres are added. These voids make the bricks more porous and lightweight, consistent with findings from previous research [35]. Notably, the decrease in bulk density is more pronounced in samples containing palm fibres, with values ranging between 1774 and 1772 kg/m³. This is likely due to the plant-based origin of palm fibres, which absorb part of the water used in the mixture, resulting in a relatively drier final product. This observation aligns with earlier studies [36].

Table 5. Results of density measurement, water absorption rate, compressive strength and thermal conductivity

Fibres (%)	Bulk density (kg/m^3)		Water absorption rate (%)				Compressive strength (MPa)		Thermal conductivity (W/mK)	
	G.F	P.F	P.F (m1)	P.F (m2)	G.F (m1)	G.F (m2)	P.F	G.F	P.F	G.F
0	1774	1772	1776	1987	1772	1986	2.1	2.1	0.42	0.42
0.05	1757	1751	1758	1976	1750	1952	2.37	2.48	0.4	0.417
0.1	1730	1728	1732	1955	1729	1932	2.53	2.88	0.395	0.41
0.15	1712	1710	1714	1946	1712	1915	2.85	3.2	0.392	0.4
0.2	1693	1687	1691	1928	1685	1896	2.9	3.07	0.38	0.39
0.25	1675	1661	1677	1911	1660	1872	2.82	2.95	0.376	0.386
0.3	1653	1648	1652	1891	1649	1865	2.77	2.83	0.37	0.38

Previous research has also demonstrated a reduction in bulk density with the addition of fibres to clay soils. For example, Yilmaz et al. investigated the effect of polypropylene fibres on the stress-strain behaviour and shear strength of clay soils, observing a decrease in density as fibre content increased [37]. Similarly, in another study, wheat straw was incorporated into expansive clay soils, showcasing a promising technique for enhancing and stabilising their properties, with researchers reporting a reduction in density as the percentage of straw increased [38]. El Ahmad et al. reported comparable results when studying the effects of hemp fibre reinforcement on clay systems [39].

Density is a critical physical property of clay samples, directly influencing other geometric characteristics. It primarily depends on the chemical composition, shape and size of clay particles, porosity (void content), and fillers used in the mixtures. Porosity can be estimated from density measurements, with fibre addition leading to an increase in voids and a consequent decrease in density. This aligns with previous studies on the mechanical properties of clay bricks reinforced with fibres [40,41].

3.2. Water absorption rate

Figure 8 highlights the differences between the dry and wet masses of compressed clay blocks submerged in water for 120 minutes. The results show that water absorption rates increase with higher fibre content, consistent with previous findings [42]. For samples containing palm fibres, the water absorption rate increases by 10.6% to 12.24% (from 1891 to 1652 g). Similarly, the addition of glass fibres results in an increase in water absorption, ranging from 10.34% to 11.58% (from 1865 to 1649 g).

This increase in water absorption is due to the addition of fibres to the pressed clay, which creates more pores and voids within the brick, leading to a higher absorption rate. These observations align with earlier research [43]. The higher water absorption rate in samples containing palm fibres can be attributed to two factors: the larger diameter of palm fibres compared to glass fibres (100 µm vs. 24 µm), and the spherical, irregular distribution of palm fibres, which generates larger voids that facilitate water movement.

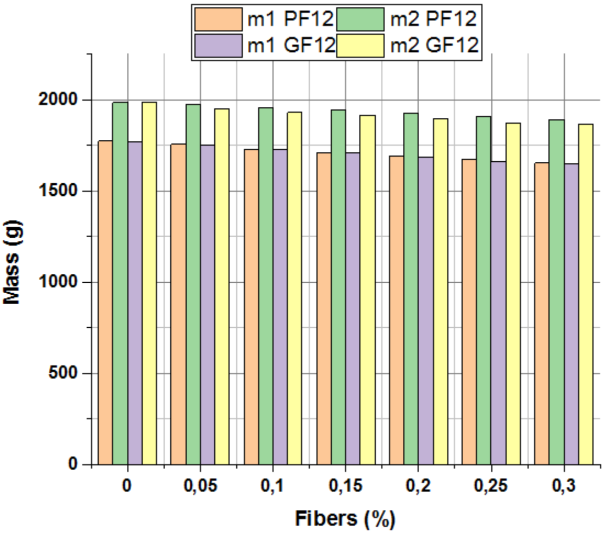

Fig. 8. Change in mass of samples after immersion in water

The water absorption rate in clay bricks generally ranges from 10.61% to 12.63%, which is considered acceptable. However, a drawback arises with mechanical strength when the samples become wet, leading to clay shrinkage and compaction. Therefore, it is crucial to carefully manage water content when working with clay soils. Adding cement is essential, as it helps reduce water absorption by the clay, a finding supported by previous research [44].

Water absorption is highly influenced by the distribution and connectivity of pores within the soil mass. In soil mechanics, "pores" refer to the void spaces present within the soil structure. Clay soils are characterised by their small particle size, ability to retain water and nutrients, and susceptibility to compaction and erosion. These properties impact fundamental characteristics of clay minerals, such as surface quality, stretchability, and symmetrical replacement. The internal pore size and texture of clay soils play a critical role in determining the rate of water absorption. Various additives can be used to modify pore size in clay soils.

The addition of fibres enhances the capillary action of clay soils [45], altering their porous structure and influencing capillary behaviour. Capillary action refers to the ability of a liquid to move through narrow spaces without external forces, and the rate of this action depends on the height to which the liquid rises.

Similar findings have been reported in previous studies. For example, Yazici and Keskin investigated the effect of adding hemp fibres to low-plasticity clay soils and observed an increase in the water absorption rate [46]. In another study, researchers examined the mechanical properties of glass fibre-reinforced clay soils, incorporating lime and nanoclay as stabilisers. They found that increasing the fibre content led to higher water absorption rates [47].

3.3. Compressive strength

Figure 9 illustrates the change in compressive strength values as fibre content increases. The compressive strength rises from 2.1 MPa to 2.9 MPa, followed by a decline when palm fibres are added, resulting in an overall increase of approximately 27.6%. A similar trend is observed with the addition of glass fibres, where the compressive strength increases from 2.1 MPa to 3.2 MPa, reflecting an increase of 34.37%. The incorporation of fibres into clay soil blocks enhances the cohesion of clay bricks, aligning with findings from previous research [48].

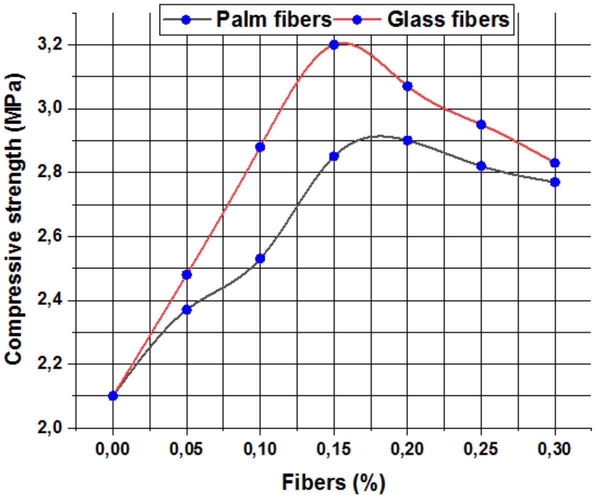

Fig. 9. Change in compressive strength with the addition of fibres

In this experiment, the stress value increased up to a specific fibre ratio before decreasing. For palm fibres, the optimal sample in terms of hardness corresponds to 0.2%, while for glass fibres, it corresponds to 0.15%. Glass fibres exhibit a compressive strength 9.3% higher than that of palm fibres, which can be attributed to the higher tensile strength of glass fibres compared to palm fibres (3500 MPa vs. 275 MPa). Refer to Table 3 for details. The addition of fibres to clay soil aggregates the soil particles, restricting their movement and providing the soil with enhanced strength to resist dislocations under mechanical stresses. This observation aligns with findings from previous research [49].

Fibres play a significant role in improving the mechanical properties of clay soils, which are critical for understanding soil behaviour under stress and ensuring the performance and safety of geotechnical structures. The introduction of fibres increases interweaving among soil particles, thereby enhancing durability.

Fibres effectively combine with clay soils, offering advantages such as increased rigidity, strength, flexibility, and durability. In recent years, considerable attention has been directed towards using fibres to stabilise clay soils and improve their mechanical properties. For example, in a study by Topçuoğlu and Gürocak, 12 mm long basalt fibres were added to bentonite clay in varying proportions (1%, 2%, 3%, 4%, and 5%), resulting in an increase in the clay's shear strength [50]. Similarly, other studies have shown that incorporating fibres into clay soils enhances the modulus of elasticity and shear strength [51].

3.4. Thermal conductivity

Figure 10 illustrates the variation in thermal conductivity values as the percentage of fibres changes. Analysis of the curve shows a reduction in thermal conductivity by 4.76% to 11.9% (from 0.42 to 0.37 W/m·K) with the addition of palm fibres. A similar reduction, ranging from 0.71% to 9.52% (from 0.42 to 0.38 W/m·K), is observed with glass fibres. The inclusion of fibres in clay bricks increases the number of voids, which hinders heat transfer, leading to a reduction in thermal conductivity [51]. This decrease also correlates with a reduction in bulk density; in general, lighter bricks exhibit lower thermal conductivity. These findings are consistent with the research conducted by Daifallah et al. [52].

The addition of fibres to clay soil further impedes heat transfer between brick components, thereby reducing thermal conductivity [51]. The thermal conductivity is lower with palm fibres, likely due to their plant-based origin and the presence of organic substances, which are porous and provide additional resistance to heat transfer [52].

When fibres are introduced into the soil mixture, air is also incorporated. Air, with its low thermal conductivity of 0.025 W/m·K, contributes to the overall reduction in thermal conductivity. Tests indicate that the addition of fibres effectively reduces thermal conductivity. This reduction is primarily achieved by increasing the torsion ratio, rather than altering the pore shape ratio. Fibre-induced convolutions around clay particles enhance the torsion ratio, slowing heat conduction and weakening heat transfer pathways, thereby improving the thermal resistance of the material.

The observed decrease in thermal conductivity in fibre-reinforced samples highlights the significant role of fibre incorporation in enhancing thermal resistance in clay soils. This work aims to deepen understanding of the mechanisms underlying thermal resistance in fibre-reinforced clay soils, offering insights into their potential for heat-insulating designs.

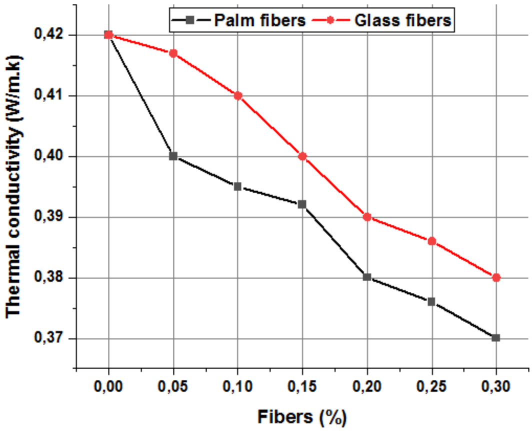

Fig. 10. Change in thermal conductivity

In a previous study, banana and lime fibres were used to enhance the thermal and structural properties of unburned clay bricks. The researchers observed a decrease in thermal conductivity values with increasing fibre content [53]. Similarly, El-Yahyaoui et al. examined the thermal conductivity of six samples containing varying proportions of Dom fibres (0%, 1%, 5%, 7%, 10%, and 12%). They reported a reduction in thermal conductivity alongside an improvement in thermal insulation [54].

An analysis of Fig. 11 reveals that heat flow is not evenly distributed during the transition process. The heat flux is highest in the area directly exposed to heat and gradually diminishes as the sample's thickness increases. Heat transfer is influenced by the duration of heat exposure, the area of exposure, the sample's thickness, and the thermal conductivity of the material [55]. To calculate the values of heat flux, relation 6 will be used:

$$q = \lambda \frac{(T2 - T1)}{A} \tag{6}$$

When fibres are added, the temperature difference between T1 and T2 increases, resulting in a reduction in thermal conductivity and an improvement in thermal insulation. This finding is consistent with previous research [56].

4. Importance of research results in geotechnics

The research results highlight several key improvements in clay soils associated with the addition of fibres and the application of compressive forces:

1. The increased mechanical stresses required to break the samples demonstrate that adding fibres to clay soils significantly enhances their tensile strength and cohesion.
2. The addition of fibres improves the soil's resistance to mechanical stresses, allowing for an increase in default load capacities in completed buildings by 27.6% to 34.37%.
3. When a significant compressive force is applied to clay soil mixed with an appropriate amount of water, it reduces the risk of slipping. The accumulation of clay minimizes pore size, making the soil less prone to swelling and bloating.
4. The water absorption experiments demonstrated that applying pressure to clay soils reduces their water permeability.

5. From a thermal perspective, adding fibres decreases the amount of heat transferred below the foundation, contributing to floor stabilization during both summer and winter.

This technique also shows potential for application in saline soils, which are prone to sliding.

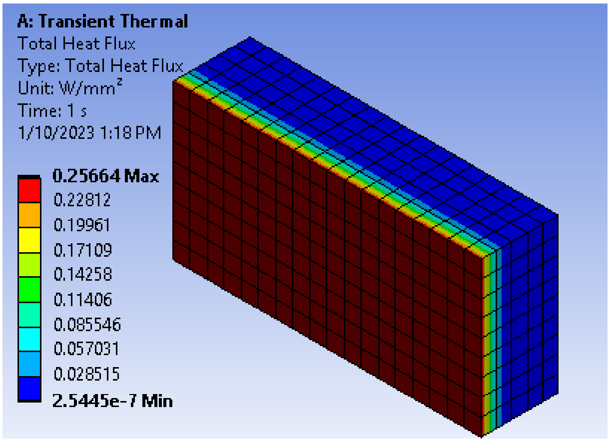

Fig. 11. Change in heat flow values

4.1. Benefits and challenges of using fibres in clay soil stabilization

The benefits of using fibres in clay soil stabilisation are numerous. Fibres primarily act as reinforcement materials, distributing the loads imposed on the clay soil over a larger area. This distribution reduces stress concentrations within the soil matrix, resulting in increased strength and transforming the clay soil from a purely cohesive material into a composite. Additionally, fibres help bridge cracks that form within the soil mass, preventing their growth under future loading conditions. Consequently, the ductility of clay soil is enhanced through the incorporation of fibres.

4.2. Importance of using this technology in engineering projects

The reinforcement of clay soil with fibres and cement offers several advantages for engineering projects. The two primary benefits of this technique are improved strength and stability, as well as reduced shrinkage and swelling.

Improved Strength and Stability: Clay soil can pose significant challenges in engineering projects due to its relatively low strength and high susceptibility to moisture changes. Reinforcing clay soil with cement and fibres significantly enhances its strength and stability. While cement or fibres alone can provide limited improvements, their combination facilitates positive interactions that reduce stress concentrations over fibre nodes – minimising the risk of cracking – and enhances the ductility of cement-soil composites.

Reduced Shrinkage and Swelling: Swelling and shrinkage are among the most problematic properties of clay soils, particularly during changes in moisture content. Although cement stabilisation improves the overall strength of clay soil, it may exacerbate its swelling and shrinkage potential. Experimental studies have demonstrated that short fibres effectively prevent crack propagation and reduce shrinkage in unconfined clay-cement materials.

5. Conclusions

To enhance the properties of clay soil used in foundations, this research investigates the combined technique of compaction with the incorporation of fibres and cement. Clay soils often present challenges as foundation materials due to undesirable characteristics such as low shear strength, significant volume shrinkage, and a high potential for swelling. While compaction is a commonly employed method to improve clay soils, it may not adequately mitigate swelling or shrinkage under varying moisture conditions. This study explores the synergy of compaction and the addition of fibres and cement to enhance the properties of clay soils, with findings indicating significant improvements.

Moreover, the following conclusions can be drawn:

- The addition of palm fibre reduces bulk density by up to 7%, increases compressive strength by 27.58%, and decreases thermal conductivity by 11.9%. A similar trend is observed with glass fibres, which increase compressive strength by 34.37%, reduce thermal conductivity by 9.5%, and decrease bulk density by 6.8%. These results suggest that glass fibres offer superior mechanical properties, while palm fibres are more effective for thermal improvements.
- However, the incorporation of fibres into clay soil increases water absorption rates, with palm fibre showing a 12.63% increase and glass fibre an 11.58% increase. This is considered a drawback, although soil permeability can be improved through enhanced compressive strength.

Fibre-reinforced compacted clay soil technology provides an economical solution to challenges such as soil sliding and dredging in infrastructure projects. Fibres add rigidity to floors and foundations, making this approach suitable for various applications.

The random incorporation of 0.15% glass fibre can significantly enhance the geotechnical properties of clay soils, making them more suitable for supporting shallow foundations and mitigating the adverse effects of poor soil conditions. Furthermore, the addition of 12% Portland cement can further improve the geotechnical performance of clay soils, rendering them appropriate for deep foundations.

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Authors contribution statement

Authors	Contribution
Abdelkader Fidjah	Conceptualisation and editing of the work
Mohamed Rabehi	Laboratory experiments
Cheikh Kezrane	Analysis and discussion of the results
Asma Bendeb	Linguistic review
Nour Elhouda Smain	Research sourcing and comparison with previous studies
Rachid Khalili	Laboratory experiments

Conflict of interest statement

The authors listed above certify that they have no affiliations with or involvement in any organisation or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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