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Combined Effect of Polypropylene Fiber and Nano Calcium Carbonate to Improve Compressed Earth Blocks Produced from Clayey Soil, Kirkuk City, Iraq

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ABSTRACT

This research studies the effect of adding polypropylene fibers and nano-calcium carbonate to compressed earth blocks. The soil used is taken from the Laylan area, north of Kirkuk City, Iraq. Chemical and physical tests are performed to determine soil properties. Different percentages of fibers (0%, 0.1%, 0.2%, 0.3%, and 0.4 %) and nano calcium carbonate (0.05%, 0.15%, and 0.25%) are added to dry weight of soil in different water percentages. Two sets of blocks are produced in both small-scale and large-scale; the blocks are compressed using a manual pressing machine with a pressure of 15 MPa. Compressive, flexural, and durability tests are performed for the block specimens to determine the effect of the added materials on the compressed earth block. The results show the best improvement by fiber and nano calcium carbonate observed at 28 days of curing period for blocks with 0.2% fiber-0.25% nano calcium carbonate treatment, and the highest compressive reaches 17.9 MPa for the small-scale blocks and 7.7 MPa for the large-scale blocks; and the highest flexural strength is 1.67 MPa. Furthermore, the results show that the durability index increases with increasing percentages of fibers and nano-calcium carbonate, which indicates mass loss percentages decrease with increasing percentages of additive improvers for the compressed earth blocks.

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التأثير المشترك لألياف البولي بروبلين وكربونات الكالسيوم النانوية لتحسين البلوك الترابي المضغوط المنتج من التربة الطينية، كركوك، العراق

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الملخص

يهدف هذا البحث إلى دراسة التأثير المشترك لأضافة ألياف البولي بروبلين وكربونات الكالسيوم النانوية على البلوك الترابي المضغوط والمنتج من تربة طينية مأخوذة من منطقة ليلان شمالي مدينة كركوك بالعراق. في البدء، تم إجراء الاختبارات الكيميائية والفيزيائية لتحديد خصائص التربة وتصنيفها ومن ثم تمت إضافة نسب وزنية مختلفة من الألياف بنسب مختلفة (0%، 0.1%، 0.2%، 0.3%، 0.4%) ومن كربونات الكالسيوم النانوية بنسب مختلفة (0.05%، 0.15%، 0.25%) من الوزن الجاف للتربة مع خلطها بنسب مائية مختلفة للحصول على المحتوى المائي الامثل. كما تم إنتاج مجموعتين من البلوك، المجموعة الاولى هي بلوك بحجم صغير، والمجموعة الثانية هي بلوك بحجم كبير؛ حيث تمت عملية الانتاج عن طريق ضغط البلوك باستخدام آلة ضغط هيدروليكية وبضغط 15 ميكا باسكال. ومن ثم تم إجراء اختبارات الانضغاط والانحناء والمتانة لعينات البلوك لتحديد تأثير المواد المضافة على البلوك الترابي المضغوط. أظهرت النتائج ان أفضل تحسن لمقاومة الانضغاط هو عند عمر 28 يوم للبلوك المعالج ب 0.2% ألياف البولي بروبلين مع 0.25% كربونات الكالسيوم النانوية، وأعلى ضغط بلغ 17.9 ميكا باسكال للبلوك الصغير و7.7 ميكا باسكال للبلوك الكبير، وأعلى قوة انثناء كانت 1.67 ميكا باسكال. علاوة على ذلك، أظهرت النتائج أن مؤشر الديمومة يزداد مع زيادة نسب الألياف وكربونات الكالسيوم النانوية، مما يدل على انخفاض نسب التفتت او تكسر وفقدان اجزاء من الكتلة الترابية عند تعرضها الى الرطوبة او الماء مع زيادة نسب المحسنات للبلوك الترابي المضغوط.

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Introduction

Since the Mesopotamian civilizations (6,000 years ago), the utilization of earth as a construction material was abundantly clear (Alhialy et al., 2024; Deboucha and Hashim, 2011; Ibrahim and Tokmachy, 2023; Mohammed and Mohammed, 2024). As Earth is abundantly available as a primary material, it has been used to construct housing systems. The environmental benefits of this technology include reduced levels of embodied energy, increased thermal mass, and optimized utilization of locally procured materials (Walker, 2004). Considerable studies have been dedicated to the development of Earth as a sustainable material for construction in recent years. Consequently, technological advances have been made utilizing unfired bricks and rammed earth, commonly called Compressed Earth Blocks (CEBs). One significant benefit of producing unfired blocks is their reduced energy consumption, which results in an 80% decrease in carbon dioxide emissions compared to fired bricks (Heath et al., 2009; Oti and Kinuthia, 2018).

Over the past fifty years, considerable effort has been devoted to developing unfired blocks as an alternative to the more costly fired bricks and concrete blocks for use as a walling unit (Al-Bayati et al., 2023; Deboucha and Hashim, 2011). By properly grading the soil mixture, compacting it, and stabilizing it with admixtures, this is accomplished. As a result, masonry blocks have enhanced resistance to frost, increased density, decreased water absorption, and most significantly, enhanced compressive strength. As an indirect measure of the durability of the blocks, the compressive strength of the block has emerged as a fundamental and universally accepted unit of measurement for determining the quality of masonry units (Morel et al., 2007; Walker, 2004).

The process of stabilization involves the incorporation of admixtures into the soil to enhance its strength, permeability, volume stability, and durability. Concerning the enhancement of soil's performance as a building material, stabilization is regarded as an important phase in the production of CEBs. Cement has been the most widely utilized soil stabilizer in the production of CEBs, among the various stabilizers that have been utilized. Numerous researchers have previously endeavored to establish the function of cement as a stabilizer in CEBs (Deboucha and Hashim, 2010; Reddy and Kumar, 2011). Furthermore, lime has gained popularity as a stabilizer in the fabrication of CEBs in comparison to cement. The application of lime to stabilize clayey soils has been documented in the scientific literature to result in a sustained increase in strength (Amu et al., 2011; Herrier et al., 2012; Nagaraj et al., 2014). The Friant-Kern irrigation canal in California serves as a notable example of the resilience of lime-stabilized soils, according to Herrier et al. (2012).

Nevertheless, even though cement/lime stabilization decreases CO_2 emissions in comparison to fired clay blocks and concrete, it continues to be a costly process that demands a significant amount of energy and is not as environmentally sustainable as fiber reinforcement. Alternative materials for environmentally sustainable and cost-effective constructions have been the focus of other researchers who have directed their attention toward soil reinforcement using natural fibers. Natural fibers, as a rule, possess desirable aspect ratios and favorable mechanical and physical properties. In the construction industry, natural fibers are one of the most suitable options for reinforcing materials due to their technical and economic benefits (Buitrago et al., 2015). However, the primary obstacle associated with natural fibers continues to be the composite's durability (Chuitou, 2019).

To decrease plastic waste globally and create more resilient and affordable soil substitutes, scientists have lately investigated the use of synthetic fibers for soil reinforcement. Compared to natural fibers, synthetic fibers are more affordable, stronger, and more flexible. They also offer superior fire and waterproof properties (Vodounon, 2018). As stated by Andal and Juanzon (2020), environmentally friendly construction materials ought to be inexpensive, non-hazardous, and energy-efficient. Kumar et al. (2019) investigated the efficacy of a porous clay and silt blend reinforced with polypropylene fiber at fiber concentrations ranging from 0.5% to 2%, and reported that the compressive strength increased with an increase in the length and amount of the fibers in the fiber-reinforced soil. Abdullah et al. (2019) found that the unconfined compressive strength of unstable soil can be increased with polypropylene fiber reinforcement; the optimal fiber content was 0.15 percent by weight of dried soil, according to a study of Peter et al. (2014). The compressive and flexural strengths of compressed stabilized earth bricks increased as the length and percentage of polypropylene fiber increased. The highest strengths were observed at 0.2% fiber content with 54 mm fiber.

Because of technological progress and development, engineers can now utilize nanoscale stabilizers as soil amendments to enhance soil properties. The intriguing characteristics of these substances arise from the substantial quantity of atoms and molecules present on their unbound surface, which consequently influences their surface characteristics in terms of reactivity, physicality, and chemistry. Due to their substantial surface area and charge, nanoparticles can significantly enhance soil behavior even when introduced in minute quantities as additives, as stated by Choobbasti et al. (2019). The incorporation of nanoparticles increases the plastic limit and decreases the liquid limit of the clayey soil. The most significant increase in soil strength, approximately one hundred percent, was detected in the 42-day-old sample supplemented with 1.2% nano-calcium carbonate. Mohammadi et al. (2022) discovered that, particularly for clayey sand specimens with minimal clay contents, the addition of nano-$CaCO_3$ increased their compressive strength, and this increase continued over time. The optimal concentration of nano-$CaCO_3$ in soil was found to be 0.7% in soil containing 10% and 20% clay and 1.1% in soil containing 30% clay.

This research aims to study the effect of adding polypropylene fibers and nano-calcium carbonate to compressed earth blocks, where the fibers are added in percentages of (0.1%-0.4%) and nano-calcium carbonate in percentages (0.05%-0.25%) of the dry weight of the soil. The effect of these materials on the compressive strength, flexural strength, and durability tests at different ages is studied.

Materials and Methods

1. Material Properties

The used soil is clayey soil collected from the Laylan area, north of Kirkuk City, Iraq, at a depth of 1 meter below the ground surface. The coordinates of the site are 35°33′22.09″ N and 44°46′72.48″ E (Fig. 1).

From a structural point of view, the Laylan area is characterized by the presence of slightly inclined folds along a northwest-to-southeast axis parallel to the Zagros Mountain Range trend, and it is covered by sediments of (Miocene-Pliocene) age. Along the northeastern part of the Laylan area, where the Kirkuk structure appears, and from the southwest of the region, the Jambur structure appears. From the stratigraphic point of view, Quaternary sediments cover the Laylan region, while the edges of the region are covered by sedimentary rock deposits of (Miocene-Pliocene) age. Quaternary sediments cover more than a third of the surface area of Iraq, and most of these deposits appear in the Mesopotamian Plain. This type of deposit forms flat areas consisting of sand deposits or silty clay sand, and their thickness ranges between 2 - 3 m or more (Ameen and Tokmachy, 2019).

The collected soil sample is crushed by a plastic hammer and air-dried, and then the basic physical properties are determined in the laboratory. Figure 2 shows the grain size distribution made by wet sieving and hydrometer test according to (ASTM D422, 2007). The liquid and plastic limits are 29.5% and 15.3%, respectively, as per (ASTM D4318-17, 2005). Therefore, its plasticity index is 14.3%. When projecting the plasticity index with the liquid limit on the plasticity chart (Fig. 3), it is observed that it falls within the recommended limits according to Houben and Boubekeur (1998). The specific gravity is 2.71 (ASTM D854-14, 2014) and the linear shrinkage is 7.3% (BS-1377-part-2, 1990). The maximum dry density and optimum water content are $1.87 g/cm3$ and 15.4%, respectively, determined by standard compaction tests (ASTM D698 − 12, 2010). According to USCS classification, the soil is CL, namely inorganic clays with low to medium plasticity. The chemical composition of the soil is determined by X-ray fluorescence (XRF), and the results are listed in Table 1.

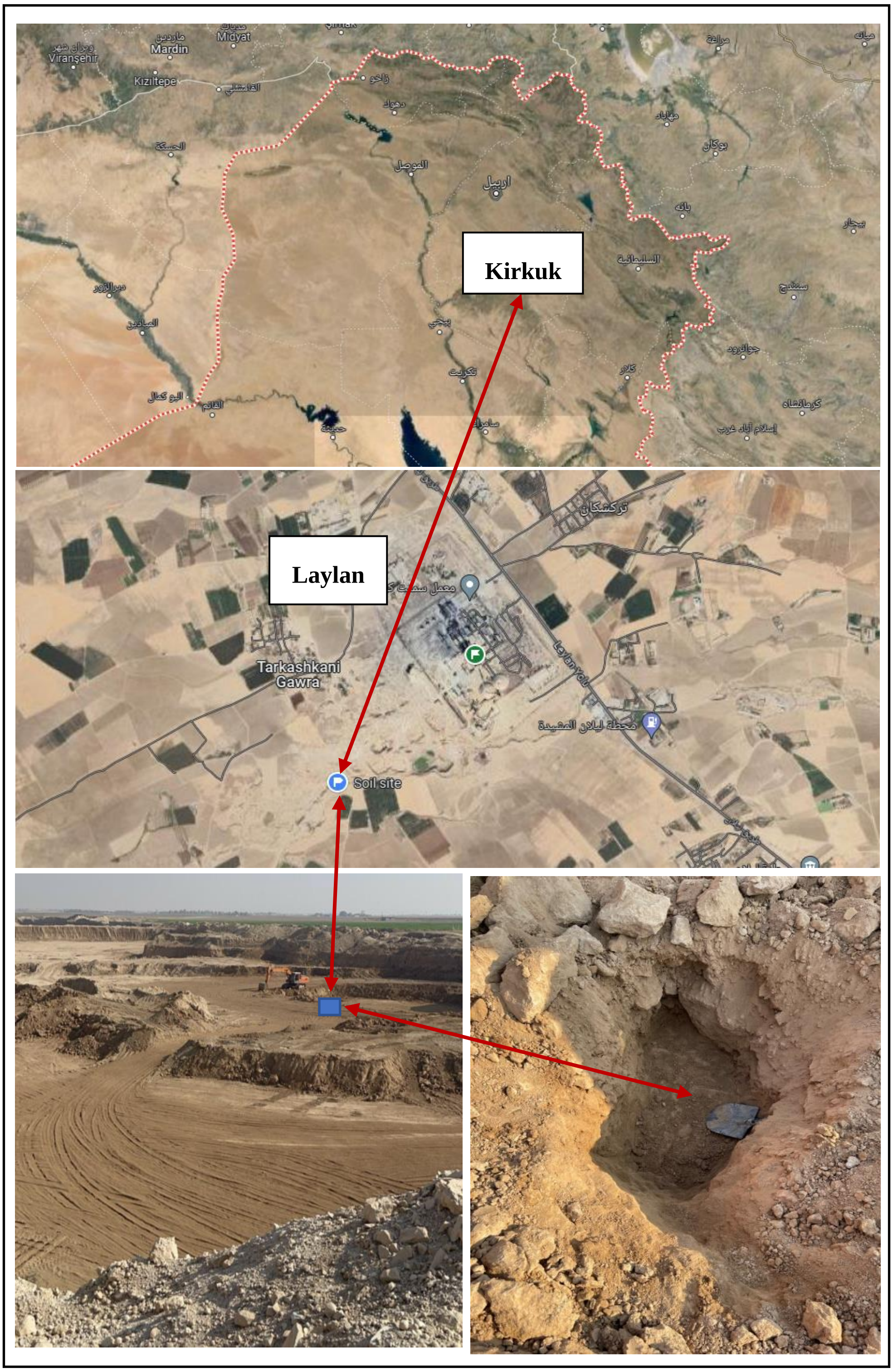

Fig. 1. Location of soil.

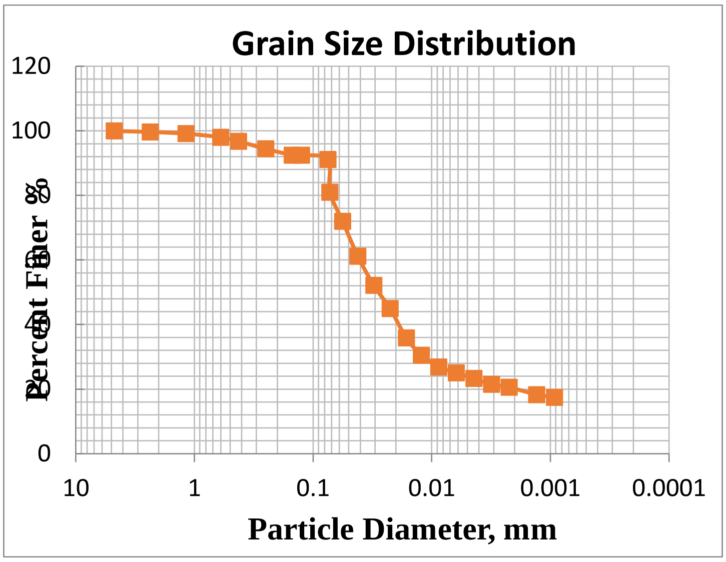

Fig. 2. Distribution of grain size.

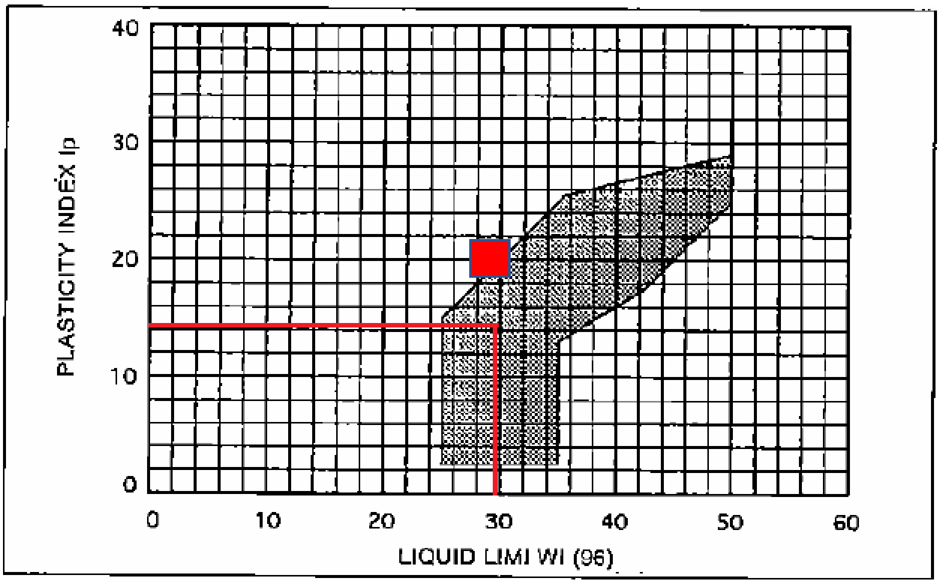

Fig. 3. Plasticity diagram indicating the recommended Atterberg limits for the soil used in the production of compressed earth blocks (Houben and Boubekeur, 1998).

Table 1: Chemical composition of soil.

Material	SiO_2	CaO	Al_2O_3	MgO	Fe_2O_3	K_2O	P_2O_5	SO_3	pH	T.S.S
%	55.83	18.08	11.19	8.41	3.91	2.1	0.13	0.097	6.55	1.52

2. Polypropylene fiber

Polypropylene fiber (PPF) is the most frequently used composite material to reinforce concrete and soil. It is often utilized in cementitious compounds and effectively reduces cracks. The main attraction lies in its economical price. It has a comparatively high melting temperature and is simple to incorporate into soil. Additionally, polypropylene is impervious to chemicals and hydrophobic; it neither reacts with nor absorbs soil moisture (Plé and Lê, 2012). The fiber utilized in this research is supplied by Sika Fiber. The fiber length is 12 mm with a diameter of 18 µm (aspect ratio = 667). The polypropylene fiber is shown in Figure 4, and the physical compositions are shown in Table 2.

Fig. 4. Polypropylene fiber.

Table 2: Compositions of fiber.

Specific gravity	Electrical Conductivity	Alkali Resistance	Melting point	Tensile Strength
(0.91, g/cm^3)	Low	High	160 ºC	– 400 N/mm²

3. Nano calcium carbonate

Nano calcium carbonate (nano CaCO3) is one of the factors that contributes to binding soil particles together due to its cement properties, creating soil with a stable structure, increasing compressive strength over time, increasing soil hardness, and decreasing deformation (Ohadian and Mokhberi, 2021). In this research, nano calcium carbonate is supplied by SkySpring Nanomaterials Inc. The nano calcium carbonate is shown in Figure 5, and the properties of the material are presented in Table 3.

Fig. 5. Nano-calcium carbonate.

Table 3: Properties of Nano $CaCO_3$.

Appearance	Whiteness (%)	Morphology	Particle size (mm)	pH	Bulk density (g/ml)	MgO (%)
White Nanopowder	>90	cubic	15-40	8.0-9.0	0.68	<0.5

Block preparation

Small-scale compressed earth block

Block preparation is one of the most important steps. In this research, a small-scale block is adopted using a hydraulic device for manufacturing and examining compressed earth blocks, as shown in Figure 6a. The produced block dimensions are (8.9 x 6.4 x 2.7 cm) with an aspect ratio of 0.42, as shown in Figure 6b. Specimens are prepared by drying the soil in the oven and passing it through a sieve No. 4. Fibers are added to the soil in five different percentages (0%, 0.1%, 0.2%, 0.3%, and 0.4%) of the dry weight of soil. The mixing is manual for five minutes in dry conditions to ensure that the fiber is distributed homogeneously throughout the soil particles and to minimize the agglomeration, then water is added gradually in different percentages to obtain the optimum moisture content for each percentage of fiber added. The mixtures are left in sealed plastic bags for fermentation for 24 hours. After that, the mixtures are compressed using a manual press device with a pressure of 15 MPa, and the blocks are left to cure for 28 days at room temperature and covered with a plastic cover.

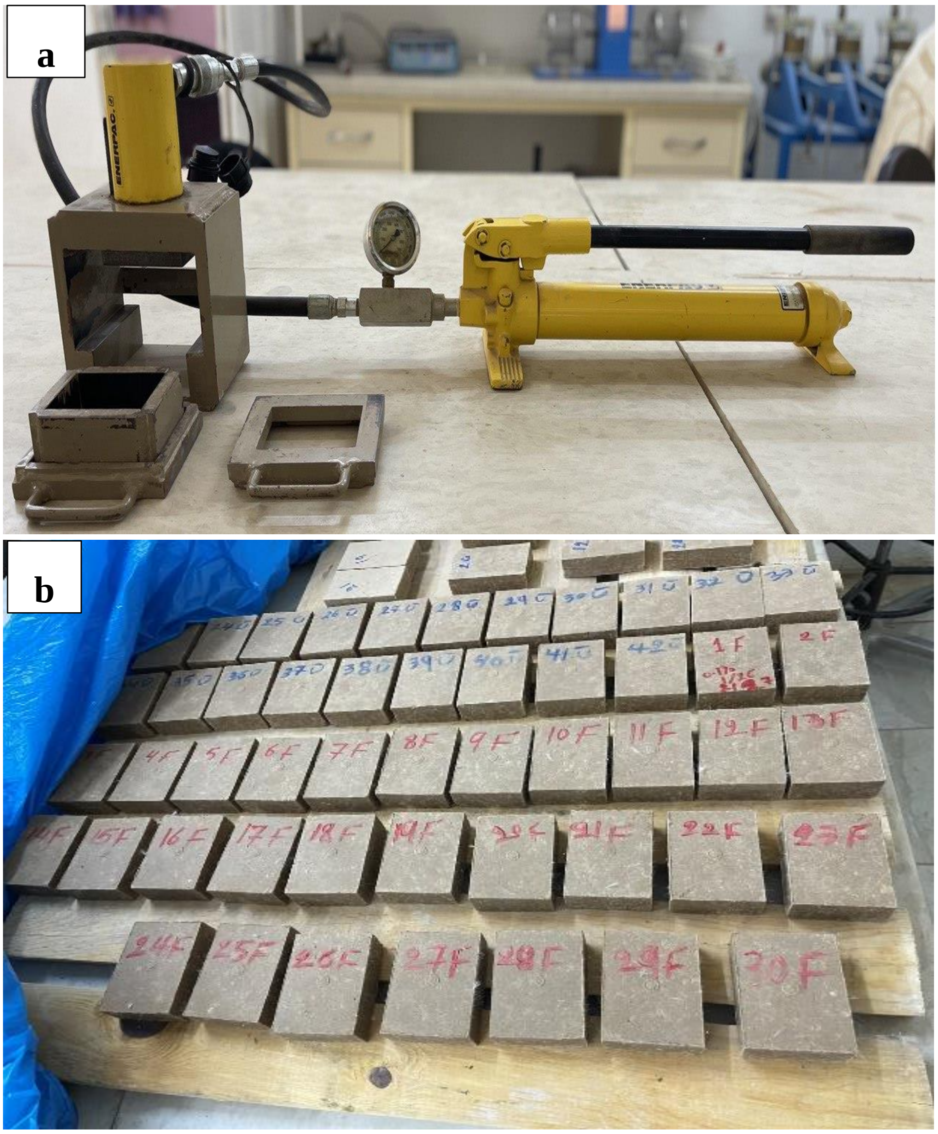

Fig. 6. (a) Hydraulic compressed machine, (b) Small-scale blocks.

Nano calcium carbonate is added at rates of 0.05%, 0.15%, and 0.25% of the dry weight. The mixing process took place by dividing the soil into five portions, and each portion is extensively mixed with a pre-determined amount of nanoparticles manually for thirty minutes, then mixing all the portions with the best percentage of fiber and adding different amounts of moisture content and leaving them to cure for 24 hours in a plastic bag. Then the samples are compressed using a compression machine with a fixed pressure of 15 MPa and left to cure for 28 days.

Large-scale compressed earth block

After obtaining small-scale blocks, the best percentages of fiber–nanomaterial mixture and optimum water content are chosen to produce the large-scale blocks using a hydraulic-pressing device as shown in Figure (7a) with larger dimensions (29.5x14.7x9.6)cm as shown in Figure (7b) with an aspect ratio of 0.65. The blocks are prepared in the same mixing method for small-scale blocks and pressed using the machine with a maximum pressure of 15 MPa and then covered with a plastic cover and left to cure for 28 days.

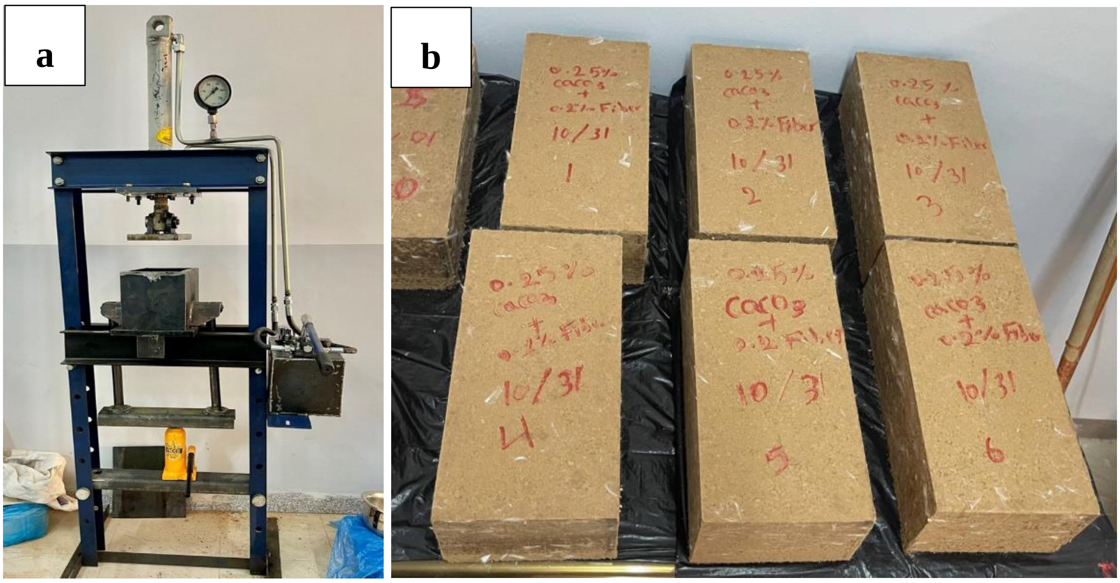

Fig. 7. (a) Pressing machine, (b) Large-scale compressed block specimens.

Block Testing

Four tests are conducted to determine the effect of polypropylene fibers and nano calcium carbonate on compressed earth blocks. These tests include the direct compressive strength test, flexural strength test, durability test, and microstructural analysis.

1. Direct Compressive Strength Test

Compressive strength is considered the most internationally accepted value to determine the quality of compressed earth blocks (Riza et al., 2010). However, it is closely related to soil types, stabilizer content, and compressed pressure used to form blocks. Small-scale block models are tested using the same compression machine, where the untreated compressed soil blocks and treated compressed soil blocks using fibers in different percentages, as well as the treated blocks using the optimum ratio of fibers and different percentages of nano calcium carbonate are tested after periods of 7, 14, and 28 days from the date of manufacture. As for large block models, they are tested using a compressive strength testing machine for concrete after 28 days from the date of manufacture. All blocks are tested in the direction in which they are pressed, which is also the direction in which they are generally placed.

One of the most important factors that should be focused on when calculating the compressive strength is the effect of the geometry of the compressed earth block specimens, as several researchers have already observed that the compressive strength increases as the aspect ratio decreases. Therefore, several correction factors are proposed to reach the real compressive strength value as shown in Table 4. (Aubert et al., 2013; Bei and Papayianni, 2003; Kumar and Surendra, 2019; Morel et al., 2007). (Heathcote, 1992; Krefeld, 1938).

Table 4: Correction factor of aspect ratio.

Correction factor	Aspect ratio				
	0.4	0.7	1	3	≥5
Krefeld's (fired clay bricks)	0.5	0.6	0.7	0.85	1
Heathcote and Jankulovski (SSB)	0.25	0.4	0.58	0.9	1

As a result of this influence, a correction factor of 0.25 is adopted for small compressed blocks, and a correction factor of 0.4 is adopted for large compressed blocks to reach a representative compressive strength value.

2. Flexural test

The flexural strength of compressed earth blocks is tested by three-point bending tests according to (ASTM D1635M −12, 2012) after 28 days. A bending test machine is used as shown in Figure 8. The bed of the flexural testing machine is provided with two steel rollers with a 20 mm diameter, on which the specimen is to be supported, and these rollers should be so mounted that the distance from center to center is 27.5 cm. The load should be applied through a single similar roller mounted at the center of the supporting span. The applied load is divided equally between the two loading rollers, and all rollers are mounted in such a way that the load is applied vertically without subjecting the specimen to any torsional stresses. The dimensions of each block are measured and recorded before testing, and marks are placed in the center of each dimension to ensure concentrated uniform loading. The blocks are loaded, and readings are recorded until failure occurs. To calculate the modulus of rupture, the following equation (1) is used:

$$R = \frac{PL}{bd2} \text{..........(1)}$$

Where: R = modulus of rupture [MPa]; P = maximum applied load [N]; L = span length [mm]; b = average width of specimen [mm]; and d = average depth of specimen [mm].

Fig. 8. Flexural testing machine.

3. Durability test

The durability characteristics of compressed earth blocks are largely unknown, while playing an essential role in the life-cycle analysis of the applied technology. The porous quality of clay blocks enables them to "breathe," or absorb and desorb moisture in cycles. While this tendency is useful for controlling indoor humidity, it may harm the blocks themselves. The hygroscopic nature and large relative specific surface area of clay particles provide multiple possibilities for water to affect the physical properties of an earthen block. Typically, when clay absorbs water, the internal vacuum areas fill up, causing the material to swell or expand. As the material releases moisture, internal empty spaces are formed, resulting in material consolidation or shrinkage. Multiple repeats of this technique might ultimately cause cracking and breaking of the material (Krosnowski, 2011).

A durability test is conducted for small-scale untreated blocks and those treated with different percentages of fibers and nanomaterials after 28 days, according to the slake durability test (ASTM D4644-16, 2016). The durability index is calculated through Equation (2) and is compared with the values of the durability index of the SDI classification system according to (Gamble et al., 1971; Kerali, 2001) as shown in Table 5.

$$SDI = \frac{Mf}{Mi} x\ 100\% \quad ……..(2)$$

where: SDI = slake durability index (%); Mf = final mass (g); Mi = initial mass (g).

Table 5: SDI classification system.

SDI%	95-100	90-94	75-89	50-75	25-49	0-24
Classification	Extremely high	Very high	high	Medium	Low	Very low

4. Microstructural analysis

Typically, 28-day blocks are selected for microstructural analysis by conducting X-ray diffraction (XRD), scanning electron microscope (SEM), and Energy Dispersive X-ray analysis (EDX) tests; the blocks were taken from the failure blocks after the direct compressive strength test. All tests are conducted by the Scientific Research Center at Soran University, Iraq.

Results and Discussion

Direct compressive strength

The results of the compressive strength after correction for aspect ratio are presented in Table 6. From the results for small-scale blocks, it is noted that blocks reinforced with polypropylene fibers have improved block strength. Whereas, the compressive strength increases with increasing curing age, as the highest strength was obtained at 0.2% fiber addition with a compressive strength of 10 MPa. It is also seen that the compressive strength of the added percentages went down after 0.2% of fiber, as shown in Figure 9. The difference in the percentages of additives also leads to a difference in strength during the same treatment period. This is because when the fibers are mixed with the soil, they fill the spaces between the soil particles, and thus the fibers can participate in carrying the pressure and increase the compressive strength. However, adding a lot of fibers makes them stick together and form lumps, which means they cannot fully contact the soil particles (Abdullah et al., 2019).

For the blocks treated by fiber-nanomaterials mixture, the compressive strength increases with the increase in the percentage of nanomaterials, as the highest compressive strength is recorded at 0.25% nano-calcium carbonate with a value of 17.9 MPa, as shown in Figure 10. Due to the incomplete interactions between nano $CaCO3$ and soil, the trend of strength variation for samples treated with nano $CaCO3$ for 7 days curing period differs from samples treated with 14 and 28 days curing periods.

The effect of weather on the compressive strength of the blocks is noted, as the loss of moisture content of the blocks increases in the curing period, the compressive strength increases. A great convergence is observed between the values of the compressive strength of the blocks treated using 0.2% and 0.3% fibers at a treatment period of 14 days because of a decrease in temperature and an increase in humidity during that period, which resulted in a decrease in the loss of moisture content of the blocks. Also, notice that the blocks reinforced using 0.2% fiber and 0.25% nanomaterial at the periods of 14 and 28 days of treatment have close compressive strength because of the greater loss of moisture content of the blocks at the period of 14 days due to higher temperatures and less air humidity.

For large-scale blocks, the compressive strength is examined, and the results show an increase in strength with the increase in the improvers' percentage. It is also noted that the compressive strength values for small-scale blocks are greater than those for large-scale blocks. This is because there is an increase in compressive strength as the aspect ratio decreases, as shown in Figure 11. The explanation is that the friction occurred between the block and the presser (Aubert et al., 2013).

During the test, cracks appeared around the edges of the specimens as the untreated blocks were cracked, leading to separation at the edges as shown in Figure 12a. However, treated blocks with fiber did not break. They maintained their shape because the fibers acted as reinforcing materials, as they bound the soil particles together, and also because of the properties of polypropylene fibers, which have high tensile strength, elastic modulus, and stress elongation as shown in Figure 12b.

Table 6: Direct compressive strength.

Mix type	Fiber content%	Nanomaterial content%	Small-scale compressive strength (MPa)			Large-scale compressive strength (MPa)
			7 days	14 days	28 days	28 days
1	0	0	4.9	5.7	7.3	5.4
2	0.1	0	4.5	6.2	9.0	
3	0.2	0	4.2	4.5	10.0	6.03
4	0.3	0	4.1	4.4	6.3	
5	0.4	0	3.6	4.4	6.1	
6	0.2	0.05	5.3	6.9	10.4	
7	0.2	0.15	5.1	6.8	10.7	
8	0.2	0.25	11.3	16.5	17.9	7.7

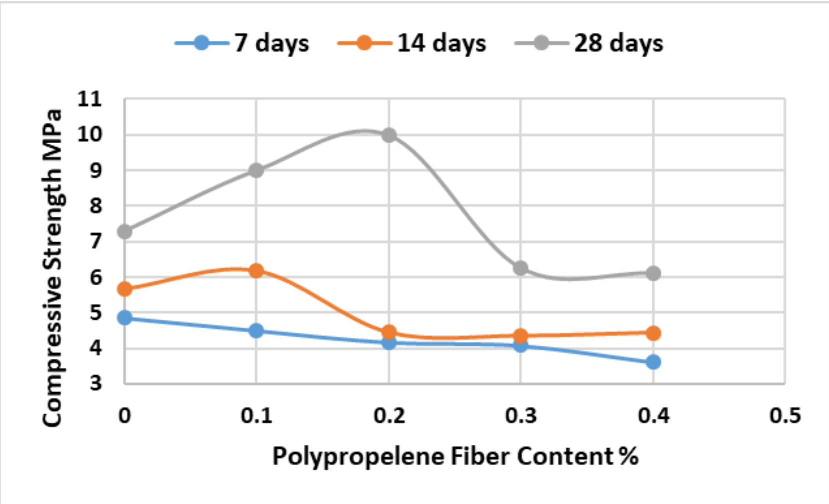

Fig. 9. Effect of fiber on compressive strength.

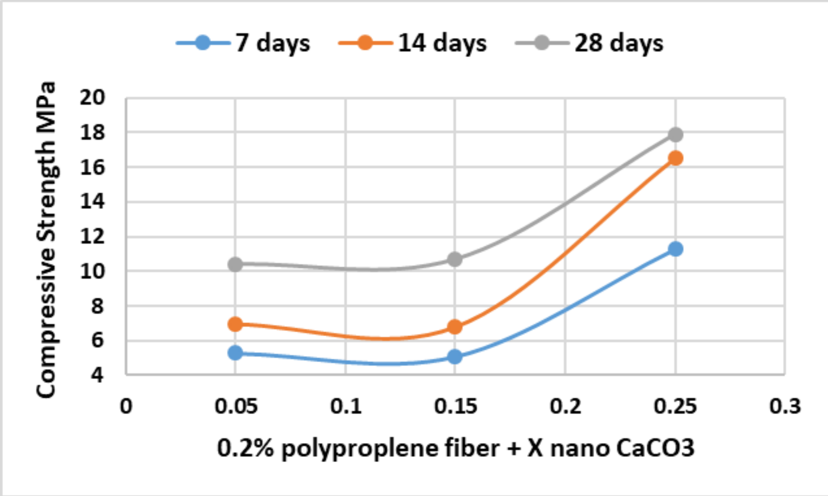

Fig. 10. Effect of nanomaterial on compressive strength.

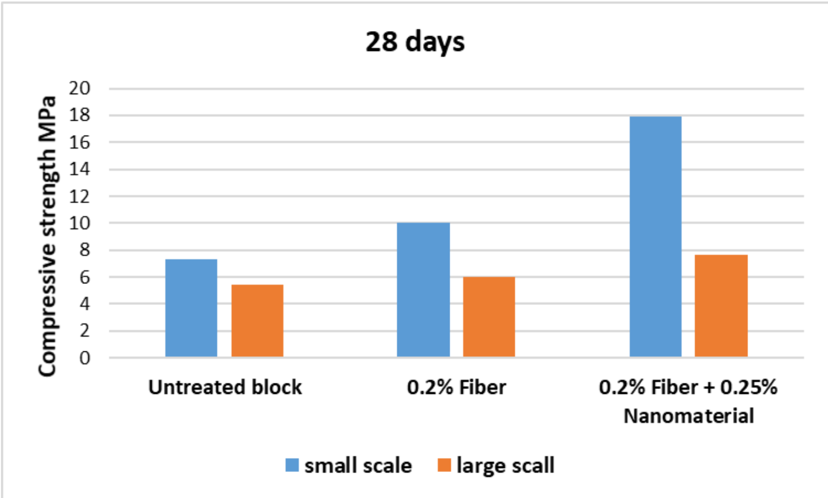

Fig. 11. Compressive strength value at 28 days.

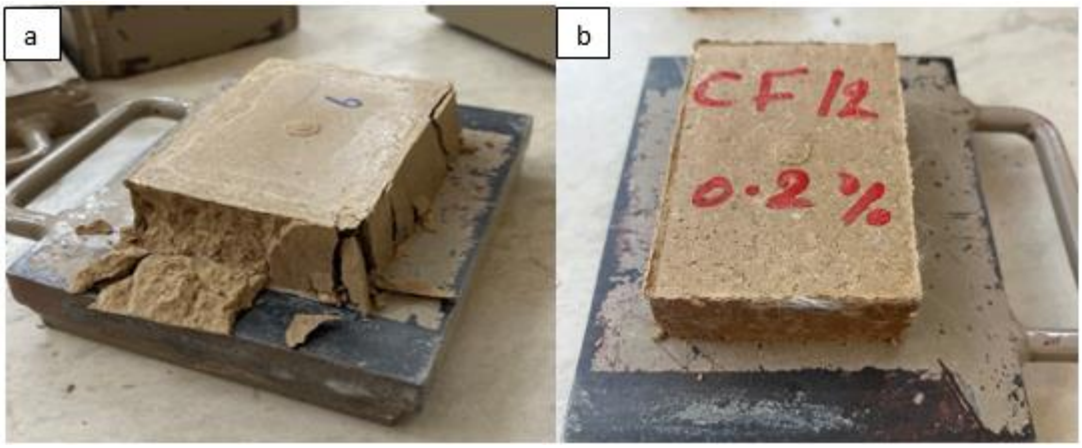

Fig. 12. Crack pattern after compression test.

Flexural test

A three-point bending test is used to test the flexural strength of the large-scale compressed earth block specimens at 28 days of curing period. The results show an increase in the flexural strength of the blocks with the addition of fibers and nano-calcium carbonate. Figure 13 shows a graphical representation of the test results. The highest flexural strength value is 1.67 MPa for the block treated with 0.2% fiber + 0.25% nano calcium carbonate. Figure

14 shows the relation between load and time. It shows that there is a sudden failure for untreated blocks, while the treated blocks fail slowly.

The patterns of cracks that occurred under flexural loading are observed during the testing of block specimens. Untreated block specimens suffered a sudden failure directly after cracks appeared in the middle, which led to the block breaking into two halves. For the fiber-reinforced blocks, there is no complete failure; and the crack is generally one straight crack extending from top to bottom in the middle third of the blocks, and most of the fibers remained intact, and the block remained cohesive after the crack appeared, as shown in Figure 15. This indicates that the fibers used have a high ability to withdraw and resist.

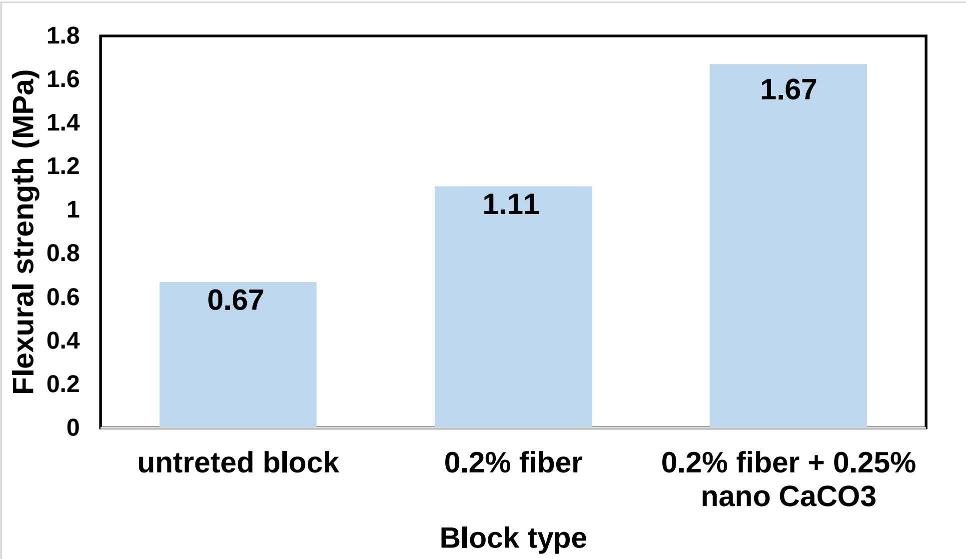

Fig. 13. Flexural test results.

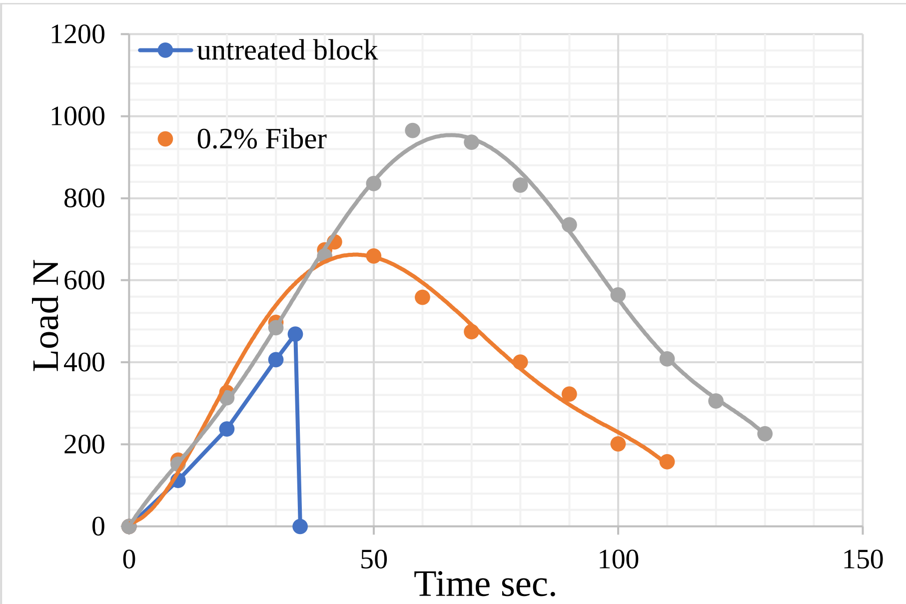

Fig. 14. Load-time relation.

Fig. 15. Fibers bridging crack during the flexural test.

Durability test

A slake durability test is conducted to determine the durability of the blocks after 28 days of curing. Table 7 shows the slake durability index and mass losses for blocks that are not treated, blocks that are treated with different amounts of fiber, and blocks that are treated with 0.2% fiber and different amounts of nano calcium carbonate. Through the results, it is shown that the values of the slack durability index increase with increasing percentages of fiber, as well as increasing percentages of nano calcium carbonate, and therefore, mass losses decrease with increasing percentages of fiber and nano calcium carbonate. The highest mass losses are observed in the untreated blocks of about 30.3%, and the lowest losses are observed in the blocks that are treated with 0.2% fiber with 0.25% nano calcium carbonate, about 12.8%. Through the SDI classification system, it is found that all blocks are classified as highly durable except the untreated soil, which is classified as medium durable.

Table 7: Slack durability test.

Mix type	Fiber content%	Nanomaterial content%	SDI%	Mass loss%	Classification
1	0	0	69.7	30.3	Medium
2	0.1	0	70.9	29.1	High
3	0.2	0	76.3	23.7	High
4	0.3	0	78.3	21.7	High
5	0.4	0	85.5	16.5	High
6	0.2	0.05	84.6	15.4	High
7	0.2	0.15	86.9	13.1	High
8	0.2	0.25	87.2	12.8	High

Microstructural results

1. X-ray diffraction (XRD)

Figure (16) shows the diffraction diagram of the tested blocks, and the mineral composition shows that the untreated block contains 47% calcite, 45% low quartz, and 8% dolomite, whereas the treated block contains 33% calcite, 35% quartz low, 22% albite (heat-treated), and 10% dolomite. The XRD patterns indicate a change in the intensity peaks and peak width after the addition of nano calcium carbonate to the soil in the calcium silicate hydrate phase, kaolin phase, calcite phase, etc., which in turn, indicate a change in the size of crystallites. The ultimate compressive strength of the soil is improved due to the recrystallization of the particles induced by nano calcium carbonate.

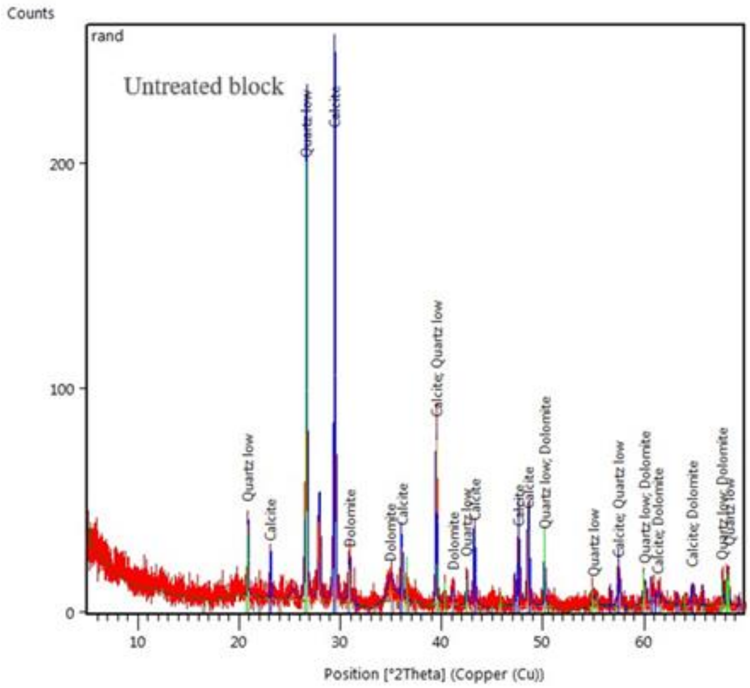

Fig. 16. (a) XRD results of the untreated block.

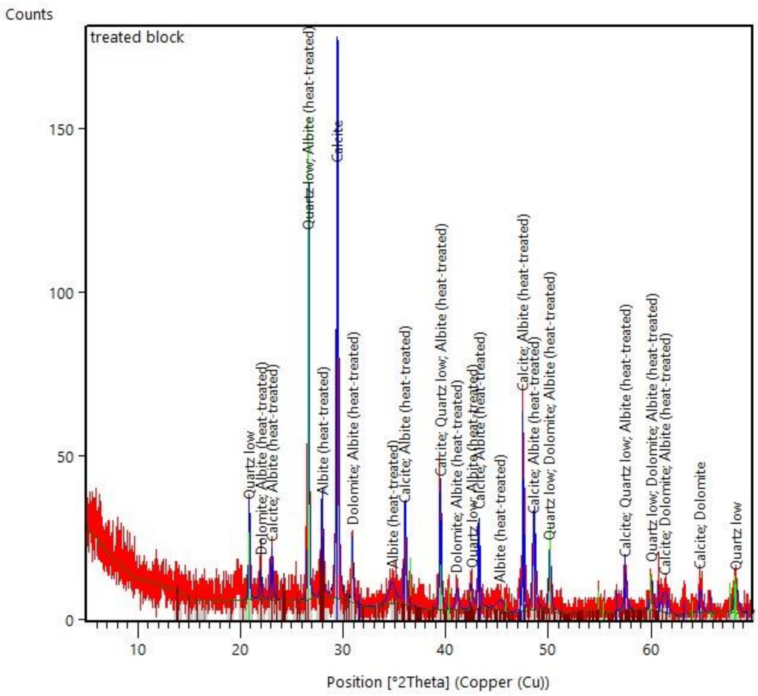

Fig. 16. (b) XRD results of treated block by 0.2%fiber-0.25% nano $CaCO_3$.

2. Scanning electron microscope (SEM)

Figure 17 shows typical SEM micrographs taken for a 28-day block with ideal mixtures. For the untreated block as shown in Figure 17a,b, clear pores between the soil particles are shown. Figure 17c,d shows the shape of the samples using fibers and nano $CaCO_3$, where it is observed that the density increases with the addition of the stabilizer. The figures show a symmetrical distribution of the fibers, and the nanomaterial also appears in the form of a white substance surrounded by soil particles stuck to it. The interaction of these materials works to bind the soil particles around them to each other, which leads to the production of compressed earth blocks with low porosity and a denser and stronger structure.

Energy Dispersive X-ray Analysis (EDX)

From the result of the EDX test shown in Figure 18, the main elements in the specified area are observed as the elements shown in Figure 18a for the untreated block are Si (32.8%), Ca (31.5%) and O (11.3%), together with small amounts of Al (9.6%), Fe (7.2%), Mg (4.5%) and C (3.1%). The elements Ca, O, and Mg in the sample are dispersed uniformly, while the other elements appear as concentrated spots in limited numbers.

While the examination of the treated block appears that the main elements in the specified area are Ca (33.7%), Si (24.2%), C (12.1%), and O (10.4%), with small percentages of elements Al (8.7%), Mg (6.1%) and Fe (4.8%). As it is shown, there is an increase in the percentage of elements Ca and C after the addition of the nanomaterial. Also, it can be seen from Figure 18b that all the elements are distributed almost uniformly in the sample, while it is observed that the carbon element is concentrated on the fibers to a greater extent than its spread in the soil. This is due to that polypropylene fiber is composed of carbon elements, also, the carbon in nano calcium carbonate is unable to dissociate because it is not exposed to a reaction resulting from chemical or heating processing.

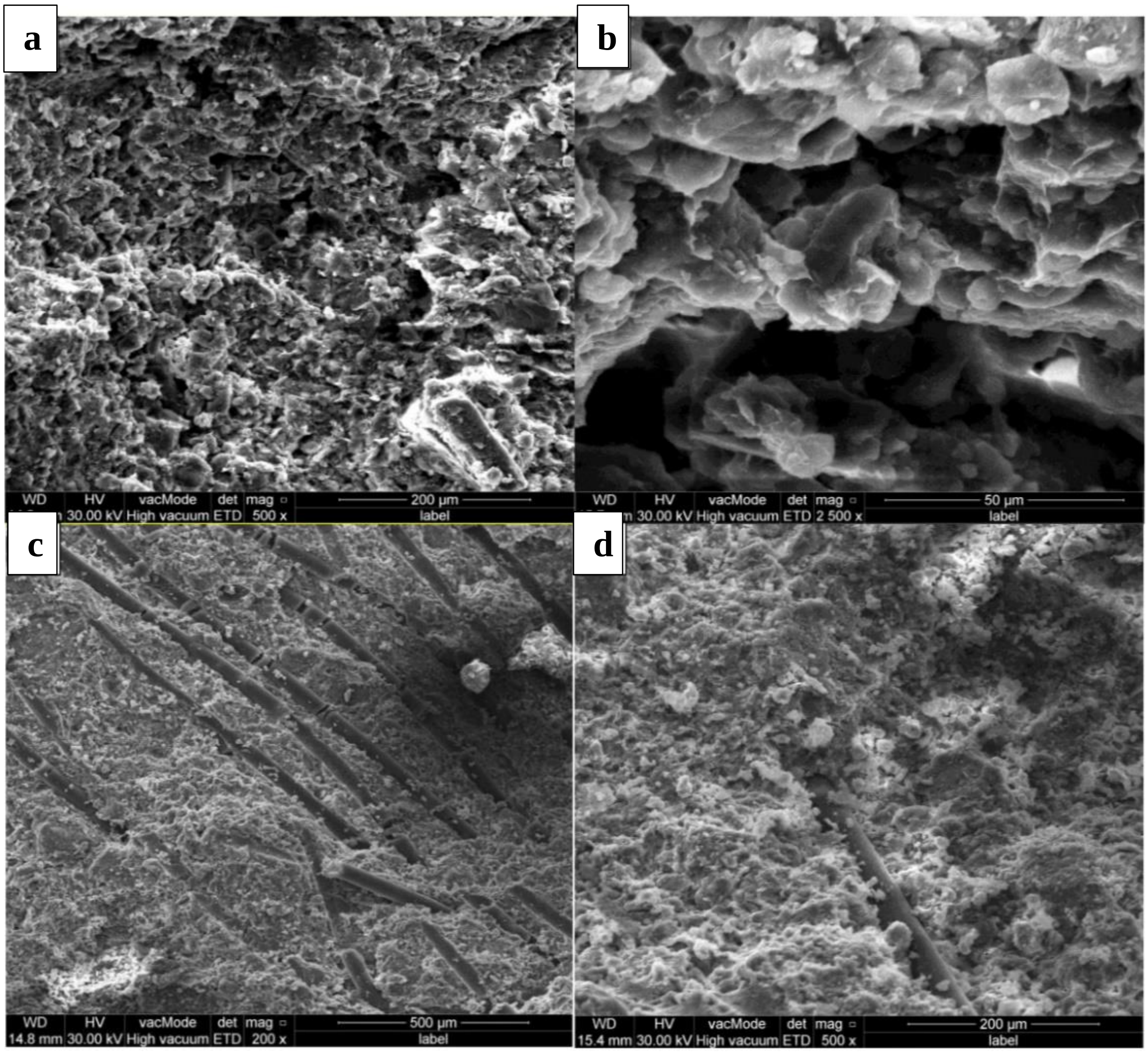

Fig.17. Scanning electron microscope (SEM) images. a, b for the untreated block and c,d for the treated with fiber and nano-$CaCO_3$.

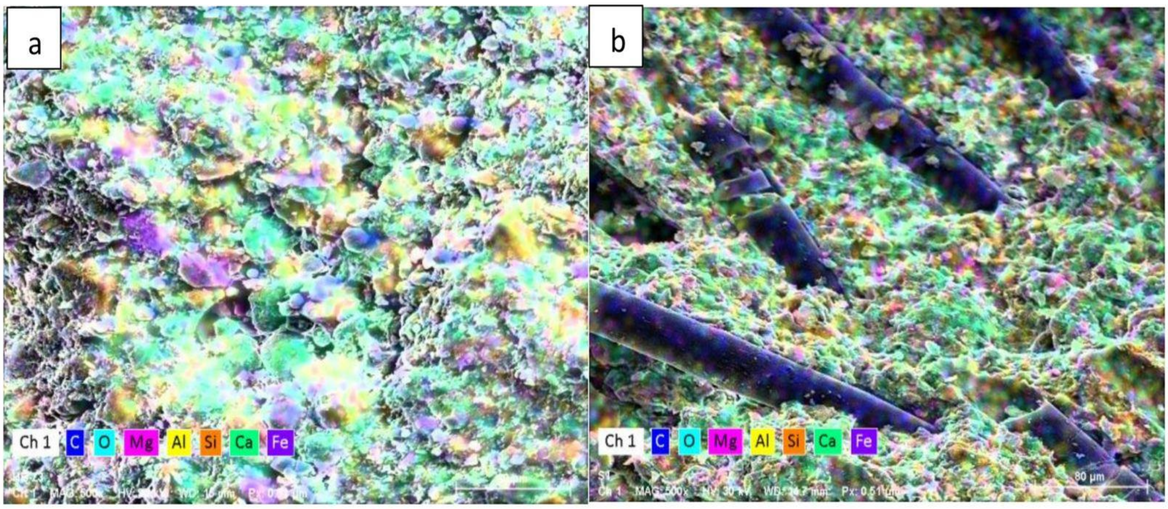

Fig.18. EDX analysis results.

Conclusion

This research focuses on studying the effect of a couple of actions of polypropylene fibers and nano-calcium carbonate on compacted earth blocks to improve their properties. Untreated and treated soil blocks with fibers in percentages (0.1%, 0.2%, 0.3%, and 0.4%) are produced, and the treated blocks with 0.2% fibers mixed with nano-calcium carbonate in percentages (0.05%, 0.15%, and 0.25%). The blocks are tested according to the global standard ASTM and BS1377 standard testing methods for compressive strength, flexural strength, and durability tests. The results show:

- Increasing the percentage of fibers increases the compressive strength of the compressed earth blocks, where the highest compressive strength is for 0.2% of the fibers with a strength of 6 MPa for the large-scale blocks and 10 MPa for the small-scale blocks at 28 days curing period.
- Increasing nano calcium carbonate percentages increases the compressive strength of the compressed earth blocks. The highest compressive strength is observed at the blocks treated with 0.25% of nano calcium carbonate and 0.2% fiber, with a strength of 7.7 MPa for blocks with large scale and 17.9 MPa for blocks with small scale.
- The compressive strength of the compressed earth blocks increases with increasing curing period.
- An effect of temperature and air humidity on the block's compressive strength is noted, where the increasing temperatures lead to the loss of moisture content of the block specimens quickly, which in turn increases the compressive strength of the blocks.
- Adding fibers changes the failure behavior of the blocks. The untreated blocks are fragile and subject to catastrophic failure. Where the cracks occurred initially, the blocks are noticeably deformed before the collapse.
- The presence of fibers and nano-calcium carbonate improves the durability of the earth blocks by decreasing the slack durability index (SDI) as the percentage of additives increases. Consequently, mass losses are reduced.
- The addition of fiber and fiber with nanomaterials increases the failure load and the duration, which indicates a ductility improvement.
- The treated specimens' flexural behavior is better than that of the untreated specimens. The average results for untreated, treated with 0.2% fiber, and treated with 0.2% fiber and 0.25% nano-calcium carbonate are 0.67 MPa, 1.11 MPa, and 1.67 MPa, respectively.
- SEM micrographs depict improved void filling after the addition of nano $CaCO_3$.
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Conflict of Interest

The authors declare there are no conflicts of interest regarding the publication of this manuscript.

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