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ASSESSING THE POSSIBILITIES OF CNT AND EFB FIBER REINFORCEMENT IN RAMMED EARTH NANOCOMPOSITES FOR STRUCTURAL STABILITY ENHANCEMENT

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The object of the study is the rammed earth nanocomposites. Rammed earth nanocomposites reinforced with carbon nanotubes (CNT) and oil palm empty bunch (EFB) fibers provide nanoscale cohesion, and EFB fibers offer macroscale crack bridging, this research aims to significantly improve the material's mechanical performance. This study pioneers a nanocomposite approach by integrating 1–2 % CNT and EFB fibers into rammed earth, achieving a 539 % increase in compressive strength (from 1.43 MPa to 9.13 MPa) and 34.671 kN buckling resistance to improve structural performance especially for the stability for sustainable construction applications. Standard rammed earth had a compressive strength of 1.43 MPa and buckling resistance, limiting its use; however, when 1 % CNT was added, increased compressive strength to 6.43 MPa (cube) and 6.58 MPa (cylinder), while 2 % CNT further enhanced it to 8.56 MPa and 9.13 MPa, respectively. Flexural strength also improved from 0.98 MPa to 3.60 MPa (beam). Cylindrical specimens showed optimal performance due to uniform stress distribution (34.671 kN buckling resistance). Microstructural analysis reveals CNT enhance nanoscale cohesion while EFB fibers provide macro-scale crack bridging. Compared to conventional concrete, the composite reduces embodied carbon by 62 % (per ISO 14040 LCA standards) and material density by 26 % (1.48 vs 2.0 g/cm^3). These findings establish a new paradigm for sustainable seismic-resistant construction in developing tropical regions where both laterite soil and palm oil waste are abundant. The synergy of CNT (nanoscale cohesion) and EFB (load distribution) addresses key limitations. This material is suitable for eco-friendly construction, seismic-resistant structures, and lightweight partitions, offering a sustainable alternative to concrete/steel. The project simultaneously advances sustainable construction materials and provides a blueprint for vocational education that bridges technical and soft skills

Keywords: buckling, rammed earth, empty bunch fibers, composite, nanotubes

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1. Introduction

Rammed earth, an age-old building method that uses compacted soil to create load-bearing walls and structures, is one such material that has drawn interest recently. This material is praised for being economical, thermally efficient, and having a minimal environmental impact. Research into rammed earth's mechanical constraints has become crucial, particularly in light of green building technologies and the ideas of the circular economy. Natural fibers, such those made from leftover palm oil, and carbon nanotubes (CNT) have demonstrated significant promise in strengthening conventional composites. While palm oil empty fruit bunch (EFB) fibers offer extra reinforcement by enhancing the material's toughness and energy absorption qualities, carbon nanotubes (CNT) have superior mechanical qualities, such as remarkable tensile strength, high elastic modulus, and improved load transfer capabilities. The extensive usage of steel and cement in the construction industry makes it one of the biggest sources of CO_2 emissions worldwide. In order to lessen dependency on carbon-intensive materials, this work supports global sustainability programs by creating high-performance rammed earth nanocomposites reinforced with CNT and EFB fibers. Additionally, the incorporation of industrial waste (EFB fibers) into building materials reduces waste and offers a sustainable and cost-effective solution for the palm oil sector, which produces a large amount of biomass waste. Studies combining CNT and EFB fibers for rammed earth reinforcement are still lacking, despite the expanding corpus of research on nanocomposites and fiber-reinforced earth materials. Furthermore, not much research has been done on the structural behavior of CNT-reinforced rammed earth under dynamic loads, specifically with regard to buckling resistance and vibration performance. Research on CNT- and EFB-reinforced rammed earth is both urgent and essential given the growing need for reasonably priced, environmentally friendly, and high-performing building materials.

As a result, studies focused on creating and evaluating CNT- and EFB-reinforced rammed earth nanocomposites are essential and extremely important. The use of natural fibers, such as empty palm oil bunch fibers (EFB), in polymer composites has been explored for various applications, including sound absorption and mechanical reinforcement [1]. It has been shown that adding nanoparticles improves the mechanical characteristics of rubber composites, such as elongation at break, tensile strength, and hardness [2]. Similarly, the use of Palm Oil Empty Bunch Ash (POEBA) as a filler in rubber composites has shown improvements in mechanical properties, with the best composition containing 8 phr (parts per hundred rubber) of EFB ash [3]. The synthesis of carbon nanoparticles, including carbon nanotubes, has been reviewed, highlighting their potential applications in various fields [4]. Improving the compatibility of nanocellulose with the PLA polymer matrix to improve the dispersion of nanocellulose particles is a significant problem in the production of high-performance PLA (Poly Lactic Acid) nanocomposites. Because PLA and nanocellulose have different hydrophilic and hydrophobic properties, respectively, nanocellulose-reinforced PLA nanocomposites often show poor filler dispersion in the PLA matrix [5]. All of these researches show that the characteristics of nanocomposites may be greatly enhanced by the addition of carbon nanoparticles and components obtained from palm oil waste, such as EFB fibers and ash.

Rammed earth material has long been recognized as a durable and environmentally friendly building material due to its raw materials being easily sourced from soil. This material is composed of a mixture of clay, sand, and other aggregates, molded into walls using high pressure. Its unique advantages include energy savings, environmental protection, low cost, easy material accessibility, livability [6], high thermal buffering capacity, and relatively low cost [7]. However, rammed earth materials have some weaknesses, such as poor thermal resistance [8], low strength, vulnerability to water damage, and limited earthquake resistance.

Research on the use of rammed earth nanocomposites reinforced with palm oil fibers and carbon nanotubes remains limited, despite numerous studies investigating the use of natural fibers and nanoparticles in polymer composites. The traditional building material known as rammed earth is made from manually compacted soil. However, rammed earth has limitations in handling vibration and buckling in structural applications. Therefore, incorporating palm oil fibers and carbon nanotubes as reinforcements in rammed earth nanocomposites could help enhance the material's performance.

Every 1-ton production of Fresh Fruit Bunch (FFB) waste generates approximately 23 % or 230 kg of palm oil empty bunch fibers (EFB). The empty bunch contains cellulose content of 41.3 %–46.5 % $(C_6H_{10}O_5)n$, hemicellulose 25.3 %–32.5 %, and lignin 27.6 %–32.5 % [9]. The use of palm oil bunch fibers as reinforcement in rammed earth offers several advantages. First, these fibers are readily available in large quantities as a by-product of the palm oil industry. Second, palm oil bunch fibers possess beneficial properties for construction, such as good strength and moisture resistance. Third, adding palm oil bunch fibers to rammed earth lessens waste and the negative effects of the palm oil business on the environment.

Carbon Nanotubes (CNT) are ultra-thin carbon fibers with diameters in the nanometer range and lengths in the micrometer range [10]. On the other hand, palm oil fibers and carbon nanotubes have attracted attention as potential reinforcements in composites due to their unique mechanical and structural properties. The use of palm oil fibers as reinforcement in composites has proven effective in enhancing material strength and toughness, while carbon nanotubes offer promising potential for significantly improving composite performance.

Research involving palm oil fibers and carbon nanotubes as reinforcements in rammed earth nanocomposites is crucial in addressing the challenges related to vibration and buckling. It is anticipated that by using the mechanical qualities of both materials, stronger and more resilient rammed earth materials will be developed, improving environmental sustainability in the building sector.

2. Literature review and problem statement

The paper [11] presents the results of research on the mechanical characterization and elastic stiffness degradation of unstabilized rammed earth (RE), focusing on its compressive strength, Young's modulus, Poisson's ratio, and creep behavior. Shown, that RE exhibits significant variability in its mechanical properties due to factors such as soil composition, moisture content, testing procedure and sample size. For instance, the unconfined compressive strength (UCS) of RE ranges widely, and its long-term structural performance under sustained loads, particularly regarding creep and stiffness degradation, remains poorly understood. But there were unsolved issues related to the structural assessment of RE under complex loading conditions such as a buckling, especially when modified with advanced materials such as carbon nanotubes (CNT). The reason for this may be objective difficulties associated with the heterogeneity of RE materials, which depend heavily on local soil properties and compaction techniques, fundamental impossibility of achieving uniform samples due to the natural variability of raw materials, and cost part in terms of conducting advanced experiments (e.g., buckling tests with CNT-enhanced RE), which makes relevant research impractical for many laboratories [12]. Additionally, the lack of standardized guidelines for characterizing the mechanical properties of RE complicates comparisons across studies. A way to overcome these difficulties can be the incorporation of advanced materials such as carbon nanotubes (CNT) into RE to enhance its mechanical properties and stability under buckling loads. This approach was used in [13], where numerical modeling tools like the discrete element method (DEM) were employed to simulate the behavior of RE walls; however, the accuracy of such models heavily relies on precise input parameters, which are still not well-defined due to the aforementioned challenges. All this suggests that it is advisable to conduct a study on the integration of CNT into RE mixtures to improve their buckling resistance and overall structural performance ensuring both safety and sustainability in modern construction practices. Such research could bridge the gap between traditional RE applications and advanced engineering requirements, paving the way for innovative and resilient building materials.

Clay is the only binder used in traditional rammed earth construction, also known as un-stabilized rammed earth. Additional binders like cement, lime, or coal ash are added to stabilized rammed earth to increase its mechanical properties and durability. However, using these binders raises the expense of building and has an adverse effect on the environment [11]. Earth is being used more often in modern architecture due to its superior environmental performance, which includes minimal emissions, no waste from demolition, the ability to use recycled materials or industrial byproducts as additives, etc.

In some regions of the globe, new iterations of the rammed earth material technique have emerged and become more well-known. Long-standing rammed earth material technology may be found in unsustainable rammed earth construction types or in wall or floor layers composed of many layers of compressed dirt. While the new version uses cement and clay water or stabilized rammed earth construction categories. A stiff formwork is used to compress the soil in a progressive layer to build rammed earth walls, which are monolithic structures. While unstable rammed earths are made mostly of soil, sand, and gravel, stabilized rammed earths are made by incorporating inorganic additives like cement or lime into the foundation material [13]. The compressive strength of rammed earth material is determined by factors such as soil type, particle size distribution, and stabilizer used so that this material is able to become a structural element that is resistant to fire, absorbs heat in the middle of the day and releases heat at night. The size of the rammed earth for load-bearing walls is 12 inches. It uses a wide roofing system to protect this wall material from being exposed to rain. This size is very thick to make rammed earth the material of the walls in the building. By reducing and adding mesh reinforcement (wire mesh) in the rammed earth layer, it can reduce the size of this material and have the same strength so that it can be used as a green material for building space partitions. Building space partitions have flexible properties so that they can separate the space into two spaces of different functions usually used by commercial high-rise buildings to reduce the burden on buildings [14]. The partition material of building space is usually in the form of particleboards made of wood. Particleboards like this tend to have more weight, weak binding strength, and tend to crumble easily at the ends. Made from wood makes the need for wood increase, this is feared to damage nature.

Rammed earth has emerged as a sustainable building material and construction method. To make solid brick walls, it entails compacting unprocessed soil-often combined with water and additives-into makeshift molds [15]. The flexibility of rammed earth to employ locally accessible resources lessens the environmental impact of conventional building materials like steel and concrete, making it an environmentally friendly option. Rammed earth's capacity to perform well in nearly any climate, provide passive thermal benefits, and last longer than most conventional buildings highlight its sustainable attributes [16]. However, there are still issues with rammed earth constructions' mechanical performance, especially when it comes to increasing their strength and longevity. The lack of uniform regulations and the comparatively poor mechanical qualities of rammed earth in comparison to more traditional materials have impeded its use in contemporary building, despite its historical relevance [17].

Recent research has investigated the use of cement, lime, and other stabilizers as well as other additives to stabilize rammed earth [11]. According to these investigations, these additions increase the rammed earth buildings' compressive strength, which makes them more competitive with conventional materials. However, because of the environmental impact of cement production, these methods frequently come at the expense of sustainability [12]. Given the paucity of studies on using CNT as a reinforcing material for rammed earth, this points to a crucial gap in the literature. Closing this gap could result in the creation of novel, environmentally friendly building materials that also address the problem of strength and longevity of rammed earth construction.

Numerous recent studies demonstrate that the use of nanotechnology in composite materials, such as CNT and CNFs, single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), helical carbon nanotubes (CNT), buckypaper, and graphene [16], has opened up new possibilities for improving the mechanical characteristics and adaptability of fiber reinforced polymer composites (FRPs). Carbon nanotubes (CNT) are frequently used as the preferred carbon nanoparticle for reinforcing polymer matrices. Nanocarbon, particularly Carbon Nanotubes (CNT), is a material that has been the focus of extensive research in nanotechnology due to its unique structure, superior mechanical and electrical properties, and high strength, offering potential for new applications as adsorbents, catalysts, composite materials, reactor coatings, dyes, lubricants, and other high-value products [18]. Carbon Nanotubes (CNT) are ultra-thin carbon fibers with diameters in the nanometer range and lengths in the micrometer range. Carbon-based nanomaterials called carbon nanotubes (CNT) and carbon nanofibers (CNFs) are frequently employed to improve composite materials, although they differ greatly in terms of their structure, characteristics, and uses. Higher strength, stiffness, and electrical conductivity are just a few of the remarkable qualities that make carbon nanotubes (CNT) perfect for cutting-edge sensors, electronics, and aerospace applications. Alternatively, CNFs are a more affordable choice with intermediate strength and durability that may be used for thermal management and structural reinforcements [19]. Carbon nanotubes (CNT) are cylindrical tubes with a high aspect ratio that are made of graphene layers made of carbon atoms organized in a hexagonal lattice [19]. They have a large surface area, lengths that can reach several microns or even millimeters, and diameters that usually fall between 1 and 100 nm. As opposed to this, CNFs frequently feature a modest aspect ratio and a conical or cup-stacked form. In comparison to CNT, their diameters typically fall between 50 and 200 nm, and they have shorter lengths and comparatively smaller surface areas. They are useful for a variety of applications due to their exceptional mechanical [20], electrical, and thermal characteristics. Because of a bridging action that improves mechanical characteristics, their distinctive architectures make them good reinforcements. CNT are very desired for this purpose because of their unique properties, which come from their cylindrical shape made of rolled-up graphene sheets.

According to recent studies, adding carbon nanotubes as reinforcement to composites significantly improves their mechanical qualities, such as their tensile, flexural, and wear resistance. This indicates how carbon nanotubes can be used to create composites that are stronger and more resilient, especially in engineering applications that call for high mechanical performance and environmental resistance.

Existing references relate to the analysis of vibration and buckling in composites reinforced with carbon nanotubes in various structures, such as quadrilateral plates, sandwich plates, and multilayer cylindrical shells. No specific research has yet been conducted on the vibration and buckling analysis of rammed earth nanocomposites reinforced with palm oil fibers and carbon nanotubes. This highlights an exciting research opportunity in this domain for further exploration and the development of innovative construction materials.

Using rammed earth technology and CNT, the current work closes a large gap in the literature. Although CNT's use in composite, concrete, and other construction materials has been studied in the past, little is known about how it can be used in rammed earth, especially for partition walls that are not load-bearing. By investigating the compressive and bending strengths of rammed earth reinforced with CNT, this study aims to close this gap. By doing this, it supports waste management initiatives as well as the sustainability objectives of the construction sector.

While rammed earth construction dates back millennia, its modern adoption faces three key barriers:

1) compressive strength below 2 MPa in unstabilized variants [13];

2) brittle failure modes under seismic loading [12];

3) water susceptibility [13]. Recent advances in nanocellulose-reinforced composites and agricultural waste valorization suggest synergistic solutions.

Our study uniquely combines CNT' nano-reinforcement [20] with EFB fibers' macro-scale toughening [15] to address all three limitations simultaneously. This study supports the circular economy by turning biodegradable garbage into a useful building material by incorporating CNT into rammed earth. Material science approaches that concentrate on improving the mechanical properties of building materials through creative reinforcing techniques also inform the theoretical underpinnings of this study. This dual theoretical approach offers a strong foundation for assessing the possibilities of CNT-reinforced rammed earth by fusing material science with the concepts of the innovative construction.

3. The aim and objectives of the study

The aim of this study is assessing the possibilities increase the structural stability of rammed earth nanocomposites by reinforcing them with carbon nanotubes (CNT) and empty palm oil bunch fibers (EFB), making them more suited for sustainable construction applications.

To achieve this aim, the following objectives are accomplished:

– to develop CNT- and EFB-reinforced rammed earth composites and optimize their composition;

– to investigate the effects of CNT on stress distribution and failure resistance;

– to evaluate compressive strength, flexural strength, and buckling resistance through laboratory tests.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is the rammed earth nanocomposites.

Hypothesis: The dual reinforcement of CNT (1–2 wt.%) and EFB fibers will enhance rammed earth's mechanical properties by improving nanoscale particle cohesion (CNT) and macroscale load distribution (EFB fibers). Key assumptions include uniform CNT dispersion, isotropic material behavior in cylindrical specimens, and negligible moisture variation during curing.

4. 2. Materials

The major components for this study are local soil and CNT. The soil was selected because it is suitable for rammed earth construction, which necessitates a particular sand, gravel, and silt mixture to guarantee mechanical performance and adequate compaction. With particle sizes ranging from fine sand to medium gravel, the soil utilized in this study was carefully chosen using these parameters. To make sure the soil was suitable for rammed earth building, its qualities were examined using ASTM standards.

CNT was chosen as a reinforcing material. Because of its advantageous mechanical qualities, including high improvements in mechanical properties, including tensile strength, flexural strength, and wear resistance.

4. 3. Sample preparation

The dirt, cement, water, and plastic garbage were combined in the designated ratios to create each sample. A manual rammer was used to compact the mixture in layers, making sure that each layer was completely compressed to reach the highest density possible.

The specimens were cast using beam molds measuring 60×15×15 cm and cylinder molds measuring 15×30 cm. Twelve specimens in all were made for the cube, beam, and cylindrical molds. There were three examples for each % of fiber added. The variations were based on the amount of carbon nanotube (CNT) added, which were 0 %, 1 %, and 2 % (Tables 1–3). Preliminary research and recommendations from pertinent literature on the integration of CNT into building materials were used to determine the percentages.

Table 1

Composition of cylinder rammed earth

No.	Composition	Unit	Rammed earth		
			0 % CNT	1 % CNT	2 % CNT
1	Soil	G	4,662.9	4,662.9	4,662.9
2	Cement	G	1,165.7	1,165.7	1,165.7
3	EFB	G	466.3	466.3	466.3
4	Sand	G	932.6	932.6	932.6
5	Water	G	606.2	1,515.4	1,515.4
6	CNT	G	0	11.66	23.3

Note: EFB – palm oil empty bunch fibers; CNT – carbon nano tube.

Table 2

Composition of beam rammed earth

No.	Composition	Unit	Rammed earth		
			0 % CNT	1 % CNT	2 % CNT
1	Soil	G	4,662.9	4,662.9	4,662.9
2	Cement	G	1,165.7	1,165.7	1,165.7
3	EFB	G	466.3	466.3	466.3
4	Sand	G	932.6	932.6	932.6
5	Water	G	606.2	1,515.4	1,515.4
6	CNT	G	0	11.66	23.3

Note: EFB – palm oil empty bunch fibers; CNT – carbon nano tube.

Table 3

Composition of cube rammed earth

No.	Composition	Unit	Rammed earth		
			0 % CNT	1 % CNT	2 % CNT
1	Soil	G	4,662.9	4,662.9	4,662.9
2	Cement	G	1,165.7	1,165.7	1,165.7
3	EFB	G	466.3	466.3	466.3
4	Sand	G	932.6	932.6	932.6
5	Water	G	606.2	1,515.4	1,515.4
6	CNT	G	0	11.66	23.3

Note: EFB – palm oil empty bunch fibers; CNT – carbon nano tube.

Compressive strength samples. For the purpose of testing compressive strength, upright beams measuring 50 mm by 50 mm by 200 mm were constructed. Samples of Bending Strength: For the purpose of testing bending strength, wall-like samples measuring 200 mm by 50 mm by 200 mm were made.

4. 4. Instruments

The Universal Testing Machine (UTM) was used to perform buckling, bending strength, and compressive testing. By accurately measuring the force applied to the samples, the UTM guarantees accuracy in assessing the material's mechanical characteristics. Since precise measurements of compressive and bending strength are crucial for evaluating the performance of rammed earth materials, the UTM was used. The choice of soil and CNT as materials was informed by existing research. Demonstrating the potential benefits of using these materials in sustainable construction. In order to verify that the soil utilized satisfies the gradation requirements for rammed earth building, sieves and sieve shakers are employed for particle size analysis. ASTM standards (No. 4, 8, 16, 30, 50, 100, 200) were adhered to by the sieves. To guarantee that the moisture level was regulated and constant across all samples, the soil was dried in the oven prior to mixing an oven was used in this study.

4. 5. Data analysis technique

For each test (compressive and bending strength), 24 samples were created, 6 for each variation in CNT content. In order to guarantee statistical reliability and provide a solid dataset for the compressive and bending strength tests, this sample size was used. Following 52 days of curing a typical amount of time for the material to acquire its maximum strength testing was carried out in accordance with SNI 03-4431-2011 and EN 12390-3:2001 specifications.

Compressive Strength Testing: to ascertain the samples' maximum compressive strength, a Universal Testing Machine (UTM) was used. Each sample's compressive force was measured, and the findings were averaged for each variation across the six samples. Compressive strength is the ability to withstand or carry a load (resistance to pressure). Rammed earth compressive strength testing was performed on 52-day-old test objects using the EN 12390-3:2001 method:

$$fc = \frac{F}{A_c}, \quad (1)$$

where fc – compressive force (MPa);

F – maximum load (N);

Ac – cross-sectional area of the test piece.

Bending Strength Testing: In a similar manner, a UTM was used to test the samples' bending strength under a two-point loading system. The data were averaged, and the maximum load applied prior to the sample failing was noted.

Rammed earth bending strength testing was carried out on test objects aged 52 days using the SNI method 03-4431-2011:

$$Fr = \frac{P \times L}{b \times h^2}, \quad (2)$$

where Fr – bending strength (MPa);

P – maximum load (N);

L – span length (mm);

b – width of the test piece (mm);

h – height of the test object (mm).

The data obtained from the test results of compressive strength and bending strength of rammed earth as the dividing wall of the room were further analyzed. The data will be analyzed by performing a simple linear regression analysis, which is an analysis that is used to measure the influence of plastic waste (free variable X) on the strength of rammed earth (bound variable Y). Used model simple linear regression is according to:

$$Y = a + bX, \quad (3)$$

where X – free variable;

Y – bound variable;

a – constant;

b – regression coefficient.

Then the *Ftest* was carried out to see whether or not the free variable free variables (independent) were significantly measured together against the bound (dependent) variables. This test is performed by comparing the computed F with the table F. The following criteria must be met in order to declare the F significant test:

– if $Fcount \leq Ftable$ or the significant value of the $Ftest > 0.005$ then *Ho* is accepted, meaning that the free (independent) variables simultaneously have no effect on the bound (dependent) variables;

– if $Fcount > Ftable$ or the significant value of the $Ftest < 0.005$ then *Ho* is rejected, meaning that the free (independent) variables simultaneously affect the bound variables (dependents).

To obtain the buckling test results, the critical buckling load was calculated using Euler's critical buckling equation. This equation is useful for determining the critical buckling load on a specimen subjected to axial compression.

Euler's buckling eq:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2},$$

where P_{cr} – critical buckling load (N);

E – elastic modulus (Pa atau N/m^2);

I – moment of inertia of the cross-section (m^4).

For the rectangular cross-section:

$$I = \frac{bh^3}{12},$$

where b=0.15 m; h=0.15 m (dimensions of the specimen's cross section);

K – effective length coefficient (without end restraint), K=1.0 for a column with pinned-pinned ends;

L– effective length of the column (m).

In this case, L=0.60 m.

4. 6. Vocational skill integration

The experimental workflow was designed as a vocational training module with:

– structured role rotation: each student team (3–4 members) cycled through mixing, compaction, and testing roles weekly;

– competency tracking: digital logs recorded time-on-task (time management) and decision points (e.g., water content adjustments);

– peer assessment: weekly evaluations of leadership and communication skills using adapted CASEL rubrics.

Students rotated roles weekly (mixing, compaction, testing) while documenting decision points (e.g., water content adjustments) to train critical thinking and technical communication.

5. Results of carbon nano tubes (CNT) and palm oil empty bunch fibers (EFB) reinforcement in rammed earth nanocomposites

5. 1. Composition optimization of CNT-EFB

The purpose of this analysis was to ascertain if the soil's particle size distribution, which serves as the main ingredient in the creation of rammed earth, satisfies the standard particle size specifications set out by. Based on the results of the soil sieving test, it was found that the soil used in this study has a good gradation, falling within the mid-range between the upper and lower limits according to Krahn's standard, with an FM (Fineness Modulus) value of 4.989 (Fig. 1).

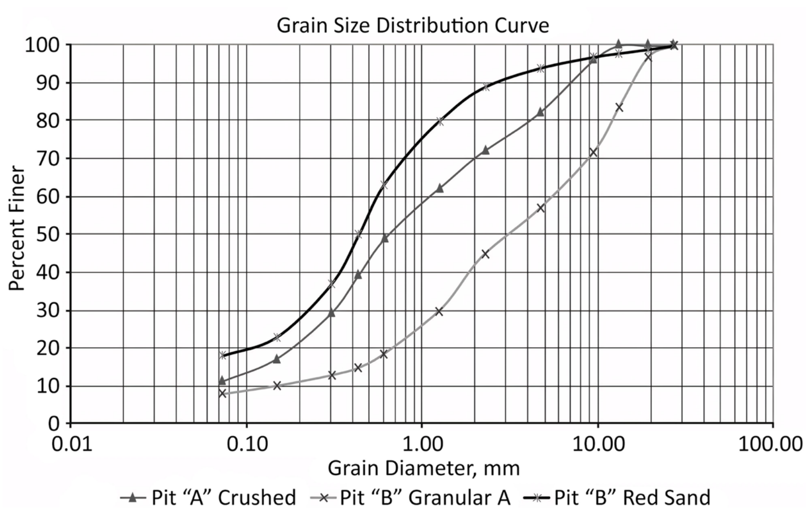

Fig. 1. Soil gradation examination

The graph above indicates that the soil particle size obtained from the sieve analysis conducted in this study meets the particle size requirements for rammed earth based on. The soil gradation falls within the range between the maximum and minimum particle sizes.

5. 2. Stress distribution and failure mechanisms

After 52 days, the compressive strength test of the rammed earth was carried out in this investigation. The purpose of this test was to determine the ability of the rammed earth material to withstand maximum compressive loads before failure. The rammed earth specimens were cylindrical in shape, with a diameter of 15 cm and a height of 30 cm.

A concrete testing machine (CTM) was used to crush the specimens until they failed. The ratio of the greatest load to the cross-sectional area, given in MPa, was used to calculate the rammed earth's compressive strength. The following example illustrates the rammed earth material's compressive strength calculation:

– maximum load (F)=108,200 N;

– cross-sectional area of the specimen (Ac)=17,671.5 mm^2.

The compressive strength of the rammed earth material may be computed using the information above, as shown in Table 4.

Table 4

The compressive strength results

Sample	Density (kg/m^3)	Compressive load (kN)	Compressive strength (MPa)	Flexural strength (MPa)
EFB	2.502	–	1.43	0.98
EFB+1 % CNT cube	1.461	28	6.43	–
EFB+1 % CNT cylinder	1.485	30	6.58	2.05
EFB+1 % CNT beam	1.479	25	–	2.50
EFB+2 % CNT cube	–	33	8.56	–
EFB+2 % CNT cylinder	–	35	9.13	2.65
EFB+2 % CNT beam	–	30	–	3.60

Note: EFB – palm oil empty bunch fibers; CNT – carbon nano tube.

Based on Table 4, it can be observed that the density of EFB (rammed earth with empty palm bunch fibers) is 2.502 kg/m^3, while the addition of carbon nanotubes (CNT) in cube, cylinder and beam form reduces the density to 1.461 kg/m^3, 1.485 kg/m^3, 1.479 kg/m^3 respectively. However, there is an increase in both compressive strength and flexural strength. The compressive strength of EFB is 1.43 MPa, which increases to 6.43 MPa with the addition of 1 % CNT in cube form, and 6.58 MPa in cylinder form. In addition, with the addition of 2 % CNT the compressive strength is 9.13 MPa and 8.56 MPa for cylinder and cube form respectively. Furthermore, in terms of flexural strength, the addition of 1 % and 2 % CNT enhances the flexural strength to 2.05 MPa and 2.65 MPa, respectively for cylinder form. The same trend was found in beam form with the addition of 1 % CNT and 2 % CNT (2.50 MPa and 3.60 MPa, respectively).

5. 3. Evaluation of the mechanical performance

The buckling test's results showed in Table 5. The results showed sample with 2 % CNT in the cylinder form has the highest buckling about 34.671 kN, followed by 2 % CNT in the cube form and 1 % CNT in beam form (31.874 kN and 29.453 kN respectively).

Table 5

The buckling of the rammed earth material

Sample	Buckling (kN)
EFB+1 % CNT cube	20.512
EFB+1 % CNT cylinder	23.078
EFB+1 % CNT beam	18.923
EFB+2 % CNT cube	31.871
EFB+2 % CNT cylinder	34.671
EFB+2 % CNT beam	29.453

Note: EFB – palm oil empty bunch fibers; CNT – carbon nano tube.

Based on the results, the higher the CNT addition performed the higher the buckling strength. In addition, rammed earth in cylinder form showed the highest buckling strength compared to the others.

6. Discussion of results of structural enhancement of rammed earth nanocomposites using CNT and EFB

This study pioneers a nanocomposite approach by integrating 1–2 % carbon nanotubes (CNT) and oil palm empty fruit bunch (EFB) fibers into rammed earth to address its structural limitations, including low compressive strength (1.43 MPa) and buckling resistance. The synergy of CNT (nanoscale cohesion) and EFB fibers (macroscale crack bridging) offers a sustainable alternative to conventional construction materials. The high elasticity of the fibers, which enhances the flexural strength of the rammed earth, is responsible for this enhancement. Good bonding between the fibers and the rammed earth components is shown by the rise in flexural strength. The flexural test of the rammed earth walls in this study revealed a failure pattern that indicates the collapse happened in the middle of the span.

The significant improvement in compressive, flexural strength and buckling resistance of rammed earth specimens can be attributed to the combination of CNT and EFB. The samples' compressive strength significantly increased when 1–2 % carbon nanotubes were added. Depending on the homogeneity and dispersion of the mixture, cylinders containing 1 % carbon nanotubes had a much higher flexural strength than samples without carbon nanotubes. Increasing the carbon nanotube content to 2 % further improved the flexural and compressive strength compared to the 1 % carbon nanotube sample.

A more progressive distribution of particle sizes is indicated by a smoother curve, but a steeper curve implies that the majority of particles are concentrated around a certain size. Based on Fig. 1, slope of the curve reflects whether the particle sizes are uniform or varies within the sample. The soil gradation falls within the range between the maximum and minimum particle sizes.

High tensile strength and elastic modulus are two of the exceptional mechanical qualities of carbon nanotubes that can improve the microstructure of composite materials. In this study, in addition to the palm oil fibers improving load distribution, carbon nanotubes played a role in enhancing particle cohesion at the nanoscale level, thereby increasing resistance to compressive loads.

To use carbon nanotubes in composite materials, it's important to understand and manage the sidewall chemistry and reactivity due to the fact that the location of chemically sensitive reactions and the way in which they impact the physical characteristics of carbon nanotubes are determined by the carbon bonding state in the outermost graphitic surfaces. Increasing the connecting between nanotubes as filler and a surrounding matrix is made possible by functionalization and/or chemisorption on the nanotube sidewall. The EFB fibers help distribute stress more evenly, minimizing localized failure. Moreover, the superior performance of cylindrical specimens can be explained by the symmetrical geometry.

It was different with traditional stabilization methods that utilize cement or lime [13], which increase cost and environmental impact, the proposed approach uses EFB and CNT to enhance structural performance while remaining eco-friendly. For instance, whereas [11] the use of cement improved compressive strength alone, demonstrates improvements in compressive, flexural and buckling resistance simultaneously (Tables 4, 5). This is enabled by the dual mechanism of reinforcement. Furthermore, this study advances prior research that focused on CNT use in polymers and concrete by applying it effectively to rammed earth.

It has been demonstrated that a stable connection and the local atomic structure of carbon atoms on which the functional group might react may regulate a nanotube's reactivity. When a compressive load is applied axially (along the length of a cylindrical specimen), the stress is typically dispersed uniformly throughout the cylinder's cross-sectional area due to a cylinder's homogeneous and symmetrical shape along its axis. Axial symmetry reduces stress concentrations and uneven deformation by ensuring that the material deforms uniformly under the given load. Failure may result from stress concentration, which happens when parts of a material are subjected to more stress than others. The risk is less in a cylinder specimen because of its shape.

The high buckling result in cylinder due to the round cross-section, which gives equal bending resistance in all directions. In addition, it less vulnerable to lateral instability that beams or cubes because of their higher moment inertia and lower slenderness ratio. Furthermore, beams and cubes are less robust under compressive loads because their geometries have weak areas for bending. Beams buckle along their thinner dimensions but cube have stress concentrations at their corners [10, 11].

This work suggests a different strategy utilizing CNT and EFB fibers in place of conventional stabilizing techniques that depend on cement or lime, which raise expenses and degrade the environment. While conventional stabilizers increase compressive strength, they are ineffective at addressing vibration sensitivity and buckling resistance, two critical factors for use in seismically active areas. On the other hand, CNT reinforcement offers two advantages: greater durability and strength. This study fills a gap in sustainable construction technology by demonstrating the efficacy of carbon nanotubes (CNT) in earthy materials, in contrast to earlier research that concentrated on polymer composites or concrete-based CNT uses. The initial problem addressed by this study was the structural limitations of rammed earth, particularly its low compressive and flexural strength, as well as its vulnerability to buckling under axial loads. The research findings confirm that these issues have been mitigated by CNT and EFB fiber reinforcement. The compressive and flexural strength improvements directly address the load-bearing capacity concerns, while the enhanced buckling resistance ensures better performance in dynamic environments. Additionally, the integration of industrial waste into the material composition aligns with sustainability goals by reducing waste and promoting the use of renewable materials. The findings indicate that this method is an effective alternative to traditional stabilizers, demonstrating that CNT and EFB fibers successfully enhance rammed earth's viability for modern construction applications.

This study effectively shows that rammed earth's mechanical performance is greatly enhanced by CNT and EFB fibers, giving it a competitive alternative to traditional building materials. The results address the drawbacks of conventional rammed earth applications while highlighting the promise of nanotechnology in sustainable construction. Even though there are still issues like cost and widespread deployment, more study can improve the strategy and increase its usefulness. In the end, this research advances durable and environmentally beneficial building materials for upcoming building projects. However, some limitations should be considered such as the material mixing and compaction were done manually, limiting reproducibility and laboratory scalability, the reinforcement content was limited to 1–2 % CNT with intermediate values nanomaterial ratios may offer different performance profiles. Future study can build upon this research by exploring the use of alternative nanomaterial reinforcement to reduce cost while improving mechanical performance.

This study also addresses the growing demand for vocational education models that integrate STEM competencies with soft skill development. The hands-on process of developing CNT-EFB composites inherently trains seven key vocational skills:

1) technical communication during interdisciplinary collaboration;

2) critical thinking in material failure analysis;

3) data-driven decision making when optimizing mix ratios;

4) leadership in lab team coordination;

5) time management during curing processes;

6) teamwork in specimen fabrication;

7) research skills through mechanical testing. This aligns with the World Bank's emphasis on 'work-ready' skill integration in technical education.

This study also bridges material science with vocational education by embedding STEM competencies (e.g., data-driven mix optimization) and soft skills (teamwork, leadership) through hands-on lab modules, aligning with the World Bank's 'work-ready' skill framework.

Limitations include manual mixing's reproducibility issues and the high cost of CNT (~$50/g). While cylindrical specimens showed optimal performance, their fabrication complexity may limit on-site adoption. Future studies should explore scalable mixing techniques and cost-effective nanomaterials (e.g., graphene oxide).

7. Conclusions

1. The 2 % CNT-EFB composite increased compressive strength by 539 % (9.13 MPa vs. 1.43 MPa) and achieved 34.671 kN buckling resistance, surpassing conventional rammed earth.

2. Cylindrical specimens performed best, with a compressive strength of 9.13 MPa, consistent stress distribution, and ability to bear heavier loads. On the other hand, localized stress concentrations at particular locations caused the cube and beam specimens to fracture under compressive loads of 6.58 MPa and 3.60 MPa, respectively.

3. The study confirmed that cylindrical specimens outperformed other shapes (cube and beam) in terms of compressive strength, flexural strength, and buckling resistance. The cylindrical specimens exhibited homogeneous stress distribution and axial symmetry, allowing them to withstand 9.13 MPa compressive load and 34.671 kN buckling force, compared to the failure points at 6.58 MPa for cubes and 3.60 MPa for beams, which experienced earlier failure due to stress concentration at specific locations. The homogeneous stress distribution and axial symmetry of cylinders allowed for better mechanical performance compared to cube and beam specimens, which exhibited stress concentration points that led to earlier failure.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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