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Case study

Experimental analysis of Compressed Earth Block (CEB) with banana fibers resisting flexural and compression forces

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ABSTRACT

The development of affordable housing is necessary due to the numerous homeless people living in developing countries; the present work is an attempt to alleviate the housing problem facing populations of these countries. Building with Compressed Earthen Blocks (CEBs) is becoming more popular due to their low cost and relative abundance of materials. The proposed innovative Banana-Compressed Earth Block (B-CEB) consists of ordinary CEB ingredients plus banana fibers, which will be the focus of this study. Banana fibers are widely available worldwide due to agricultural waste from banana cultivation. Additionally, banana fibers are environmentally friendly and present important attributes, such as low density, light weight, low cost, high tensile strength, as well as being water repellent and fire resistant. This kind of waste has a greater chance of being utilized for different applications in construction and building materials in order to enhance the mechanical properties of the CEBs. Such enhancements will raise the number of storeys of a building that can be built with CEBs. Experimental work studies on the classic CEB with no fibers and B-CEB were performed, including an axial compression test and flexural test (three-point bending test) by using testing methods according to American Society for Testing and Materials (ASTM) standards (ASTM C-67). Also, in order to obtain the load-deflection curve and bending modulus (E) from the flexural test, the Linear Variable Differential Transformer (LVDT) sensor was placed under the mid-span of the block for vertical displacement measurements. The results of this study will highlight general trends in the strength properties of different design mixes by adding different lengths of banana fibers in the CEBs. These efforts are necessary to ensure that B-CEB technology becomes a more widely accepted building material that will verify the earth building technology for offering affordable houses.

1. Introduction

The succession of scientific discoveries and innovations in the field of construction caused changes in public economic systems for several developed countries. The demand for sustainable construction materials at low cost is growing as social, economic, and environmental issues evolve in today's society. As architectural heritage, earth block masonry attracts the interest of engineers for maintenance and modern construction since it is a material of high environmental and economical profile. Over the past five decades, earthen buildings were the most sustainable and widely used construction materials in

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developing countries. The recent interest in using natural materials is due to the increasing demand for housing as populations increase and to facilitate reduction of energy consumption in the building industry. The utilization of earth in housing construction offers a very high resistance to fire and provides a comfortably built living environment due to its high thermal and heat insulation value. It also offers other important factors that attribute to the achievement of a good house planning/design and construction solution [1]. Earthen building techniques have been in use for thousands of years; the process of forming blocks by compacting earth into molds is an ancient technique, and structures built with these blocks have sustained and endured for a long time.

In Egypt, almost 95% of land is desert and most of the current building structures are concentrated in only 5% of Egypt's land [2]. Therefore, the majority of the current construction is being spread vertically through the mid and high rise buildings mostly made of reinforced concrete (RC) which is also not affordable to most of the Egyptians. Moreover, the housing problem in Egypt is a serious issue that needs to be solved immediately. The need to rethink the century old structural design of housing and to harness emerging materials has never been greater. Accordingly, the need for new building materials that could bring advantages of low weight, high strength, and affordable cost becomes an urgency. In addition to these new building materials, Egypt's unused land should be integrated by spreading the building structures horizontally rather than vertically through the low rise buildings using load bearing masonry units.

For many centuries hand molded un-burnt mud block adobes have been used for load bearing masonry structures. However, adobes are mostly used for lightly loaded single and two-storey residential buildings [3]. Fibers such as sisal, coconut fiber, and straw are good examples of natural fibers that have been used as reinforcement for CEBs and that have recorded some promising results. Polyethylene fiber is the most popular synthetic fiber that has been used in CEB and in other construction materials like concrete [4,5]. Nevertheless, the environmental loss suffered by the society due to the pollution generated during the production and recycling of such synthetic fibers based materials has once again drawn the attention for the use of natural fiber. The use of B-CEBs using sustainable natural plant fibers for proposed rigid masonry unit systems represents significant potential for the reduction of material and energy resource consumption and pollutant emissions. Additionally, the incorporation of agricultural waste streamed into new construction materials can successfully divert large waste flows from landfills. This study presents a new integrated approach to materials, experimental tests, and structure design for non-seismic zone that leverages green materials and structural design. The results create a potential reduction of primary energy use and CO_2 emissions significantly. Banana fibers are widely available around the world as a sort of agricultural waste from banana cultivation due to the remnants being left to decompose, emitting a huge amount of carbon dioxide and methane gases (see Fig. 1). These emissions, which increase global warming every year, have a negative impact on the environment [6].

Banana fibers will be a new bonus to construction materials. Adding banana fibers to the mix design is intended to increase the internal strength of the B-CEB significantly over CEB. Egypt is a great case in which such plants are commonly available and generate tons of waste annually. This study will focus on the effect of banana fibers on block mechanical properties.

1.1. Objectives

The earthen houses made from CEBs are unable to resist high loads due to its low strength which forms cracks that appear on the walls and limits its construction to one storey building. Cracks appear because the soil particles are not held together with sufficient bonding strength. Previous studies have shown that the use of traditional hydraulic stabilizers, such as cement or lime, or waterproofing agents, such as bitumen, do significantly improve the strength of CEB. However, these additives are accompanied by an increase in materials cost. This is not a sustainable model or a good solution, especially for the poor rural communities of the developing nations. This also creates a huge environmental problem. Therefore, the aim of the present investigation is to show that these traditional binders can be replaced by environmentally friendly and sustainable alternatives from unutilized wastes (i.e. banana fibers). These kinds of waste should be investigated which would

Fig. 1. Tons of banana agriculture waste in Egypt.

provide reliable statistics allowing and justifying such wastes being used in different applications in building and construction materials.

The main focus in this case study is to establish a new model of B-CEB by adding natural banana fibers that will create stronger, more durable, and sustainable materials. Therefore all of the tremendous benefits of using waste materials like banana fibers in construction applications are going to be a Win-Win situation. This will not only eliminate the disaster carbon dioxide problem, but it will also be added to the CEB components in order to enhance its mechanical properties over the ordinary CEB. The broad impact will be to transform the B-CEB fabrication materials, design and construction, locally and globally.

2. Background of CEB technology

The first Compressed Earth Blocks (CEBs) were produced by using wooden tamps to compress molded earth blocks (adobe) to improve their quality and performance. The earliest recorded use of presses for CEB dates back to the 18th century in France [7]. CEBs are a relatively recent development in construction and have become more popular over the last 50 years. Additionally, they have been successfully built in both developing and developed countries. CEBs are formed by using moist soil compacted to improve its physical characteristics. Using earth for CEBs, instead of adobe, have results in a building product with improved durability and strength. In addition, CEB records lower inherent energy levels than other materials. CEB's problems manifest, however, from the material's brittle behavior, its deterioration in the presence of water and its low tensile strength. Strength and water resistance can be significantly improved by introduction of a hydraulic binder, such as lime or cement, or by the use of bitumen as a waterproofing agent [8].

Typically, binders are added at between 5 and 10% of the soil's dry weight. However, use of these additives also significantly increases both material costs and their environmental impact. As a more sustainable alternative to cement and bitumen, natural fibers, such as straw, have been used in adobe and other traditional forms of earthen construction for many thousands of years, to reduce shrinkage cracking and improve tensile and compressive strength. In recent tests, natural fibers in compressed earth blocks have also been shown to reduce the size of shrinkage cracks and to improve durability [9]. There are currently several types of stabilizing agents being used in CEB production which include cement, lime, bitumen, and gypsum, to name a few. Compared to traditional adobe, compacting moist soil mixed with between 5 and 10% of Portland cement as a stabilizing agent can result in a significant improvement in compressive strength, water resistance, and dimensional stability of the CEBs [10]. Typically, CEBs are formed using a mixture (by weight) of angular sand aggregate (40–70%), clayey soil (30–60%), cement (4–10%), and water (8–12%) [10]. The components are thoroughly mixed and then placed into a mold, and compressed, either manually or hydraulically, to form blocks. This limits the use of stabilizers such as Portland cement to low quantities.

The compressive strength of the CEB basically depends on the block density, amount of stabilizer such as lime or cement, and composition of the soil. 3–4 MPa in compressive strength is an average result of 7% cement in sandy soil composition [11]. When used in volumes greater than 10%, cement stabilization generally becomes uneconomical and unfriendly [12]. Such improvements encourage the use of CEBs in construction applications in which acceptable masonry units are alternative to Concrete Masonry Units (CMU) and the burned clay brick [13]. The use of straw fibers in reinforcing CEBs, as per the investigations of past researchers, has been illustrated. Straw fiber as a structural reinforcement agent allows an increase in compressive strength of at least 15% compared to non-reinforced materials [14]. Polypropylene (PP) is one of the most popular types of synthetic fibers that has been used in construction since the early 1960s as a reinforcement to enhance the mechanical properties of building materials. Previous research has been conducted by Donkor et al. (2014) which has proven that adding 0.4% weight of PP fibers in (CEB mix), increases the compressive strength significantly. However, adding PP fibers with an amount of more than 0.4% weight leads to a drop in its compressive strength with 8% cement content. Compared to the unreinforced blocks, the compressive strength of the PP fiber reinforced blocks with 0.2, 0.4, and 0.6% weight of PP fibers were 10%, 22.5%, and 3.0% higher respectively [15].

The development of strength properties of soil-cement-fiber mixes mostly depends on the formation of fiber-matrix, matrix-matrix and fiber-fiber bonds. These formation identified that bonds can be affected by the quantity of fiber present. The increase in fiber content therefore resulted in a decrease in fiber-matrix and matrix-matrix bond, and on the other hand, an increase in fiber-fiber bonds, leading to a lower compressive strength. These results have illustrated and proven successful use of fibers in CEBs. However, the use of natural banana fibers in CEBs is not demonstrated yet. Research appears to focus more on straw, sisal, flax, and other natural fibers. Therefore, for the first time ever this paper will focus on the impact of using innovative banana fibers on CEB building.

3. Banana fibers background

Today, the exploration for alternative sources of fibers is expanding due to the growing shortage of fibers from the wood of forest trees in many countries, which are currently the primary source of fiber and are facing important sustainability, environmental and regulatory issues. The usage of fibers from fast growing and high biomass plants are a great solution to overcome this shortage and should be considered the best alternative source of raw materials [16]. Specific agricultural plants that are producing high biomass after harvesting are found to be suitable substitutes for specific fiber based industries [17]. Banana is one of the greatest applicable examples, due to them growing fast and having high biomass. It is a huge herb

Table 1
Composition of studied banana trunk fibers.

Banana Cultivar	Elements (%)			
	Celluloses	Hemicelluloses	Lignin	Pectin
Grand Naine	48.2	15.9	19.2	3.5
Poovan	57.6	12.7	16.7	2.8
Nendran	59.2	12.1	14.4	2.7
Monthan	48.6	15.8	21.6	4.1

with a pure adventitious root system. Also, banana fibers are useful to making grease-proof paper when blended with 20% bamboo pulp as a result of its good physical strength and higher mucilage contents [18].

To process banana fibers, they are extracted from banana tree trunks. Longitudinal slices, prepared from stems, are then fed to a fiber extracting machine, also known as a mechanical decorticator. The decorticator consists of two feed rollers and a beater. The beater receives the slices as they pass between the scrapper and the squeezing rollers. Next, the pulp gets alienated and fibers are pulled out and air-dried [19].

3.1. Banana fiber properties of different banana species

Preethi and Balakrishna [20] studied the chemical and physical properties of banana fibers extracted from the stem of different commercial banana cultivars. The varieties selected by the authors were Grand Naine, Poovan, Nendran and Monthan.

3.2. Chemical properties of banana fiber

Banana fibers are generally made up of lignocelluloses materials which contain Celluloses, Hemicelluloses, Lignin, and Pectin. Lignin is associated with the Hemicelluloses and plays a significant role in the natural decomposition resistance of the lignocellulosic material. Additionally, Hemicelluloses, Lignin, and Pectin content of fibers vary significantly with the different banana cultivars. Cellulose has the most important role in selecting the quality of the fibers. The composition of banana fiber species taken by elemental analysis are as given in Table 1 [20].

3.3. Physical properties of banana fiber

Single fiber tensile tests were carried out in the Universal Instron Tester (Model 3345) by Preethi and Balakrishna. The breaking load and breaking extension were recorded at the point of rupture using computer software (Blue hill). The peak force applied to the fiber carried to break is generally expressed as Newton (N) and the extension to the length of fiber (Strain) is expressed in percentage (%). The diameter of the fiber was calculated by using the (ocular meter). The results of the tensile strength and fiber strain of the different species of banana fibers were recorded and are presented in Table 2.

Preethi and Balakrishna showed significant variations between fiber stress and strain values among different cultivars of banana. Also they showed that the highest tensile strength and strain was in the Nendran banana cultivar (288.7 MPa and 1.67%) and the lowest ones were observed in the Grand Naine banana cultivar (24.6 MPa and 1.02%) [20]. According to the high tensile strength results of the banana fibers, this could significantly indicate their consequent behavior as a natural reinforcement material in construction and building industries.

Banana fiber currently is a waste product of banana cultivation and not properly put to use. A large amount of the banana tree trunk is not used for fiber production and the extraction of fiber from the Banana Tree Trunk (BTT) is not a common practice. Since the fiber's behavior provides an important clue about their use as reinforcements in building materials, the scope of this study will exploit the banana fiber wastes and facilitate suitable applications to enhance the quality of Compressed Earth Block (CEB) in construction.

Table 2
Stress and strain results of banana fiber species.

Fiber Type	Diameter (mm)	Force (N)	Tensile Strength (MPa)	Strain (%)
Grand Naine	0.225	0.98	24.6	1.02
Poovan	0.142	1.83	115.5	1.23
Nendran	0.119	3.21	288.7	1.67
Monthan	0.170	1.14	50.2	1.34

Table 3
Mixture Proportions of B-CEB.

Mixture	Proportion	Relation
Clay	35%	In relation to the dry mixture (Clay, Sand, Aggregate)
Sand	35%	
Aggregate	30%	
Cement	7%	In relation to the total dry mixture
Banana Fiber	0%–5%	In relation to the cement
Water	10%–12%	

Table 4
Grain Size Distribution of Soil.

Soil	Sieve size	Sieve No.	Grain Size Distribution (%)
–	(>4.75 mm)	4	0
Aggregate	(4.75 mm > size > 2 mm)	10	29.65%
Sand	(2 mm > size > 425 μm)	40	27.82%
	(425 μm > size > 75 μm)	200	6.22%
Clay	(<75 μm)	Remaining	36.31%

4. Production of B-CEB

Generally, the main stabilized CEB ingredients are soil and variables. Soil includes aggregate, sand, and clay; variables include cement and natural waste banana fibers. The global dry weights of the mixture for all blocks were kept constant during all stages of this study in order to observe the effect of the banana fibers on the mechanical properties of the blocks. Based on the literature review and the background study, the details of the mixtures proportions by weight are given in Table 3.

4.1. Materials

4.1.1. Soil

The local soil used in this research was sourced from the settled soil along the fertile banks of the Delta Nile River located in northern Egypt. The sand used in all mixtures was from the west desert region in Egypt. A grain size sieve analysis is required to classify a soil, which was performed according to the American Society for Testing and Materials (ASTM D422) [21] in order to determine the soil grain size distribution. A grain size analysis was performed by shaking the soil samples in sieves, passing the soil through sieves of decreasing opening sizes and measuring the gravitational amounts passing through each sieve size. The grain size distribution is given in Table 4.

The Atterberg limits test was carried out to determine the Plastic Limit, Liquid Limit, and the Plasticity Index of the soil (ASTM D4318) [22]. The Atterberg limits test provides a method for measuring the soil's plasticity, providing information regarding the amount of clay present. First, the soil specimen was passed through sieve (No. 40) 425 μm to remove any materials retained on the sieve. The physical properties of the soil are given in Table 5.

4.1.2. Aggregate

Aggregates, made of geological resources like sand, stones, and gravel are used in almost all types of construction. Aggregate can be used in its natural shape or can be crushed into smaller pieces. The average size of the used aggregates was (2.5 mm). The Dolomite aggregates used in this research were sourced from the best locations on Ataka Mountain located between the provinces of Suez and the Red Sea in Egypt. In the Middle East region, Dolomite is considered to be one of the best reliable material used as a coarse aggregate in construction.

Table 5
Physical properties of the soil.

Soil Property	Composition (%)
Liquid Limit	26.4%
Plastic Limit	13.8%
Plasticity Index	12.6%

(a) Test set-up (b) Mode of failure

Fig. 2. Compressive strength test of B-CEB.

4.1.3. Cement

The Ordinary Portland Cement (Type II) (Moderate Sulfate Resistance) was used in all mixture for better performance and durability of the block. This type is generally used for construction exposed to soil or water containing sulfate ions.

4.1.4. Banana fiber

The banana fiber used in this case study was the Poovan type. The fibers were extracted from the Banana Tree Trunk (Pseudo-stem). The fibers were received in bundles about 1.5 meter long; then were separated and cut into pieces of lengths between 50 mm and 100 mm.

5. Experimental program

5.1. Compressive strength test

The nominal dimensions of blocks produced for compressive testing were 12 cm x 12 cm x 9 cm, with a dry density of 1968 kg/m^3 and 1947 kg/m^3 for CEB and B-CEB respectively. The specimens for the compressive strength tests were tested according to the American Society for Testing and Materials (ASTM) international C67- 07 [23]. A total of 35 B-CEBs were tested for compressive strength; (5 blocks for each of the 7 mix designs). The blocks were tested under uni-axial compression using a COMTEST Impact 2000 KN block, cube and cylinder compression machine with a maximum load capacity of 2000 KN as shown in Fig. 2. The rate of compression was set at 3 KN/s until failure.

5.2. Compressive test results and discussion

Reinforced blocks with randomly distributed natural banana fibers, recorded higher compressive strength results compared to the unreinforced blocks as shown in Table 6 and Fig. 3. The average compressive strength of block with 60 mm natural banana fiber (mix#3) and with 70 mm banana fibers (mix#4) recorded the higher stresses with about 71% and 68% increase respectively over CEB with no fibers (mix#1). This was a significant increase of the reinforced fiber blocks relative to the unreinforced blocks. Also, the mode of failure of CEB was conical break failure mode which contributes to the consistency of the CEB ingredients to the banana fibers.

Table 6
Average Compressive Strength Results of CEB and B-CEB.

Mix	Fiber Length (mm)	Sample (MPa)					Avg. Compressive Strength (MPa)	Standard Deviation
		# 1	# 2	# 3	# 4	# 5		
1	0 **(Lowest)**	**3.71**	**3.96**	**4.02**	**3.98**	**3.77**	**3.84**	**0.07**
2	50	5.68	6.13	6.21	6.02	5.76	**6.02**	0.13
3	60 **(Highest)**	**6.16**	**5.89**	**6.18**	**6.19**	**5.78**	**6.58**	**0.12**
4	70	5.7	6.25	5.88	6.13	6.02	**6.47**	0.10
5	80	5.88	6.18	6.15	6.02	5.57	**6.39**	0.11
6	90	5.81	6.17	5.87	5.68	6.02	**6.13**	0.13
7	100	5.68	5.67	6.08	5.81	6.05	**5.95**	0.12

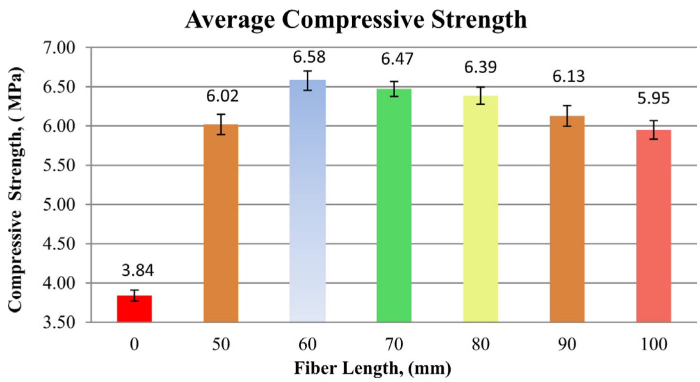


Fig. 3. Average Compressive Strength Results of CEB and B-CEB.

Cracks during testing were normally created before the peak load was achieved. These cracks observation were true for both reinforced and unreinforced specimens. This increase of strength results from the high stiffness of the fibers and the internal lateral confinement by the stiff fibers. After first cracking, load was transferred to the fibers at the crack site and one of several types of behavior may then ensue, depending on the strength, volume fraction and length of fibers.

5.3. Modulus of rupture (Three-Point Bending test)

The modulus of rupture (MOR) quantifies a B-CEB's ability to resist a certain amount of bending stress. MOR testing was performed on full-size block (24 cm $\times$ 12 cm $\times$ 9 cm) according to ASTM C-67-07 [23]. The devices used for this test consisted of a UH Series Shimadzu universal hydraulic press with a load capacity of 1000 KN, and a Linear Variable Differential Transformer (LVDT) displacement sensor to record mid-span displacement.

The LVDT and the force were connected to a data acquisition system by which the displacements and the force were recorded every second. The blocks were centered between the two supports of the hydraulic press under the loading so that the span to depth ratio was approximately 2 (see Fig. 4). The loading scheme was modified from third-point loading to center-point loading. The loading was then gradually increased at a steady rate of 50 N/s. Five samples were tested for each B-CEB mix. The data collected were then treated through calculations in Excel software. The (MOR) and (E) were calculated using the following equations respectively: $S = 3FL/2\,wh^2$ and $E = FL^3/4\,wh^3d$.

Where:

S = Modulus of rupture of the block at the plane of failure, (MPa)
E = Flexural modulus of the block at the plane of failure, (MPa)
F = Maximum load indicated by the testing machine, (N)
L = Span length between the supports, (mm)
w = Average width of the block at the plane of failure, (mm)
h = Average height of the block at the plane of failure, (mm)
d = Maximum deflection at mid-span of the block, (mm)

(a) Three-point bending test set-up

(b) LVDT test set-up

Fig. 4. Flexural strength test of B-CEB.

Table 7
Average Flexural Strength and Maximum Mid-span Displacement of all Blocks.

Mix	Sample (MPa)					(MOR) (MPa)	(SD)	Displacement (mm)	(E) (MPa)
	# 1	# 2	# 3	# 4	# 5				
1 (Lowest)	0.53	0.59	0.51	0.54	0.63	0.56	**0.049**	**0.258**	**175**
2	0.86	0.79	0.83	0.89	0.80	0.83	0.042	0.666	76
3	1.04	0.97	1.01	0.99	0.92	0.99	0.045	0.906	75
4 (Highest)	1.06	1.00	0.98	1.02	1.04	1.02	**0.032**	**0.912**	**84**
5	0.95	0.99	0.95	0.89	0.92	0.94	0.037	0.894	64
6	0.90	0.79	0.84	0.90	0.87	0.86	0.046	0.697	73
7	0.72	0.83	0.75	0.80	0.85	0.79	0.054	0.598	132

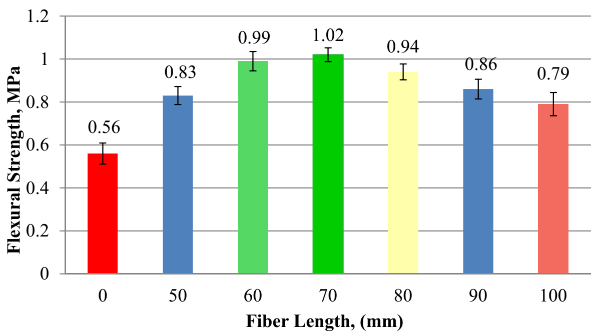


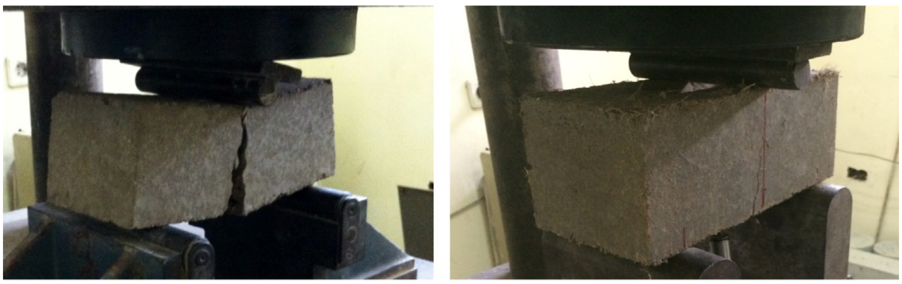
Fig. 5. Average Flexural Strength and Maximum mid-span Displacement of all Blocks.

5.4. Flexural test result and discussion

The results are given in Table 7 and Fig. 5 indicates how the fiber reinforced B-CEBs of (mix#3) with fiber length of 60 mm and (mix#4) with fiber length 70 mm performed the highest stresses with a significant increase by 77% and 82% respectively compared to (mix #1) with no fibers. There were slight differences between fiber reinforced B-CEB mixes in the flexural strength and mid span deflection; however, there were a tremendous increase in the ultimate stresses and maximum displacement at failure of the fiber-reinforced blocks over the unreinforced block due to the presence of banana fibers which carried a lot of tensions.

The results also suggested that the fibers affect the brittle behavior of the matrices. The unreinforced blocks exhibited a sudden failure in all instances, while fiber reinforced blocks experienced a gradual failure as shown in Fig. 6. These modes of failure could be explained as a result of the fibers bridging the cracks before failure.

Fibers are known to oppose (1) crack formation in step with increasing stress, and (2) bridge micro cracks from expanding [24]. Linear elastic characteristics were noted in each tested sample prior to initial cracking, which typically occurred at peak



(a) Unreinforced CEB Bending Failure (b) Reinforced B-CEB Bending Failure

Fig. 6. Blocks Failure Modes of Three-Point Bending Test.

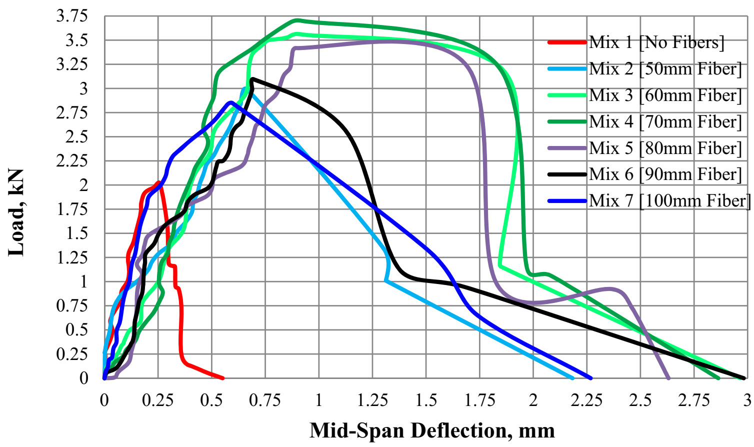


Fig. 7. Typical load-deflection curves of 7 CEB mixes.

Fig. 8. Banana Fibers Bridging the B-CEB Cracks During Failure.

load. The load-deflection responses of the fiber-reinforced samples were different from the unreinforced ones. Typical load-deflection curves of the tested blocks are presented in Fig. 7. The fiber-reinforced blocks performed better in post-initial crack behavior when compared with the unreinforced blocks.

All the fiber-reinforced blocks were exposed to mid-span deflection ranges between 0.6 mm and 1 mm, depending on the fiber length, while the unreinforced blocks exhibited maximum mid-span deflection of 0.26 mm. The maximum post-initial crack load for the matrices reinforced with 70 mm fibers (mix #4) was the highest peak load recorded for all matrices as shown in Fig. 8.

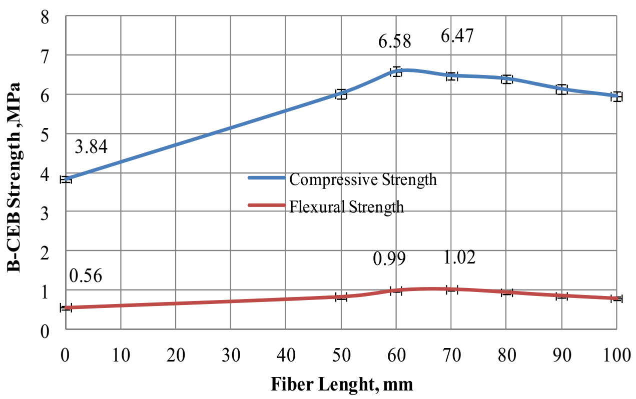


Fig. 9. Relationship Between Compressive and Flexural Strength of B-CEB Mixes.

The observations from the load-deflection curve showed that the strength rebound occurred when fibers broke down. The fibers at the crack zone allow the flexural stresses to be transmitted from the rupture section. Test results indicated that higher aspect ratio provides better flexural properties as longer fibers tend to bridge more cracks and absorb more energy. In this experimental study, results proved that the optimum fiber length was 70 mm which produced a higher tensile strength in blocks; this could be indicate that the distribution and the number of fibers in 70 mm length was the best design for B-CEB.

5.5. Relationship between flexural strength, compressive strength, and fiber length

Fig. 9 summarizes the average compressive and flexural strength results in each of the seven mixes. The recorded compressive strength values were on average 7 times higher than the flexural strength values. The fiber-reinforced blocks with fiber length of 60 mm and 70 mm recorded for the highest in both compressive strength and flexural strength compared to all fiber-reinforced blocks with fiber length ranges from 50 mm to 100 mm.

6. Summary and conclusions

Banana-Compressed Earth Block (B-CEB) as an alternative building material is critical to developing technology which can be adopted and implemented wherever affordable housing is needed. This study provided a foundation for developing an appropriate standard of care applied to B-CEB technology. Influence of banana fibers on the mechanical properties of CEBs were studied in this investigation.

Based on the experimental and analytical works, the following summary and conclusions were made:

1. From the experimental work, it is concluded that the blocks constructed by adding banana fibers (B-CEB) throughout the mix performed better than the block with no fibers (CEB) in both compressive and flexural strength.
2. The average compressive strength of block with 60 mm natural banana fiber (mix #3) and with 70 mm banana fibers (mix #4) recorded the higher stresses with about 71% and 68% increase respectively over CEB with no fibers (mix #1).
3. The fiber reinforced B-CEBs of (mix#3) with fiber length of 60 mm and (mix#4) with fiber length 70 mm performed the highest stresses with a significant increase by 77% and 82% respectively compared to (mix #1) with no fibers.
4. All the fiber-reinforced blocks were exposed to mid-span deflection ranges between 0.6 mm and 1 mm, depending on the fiber length, while the unreinforced blocks were exposed to maximum mid-span deflection of 0.26 mm.
5. Strength increase was due to the creation of isotropic matrix between the structure soil mix and the fiber network; such a matrix opposed movement of particles and created stability mainly because fibers appeared to distribute tension throughout the bulk of material. In other words, the presence of all-directional fibers improved tensile and compressive strength, which was contributed to banana fibers.
6. This case study aims to use local raw earth as a building construction material extensively which also using a local resource that is energy saving, eco-friendly, higher strength and sustainable development to help develop technologies.

Finally, the increase in toughness is arguably the most valuable outcome of adding banana fibers as it extended the application range of these materials to conditions where toughness was necessary. If compressed earth blocks can be produced to meet standards of strength, toughness and durability, they can be a versatile, affordable and environmentally appropriate building material for the housing sectors in both developed and developing regions.

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