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Mechanisms by which the inclusion of natural fibres enhance the properties of soil blocks for construction

Humphrey Danso[1], D Brett Martinson[2], Muhammad Ali[2] and John B Williams[2]

Abstract

Soil blocks are widely used for construction, especially in less economically developed countries. Addition of agricultural waste fibres has been shown to improve the properties of these blocks, however unlike most composites the fibres are not bound to the soil matrix. Therefore, the reinforcement mechanisms are different and not well characterised. This article investigates these mechanisms through a series of experimental studies to inform the development of better guidance for practitioners, and hence improve housing for low-income communities. The microstructural characteristics were investigated using scanning electron microscopy, computerised tomography scan, optical microscope analysis and pull out testing. It was established that fibres in the soil matrix are randomly distributed with gaps between the fibres and soil matrix due to fibre shrinkage during drying of the blocks. It also found that natural fibres in soil matrix can either be pulled-out or rupture under load depending on the depth of fibres embedment in the soil matrix.

Keywords

Natural fibres, computerised tomography analysis, optical microscopy, scanning electron microscopy, soil blocks, pull out test

Introduction

The technique of using fibres to improve or enhance the strength properties of soil blocks is widely used in the field of construction and building materials. This practice is not new as the ancient civilisations have used straw and hay to reinforce mud blocks for centuries in order to increase their strength properties for building construction purposes. Natural fibre–soil composite has the advantage of providing houses with low embodied energy, minimal impact on the environment and the ability to provide better occupant comfort.

Fibre reinforced soil composite is defined as a soil mass that contains randomly distributed, discrete elements (fibres) that provide an improvement in the mechanical performance of the fibre–soil composite.[1] The performance of the fibre reinforced soil matrix is dependent on factors such as fibre type, particle size distribution of soil, aspect ratio of fibres, fraction of fibre to soil and fibre characteristics. Natural fibres can be used as reinforcement in eco-friendly composites suitable for the building industry as reinforcing materials in order to improve the engineering properties of different types of soil.[2,3]

This study scientifically investigates the microstructure and mechanisms of this novel composite material, i.e. compacted soil blocks reinforced with natural fibres to inform the development of better guidance for practitioners. This material is distinct from many other composites due to the heterogeneous nature of the soil matrix resulting in more complex behaviour than is normally found in homogeneous matrices such as concrete or polymers. The interaction between fibre and soil matrix is further complicated by the addition of water with each component differing in expansion

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[1] Department of Construction & Wood Technology, University of Education Winneba, Ghana
[2] School of Civil Engineering and Surveying, University of Portsmouth, UK

Corresponding author:
Humphrey Danso, Department of Construction & Wood Technology Education, University of Education Winneba, P. O. Box 1277, Kumasi, Ghana.
Email: hdanso@uew.edu.gh

resulting in relative dimensional changes upon drying and subsequent debonding.

Lately, there has been increased research interest in soil matrices reinforced with natural fibres, due to the fact that they are renewable, biodegradable, environmentally friendly and low-cost. It has been demonstrated that fibres can be considered as good earth reinforcement material.[4] A number of studies also showed improvement in properties of fibre reinforced soil blocks over the unreinforced blocks.[5–22] However, there is limited information on the microstructure and mechanisms of how the fibre–soil matrix affect the strength properties.

While widely used informally, at present, the technology of fibre reinforcement of soils has not been decisively adopted by the formal building sector mainly because of the lack of methodical performance appraisal, which requires the understanding of the interaction between the soil and the fibre.[23] The benefit of fibre reinforcement comes from fibre–soil interaction, and insight into the internal mechanism of the interaction between fibre and soil is therefore important to improve design processes and for wider acceptance of the material in the formal construction industry. This study therefore investigates the mechanisms by which a compacted soil matrix is reinforced with natural fibres to determine the distribution of the fibres in matrix, any existence of gaps at the interface of the fibres with the matrix and the fibre pull-out from the matrix. The research presented in this article is part of a larger research effort aimed at developing fibre reinforced soil blocks for low-cost housing in less economically developed countries (LEDCs). Some of the findings of the larger research effort have been reported in other publications.[24–26]

Experimental materials and methods

To characterise the mechanisms by which fibres enhance the properties of soil blocks, it is necessary to understand (a) the distribution of fibres, (b) the nature of the interface between the fibres and soil matrix and (c) the pull-out characteristics of the fibres embedded in the soil matrix. To assess the distribution of fibres, computerised tomography (CT) scanning was used. To investigate the nature of the interface between the fibres and soil matrix, optical microscopy and scanning electron microscopy (SEM) were used. The pull-out was measured directly by mechanically testing the resistance of single fibres embedded in a soil specimen.

Materials

Table 1. Properties of the experimental soil.

Properties	Value
Proctor test	
Optimum moisture content (%)	11.8
Maximum dry density (mg/m^3)	1.83
Atterberg limits	
Liquid limit (%)	18.0
Plastic limit (%)	31.7
Plasticity index (%)	13.7
Soil classification	
USCS	CL
Particle size distribution	
Gravel (>2 mm) (%)	8
Sand (2–0.063 mm) (%)	64
Silt (0.063–0.002 mm) (%)	16
Clay (<0.002 mm) (%)	12
pH	
Value	6.67

The main materials used for the experiment were soil, agricultural waste fibres (sugarcane bagasse, coconut and oil palm) and water. The soil sample was obtained from Horsea Island, Portsmouth, UK. Properties of the soil are reported in Table 1, and the particle size distribution curve is shown in Figure 1. The soil has a liquid limit of 18% and a plasticity index of 13.7% and hence could be classified as low plasticity clay soil (CL) according to BS1377:2.[27] The optimum moisture content (OMC) for the soil without stabilisation was obtained by using a Standard Proctor test[28] and was 11.8%, the maximum dry density (MDD) was 1.83 mg/m^3. The pH of the soil was 6.67, which is close to neutral. Chemical element/composition of the soil was determined through inductively coupled plasma–mass spectrometry (ICP-MS) analysis method in accordance with BS EN ISO 1729:4[29] and the result is presented in Table 2.

Coconut, sugarcane bagasse and oil palm fruit fibres obtained from Ghana were used as reinforcing materials in the soil blocks. These fibres have been selected as they cover a wide range of properties, and are also abundant agricultural waste materials in West Africa. The images of each fibre type are shown in Figure 2. SEM images of single fibre were determined with JSM-6100 scanning microscope at 35× magnification for each fibre type to show the texture of the fibres. The bagasse fibre appears to be very rough in texture as compared to coconut and oil palm fibres. The difference between dry and wet fibres' diameter was determined using computerised optical microscope (OLYMPUS BX40) with Leica Application Suite version 3.4.0. More information on the preparation of these fibres can be found in the study by Danso et al.[25] The properties of the fibres such as diameter,

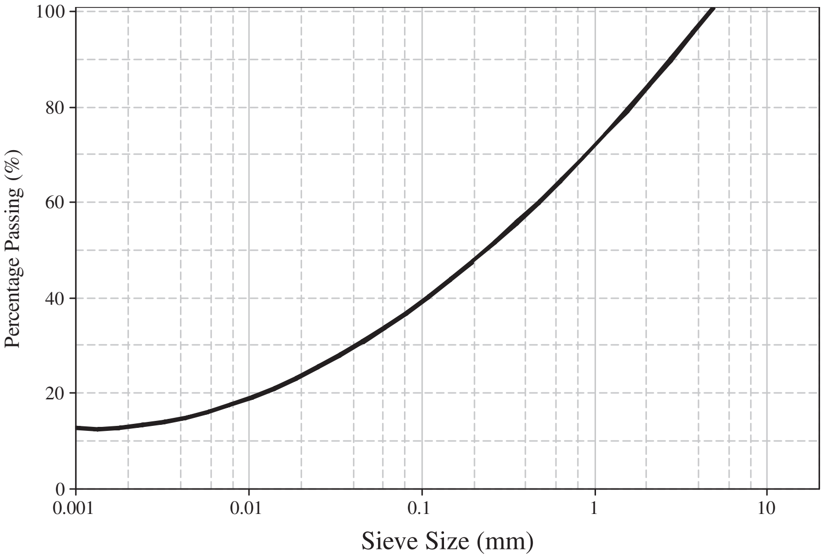


Figure 1. Particle size distribution of the experimental soil.

Table 2. Chemical element/composition of experimental soil.

Element/compound	Concentration (mg/l)
Al^{3+}	2.84
Ca^{2+}	5.68
SiO_2	76.62
K	2.40
Zn	0.31
Pb	4.47
Fe^{2+}	2.36
Mg^{2+}	10.50
Cl^{-}	9.00
PO_4^{3-}	0.15
SO_4^{2-}	3.00

tensile strength, modulus of elasticity and water absorption are presented in Table 3.

Specimen preparation

Fibres were added at 1.0% by weight of soil as recommended by previous studies[31,30] and 11.8% water (as obtained by OMC) was used for making the specimen. The soil was first spread on a platform, the fibres were then spread on the soil and turned over and over until a uniform mixture was obtained. Water was sprinkled on the soil-fibre mixture and turned over and again to obtain a homogenous mixture. Cylindrical specimens of 80 mm length × 40 mm diameter (Figure 3) were prepared by placing 200 g of the mixture into a cylindrical mould with 40 mm internal diameter and 125 mm length and quasi-statically compressing at 10 MPa pressure, using a close fitting piston with a Tinius Olsen H50KS resulting in a length of about 80 mm. These specimens were used to find out the distribution of the fibres in the soil matrix. Fifty-millimetre cube specimens (Figure 3) were prepared with a steel mould with internal dimension 50 × 50 × 50 mm and compressed at 10 MPa pressure with a Tinius Olsen H50KS. One mould was placed on the other which allowed the mixture to be placed inside and compressed to 50 mm with a wooden plate on top. The cubes were used to determine the gaps between the fibres and the soil matrix. All the specimens were dried in fan assisted Genlab electronic oven at a temperature of 40°C for 5 days when the mass had stabilised.

Soil block specimens of 20 × 20 × 60 mm were prepared with single fibre embedded in each sample for the pull-out test. Four different fibre lengths representing 1/2, 1/4, 1/8 and 1/16 of the total length of each fibre were embedded in the soil matrix leaving the remaining length out of the specimen. Details of the fibre length and diameter are presented in Table 4.

The specimen were made with a steel mould and a press with 1-mm hole drilled in the middle to keep the fibre outside the soil and then pressed with Tinius Olsen H50KS at 10 MPa pressure. The specimen were then pushed out of the mould and allowed to air dry (Figure 4) for 3 weeks when the mass stabilised.

Testing methods

Fibre distribution in soil matrix.

A CT scan analysis was conducted to investigate the distribution of the fibres in the soil matrix. A Metric XT H 225 Microfocus CT

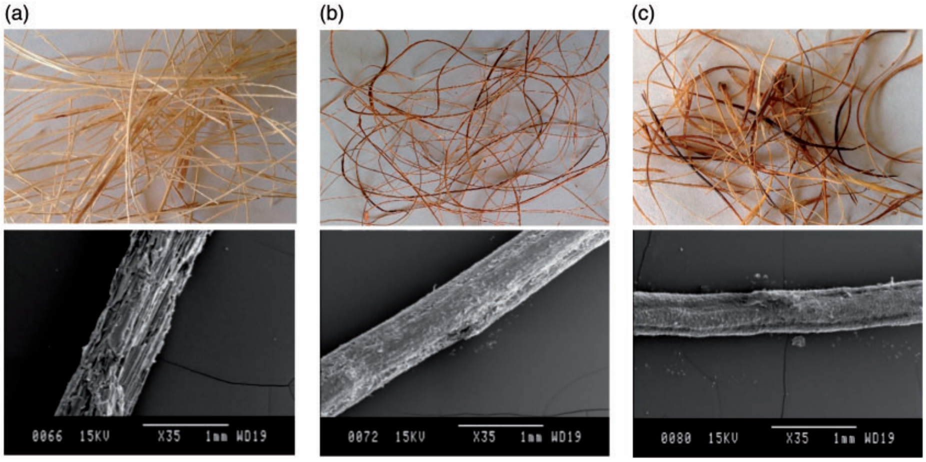


Figure 2. Photographs and scanning electron micrographs of the fibre types. (a) Bagasse fibre, (b) Coconut fibre, (c) Oil palm fibre.

Table 3. Properties of experimental fibres.

	Property			
Fibre type	Diameter (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Water absorption (%)
Bagasse	0.31–1.19	25–62	0.5–1.3	153–219
Coconut	0.18–1.01	83–222	2.3–2.8	145–209
Oil Palm	0.19–0.82	65–141	0.7–1.1	54–103

Scanner was used to scan the cylinder specimens. The CT scan produced images (slices) which were modelled with VGStudio MAX version 2.0 to produce 3D and 2D images of the cylinder specimen showing the orientation of the fibres.

Gaps between fibre and soil matrix. SEM and optical microscope analysis were conducted to investigate the soil-fibre interface at the periphery of the specimen. Selected cubes from each fibre type were broken to expose the internal parts for the analysis with a JSM-6100 scanning microscope and a computerised optical microscope (OLYMPUS BX40) with Leica Application Suite version 3.4.0 (Figure 5). Each specimen was placed in the JSM-6100 scanning microscope at 100× magnification, which revealed gaps at the edge of the fibres in the soil matrix. Each specimen was also placed in the optical microscope. With the help of the Leica Application Suite installed on the computer, the gaps were measured and recorded.

Pull-out test. The pull-out test was conducted to ascertain if the fibres in the soil matrix pull-out or rupture when load is applied on the reinforced soil bocks. A single-fibre pull-out test was carried out following the method used in previous studies on steel fibres in cement composite.[35,36] The specimens were subjected to pull-out using a Tinius Olsen H50KS as shown in Figure 6. The test specimen was fixed to the bottom jaw of the test machine while the free end of the fibre was held by the upper jaw. The matrix remained rigid while, the fibre-held upper jaw moved upward with a rate of 1 mm/min until fibre failed or pulled-out.

Results and discussion

Fibre distribution in soil matrix

The result obtained from the CT scan and modelling of the slices is shown in Figure 7. The images obtained show the cylindrical specimen with the fibres distributed in it. The 3D view shows the fibres are general well distributed however the 2D slice shows some edge effects and alignment with the walls. This is probably an artefact of the preparation of the cylindrical specimen, where friction with the mould would be greater than a rectangular block mould. Overall the fibres in the soil matrix are generally well distributed. This agrees well with Diambra et al.[23] who observed that the use of flexible fibres are usually randomly distributed throughout the soil mass when fibres are used in geotechnical applications. Studies by Ibraim et al.[37] and Maeda and Ibraim[38] found that randomly distributed flexible fibres generate a bond within the soil. This means the orientation of the fibres in the soil matrix have effect on the performance properties of the soil blocks. In the studies of fibre reinforced cement, Maalej et al.[39] and Slosarczyk[40] found that the use of randomly distributed fibres in a brittle matrix increase toughness, increase tensile strength, reduce shrinkage and provide good crack-width control. This means the even distribution of the fibres in the soil matrix

Figure 3. Cube and cylindrical specimen.

Table 4. Fibre diameter and length used for pull-out test.

Fibre type	Mean diameter ±SD (mm)	Mean length ±SD (mm)	Length embedded in soil matrix (mm)			
			1/2	1/4	1/8	1/16
Bagasse	0.78 ± 0.19	110 ± 28.93	55	28	14	7
Coconut	0.40 ± 0.17	103 ± 17.94	52	26	13	6
Oil palm	0.38 ± 0.08	38 ± 5.84	19	10	5	3

One hundred fibres (from each fibre type) were randomly selected for determining the length and diameter as described in Danso et al.[25]

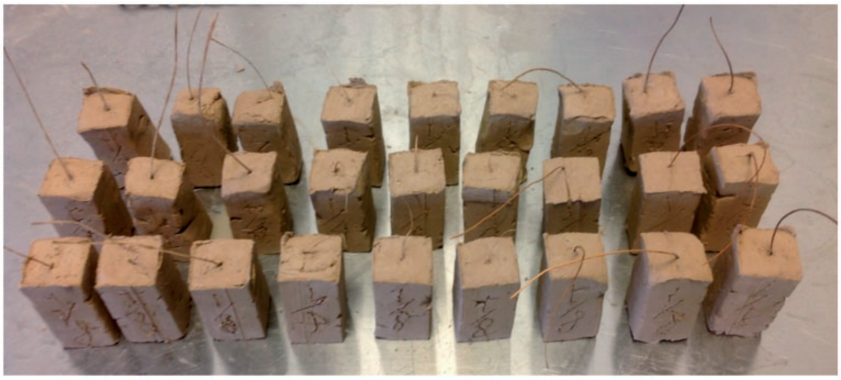


Figure 4. Drying samples for pull-out test.

can help to improve the strength properties in the soil blocks.

Gaps between fibre and soil matrix

The images obtained from SEM analysis (with small broken samples) are shown in Figure 8 and images from optical microscopy are shown in Figure 9. They illustrate the inter-spatial relationship between fibres and the soil matrix of the enhanced soil blocks. Critical observations of the images show that there are gaps formed between the fibres and the soil matrix. Studies by Cao et al.[41] on biodegradable aliphatic polyester composites reinforced with bagasse, Rivera-Gómez et al.[2] on wool fibre in the soil and Zhu et al.[42] on flax/epoxy composites obtained similar results. The extent of these gaps may be attributed to the disturbances during breakage of the specimen or differential shrinkage of the fibres and matrix during drying. The gaps sizes were measured and the mean and standard deviation values estimated from 20 measurements taken from each fibre type (Table 5).

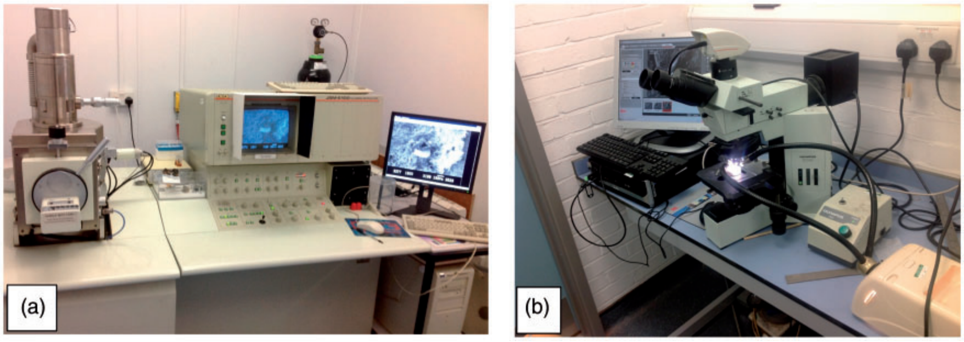
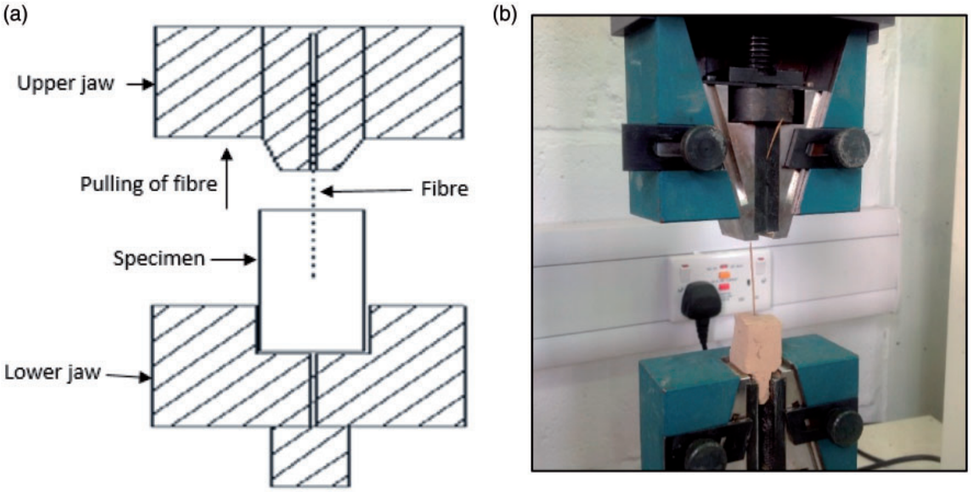


Figure 5. Analysing specimens for gaps with (a) JSM-6100 scanning microscope and (b) OLYMPUS BX40 computerised optical microscope.



Schematic diagram *Laboratory photo*

Figure 6. Pull-out test setup. (a) Schematic diagram and (b) laboratory photo.

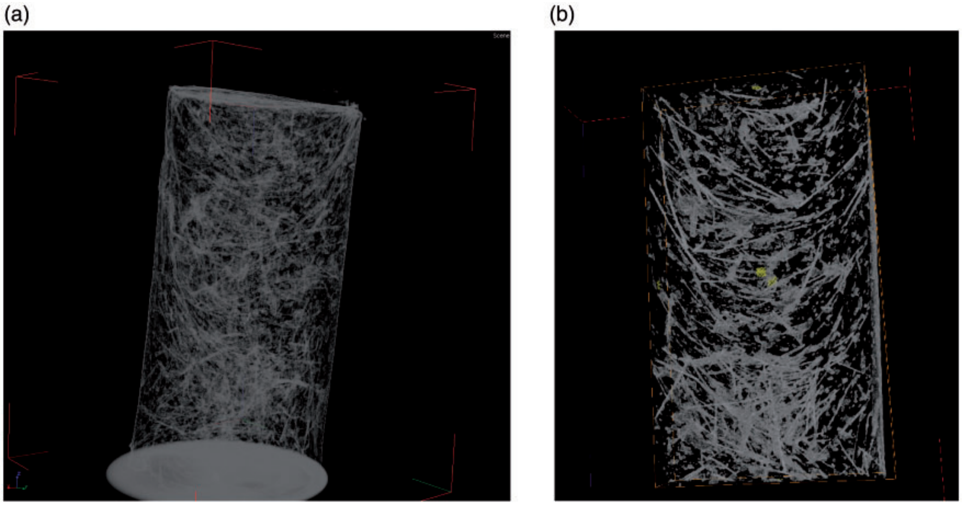


Figure 7. Image from modelled CT scan: Slices. The grey curved lines show the fibres. (a) Full 3D view and (b) sliced internal 2D view.

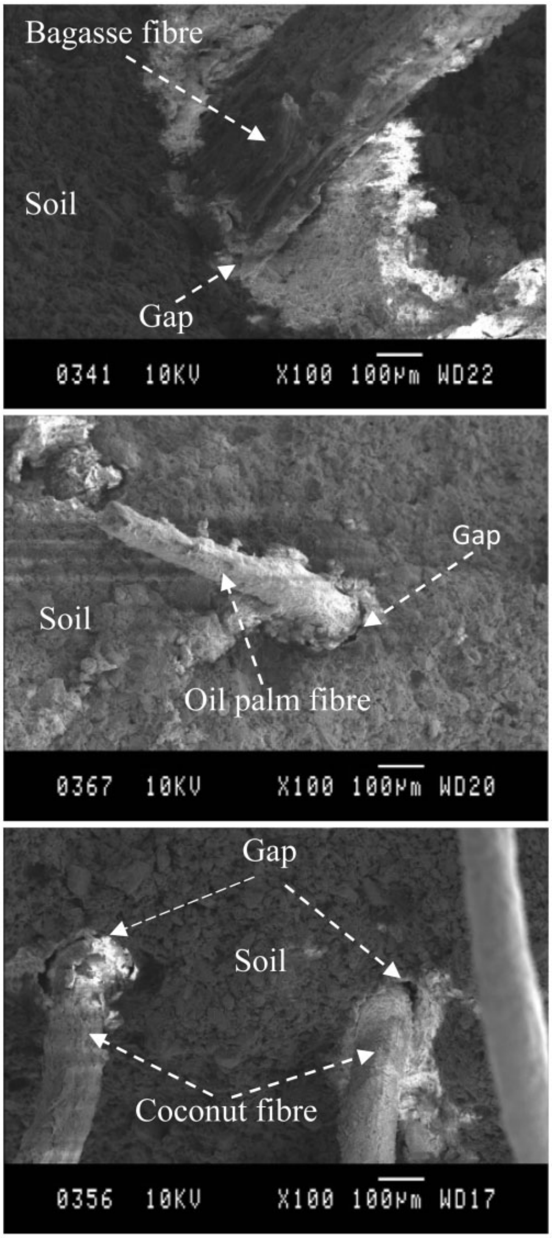


Figure 8. Scanning electron micrographs showing gaps between fibre and soil matrix.

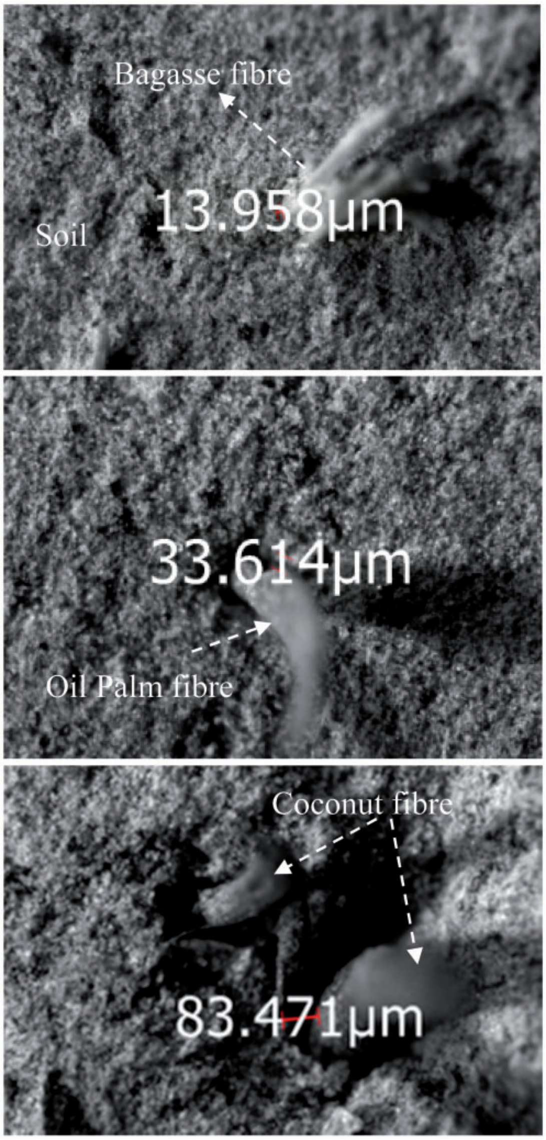


Figure 9. Optical microscope micrographs showing measured gaps between fibres and soil matrix.

The images and measurements indicate that gaps found between coconut fibres and the soil matrix are bigger than those between sugarcane bagasse and oil palm fibre reinforced blocks. The average gap out of 20 fibre–soil specimens of each fibre type showed that the coconut fibre–soil matrix had the largest gaps, the oil palm fibre–soil matrix gaps were approximately half of the size, and the bagasse fibre–soil matrix had gaps approximately a quarter of the size of the coconut fibre reinforced blocks.

To determine whether these gaps were caused by shrinking of the fibres or the soil matrix, 20 fibres from each fibre type were randomly selected and measured in dried state and wet state after immersing in water for 48 h. The results are also shown in Table 5. The results show that the different fibres had different rates of shrinkage during drying. The rank order of gaps followed the rank order of shrinkage (coconut > palm oil > bagasse). This suggests the gaps found between the fibres and the soil matrix is largely caused by shrinking of the fibres from wet state to dry state. The differences in the radius of the dry and wet fibres were, however, found to be larger than the gaps measured between fibres and the soil matrix.

This could be explained considering that, when the fibres are kept in water, they absorb moisture and therefore fully expand, and on the other hand, when mixed with soil and compacted the fibres undergo shrinkage due to the applied pressure, and therefore have less shrinkage on drying in situ. This means that there are two stages of fibre shrinkage: (a) shrinkage due to the compaction force when making the blocks and (b) shrinkage due to drying of the blocks. As the first shrinkage is made in intimate contact with the soil, the gaps found in the optical microscope analysis represent the gaps created by the drying of the blocks (second shrinkage). It must be noted that these two shrinkage stages are all caused by loss of absorbed water in the fibres, which is the difference in dry and wet fibre diameter.

Table 5. Gaps in fibre–soil matrix and difference b/t dry and wet fibre diameters.

	Fibre diameter (mm)		
	Bagasse	Coconut	Oil palm
Difference	Mean ± SD	Mean ± SD	Mean ± SD
Gap b/t fibre and soil matrix (mm)	0.018 ± 0.009	0.077 ± 0.022	0.038 ± 0.006
Saturated fibre diameter (mm)	0.794 ± 0.209	0.623 ± 0.227	0.403 ± 0.132
Dry fibre diameter (mm)	0.769 ± 0.204	0.529 ± 0.211	0.352 ± 0.128
Shrinkage (dif. b/t saturated and dry fibre diameter (mm))	0.025 ± 0.009	0.094 ± 0.023	0.051 ± 0.007
Ratio of gap to shrinkage	0.720 ± –	0.819 ± –	0.745 ± –

Table 6. Pull-out test results of fibre–soil composite.

	Length of fibre embedded in soil (mm)											
Fibre	55	28	14	7	52	26	13	6	19	10	5	3
Bagasse	0/3	0/3	0/3	3/3								
Coconut					0/3	0/3	2/3	3/3				
Oil palm									0/3	0/3	0/3	3/3

Fraction indicates fibres pulled out over test replicates.

The fibre–soil matrix is generally affected by the dimensional changes of the fibres, which can occur due to changes in moisture and temperature.[43] The changes in fibre dimension occur during the drying of the fibre–soil matrix, which may result in a poor interfacial bond.[44] This behaviour of the fibres in the soil can weaken the bond between the fibres and the soil matrix.[43,44] If the gap between the composites is large, it contributes to making it easier for fibres to pull out from the soil matrix, which results in adhesion failure.[45] To determine if gaps contribute to ease of pull out from the fibre reinforced soil matrix, pull out tests were conducted.

Pull-out result

The pull-out test results are reported in Table 6 as the number of fibres from three replicates which pulled out during the test and those that did not pull out were tested to failure. It can be seen that all the three replicates of bagasse fibre–soil specimens pulled out with fibre lengths 7 mm embedded in the soil matrix, while oil palm pulled out at 3 mm lengths. With coconut fibres, two out of three replicates for 13 mm and all the three replicates for 6 mm pulled out of the soil matrix.

The results show that the fibres with low embedded length tended to pull out, whereas the fibres with high embedded lengths ruptured. Examples of fibres failure are presented in Figure 10. It therefore means the critical pull out of fibre length lies between the values

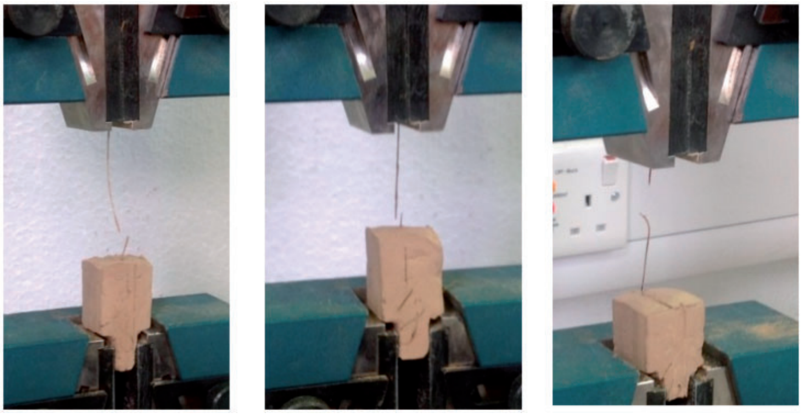


Figure 10. Fibres failure under pull-out test.

where they rupture and the values where they pull-out, thus 7–14, 3–5 and 13–26 mm, respectively, for bagasse, oil palm and coconut fibres. The highest fibre length pull out was seen from coconut, which has the highest tensile strength of the three fibres as demonstrated in a previous study.[26]

Studies by Danso et al.[32,26] also demonstrated that the compressive strength of the coconut fibre reinforced soil blocks performed better than the bagasse and oil palm fibres reinforced soil blocks. The pull out for all the fibre lengths can be explained by fibres poor interfacial bond with the soil matrix and short lengths of the fibres implanted in the soil matrix. The results mean that with natural fibres in soil, the mechanism can either be pull-out *or* rupture of the fibres, whereas studies[35,36] on steel fibres in cement composite the mechanism is almost *always* pull-out because steel fibres are *designed* that way. If they were long enough, they would rupture.

Conclusion

This study investigated the mechanisms by which a compacted soil matrix is reinforced with natural fibres to determine the distribution of the fibres in matrix, any existence of gaps at the peripheral of the fibres in the matrix and the fibres pull-out from the matrix. On the basis of the experimental results obtained, the following summary can be made:

- CT scan micrograph revealed that the fibres in the soil matrix are generally well distributed with some localised directionality observed near to the surface, likely caused by shearing as the soil is compacted. This implies that the fibres in the matrix have unsystematic orientation as compared to steel bars in reinforced concrete. This is however good to reduce cracking effect and also increase strength.
- SEM and optical microscope analysis found that gaps exist between the fibres and the soil matrix. Coconut fibres-soil matrix recorded the biggest gap while bagasse obtained the least gap between the fibres and the soil matrix. This relates to the ratio of different fibres shrinkage during drying, but in situ conditions (e.g. compaction) mean that this is not directly proportional to radial drying shrinkage seen in ex situ laboratory testing.
- Shrinkage was also found to consist of two stages: (a) shrinkage due to applied pressure during block formation and (b) shrinkage due to drying. It may therefore be possible that by controlling the water content of the natural fibres to reduce expansion within the limits of shrinkage (a) and to eliminate the gaps between fibre and soil.
- Natural fibres in soil matrix can either be pull-out or rupture under failure force depending on the depth of fibres embedment in the soil matrix. This is contrarily to steel fibres in cement composite, which almost always pull-out.
- Further work is required to establish the exact point of fibres pull-out, as the pull-out found in this study was between two fibre lengths. The effect of fibre shrinkage under pressure and with different water content could also be investigated. These are important to fully understand the interactions between the fibres and the soil matrix as a composite material.

The article therefore concludes that, though the fibres are randomly distributed in the soil matrix which has the potential of improving the engineering properties of the composite, the fibres are not well bonded with the soil matrix. This means the full benefit of the inclusion of natural fibres in the soil blocks may not be achieved even though studies have shown improvement of the properties of the blocks. Studies by Subrianto et al.[43] and Tang et al.[44] found that cement inclusion dramatically improved the interfacial bond between the fibres and the soil matrix.

Declaration of Conflicting Interests

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