Research Article

Experimental Investigation on Microhydration and Micromechanical Properties of Cement-Sandy Soil Mixtures Reinforced with Cotton/linen-blended Fiber

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The micro-hydration degree plays a significant role in the strength of cement-sandy soil mixtures. The present study used cement-fiber-sandy soil mixtures in which the fiber was sourced from waste cotton/linen-blended fabric to investigate the impacts of different levels of fiber content on the hydration mechanisms and micromechanical performance. Experiments using scanning electron microscopy (SEM) and X-ray powder diffraction (XRD) were carried out to determine how the component content of the different constituents changed with the fiber content (0%, 0.5%, 1.0%, and 1.5%) during the microhydration of the mixtures. A comparative analysis of the strength characteristic curves and the tensile strength variations for different groups of reinforced cement-sandy soil mixtures were conducted by performing triaxial shear tests. The results show that the peak unconfined compressive strength of the mixtures gradually increases with the quartz content of the matrix. The compressive strength of the matrix reaches a peak of 1.5938 MPa, an increase of 24.17%, when the cement and fiber contents were 3% and 1.5% (weight), respectively, with a fiber length of 9 mm. This paper has reference values for the green reinforcement of cement-sandy soil mixtures in the development of underground space.

1. Introduction

Reinforced soil has emerged as a prominent engineering material in recent years and, as such, has been the focus of considerable attention from researchers, with many undertaking exploratory experiments and investigations. We conducted an in-depth systematic analysis of the shear properties of Portland cement based on the obtained results [1] and added fiber to the cement mortar to improve its mechanical properties and to increase its durability [2].

A considerable amount of research has addressed polypropylene-fiber-reinforced soils. Polypropylene fiber may be used to reinforce engineering soils such as clay, soil cement, and tailings sand to some degree. However, the primary constituents of polypropylene fiber are isotactic polypropylene and atactic or syndiotactic polypropylene. These barely degrade under normal conditions and therefore are a source of environmental pollution. They are, therefore, incompatible with an environmentally friendly construction philosophy [3].

In this situation, people began to pay their attention to the plant fiber field. Garcia [4] used potato starch as plasticizer and plant residue (giant reed) as raw material to obtain particleboard with cement. Niu and Kim [5] prepared cement-based composites by using corn straw plants, and all of them obtained high-efficient concrete composites. Machaka et al., [6] extracted natural fiber from plant reed (PA) for concrete admixture. The study found that adding 1.5% natural PA fiber to concrete is a feasible strategy for the production of eco-friendly materials. Labib [7] developed a conceptual framework to evaluate the factors affecting plant-based natural fiber and cement composites. The study found
that coconut jujube fiber can improve the mechanical properties of composites at a relatively low cost and reduce the weight of buildings. A large number of studies have found that plant fibers have a positive impact on concrete composite materials [8].

The survey found that in more than 600 cities in China, 160 million tonnes of various kinds of garbage will be produced every year, and cotton/linen blended fabrics account for about 17% of the recyclable wastes. This available resource is seriously neglected [9, 10]. In summary, previous studies show that while cement improves durability and increases strength and stiffness, plant fiber brings ductility and can improve strength. However, the research focused on using waste cotton/linen-blended fiber to improve the mechanical properties of cement-sandy soil mixtures. Inspired by this, we attempt using waste cotton/linen-blended fiber to enhance the performance of cement-sandy soil mixtures because it is environmentally friendly.

The present study examined cement–fiber–sandy soil mixtures with varying fiber contents (0%, 0.5%, 1.0%, and 1.5% of the weight of the cement-fiber-sandy soil mixtures) prepared by adjusting the compositions of the cement-sandy soil and fiber. The fiber was obtained through recycling and fragmentation processing of waste cotton/linen-blended fabric. Scanning electron microscopy (SEM), X-ray powder diffraction (XRD), and triaxial shear tests were employed to determine the mechanism whereby fiber contents influence the hydration processes and compositions of cement-sandy soil. Further analyses at the microscopic level were undertaken to determine the intrinsic link between the cement-sandy soil/fiber connection model and interface effects and the strength of the mixtures. The results provide a theoretical basis for the research and development of new mix materials such as cotton/linen-blended fiber reinforced cement-sandy soil.

2. Materials Selection and Testing Methods

2.1. Materials Selection

2.1.1. Cement. The test cement was Portland No. 2 cement. Its main constituent ingredients are $3\text{CaO} \cdot \text{SiO}_2$, $2\text{CaO} \cdot \text{SiO}_2$, $3\text{CaO} \cdot \text{Al}_2\text{O}_3$, and $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$ [11]. The relative unit weight of the cement was found to be 3.08 and the water-cement ratio was 0.485 [12]. The tensile and compressive strength were measured with reference to ASTM C 109 [13] and ASTM C 190 [14]. The main physical properties of cement are given in Table 1.

2.1.2. Sandy Soil. The sandy soil selected for the testing was taken from a depth of 4.4–4.8 m at a pipe-gallery project in Yanqing District, Beijing. The physical indexes to test the sandy soil obtained through drilling are listed in Table 2. The contents of each constituent are given in Table 3. The particle size distribution curve is shown in Figure 1. Prior to the testing, vibration sieving was performed to sift out particulate components larger than 2 mm, and the sandy soil was then air-dried.

2.1.3. Cotton/Linen-Blended Fiber. The cotton/linen-blended fiber used in the present study were obtained from low-quality cotton/linen-blended clothing discarded by residents and collected from a Beijing recycling station. A fiber cutting machine was used to cut the waste clothing into two groups of fiber strips (cotton fiber content is 60%, and linen fiber content is 40%) specifically, 6- and 9-mm long, for
use in the experiments. The monofilament diameter of the waste cotton/linen-blended fiber was 0.40 mm, with a relative density of 1.35, a water absorption percentage of 16.2%, and an elongation percentage of 6.8% [15]. The monofilament tensile strength and elastic modulus were determined to be 355 and 2950 MPa, respectively [16, 17], as summarized in Table 4.

2.2. Preparation of Test Blocks. The present study used round test blocks measuring Ø40 × 50 mm. To prepare these test blocks, water, cement, and sandy soil were mixed at a ratio of 3:0.38:1:1:11 [18]. This mixture was placed in a mixing machine and then stirred for 5 min until uniform. Then, the cut fiber (6 or 9 mm) was gradually added to the cement-sandy soil mixture and then mixed thoroughly for 3 min. The homogenous mixture was poured into a metal cylindrical mortar measuring Ø40 × 50 mm [19]. The mixture was then hammered 20–30 times with a metal hammer to remove any trapped air. The hammering was stopped once the height of the test block reached 10 ± 0.2 mm. After the test block had been fabricated, it was sealed in a black plastic film, and then labelled (as shown in Figure 2(a)). Then, the sample was placed in a standard curing room at a temperature of ± 3°C and a humidity of more than 90% for 7 days. After curing, the plastic film was removed and the test block was placed in a dry box at 50°C. The drying was stopped when the variations in the test sample mass were less than 0.01 g. The resulting test blocks were used for testing. The final micromorphology of the test block is shown in Figure 2(b).

2.3. Experimental Methods

2.3.1. SEM Scans. A KYKY-2800B SEM was used (as shown in Figure 3) to obtain the micromorphological features of the cement-fiber-sandy soil mixture modified with the cotton/linen-blended fiber. A small piece of a prepared test block was placed on the mount of the SEM. The brightness was then adjusted to obtain a clear image. The contrast was adjusted to 150, after which the pressure was gradually increased 20–25 kV [20]. Any blurriness was corrected by carefully focusing the observed image in the central area. Multiple morphological observations of the mixtures were obtained at 50×, 100×, and 500× magnifications by gradually increasing the SEM magnification.

2.3.2. X-Ray Diffraction Spectroscopic Analysis. A Bruker D8 ADVANCE X-ray power diffractometer (shown in Figure 4) was used to analyze the compositions of the fiber samples. The step-scan mode with an operating voltage of 40 kV and a working current of 100 mA was selected [21]. The diffractometer was equipped using a graphite curved crystal monochromator. The 2θ scan range was 8.5°–9.5° and the scan rate was 0.02°/step with a pause of 4 s/ step [22]. Based on the XRD spectra, an analysis of the phase changes in the mixtures with different fiber contents has undertaken to obtain the hydration patterns for the cement-fiber-sandy soil mixtures under cellulose phase-change excitation.

2.3.3. Triaxial Shear Test. An indoor triaxial shear test was performed, with the fiber length and content being regarded as variables. The micro-mechanical properties of the different cement-fiber-sandy soil mixture groups (9/0.5%, 9/1.0%, 9/1.5%, 6/0.5%, 6/1.0%, and 6/1.5%) were compared. For these tests, a TSZ-1 automatic triaxial test system was used. The test blocks used in the triaxial tests were prepared in the same way as described in Section 2.14, except that the dimensions of the test blocks were increased to facilitate the observations. Specifically, the test blocks measured Ø50 × 80 mm. In the test, the end smoothness of each group of specimens was strictly controlled, and Vaseline was smeared on the upper and lower end faces before triaxial loading to reduce the end friction effect. Compared with ordinary cement-soil materials, the overall toughness of cotton fiber reinforced cement-soil is stronger, and its failure morphology is not obvious. In order to facilitate the experimental observation of the failure process, the surface area of the specimen column is increased in the study.

3. Results and Analysis

3.1. Cementation and Fiber Interfacing Effects. SEM observations of the cement-cotton/linen blended fiber-sandy soil mixtures at different magnifications were acquired using a KYKY-2800B SEM system. Due to space limitation, take a cotton fiber sample with a fiber length of 6 mm and a fiber content of 1.0% as an example, and the acquired results are shown in Figure 5.

Figure 5(a) shows the cotton/linen blended fiber embedded in the soil-cement matrix, with inflected filaments clearly visibly, which means cotton/linen-blended fiber can increase the structure integrity of cement-sandy soil mixtures. In this case, when the substrate receives tensile or shearing forces, the fiber play a role in connecting the axis and the rope. It strengthens the connection between the matrix particles and significantly improves the mechanical

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### Table 4: Basic physical parameters of cotton/linen blended fiber.

| Type                | Relative density | Monofilament diameter (mm) | Mean water absorption percentage (%) | Monofilament tensile strength (MPa) | Elastic modulus (MPa) | Cellulose content (%) | Aspect ratio |
|---------------------|------------------|----------------------------|--------------------------------------|-------------------------------------|-----------------------|-----------------------|--------------|
| Cotton/linen blended fiber | 1.35             | 0.40                       | 15.6                                 | 355                                 | 2950                  | 78.3                  | 961          |

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properties such as tensile and shear strength of cement-sandy soil.

Figure 5(b) (100× magnification) shows that the cotton/linen-blended fiber integrates into the soil-cement matrix by either insertion or embedding. The fiber exhibits excellent interconnection with the matrix, while the inverted voids diameters are 0.1–0.8 mm. In addition, the surfaces of the fiber were wrapped in gel to which many granular substances of varying diameters had become attached. This gel (CaO-SiO$_2$·YH$_2$O) is formed during the hydration of the cement-sandy soil mixture. It wraps around the grains and becomes attached to the surfaces of the fiber. As a result, it is able to strengthen the bonding between cement-fiber-sandy soil mixture and reduce the influence of the interface effect.
Figure 5(c) (500× magnification) shows exposed fiber on the surface of the part of the test block. The fiber was 185 um in length and separated into several filaments. Moreover, it can be seen that the fiber is connected to the cement-sandy soil matrix by inserting it. The exposed part is about 145um. Most of the fiber body is inserted into the matrix.

Overall, SEM tests show that the cementation function of the gel particle produced on a cotton/linen-blended fiber surface strengthens the bonding between cement-fiber-sandy soil mixture and improves the fiber interface effects.

3.2. Analysis of Impacts of Fiber Content on Cement-Sandy Soil Hydration. The phase content variation curve (Figure 6) for fiber reinforced cement-sandy soil under four varying levels of fiber content (0%, 0.5%, 1.0%, and 1.5%) was obtained via SEM observations.

Figure 6(a) shows the diffraction spectrum of the cement-sandy soil mixture without the cotton/linen-blended fiber. The spectrum reveals the primary phase composition of the cement-sandy soil mixture after hydration: quartz (SiO₂), albite (Na₂O·Al₂O₃·6SiO₂), calcite (CaCO₃), and ettringite (3CaO·Al₂O₃·3CaSO₄·32H₂O) [24]. From this, the hydration reactions that occur during the hydration of the cement-sandy soil mixture can be deduced by comparing the hydration of a cement-sandy soil mixture with that of cement. In the first stage, the hydration reactions of tricalcium silicate and dicalcium silicate produce hydrated calcium silicate (C–S–H gel) and calcium hydroxide (Ca(OH)₂). The calcium hydroxide reacts with CO₂ in water to produce a certain amount of calcium carbonate, which is the main constituent of calcite [25]. In the second stage, the hydration of tricalcium aluminate produces hydrated calcium alumininate. The hydrated calcium alumininate is in a meta-stable state, making it prone to reacting with other chemicals. During hydration, hydrated calcium aluminate combines with NaO in the grains to produce albite. In the third stage, the hydration of the tetracalcium aluminoferrite produces ettringite (3CaO·Al₂O₃·3CaSO₄·32H₂O) [26].

(1) Hydration reaction of tricalcium silicate:

\[3\text{CaO} \cdot \text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{CaO} \cdot \text{SiO}_2 \cdot \text{YH}_2\text{O} \text{ (gel)} + \text{Ca (OH)}_2.\]  

(2) Hydration reaction of dicalcium silicate:

\[2\text{CaO} \cdot \text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{CaO} \cdot \text{SiO}_2 \cdot \text{YH}_2\text{O} \text{ (gel)} + \text{Ca (OH)}_2.\]  

(3) Hydration reaction of tricalcium aluminate:

\[3\text{CaO} \cdot \text{Al}_2\text{O}_3 + 6\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} \text{ (hydrated calcium aluminate, unstable).}\]  

(4) Hydration reaction of tetracalcium aluminoferrite:
CaO $\cdot$ Al$_2$O$_3$ + 3CaSO$_4$ $\cdot$ 2H$_2$O + 26H$_2$O $\rightarrow$ 3CaO $\cdot$ Al$_2$O$_3$ $\cdot$ 3CaSO$_4$ $\cdot$ 32H$_2$O. \hfill (4)

Figures 6(b), 6(c), and 6(d) show the diffraction spectra for cotton/linen-blended fiber contents of 5%, 10%, and 15%, respectively. Figure 7 clearly shows a significant change in the waveforms and shapes of the diffraction peaks following the addition of cotton/linen-blended fiber. However, the amount of each component changes significantly with the fiber content. The cellulose in the cotton/linen blended fiber selected for these experiments is, molecularly speaking, a macropolymer with a polysaccharide structure (C$_6$H$_{10}$O$_5$), which decomposes into a reducing polyhydroxy aldehyde (C$_6$H$_{12}$O$_6$) during hydration \cite{27}. The addition of the reducing agent inhibits the alkali–aggregate reaction of the active silica and oxides during the hydration of the cement-sandy soil mixture, causing a progressive increase in the quartz content with the fiber content. The main source of albite is the further chemical reaction between the oxides in the mixture such as Na$_2$O, CaO, and the hydrated calcium aluminate produced in the third stage of hydration. The chemical formula of calcite is CaCO$_3$. A significant amount of calcium hydroxide is produced during the hydration of tricalcium silicate and dicalcium silicate in the first stage of hydration. The reaction between calcium hydroxide and the CO$_2$ in water produces trace amounts of calcite \cite{28, 29}. Hydroxy aldoses in the fiber are adsorbed onto the surfaces of the cement and sandy soil granules as the fiber content increases, thus forming a dense absorption film. This damages the electrical double layer structure of the cement particles and inhibits the hydration and secondary hydration processes. There is an overall declining trend in the albite and calcite contents. The variations in the diffraction peaks of ettringite in the diffraction spectra are small. The overall ettringite content changes from 0.24% to 0.21% when the fiber content is 15%. In general, the fluctuations are insignificant. The cellulose has a relatively small impact on the hydration reactions of tetracalcium aluminoferrite. Moreover, according to Figure 7, with the increase of fiber content, the ettringite content increases first and then decreases, while the contents of calcite and albite continue to decrease at different rates. It is worth noting that the quartz content gradually increases in this process. According to investigation results, the hardness on the Mohs scale of ettringite, calcite, albite, and quartz are 5, 6, 3, and 7, which
Figure 7: Content variation curves for four primary components with fiber content.

Figure 8: Relationship between unconfined compressive strength and axial strain (a) Fiber length = 9 mm. (b) Fiber length = 6 mm.
indicates that the strengthening effect of fiber on reinforced soil is characterized by the increase of quartz content.

In summary, the impacts of fiber content on cement-sandy soil hydration are expressed by the changes of ettringite, calcite, albite, and quartz contents, and the increase of quartz content enhances the strength of cement-sandy soil mixtures.

### 3.3. Impacts of Fiber Content on the Mechanical Properties of Cement-Sandy Soil Mixture

#### 3.3.1. Compressive Strength

Figure 8 shows the relationship between the unconfined compressive strength of cotton/linen-blended fiber-reinforced cement-sandy soil and the axial strain. By comparing the curves of the two groups (Figure 8(a) and 8(b) for fiber lengths of 9 and 6 mm, respectively), when the length of the fiber remains unchanged, there is a gradual increase in the ultimate compressive strength of the matrix with an increase in the fiber content. During the hydration of the cement-sandy soil mixture,

![Graph of silica content vs. unconfined compressive strength](image1)

![Graph of sodium aluminum oxide content vs. unconfined compressive strength](image2)

![Graph of calcium carbonate content vs. unconfined compressive strength](image3)

![Graph of 3CaO·Al₂O₃·3CaSO₄·32H₂O content vs. unconfined compressive strength](image4)

**Figure 9:** Relationship between the phase content and unconfined compressive strength. (a) Quartz. (b) Albite. (c) Calcite. (d) Ettringite.

**Figure 10:** Relationship between cohesive strength and internal friction angle.
when the fiber content reaches 1.5% (the cellulose content is 1.1745%), the peak value exhibits an obvious shift backwards. This indicates that there is a greater axial strain under ultimate breaking strength and that the soil-cement matrix gradually transforms from brittle fracture to plastic fracture. For fiber of different lengths, the peak value is higher for longer fiber (9 mm), as is the compressive strength. Hence, the compressive capacity is improved.

The same variation is noted for the peak unconfined compressive strength and the silica content when the various phase changes described in Section 3.2 are compared. Hence, it may be deduced that changes in the compressive strength of the matrix are related to its silica content. It could be deduced, by looking at the similarity between the hardness and compressive strength, that an increase in the quartz content is a major influence in the rise in the peak unconfined compressive strength of the fiber-reinforced cement-sandy soil mixture. This conclusion is agreement with the literature [30] and [31]. The curve of the peak unconfined compressive strength versus the quartz content is obtained from the experimental data (as shown in Figure 9(a)). The curve indicates a linear change which further demonstrates the intrinsic link between the two. Similarly, the correlation curves between the variations in the content of the other three types of constituents and the peak unconfined compressive strength can be obtained (as shown in Figure 9(b), 9(c), and 9(d)). The curves for albite and calcite show an overall negative correlation. Calcium hydroxide combines to form calcium carbonate during the transformation of calcite, which leads to a decline in the alkalinity of the cement paste. Subsequently, the decomposition and dissolution of the hydration products lead to a reduction in the overall strength of the matrix. As illustrated in Figure 9(d), the curve for ettringite does not exhibit a clear correlation.

In summary, the peak unconfined compressive strength of the cement-fiber-sandy soil mixtures gradually increases with the fiber content (from 0% to 1.5%). There is a backward shift in the peak axial strain with an increase from 1.2835 to 1.5938 MPa. XRD tests indicate a gradual increase in the quartz content in the mixture and a gradual reduction in that of the calcite, albite, and ettringite with a gradual increase in the fiber content. This is one of the reasons for the increase in the peak unconfined compressive strength of the mixture.

3.3.2. Shear Strength Properties. Figure 10 shows the measured shear strength constants for the two groups of fiber with different lengths (6 and 9 mm, respectively) and varying fiber contents. There is a clear improvement in the cohesion and internal friction angles when the fiber content is raised from 0% to 0.5%, illustrating that the fiber is capable of effectively enhancing the shear strength of the cement-sandy soil mixtures. In combination with the previous analysis, cementation function of the gel particle and the increase of quartz contents enhance the strength of cement-sandy soil mixtures.

Moreover, Figure 10 shows an overall increasing trend in the matrix cohesion with the fiber content when the fiber is 6-mm long. The internal friction angle shows an increase and then a decrease, reaching a maximum of 40.2° for a fiber content of 1.0%. In the case of the 9-mm fiber, the internal friction angle gradually increases with the fiber content. For a fiber content of 1.0%, the cohesion peaks at 10.4531 MPa. The maximum shear strength was obtained with a fiber length of 9 mm and a fiber content of 1.0%, as determined from the experimental data and in accordance with Coulomb’s law. The change trend has a high degree of agreement with the XRD test result. The fiber content is 1.0% (the cellulose content is 0.783%). When the shear strength reaches the peak strength.

In summary, cotton/linen blended fiber can effectively improve the shear strength of a cement-sandy soil mixture. There is a clear improvement in both the cohesion and the internal friction angle following an increase in the fiber content. The maximum shear strength is attained with a cohesion strength of 0.4531 MPa, and an internal friction angle of 41.2° with 9-mm fiber and a fiber content of 1.0%.

3.4. Limitations of the Present Study. As we all known, compared with polypropylene-fiber, plant fibers are likely to degrade as time goes by. Cotton-hemp-blended fabric contains a large amount of cellulose \((C_6H_{10}O_5)_n\), which can be degraded under certain conditions (microbial environment). This paper does not take this factor into consideration but assumes cotton-hemp-blended fabric as a reinforced material does not produce a degradation reaction in cement soil and affects material stability further. However, we perceive it is necessary to consider this factor in future research.

4. Conclusion

The following conclusions were drawn from the results of an investigation of cement-sandy soil mixtures reinforced with varying fiber contents (0%, 0.5%, 1.0%, and 1.5%) by using SEM scans, X-ray diffraction spectroscopic analysis, and triaxial shear tests to study their microhydration mechanisms and micromechanical performance:

(1) Cotton/linen-blended fiber and cement-sandy soil mixtures become well interconnected, with a surface pore diameter of 0.1–0.8 mm. Because of the interfacing effects and gel cementation between the fiber and cement-sandy soil mixture, the matrix’s overall connection is strengthened and the matrix transforms from brittle to ductile. There is an increase in the mixture’s overall tensile strength and a reduction in its Britteness Index. Comparing the compressive properties of specimens with different fiber content, when the fiber content is 1.5%, the compressive strength of the specimen is the largest and the compressive capacity is the best, and that excessive fiber will cause smaller interfacing effects and declining overall performance.

(2) Cellulose can effectively slow down the hydration of a cement-sandy soil mixture and hence act as a retarder. In the course of the hydration process, the
hydrolysis of the cellulose reduces the polyhydroxy aldehyde, which inhibits the secondary hydration reaction. It therefore reduces the degradation of the cement–fiber–sandy soil mixture and improves the overall strength of the mixture.

(3) The peak unconfined compressive strength of the cement–fiber–sandy soil mixtures gradually increases with the fiber content (from 0% to 1.5%). There is a backward shift in the peak axial strain with an increase from 1.2835 to 1.5938 MPa. XRD tests indicate a gradual increase in the quartz content in the mixture and a gradual reduction in that of calcite, albite, and ettringite with a gradual increase in the fiber content. This is one of the reasons for the increase in the peak unconfined compressive strength of the mixture.

(4) Cotton/linen-blended fiber can effectively improve the shear strength of a cement–sandy soil mixture. The maximum shear strength is attained with a cohesion strength of 0.4531 MPa and an internal friction angle of 41.2° with 9-mm fiber and a fiber content of 1.0%.

This paper employs waste cotton/linen-blended fiber to enhance the performance of cement–sandy soil mixtures from the perspective of environmental protection. The conclusions are conductive the green reinforcement of cement–sandy soil mixtures in the development of underground space. [23].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] Z. Yin, Q. Zhang, X. Zhang, J. Zhang, and X. Li, “Shear strength of grouted clay: comparison of triaxial tests to direct shear tests,” Bulletin of Engineering Geology and the Environment, vol. 8, 2022.

[2] R. Haigh, Y. Bouras, M. Sandanayake, and Z. Vrcelj, “The mechanical performance of recycled cardboard kraft fibres within cement and concrete composites,” Construction and Building Materials, vol. 317, Article ID 125920, 2022.

[3] M. U. Farooqi and M. Ali, “Contribution of plant fibers in improving the behavior and capacity of reinforced concrete for structural applications,” Construction and Building Materials, vol. 182, pp. 94–107, 2018.

[4] A. A. Ferrandez-García, T. G. Ortuno, M. Ferrandez-Villena, A. Ferrandez-Garcia, and M. T. Ferrandez-Garcia, “Evaluation of particleboards made from giant reed (arundo donax L.) bonded with cement and potato starch,” Polymers, vol. 14, no. 1, p. 111, 2021.

[5] B. Niu and B. H. Kim, “Method for manufacturing corn straw cement-based composite and its physical properties,” Materials, vol. 15, no. 9, p. 3199, 2022.

[6] M. Machaka, J. Khatab, S. Baydoun, A. Elkordi, and J. J. Assaad, “The effect of adding phragmites australis fibers on the properties of concrete,” Buildings, vol. 12, no. 3, p. 278, 2022.

[7] W. A. Labib, “Plant-based fibres in cement composites: a conceptual framework,” Journal of Engineered Fibers and Fabrics, vol. 17, Article ID 155892502210789, 2022.

[8] C. Signorini and V. Volpini, “Mechanical performance of fiber reinforced cement composites including fully-recycled plastic fibers,” Fibers, vol. 9, no. 3, p. 16, 2021.

[9] Z. Lei, “Research on the evolution process and influencing factors of municipal solid waste classification policy in china,” China Resources Comprehensive Utilization, no. 03, pp. 93–97, 2022.

[10] L. Yufeng, “Study on evolution process and influencing factors of municipal solid waste classification policy in china,” Low Carbon World, vol. 5, no. 05, pp. 19-20, 2020.

[11] ASTM (American Society for Testing and Materials), Standard Specification for Portland Cement, ASTM C150-12, Philadelphia: PA, 2012.

[12] ASTM (American Society for Testing and Materials), Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste, ASTM C187-16, West Conshohocchen: PA, 2016.

[13] ASTM (American Society for Testing and Materials), Standard Test Method for Compressive Strength of Hydraulic Cement Mortars, ASTM C109-20, West Conshohocthen: PA, 2020.

[14] ASTM (American Society for Testing and Materials), Standard Test Method for Tensile Strength of Hydraulic Cement Mortars, ASTM C190-85, 1985.

[15] M.-B. Hågg, A. Lindbråthen, X. He, S. Nodeland, and T. Cantero, "Pilot demonstration-reporting on CO2 capture from a cement plant using hollow fiber process," Energy Procedia, vol. 114, pp. 6150–6165, 2017.

[16] ASTM (American Society for Testing and Materials), Standard Practice for Making and Curing Soil–Cement Compresion and Flexure Test Specimens in the Laboratory, ASTM D1632-17, West Conshohocken: PA, 2017.

[17] ASTM (American Society for Testing and Materials), Standard Test Methods for Compression Strength of Molded Soil–Cement Cylinders, ASTM D1633-17, West Conshohocthen: PA, 2017.

[18] S. Wansom and S. Janjaturaphan, “Evaluation of fiber orientation in plant fiber-cement composites using AC-impedance spectroscopy,” Cement and Concrete Research, vol. 45, pp. 37–44, 2013.

[19] G. Mármol and H. Savastano, “Study of the degradation of non-conventional MgO-SiO2 cement reinforced with lignocellulosic fibers,” Cement and Concrete Composites, vol. 80, pp. 258–267, 2017.

[20] A. Pawłowska, M. Stępczynska, and M. Walczak, “Flax fibres modified with a natural plant agent used as a reinforcement for the poly lactide-based biocomposites,” Industrial Crops and Products, vol. 184, Article ID 115061, 2022.
[21] J. Zhang, X. Pei, T. Ni, and M. Fan, “Study on a novel chemical slurry and the mechanical behavior of cemented sand,” Journal of Adhesion Science and Technology, vol. 34, no. 23, pp. 2551–2568, 2020.

[22] B. Çomak, A. Bideci, and Ö. Salli Bideci, “Effects of hemp fibers on characteristics of cement based mortar,” Construction and Building Materials, vol. 169, pp. 794–799, 2018.

[23] Y. Huang, J. Tan, X. Xuan et al., “Study on untreated and alkali treated rice straw reinforced geopolymer composites,” Materials Chemistry and Physics, vol. 262, Article ID 124304, 2021.

[24] O. S. Abiola, “Natural fibre cement composites,” Advanced High Strength Natural Fibre Composites in Construction, pp. 205–214, 2017.

[25] L. Zhao, S. Q. Zhu, H. Wu et al., “The improved resistance against the degradation of sisal fibers under the environment of cement hydration by surface coating of graphene oxide (GO) based membranes,” Construction and Building Materials, vol. 305, Article ID 124694, 2021.

[26] R. Motahareh, O. A. Hisseine, and T.-H. Arezki, “Effectiveness of treated flax fibers in improving the early age behavior of high-performance concrete” Journal of Building Engineering, vol. 45, Article ID 103448, 2021.

[27] G. Ren, B. Yao, M. Ren, and X. Gao, “Utilization of natural sisal fibers to manufacture eco-friendly ultra-high performance concrete with low autogenous shrinkage,” Journal of Cleaner Production, vol. 332, Article ID 130105, 2022.

[28] B. Zukowski, F. de Andrade Silva, and R. D. Toledo Filho, “Design of strain hardening cement-based composites with alkali treated natural curauá fiber,” Cement and Concrete Composites, vol. 89, pp. 150–159, 2018.

[29] G. Adil, J. T. Kevern, and D. Mann, “Influence of silica fume on mechanical and durability of pervious concrete,” Construction and Building Materials, vol. 247, Article ID 118453, 2020.

[30] M. Khan, A. Rehman, and M. Ali, “Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road,” Construction and Building Materials, vol. 244, Article ID 118382, 2020.