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Effects of different lengths and doses of raw and treated sisal fibers in the cement composite material

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Sisal fiber moisture sensitivity and degradation are treated by alkaline and pozzolanic methods, such as silica fume and kaolin surface coating. However, it is novel that the treatment of sisal fiber by calcined bentonite slurry can coat sisal fiber from moisture and protect it from cement hydration by consuming free lime and reducing cement matrix alkalinity. Therefore, the present study treated sisal fibers with calcined bentonite slurry and investigated the effect of using different lengths and doses of treated and raw sisal fibers in a mortar. The results indicate that the treatment of sisal fiber with bentonite slurry improved the roughness of the fiber, reduced fresh bulk density, improved resistance in acid, salt, and alkaline conditions, and increased compressive and flexural strength at 28 and 56 days compared to the control mixture and raw sisal fiber-employed mortar. Therefore, TS1L10 improved compressive strength by 30.62% and 1.8% at 28 and 56 days, respectively. Also, TS1L10 enhanced strength and residual strength in 5% HCl by 54.54% and 72.25%, respectively, compared to the control mixture at 56 days. Generally, the present study revealed the importance of calcined bentonite-treated sisal fibers in a mortar mixture for improved durability, physical and mechanical properties.

Keywords Sisal fiber, Calcined bentonite, Moisture sensitivity, Cement composite materials, Deterioration, Pozzolanic treatment

In many construction works, concrete is the most commonly used construction material; however, it is brittle, has low tensile strength, poor fracture toughness, weak energy absorption, and easy cracking[1,2]. Hence, the reinforcement of steel bars and fibers significantly enhances the ductility, toughness, and impact resistance of concrete[3,4]. Fiber incorporation in cement composite materials is important for reducing shrinkage cracks, improving tensile strength, and resisting hazardous environments[5–7]. Also, fiber employment in concrete improves the resistance of maximum stresses and relatively large strain on the post-cracking, form a good bond between aggregate and cement matrix[8–10]. However, synthetic fibers are expensive, and their production pollutes the environment[11]. Therefore, employing natural fibers in construction materials is renewable, cost-effective, enhances strength, and reduces the impact of carbon dioxide on the environment[12,13]. Besides these, adding natural fibers to concrete improves its mechanical and durability properties[14,15] and can mitigate the occurrence of minor and major cracks in concrete[16].

Sisal fiber is a strong and most cultivated natural fiber extracted from the Agave-sisalana plant leaf, which mainly grows in tropical and sub-tropical regions of the world[17,18]. Hence, sisal fiber is an excellent secondary structural component with low weight, improves strength and ductility, reduces shrinkage cracks, and is less expensive than synthetic fibers[19–21]. This is mainly through the cellulose part, which increases the mechanical properties of concrete and is covered by other parts of the fibers such as hemicellulose, lignin, and some impurities[22,23].

Reinforcing cement composite materials with sisal fibers promotes the use of renewable, nonhazardous, and biodegradable materials, which permits the development of sustainable construction materials[20,24]. In addition, replacing the sisal fiber with steel fiber is crucial, which encourages economical construction and supports

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upcoming green building technologies[25,26]. However, sisal fibers are highly moisture-sensitive and deteriorate owing to the mineralization of cementing minerals. Hence, sisal fiber surface treatment modifies the fiber surface and reduces moisture sensitivity and water absorption by filling the surface pores of the fiber, consequently, improves the performance and durability of natural fibers for reinforcing cement composite materials[27,28].

Sisal fiber deterioration in cement composite materials starts from the outer layers of lignin and hemicellulose and then proceeds slowly to the inside cell walls of cellulose. This is due to alkaline pore solution infiltration in the fibers, which leads to the deterioration of cellulose fibrils, causing premature failure of sisal fibers[29]. Hence, the usability of sisal fibers in alkaline environments, such as cement composite materials, is limited[30]. Hence, ways to reduce moisture absorption are required, which can make the sisal fiber surface hydrophobic while protecting the fiber from mineralization of the cement matrix[31].

Hence, many researchers have used alkaline NaOH and Na_2CO_3 to reduce sisal fiber deterioration in cement composite materials[32,33]. Also, the sisal fiber surface is coated with pozzolana, such as kaolin and silica fume, for the sustainable use of sisal fiber in cement composite materials[34]. However, it is novel that the treatment of sisal fiber by calcined bentonite slurry, which is a natural pozzolana, can coat sisal fiber as well as protect it from cement hydration by consuming free lime and reducing the alkalinity of the cement matrix. This is because calcined bentonite highly reacts with cement free-lime[35,36], consequently reduces sisal fiber degradation caused by free-lime[37].

Therefore, this study investigated the effects of reinforcing cement composite materials using treated and raw sisal fibers, which treated with calcined bentonite slurry, that have different lengths and doses, on the mechanical and physical properties of cement composite materials. Also, the effects of using treated and raw sisal fibers in mortar were assessed in different adverse environments, such as acidic, alkaline, elevated-temperature, and salty environments. In the present study, the employment of treated and raw sisal fibers in cement composite materials is investigated in detail to effectively implement sisal fiber in construction materials. Also, the present study can direct future researchers to explore more ways to reduce sisal fiber degradation for cementing materials using similar treatment methods and more effective ways.

Materials and methods
Materials
The mortar samples produced by using CEM I 32.5R ordinary Portland cement (OPC), washed river sand, water, and sisal fiber. Distilled water was used for mixing, and washed river sand was used as the standard for ASTM C109M-02[38]. Washed and brushed raw sisal fiber was collected from Sisalana (T) Co. LTD, Korogwe, Tanzania. It has a diameter of 0.05–0.18 mm, a specific gravity of 37.99–38.91 tex, and a maximum length of 60 cm. Hence, in the present study, treated and raw sisal fibers with lengths of 10 and 20 mm by 1%, 1.5%, and 2% to the mass of cement were used for reinforcing mortar sample[39], and its detailed design mix is shown in Table 2, which was standardized as ASTM C109M-02[38]. The chemical compositions of the calcined bentonite used for sisal fiber treatment and OPC are shown in Table 1, which were determined using an X-ray fluorescence (XRF) machine.

LOI- Loss of Ignition.

Methods
Sisal fiber treatment

The raw extracted bentonite was powdered using a laboratory mill and sieved through a 45 μm sieve. Subsequently, the ground bentonite was calcined in a box furnace because of the consolidated form of raw bentonite, which requires heating to activate its pozzolanic reactivity[40]. Hence, the treatment of sisal fiber was by the slurry, which is made from the mixture of bentonite calcined at 800 °C for 3 h, cement, and water; that is taken from Reddy & Reddy[40] found bentonite calcination at 800 °C for 3 h is the highest bentonite reactivity level that can highly consume free calcium hydroxide of cement composite materials, hence, can protect the aging of sisal fiber due to mineralization of cementing materials. The treatment was performed by immersing the sisal fiber in the prepared slurry with different water-to-binder ratios to obtain a fully coated surface of the sisal fiber, which was then dried for 24 h and brushed to be used in the mortar mixture at the required doses and lengths. The uniformity of the fiber surface coating was controlled by visual inspection. However, before reinforcing the mortar, the treated and raw sisal fibers were exposed to a single fiber tensile strength test after aging for 10-times wetting and drying cycles in hot water at 75 °C[41].

Mineral composition, roughness, and microstructural properties

The surface roughness and mineralogical changes of the treated and raw sisal fibers were determined respectively using an atomic force microscope (AFM) with an XE-150 and X-ray diffractometer (XRD) PAN alytical X′Pert Pro MPD (Cu-Kα radiation generated by tube current 30 mA and voltage 40 kV at a scanning rate of 0.02º/sec in the 2θ range of 5 to 65º). Also, the sisal fiber microstructure pulled out from the mortar matrix was examined using a Hitachi model s-4800 scanning electron microscope (SEM).

Compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	P_2O_5	LOI
OPC	17.57	4.07	2.63	61.48	0.41	1.79	0.11	0.04	0.29	0.13	10.74
Calcined bentonite	58.30	10.93	8.05	7.75	6.00	0.10	2.36	3.49	0.91	0.21	2.18

Table 1. OPC and calcined bentonite chemical composition.

Sample name	W/C	Cement (Kg/m^3)	Sand (Kg/m^3)	Sisal fiber length (mm)	Sisal fiber dose	
					Raw (Kg/m^3)	Treated (Kg/m^3)
Control	0.5	591.36	1694	0	0	0
S1L10	0.5	585.45	1694	10	5.91	0
S1L20	0.5	585.45	1694	20	5.91	0
S1.5L10	0.5	582.49	1694	10	8.87	0
S1.5L20	0.5	582.49	1694	20	8.87	0
S2L10	0.5	579.53	1694	10	11.83	0
S2L20	0.5	579.53	1694	20	11.83	0
TS1L10	0.5	585.45	1694	10	0	5.91
TS1L20	0.5	585.45	1694	20	0	5.91
TS1.5L10	0.5	582.49	1694	10	0	8.87
TS1.5L20	0.5	582.49	1694	20	0	8.87
TS2L10	0.5	579.53	1694	10	0	11.83
TS2L20	0.5	579.53	1694	20	0	11.83

Table 2. The design mix for the preparation of mortar employed raw and treated sisal fibers at different fiber lengths and doses.

Fresh properties

The effect of treated and raw sisal fibers on mortar fresh bulk density is directly proportional to the capacity of the water absorbed in both fibers and the specific gravity of the fiber and cement. Therefore, the mortar fresh bulk density with different doses and lengths of treated and raw sisal fibers was conducted as ASTMC138M – 17a[42] by measuring the mass of the mortar sample at a known volume of one-liter cylinder. Additionally, mortar employing raw and treated sisal fibers at different doses and lengths was assessed for its workability, as stated in ASTM 1437[43].

Hardened properties

The flexural load is the ability of the material to bend and is a combination of tensile, compression, and shear loads. This means that when a flexural load is applied to the partition's center section shears, the bottom face is in tension, and the upper surface is in compression[44]. Therefore, the present study assessed the flexural strength of treated and raw sisal fibers reinforced mortars. This is using a three-point loading machine flexural strength test, and for the compressive strength test, a compressive machine at the rate of 1800 N/sec was used respectively done by 40*40*160 mm^{3}and 50*50*50 mm^{3}mortar specimens as ASTM C618[45]. The compressive and flexural strength tests for all the samples were measured at 28 and 56 days. For the flexural and compressive strength tests, for each mix design three samples were cured in water and recorded the average. Also, the residual compressive strength was measured again to assess the strength of the post-cracking mortar cube reinforced by the treated and raw sisal fibers.

The 50 mm^3 mortar specimen that was cured in 5% hydrochloric acid for 56 days was used to test the acid threat. The mass of the mortar cube was measured before and after acid immersion. After 56 days in the 5% HCl solution, the mortar specimen was removed and taken to dry for 24 h at ambient temperature, then the compressive strength test was carried out. The resistance of the mortar to acidic attack was determined by analyzing the cube mass loss and comparing its strength in an acidic environment to samples that were cured in water, as reported in reference[46].

In addition to this, alkaline and salt attack tests were carried out using 50 mm^3 mortar specimen reinforced with treated and raw sisal fibers submerged separately in 10% NaOH and NaCl solutions. After 56 days, the samples submerged in the alkaline and salt solutions were removed and allowed to dry for 24 h at room temperature. Subsequently, an investigation was conducted on the strength loss caused by salt and alkaline environments. Also, a 50 mm^3 mortar specimen that had been cured in water for 56 days was used to examine the effects of elevated temperatures. It was then placed in a furnace for two hours at 200 °C and 950 °C. Then, the recording of the mass variation before and after exposure to elevated temperatures, a compressive strength test was carried out.

Water absorption was also conducted after 56 days of the reinforced mortar by treated and raw sisal fibers using a specimen of 50 mm^3, which were removed from the water curing medium at 21 °C and kept until a constant weight was obtained in a dry oven at 105 °C as[47]. The lateral surfaces of the mortar specimens were coated with paraffin wax to ensure uniaxial water absorption and then immersed in water from the direction of the vertical uncoated face up to a depth of 5 mm. All mortar specimens with different doses and lengths of treated and raw sisal fibers were weighed before and after submerging for 5, 10, 15, 30, 60, 90, 120, and 150 min[48]. So, the percentage of water absorbed within the specified period was recorded for all samples.

Results and discussion
Sisal fiber treatment
The treatment of sisal fibers has been conducted by different researchers using alkaline methods, either NaOH or KOH. However, the alkaline method can reduce the mechanical strength of the fiber when soaked for a

long time[49,50]. Additionally, alkaline treatment may have drawbacks in terms of chemical disposal, which causes environmental pollution and requires the cost of chemical production[51]. However, bentonite is a natural pozzolanic material that is eco-friendly and mostly exists in many countries, which can be beneficial for the treatment of sisal fiber degradation. Therefore, the present study used calcined bentonite for the treatment of sisal fiber degradation, and the study found a water-to-binder ratio of 0.8 in various trials for a perfect mix design that can effectively cover the fiber surface, as shown in Fig. 2. However, Filho et al.[52] found that sisal fibers treated with metakaolin fully covered the surface of the fibers at a water-to-binder ratio of 0.4. As shown in Fig. 2, the treated sisal fiber has a red-gray color, which is mainly the color change from the calcined bentonite used for the treatment.

As shown in Fig. 1, the average of six single-fiber test results after wetting and drying is used for the comparison of raw and treated sisal fibers tensile strength. The results indicate that the treatment of the sisal fiber surface with calcined bentonite slurry has a higher tensile strength than the raw sisal fiber after undergoing 10-times wetting and drying cycles in hot water at 75 °C. This is mainly because the calcined bentonite-treated sisal fiber may not easily transfer water to the sisal fiber matrix due to bentonite-coated and free calcium hydroxide consumption can form C-S-H gel[53,54], which is a hard structure that protects the aging condition from hot water. Also, the treated sisal fiber coated with calcined bentonite slurry can fill the pores of the sisal fiber, which reduces water absorption, and consequently, sisal fiber resists the strength loss due to water absorption. This observation is similar to that of Wei and Meyer[55], who found that the treatment of sisal fibers with natural pozzolana improved the degradation resistance of the fiber. However, the tensile breaking load of raw sisal fiber is lower than the treated sisal fiber after 10 times wetting and drying cycles, which is mainly due to raw sisal fiber has higher water absorption capacity which can degrade its strength[56,57]. Besides these, the extension at break of the treated sisal fiber was lower than that of the raw sisal fiber, which may be due to the coated slurry not allowing elongation of the fiber.

The XRD result of sisal fiber

The mineralogical composition result for raw and treated sisal fibers is shown in Fig. 3. As a result indicates, the peaks at 16° and 20° are reduced in the treated sisal fiber compared to raw sisal fiber, which is basically due to the peaks at 15–16°can represent lignin, hemicellulose, and pectin[58] that lessened by the treatment of sisal fiber through calcined bentonite slurry. Also, for the raw and treated sisal fibers peaks at 22° and 23° have very similar spectra, which represents cellulose[59]. In addition to this, the peak at 30° only exists on the treated sisal fiber that is clay mineral quartz SiO_2 at 30–35°[60], which is directly from the calcined bentonite slurry used for sisal fiber treatment. Similarly, peaks at points 36°, 40°, and 44° are only observed in the treated sisal fiber, which is also from calcined bentonite respectively representing calcium carbonate, quartz, and montmorillonite[54]. Hence, it is observed due to all additional minerals in the calcined bentonite treated sisal fiber it can protect fiber surface from moisture absorption and react actively with free lime from the cementing material matrix, produce extra CSH that can mitigate the aging of the sisal fiber.

The roughness of sisal fiber

To establish good bonds between cement composite materials and sisal fibers, the roughness of the sisal fiber is the main property. As shown in Fig. 4, the raw sisal fiber varies from − 250 nm to + 750 nm and the treated sisal fiber from − 1000 nm to + 1000 nm, indicating that the treated sisal fiber has a rougher surface than the raw sisal fiber, which is mainly due to the coated slurry used for the treatment. Hence, the rougher treated sisal fiber surface is beneficial to strengthen the bond and adhesion of the fiber with the cement composite matrix. This observation is the same as that of Orue et al.[61], who found that treated sisal fiber had a rougher surface than raw sisal fiber.

Microstructure

The microstructure results for the pulled-out treated and raw sisal fibers from the cement composite matrix are shown in Fig. 5(a-d). As a result indicates, the pulled-out raw sisal fiber from mortar has very low damage; however, the treated sisal fiber has higher damage on the surface of the fiber and is more susceptible to pull-out from the cement composite. Hence, the higher damage indicates that a higher interface bond occurred between the fiber and cement composite matrix for the treated sisal fiber than for the raw sisal fiber. This is the same observation as Orue E. and Arbelaiz[63] found an easy pull-out force for untreated sisal fibers owing to poor interfacial adhesion between the fiber and cement composite. In addition, the study found that it was challenging to distinguish the treated sisal fibers from the cement composite material matrix. This further indicates the improvement of the fiber surface bonding with the cement composite owing to the treatment.

Mortar workability

The results of the mortar workability employed the raw and treated sisal fibers are presented in Fig. 6. The results indicate that the use of raw and treated sisal fibers in mortar reduces the mortar workability. Specifically, the use of raw sisal fibers in mortar significantly reduces mortar workability. This is due to the high water absorption of the raw sisal fiber, which reduces the water level of the mortar. In addition, increasing the raw sisal fiber dose in mortar reduces the water level and, consequently, the mortar workability.

Besides these, the use of treated sisal fibers in mortar reduces mortar workability. This is because the sisal fiber treated with calcined bentonite slurry reduced sisal fiber water absorption by 60.95% compared to raw sisal fiber[62]. Hence, the remaining can cause a reduction in the water level and consequently lessen the mortar workability. However, it was observed that the length variation with the employment of sisal fibers did not significantly change the mortar workability. These results are similar to Shah et al.[64] found the employment of sisal fiber in concrete significantly reduced the workability.

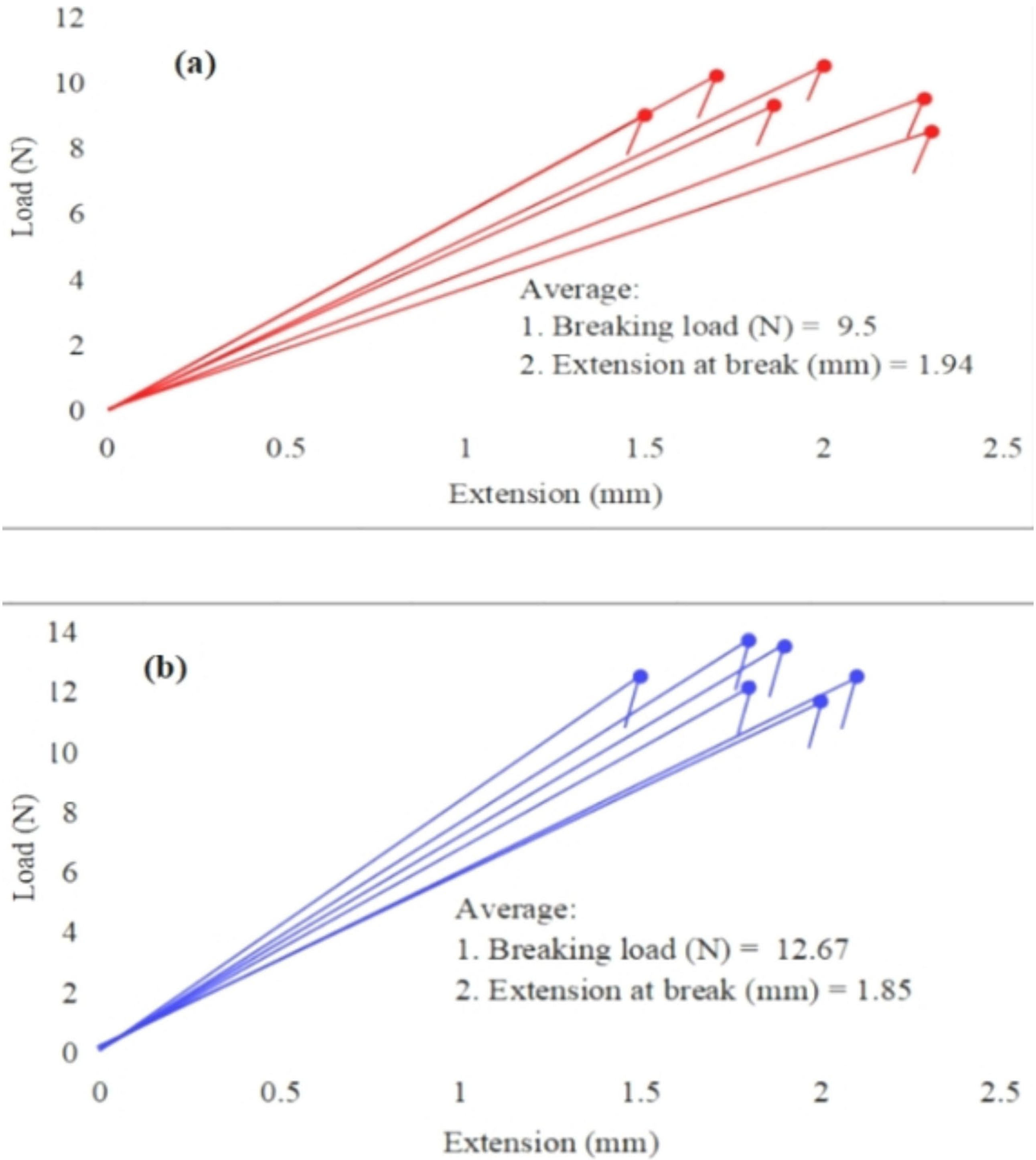

Fig. 1. Single fiber breaking load and extension at break for (a) raw sisal fiber and (b) treated sisal fiber after 10 times wetting and drying.

Density of fresh mortar

The fresh bulk density results for mortar with different doses and lengths of treated and raw sisal fibers are shown in Fig. 7. The results indicated, reinforcing cementing materials with treated and raw sisal fibers significantly decreased the fresh bulk density compared to the conventional mixture. Especially, increasing the dose and length of the treated and raw sisal fibers reduces the density of fresh mortar. This is mainly because the density of sisal fibers is much lower than that of cementing materials[65]. Also, there is a variation in the fresh bulk density with increasing fiber dose in the mortar mixes. Specifically, increasing the length of the raw and treated sisal fibers decreased the fresh bulk density. Besides these, increasing the dose of raw and treated sisal fibers reduced

Fig. 2. The color difference of used treated and raw sisal fibers.

the bulk density of fresh mortar. This is basically due to the sisal fiber having a lower density compared to the mortar compositions.

A similar observation by Achour et al.[66] reported that increasing the reinforcing doses of natural fiber in mortar significantly reduced the density of cementitious materials. However, the present study discovered that reinforcing the cement composite material with calcined bentonite slurry-treated sisal fiber slightly reduces the fresh bulk density compared to employing raw sisal fiber. That is basically due to the calcined bentonite having lower specific gravity than cement particles which can replace the position of cement particles while coating the sisal fiber consequently lessens the fresh mortar density[67].

Compressive strength

As shown in Fig. 8, the use of treated and raw sisal fibers in mortar improved the compressive strength compared to the control mixture at 28 days of mortar age. This is because employing treated and raw sisal fibers in mortar can tighten the mortar matrix, paste, and sand together, which can provide a higher strength than the control mixture. Similar results were reported by Asaduzzaman & Islam; Sridhar et al.[68,69] found that all sampled jute fibers employed cement composite exhibited greater compressive strength than the control mixture. However, in the present study, the addition of raw sisal fiber reduced the compressive strength at 56 days compared to the control mixture. Furthermore, the reduction of compressive strength significantly increases with the increasing of the doses and the lengths of raw sisal fiber at both 28 and 56 days of mortar age. This is because raw sisal fiber is moisture-sensitive and loses its initial strength in the cement composite[56,70–72]. Also, this may be because the raw sisal fiber employed in the mortar mixture absorbs water after water curing for 28 and 56 days. Hence, owing to the absorbed water, the fiber can lose strength and lessen the bond, which can tighten the mortar matrix.

Also, its observed increased compressive strength of mortar employed treated sisal fiber compared to the control mixture at 28 and 56 days of mortar age. This is because the treated sisal fiber can resist moisture and mineralization owing to the cement alkaline part, which cannot lose strength, while the age of the mortar increases. The substitution of treated sisal fiber TS1L10 resulted in the highest compressive strength at both 28 and 56 days. Hence, TS1L10 improved the compressive strength by 30.62% and 1.8% compared to the control mixture at 28 and 56 days, respectively. The same observation with Abirami & Sangeetha[39] found the highest compressive strength of cement composite material by reinforcing 1% of chemically treated sisal fiber. However, as the result indicates for both 28 and 56 days compressive strength of treated sisal fiber lengths 10 and 20 mm not seen a significant difference in the strength changes, which may be due to fibers being ductile materials that more resist tensile force than compressive. This observation is similar to that of Nasr et al.[73], who found a significant change in tensile strength compared to compressive strength owing to fiber size and dose variations.

Furthermore, as shown in Fig. 9, the residual compressive strength of mortar employed sisal fiber was significantly higher than that of the control mixture. However, the addition of raw sisal fiber in mortar resulted in a lower compressive strength than that of the treated sisal fiber-reinforced mortar. This shows the strength degradation of the raw sisal fiber, which has a lower strength than the treated sisal fiber[74]. Hence, the employment of TS1L10 in mortar has the highest residual compressive strength than all the samples. In addition, TS1L10 improved mortar residual strength by four times that of the control. This is mainly because the surface coating of sisal fibers modifies the structural and surface properties of the fiber without transforming the chemical

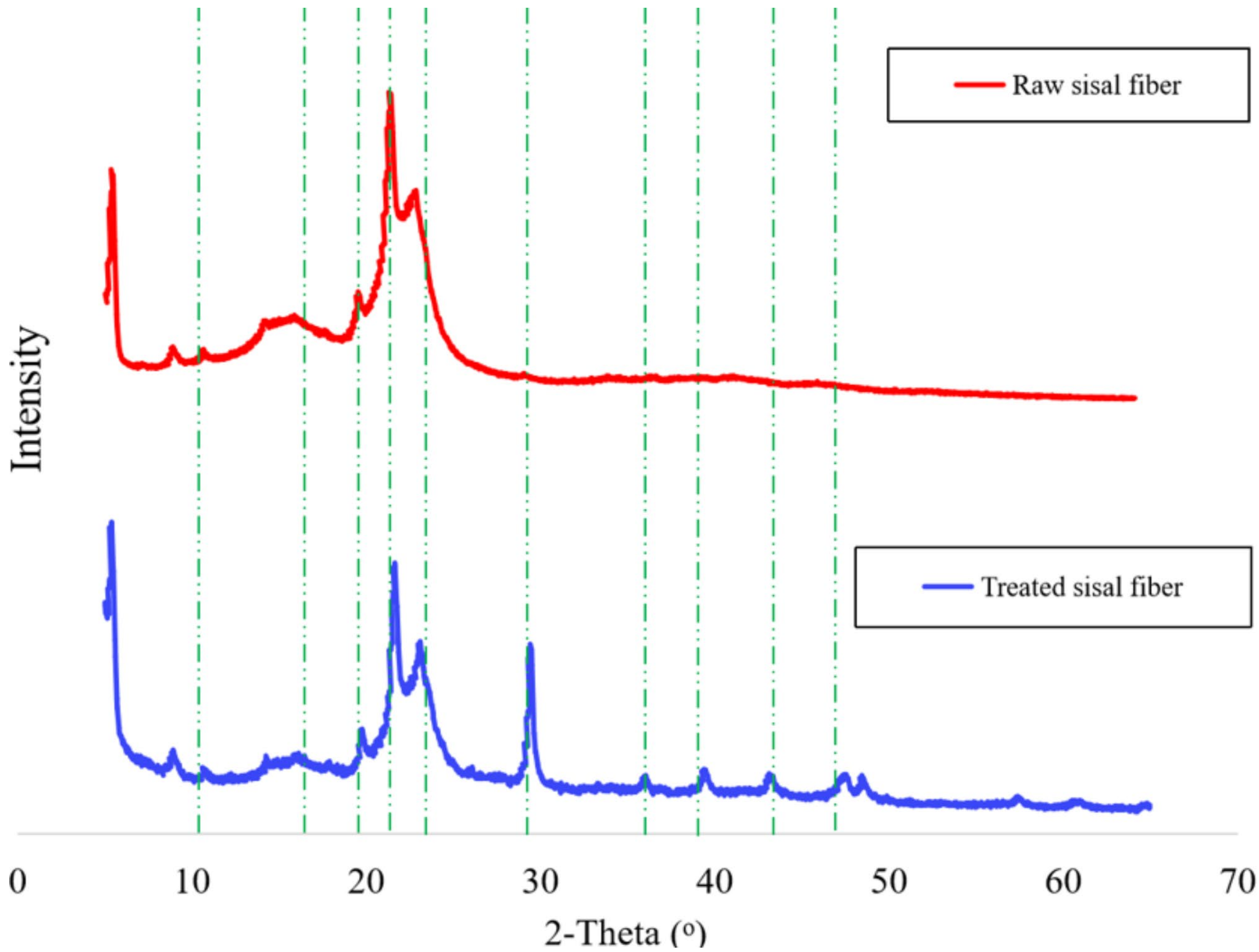

Fig. 3. The mineralogical composition of treated and raw sisal fibers.

composition, which can improve the mechanical properties through good adhesion bonds with the fiber and cement matrix[75,76].

Besides these, Fidelis et al.[77] observed that the surface coating of natural fiber by pozzolanic materials can lessen the alkalinity of the cement matrix owing to the pozzolanic reaction, and the hydration product fills the pores of the fiber interphase and the matrix. Hence, it reduces the total porosity of the composite and consequently, improves the mechanical properties while reducing the deterioration of the fibers due to cement alkalinity and mineralization.

Flexural strength

The flexural strength test results for mortar employed treated and raw sisal fibers with different doses and lengths are shown in Fig. 10. The results indicated that the use of both treated and raw sisal fibers improved the flexural strength of the cement composite materials at 28 days compared to the control mixture. That is, fibers are more ductile than cementitious materials, which improves the bending strength of the cement matrix[78,79]. However, at 56 days of mortar age, the flexural strength of the raw sisal fiber-reinforced mortar reduced compared to the respective mortar strength at 28 days and significantly reduced with increasing doses and lengths of the fiber. This is one of the main challenges in reinforcing raw natural fibers in cement composite materials, which can lessen the durability of the composite at longer ages by losing the initial strength due to deterioration. Also, the raw sisal fiber aging process by humidity causes a reduction in alkaline resistance, higher absorbance of humidity, and mineralization of cement composite materials, which consequently can affect the matrix strength[75].

Furthermore, the use of treated sisal fibers in mortar improved flexural strength compared to the control mix and raw sisal fiber-reinforced mortar sample. This is because the treated sisal fiber has a higher tensile strength than the raw fiber, which can increase the mortar strength, as shown in Sect. 2. In addition, the interphase bond between the fiber and cement composite matrix improved by surface coating, as shown in Sect. 3.1.2, which mainly increased the flexural strength of mortar employed treated sisal fiber[55]. Thus, it was found that TS1.5L20 had the highest flexural strength at 56 days, which improved by 12.35% and 10.33% compared to the control mixture, respectively, at 28 and 56 days of age. This result is similar to that of Veigas et al.[30], found the sisal fiber improves the flexural strength of cement composite while increasing the length and dose compared

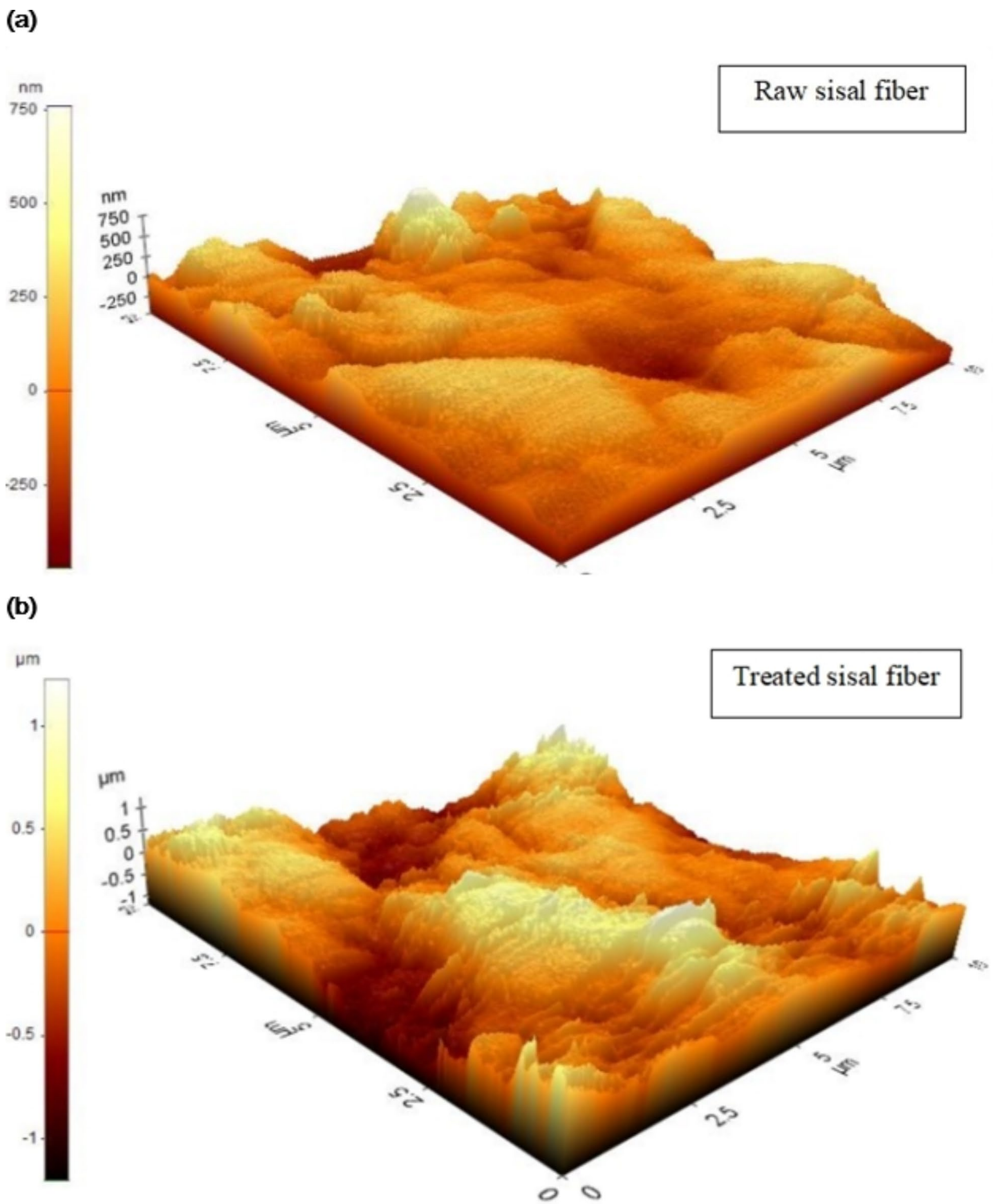

Fig. 4. Surface roughness of raw and treated sisal fibers using atomic force microscope[62].

with the control mixture. However, increasing the treated sisal fiber dose and length, especially for TS1.5L20 and TS2L20, significantly reduced the flexural strength, which may be due to the sisal fiber is a ductile material, which increases the deformation of the cement composite material while increasing the dose and length of the fiber. This is the same observation as that of Tiwari et al.[80], who found a decrease in flexural strength with an increase in the fiber dose.

Generally, the results indicated that the use of raw sisal fiber can affect the flexural strength more than the compressive strength of the mortar, which shows that the employment of raw sisal fiber reduced the flexural

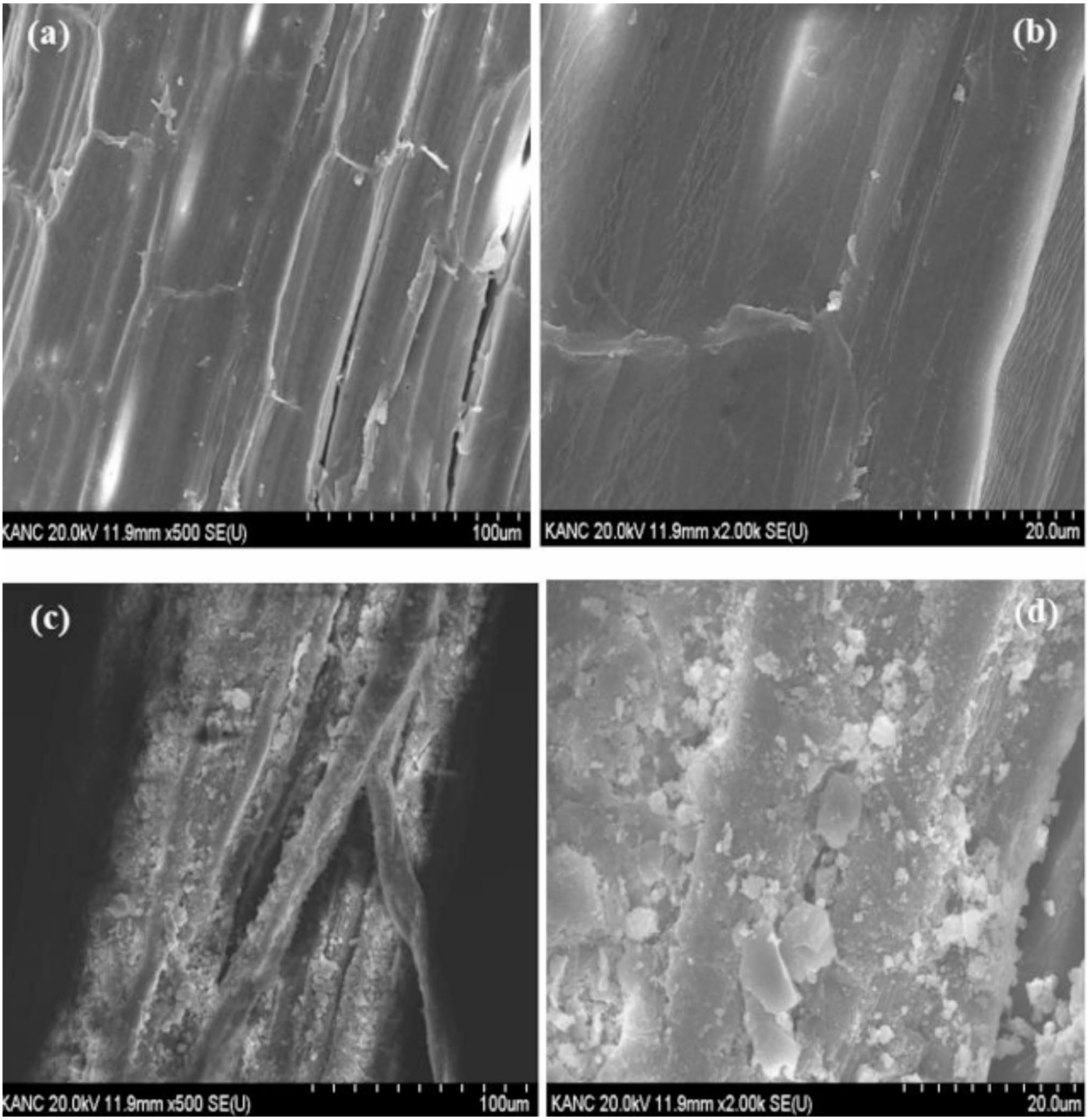

Fig. 5. The microstructure for (a) raw sisal fiber, (b) magnified shown at (a), (c) treated sisal fiber, and (d) magnified shown at (c), all after pulled-out from the mortar matrix.

strength more at 56 days. In addition, the length variation has a significant effect on the improvement of flexural strength compared to the compressive strength of mortar, this is because when the length increases, the capability to resist deformation increases. Rai and Joshi[44] reported that reinforcing natural fibers has a greater effect on the flexural and tensile strength of cement composite materials.

Acidic attack

The strength of the mortar cubes after immersion in 5% hydrochloric acid are shown in Fig. 11. The results indicate that the addition of treated and raw sisal fibers in the mortar improved strength in the 5% HCl solution cured for 56 days compared to the control mixture. This is commonly due to the employed sisal fiber tie and compact mortar matrix that mitigates the entrance of acid, which cannot affect the strength. However, all the additions of raw sisal fiber had a lower strength resistance in 5% HCl compared to the respective dose and length of the treated sisal fiber employed mortar. This is because, as Wei and Meyer[55] found, the treatment of sisal

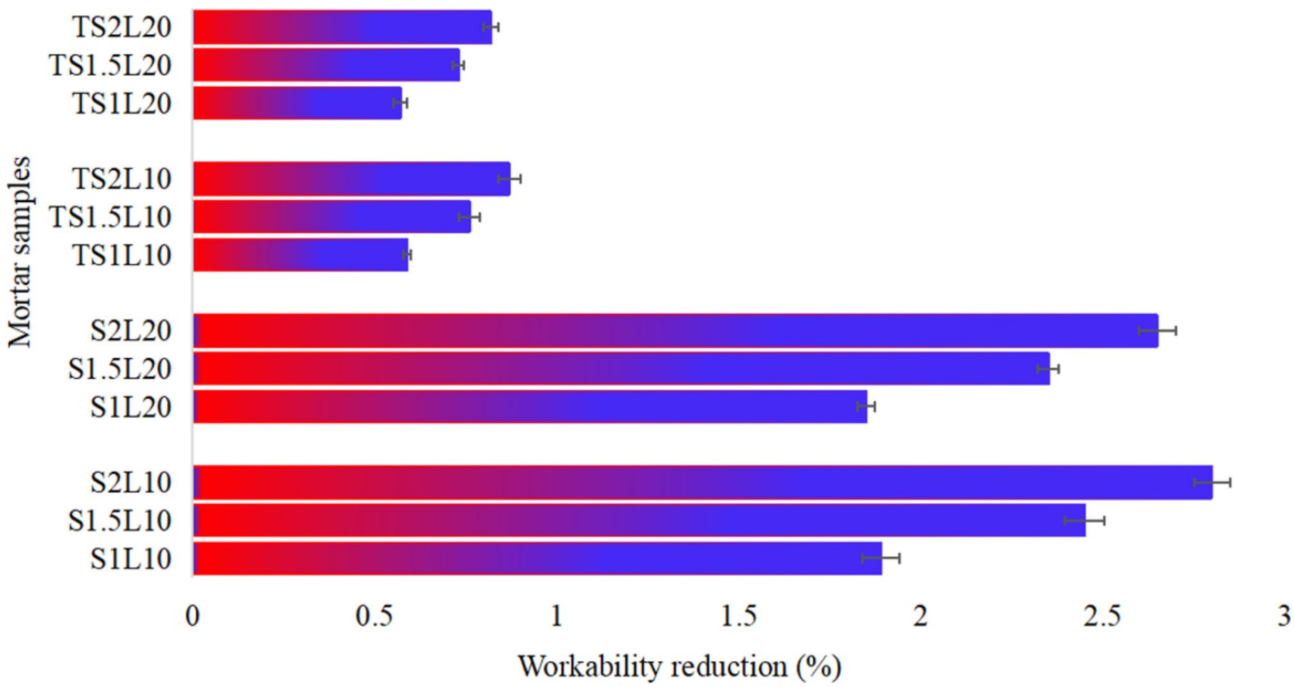

Fig. 6. Workability of mortar reinforced by raw and treated sisal fibers.

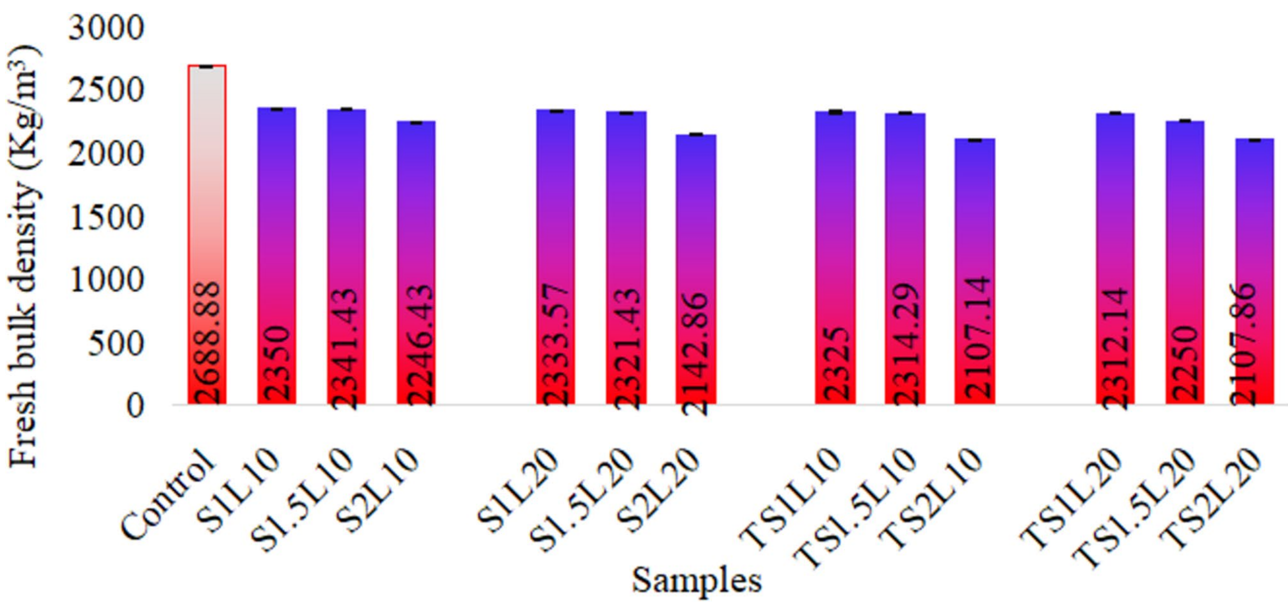

Fig. 7. The fresh density of mortar reinforced by treated and raw sisal fibers.

fiber by pozzolanic materials effectively enhances the adhesion between the cement matrix and sisal fiber, and consequently, can barrier the entrance of acid to the cement composite matrix.

Besides these, all the mortar residues reinforced by treated and raw sisal fibers cured for 56 days in a 5% HCl solution had higher strength than the control mixture. However, the treated sisal fiber-reinforced cement material residue significantly improved the strength owing to immersion in the 5% HCl solution. Hence, TS1L10 enhanced the strength by 54.54% and 72.25%, respectively, compared to the strength and residual strength in the 5% HCl solution. This is because the treated sisal fiber cannot be easily degraded by moisture and mineralization of cementing materials[81]; hence, the strength of the acidic attack is higher than that of the control mixture. Additionally, it has been observed that increasing the doses and lengths of sisal fiber employed in the mortar cannot improve the strength resistance of the acidic attack, possibly because, while increasing the fiber dose, the binding of the cementing materials can decrease.

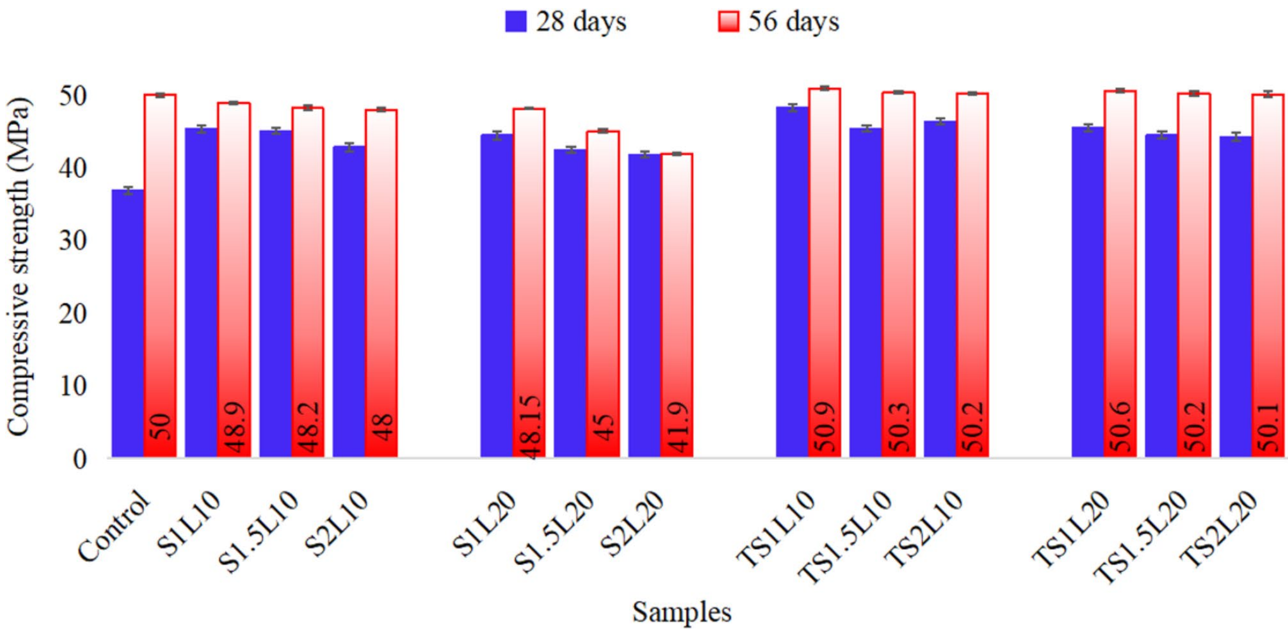

Fig. 8. Compressive strength of mortar employed treated and raw sisal fibers at 28 and 56 days.

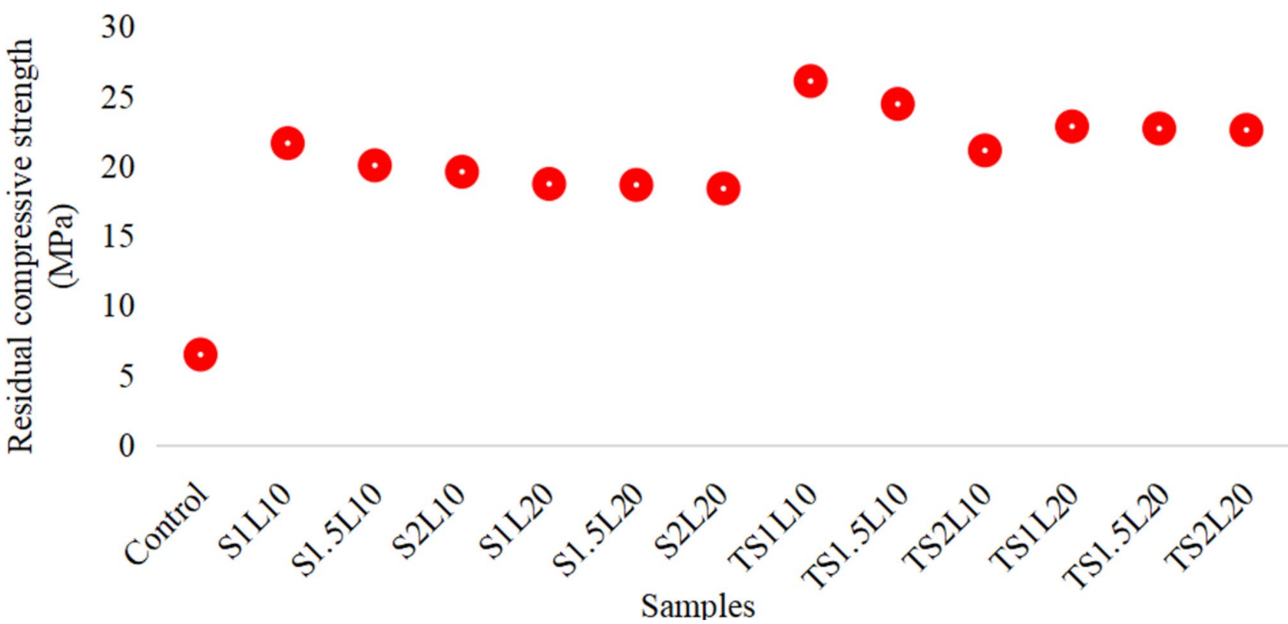

Fig. 9. The residual compressive strength of mortar having treated and raw sisal fibers at 56 days.

The mass loss due to immersion in 5% HCl for 56 days is shown in Fig. 12. The mass loss of the treated and raw sisal fiber-reinforced cement composite materials was lower than that of the control mixture. However, the mortar mass loss due to the use of raw sisal fiber was higher than that of the treated sisal fiber. This could be because the raw natural fiber can increase in volume owing to the high water absorption and moisture sensitivity of the fiber surface. Hence, this leads to a poor fiber–matrix interface that reduces the adhesion of the fibers to the matrix, so that acids can penetrate into the composite matrix, which can deteriorate and reduce the mass of the cement composite materials[82].

In addition to this, the mass loss of mortar decreased by the reinforcement of treated and raw sisal fibers after 24 h taken from a 5% HCl solution. However, higher mass loss in 24 h dry in the atmosphere while increasing the doses and lengths of employed sisal fiber. This indicates the existence of voids while increasing the doses and lengths of the fiber, which may be caused by the lack of binding of the fiber and the cement matrix at higher substitution. However, the cementing material reinforced by the treated and raw sisal fibers had a lower mass loss

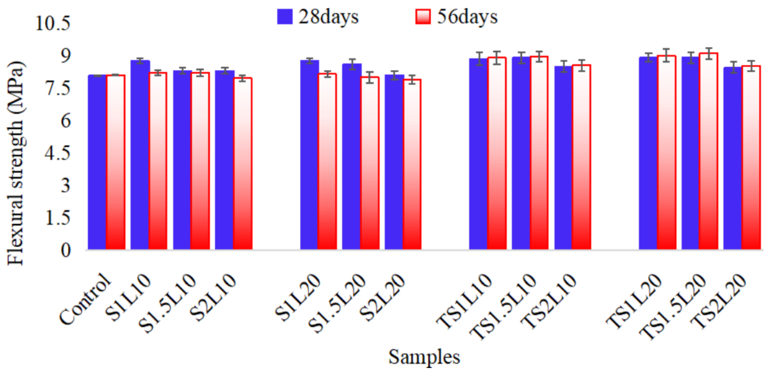

Fig. 10. The flexural strength of mortar incorporated treated and raw sisal fibers at 28 and 56 days.

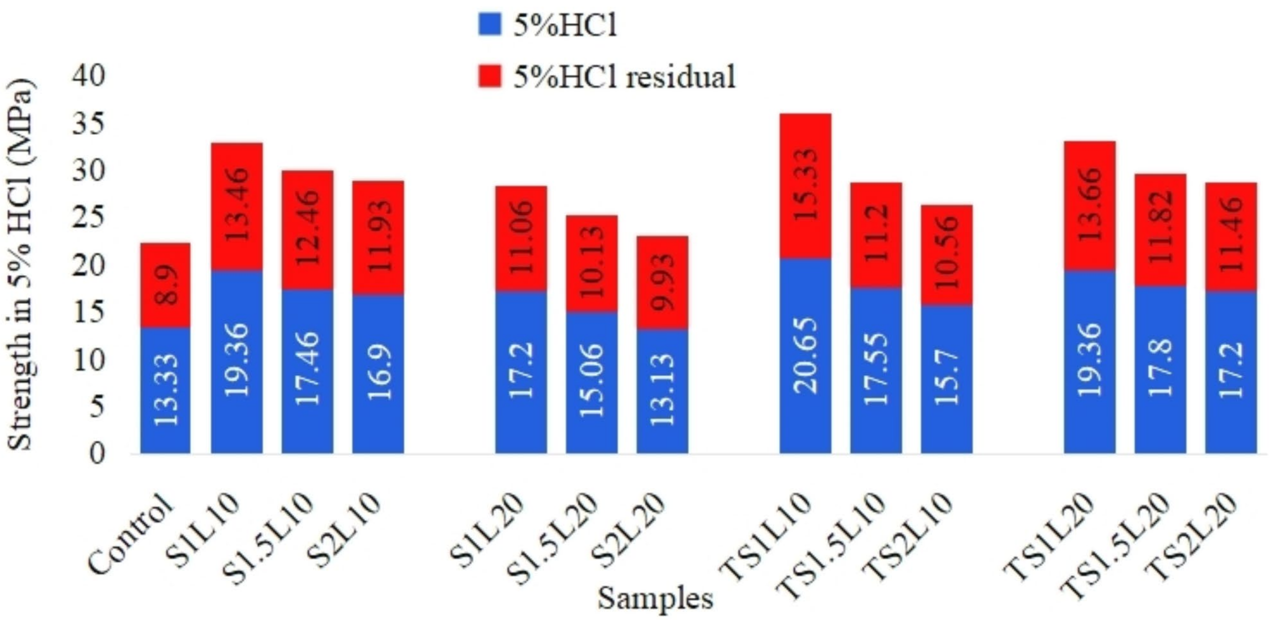

Fig. 11. The strength of mortar cube at 56 days in 5% HCl solution.

compared to the control mixture. This is because of the adhesion and reinforcing effect of the fibers on cement composite materials.

Alkaline attack

The result of 10% NaOH solution effect on mortar cubes reinforced with treated and raw sisal fibers, which have different doses and lengths cured for 56 days is shown in Fig. 13. The results indicate that the reinforcement of mortar with raw sisal fiber reduces the strength compared to the control mixture. This is because raw sisal fiber is a hydrophilic material that can absorb the alkaline solution and water into the cement composite matrix, consequently reduces its strength[83].

Also, the use of treated sisal fiber slightly improved the strength in the 10% NaOH solution compared with the control mixture and reinforcement of raw sisal fiber in mortar. In particular, TS1L10 had the highest strength in 10% NaOH solution from all the samples and improved strength in alkaline conditions by 5.8% compared to the control mixture. This is because the treated sisal fiber can effectively form a bond with the cement matrix, which can mitigate the entrance of alkaline and water to the matrix of the cement composite material and consequently, reduce the effect of alkalinity on strength loss.

Salt effect

The results of the mortar cubes reinforced with treated and raw sisal fibers immersed in a solution of 10% NaCl for 56 days are shown in Fig. 14. As a result shows, a lower strength loss with the addition of treated and raw sisal fibers in the mortar compared to the control mixture. However, the reinforcement of treated sisal fibers can reduce more the strength loss of cement composite materials. This is because the treated sisal fiber can form a good interface bond between the fiber and cement composite matrix[84,85]. Also, as seen in Sect.

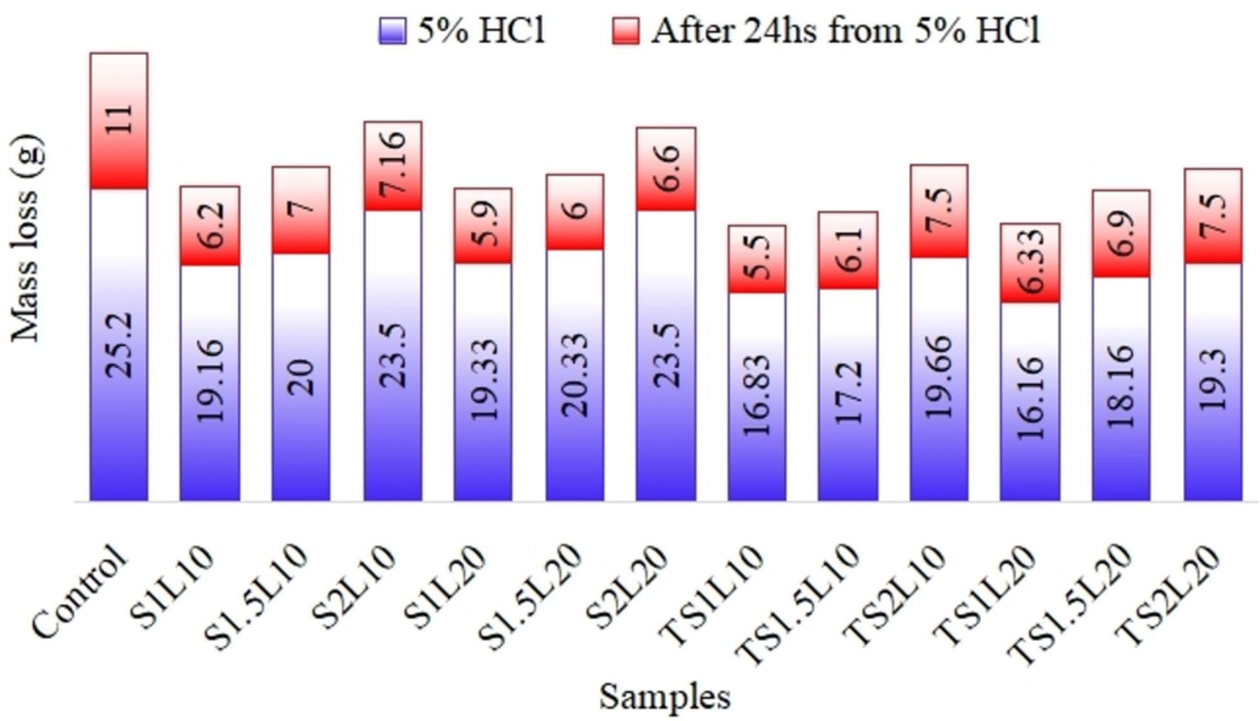

Fig. 12. The mass loss of mortar cube at 56 days in 5% HCl and after 24 h taken from 5% HCl.

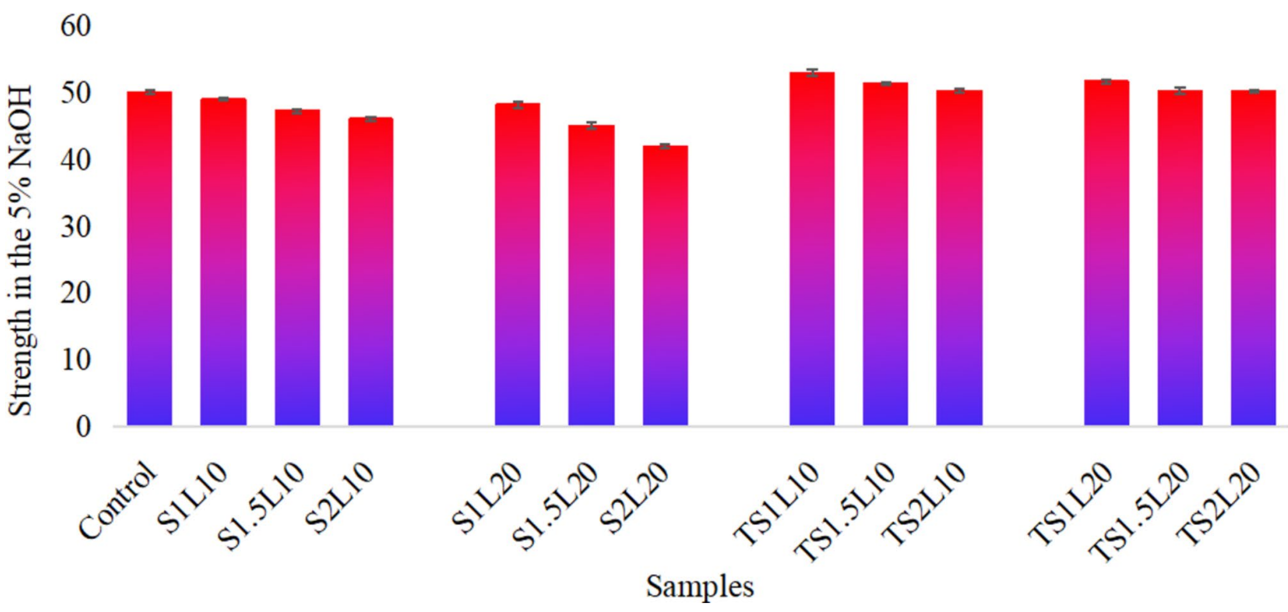

Fig. 13. The strength of mortar cube at 56 days in 10% NaOH solution.

3.1.2, the surface of the treated sisal fiber is rough, which can form a good bond between the fiber and cement composite matrix that can barrier the entrance of the salt solution. Similarly, Filho et al.[52] found that the sisal fiber with the pozzolanic material meta-kaolin formed a strong interface bond in the cement composite material. Furthermore, the same finding as Bao et al.[86] reported that the reinforcement of sisal fibers in concrete highly resists the effect of seawater owing to salt and shrinkage cracks. Hence, the study found that the lower migration of 10% NaCl into the matrix of cement composite materials; consequently, the corrosion rate of the concrete can be improved in the marine environment.

Additionally, the treated and raw sisal fibers reinforced mortar residues exhibited greater resistance to the 10% NaCl solution cured for 56 days. However, a higher sisal fiber substitution cannot provide resistance to the salt environment. This is mostly because a higher fiber dose can lessen the binding, which lowers the strength.

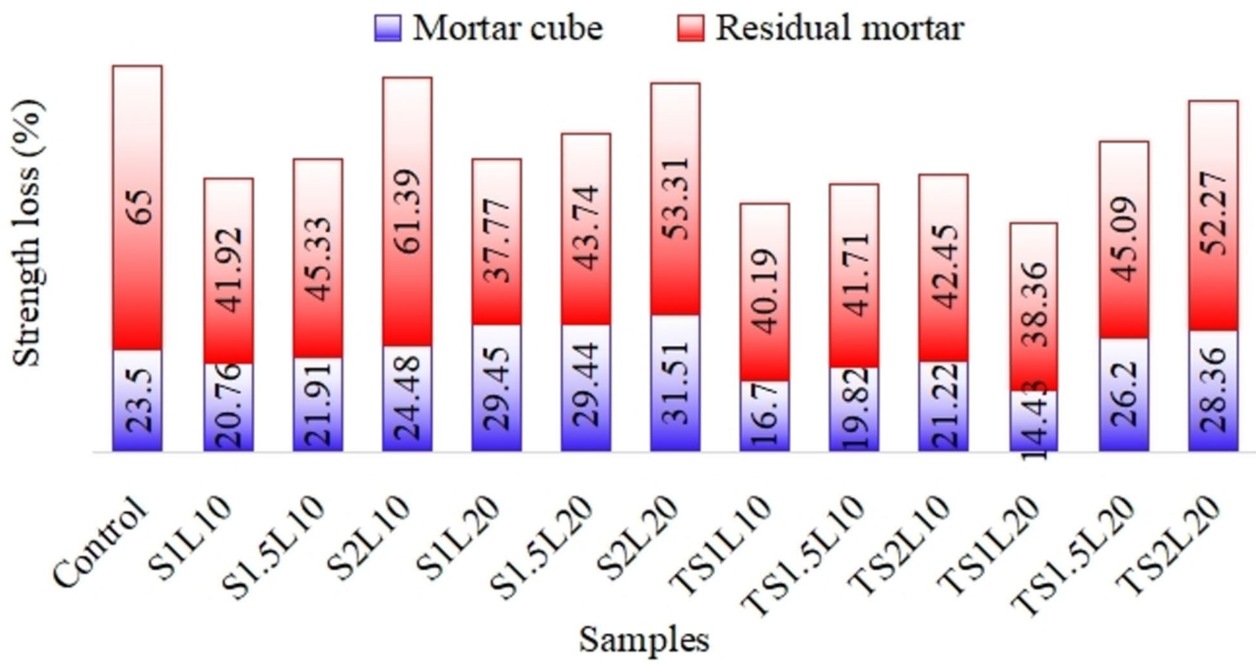

Fig. 14. The strength of mortar cube at 56 days in 10% NaCl solution.

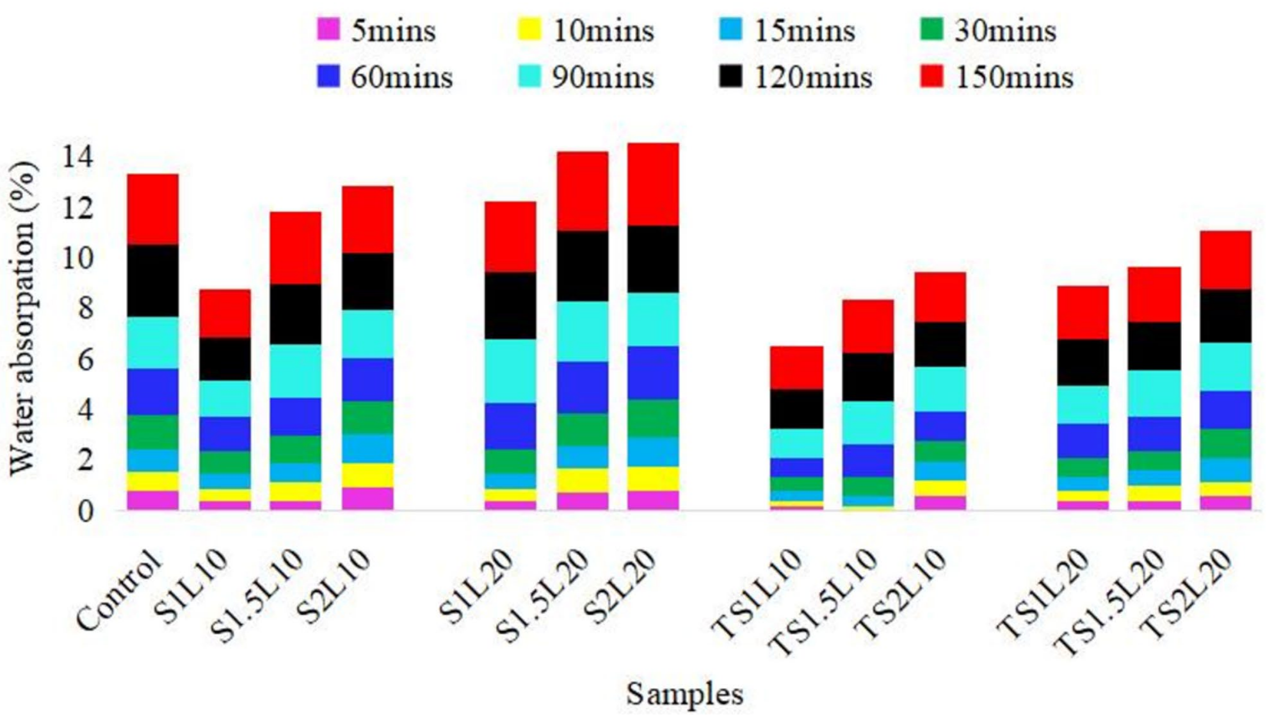

Fig. 15. The water absorption of mortar incorporated treated and raw sisal fibers.

Water absorption

The water absorption results for mortar cubes reinforced with treated and raw sisal fibers at different doses and lengths are shown in Fig. 15. The water absorption of mortar reinforced by raw sisal fiber at lower substitution is significantly lower than that of the control mixture; however, the employment of raw sisal fiber at a higher dose reflects higher water absorption. This is because the raw sisal fiber is moisture sensitive and can absorb much water; hence, a higher substitution increases the water absorption in the raw sisal fiber-embedded cement composite materials. However, the reinforcement of mortar by the treated sisal fiber can resist the absorption of water. This is because the treated sisal fiber enhances the interfacial adhesion bond between the fiber and the cement matrix, thus mitigating the penetration of water[84,85]. Additionally, this is due to the quantity reduction in the amorphous materials present on the natural fibers covered by physical treatment, which reduces the water absorption by making a rough surface, which can enhance the adhesion between the fiber and the composite matrix[66].

Effect of elevated temperature

The strength of mortar cubes reinforced with the treated and raw sisal fibers exposed to an elevated temperature of 200 °C for 2 h is shown in Fig. 16. As results indicate, all the reinforced mortar samples with treated and raw sisal fibers had reduced strength at elevated temperatures compared to the control mixture. This is because natural fibers can easily lose weight at high temperatures, which consequently reduces the strength of the reinforced mortar. Hence, increasing the doses of both the treated and raw sisal fibers in the cementing material can reduce the strength at elevated temperatures. However, the use of treated sisal fibers improves the strength at elevated temperatures compared to the addition of raw sisal fibers to cement composite materials. This is mainly because the treated sisal fiber is coated with slurry, which cannot be easily affected by elevated temperatures.

The mass loss results for mortars employing raw and treated sisal fibers at elevated temperatures of 200 °C and 950 °C for 2 h are shown in Fig. 17. The results indicate that the use of treated sisal fibers in cement composite materials can slightly reduce the mass loss compared to the control mixture and raw sisal fiber employed mortar at an elevated temperature of 200 °C. However, at 950 °C, all treated and raw sisal fibers significantly lost their mass compared to the control mixture. This was mainly due to sisal fiber dehydroxylation/decomposition at 950 °C, which directly reduced the mass of the fiber-reinforced mortar. In addition, it is observed that the treated sisal fiber-employed mortar has a lower mass loss than that of raw sisal fiber.

Residual analysis

As shown in Fig. 18, the residuals of the control mix and sisal fiber-reinforced mortar after the compressive strength test were significantly different. As shown in Fig. 18(a-c), the residual of the control mortar without fiber is fractured from all its face by the V-shaped pattern taken from our previous study[54]. However, after the compressive strength test, the sisal fiber-reinforced mortar exhibited very small cracks, as shown in Fig. 18b, and the residue was again taken for the compressive strength. Small increases in the width of the cracks were observed; however, the faces of all the mortar cubes were not fractured, as indicated in Fig. 18c. This is because of the fiber ductile behavior, which ties the cement matrix from the fracture and reduces the number and width of cementitious material cracks[87,88]. This shows the most beneficial part of the sisal fiber reinforcement in cement composite materials, which can significantly reduce the occurrence of cracks and lessen the sudden fracture of cementing materials compared to conventional cement composite materials.

In addition to this, the same advantage in the acidic environment is shown in Fig. 18(d-f): the conventional mortar without fiber loss mass due to the compressive strength test and broken into two at the middle part; however, the sisal fiber-reinforced mortar did not lose any mass due to the compressive strength test and had very small cracks. Also, the residue was exposed to the compressive strength test again, as shown in Fig. 18e; it only increased the crack width, unless it was not broken apart as in the control mixture. This is due to the fiber employment in cement composite materials, which improves the ductility and load-carrying capacity at post-cracking[44].

Generally, the addition of calcined bentonite-treated sisal fibers in mortar improves the mechanical and durability properties. In addition, surface-coated sisal fiber is inexpensive and simple method to enhance the

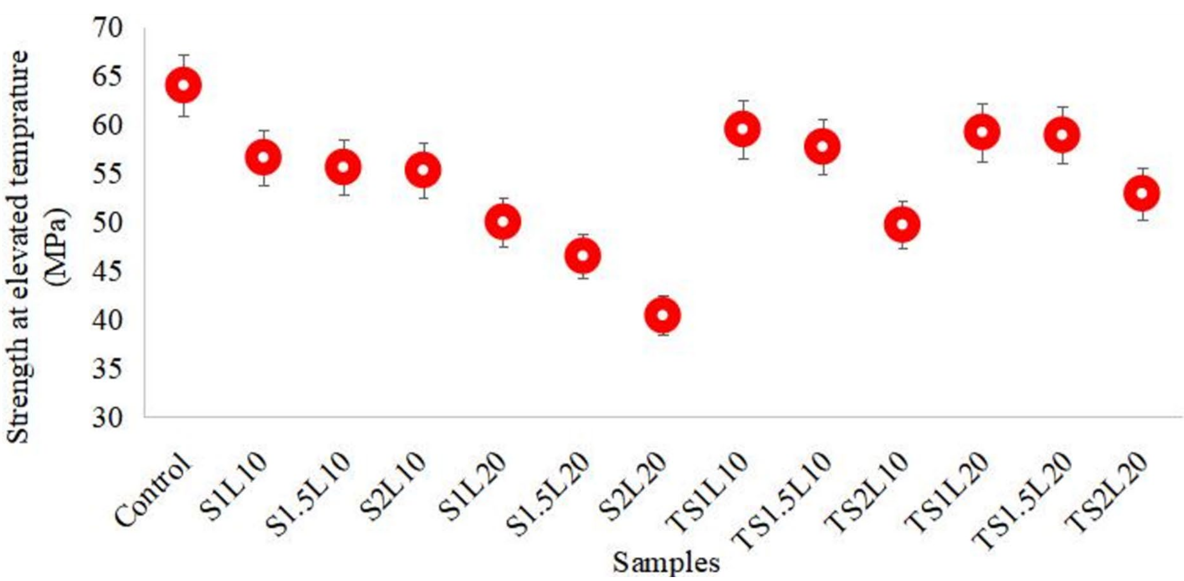

Fig. 16. Strength at elevated temperature for mortar cube reinforced by treated and raw sisal fibers.

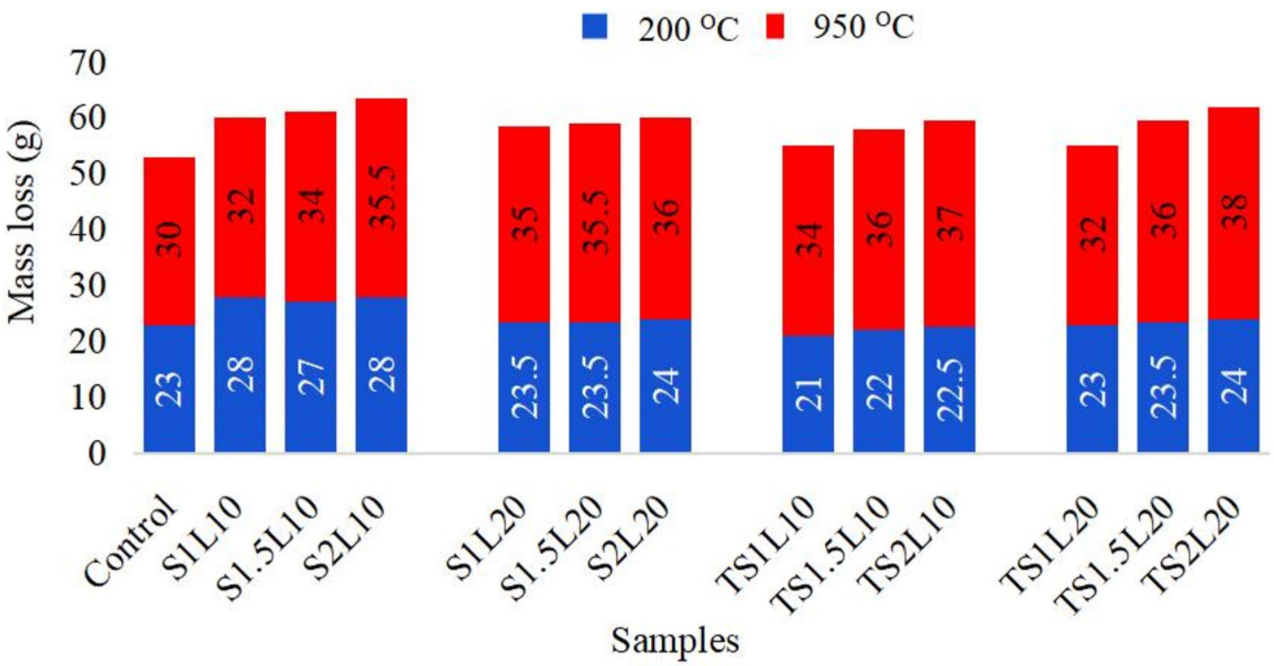

Fig. 17. The mass loss by elevated temperature for mortar cube having treated and raw sisal fibers.

mechanical and durability properties of fiber-reinforced cement composite materials[89]. Therefore, from the present study broadly seen, calcined bentonite slurry treated sisal fiber can be effectively implemented in the cement composite material, especially for the application of reinforcing cement based mortar production.

Conclusions

This study investigated the effect of reinforcing mortar using treated and raw sisal fibers with different lengths and doses on the physical and mechanical properties of cement composite materials. In particular, reinforcing mortar by treated and raw sisal fibers with different doses and lengths in various adverse environments was also assessed, and the following conclusions were reached.

- The reinforcement of mortar with treated and raw sisal fibers significantly reduced the fresh bulk density and workability compared to the control mortar mixture. In particular, increasing the dose and length of the treated and raw sisal fibers decreased the fresh density compared to the control mixture.
- The use of treated and raw sisal fibers improved 28 days compressive and flexural strengths of cement composite materials compared to the control mixture. However, the addition of raw fiber in the mortar reduced the compressive strength compared to the control mixture at 56 days of mortar age. Also, mortar compressive strength significantly reduced with increasing the dose and length of raw sisal fiber. The substitution of treated sisal fibers TS1L10 and TS1.5L20 had the highest compressive and flexural strength, which improved by 30.62% and 1.8% for compressive strength, and 12.35% and 10.33% for flexural strength, respectively, at 28 and 56 days compared to the control mixture.
- The addition of treated sisal fiber in mortar improved strength resistance in 5% HCl compared to the respective dose and length of the raw sisal fiber employed in mortar. Also, the use of treated sisal fibers reduced water absorption and improved the strength in 10% NaOH and NaCl solutions compared with the control mixture and reinforcement of raw sisal fibers in mortar.
- The reinforcement of mortar by treated and raw sisal fibers reduced the strength at 200 °C elevated temperature compared to the control mixture. In addition to this, at 950 °C, all treated and raw sisal fibers significantly lost mass compared to the control mixture.
- The residual of the control mortar cured in water was fractured from all its faces in a V-shaped pattern. However, after the compressive strength test, the sisal fiber-reinforced mortar exhibited very small cracks. Also, after the second strength test of the mortar residue, the specimen increased in the width of the cracks, but still not fractured.

Generally, the study observed many advantages of calcined bentonite-treated sisal fiber employment in mortar for the durability, physical and mechanical properties. In particular, reinforcing treated sisal fiber can resist various adverse environments, such as acidic, alkaline, and salt environments, and reduce water absorption compared to the control mixture.

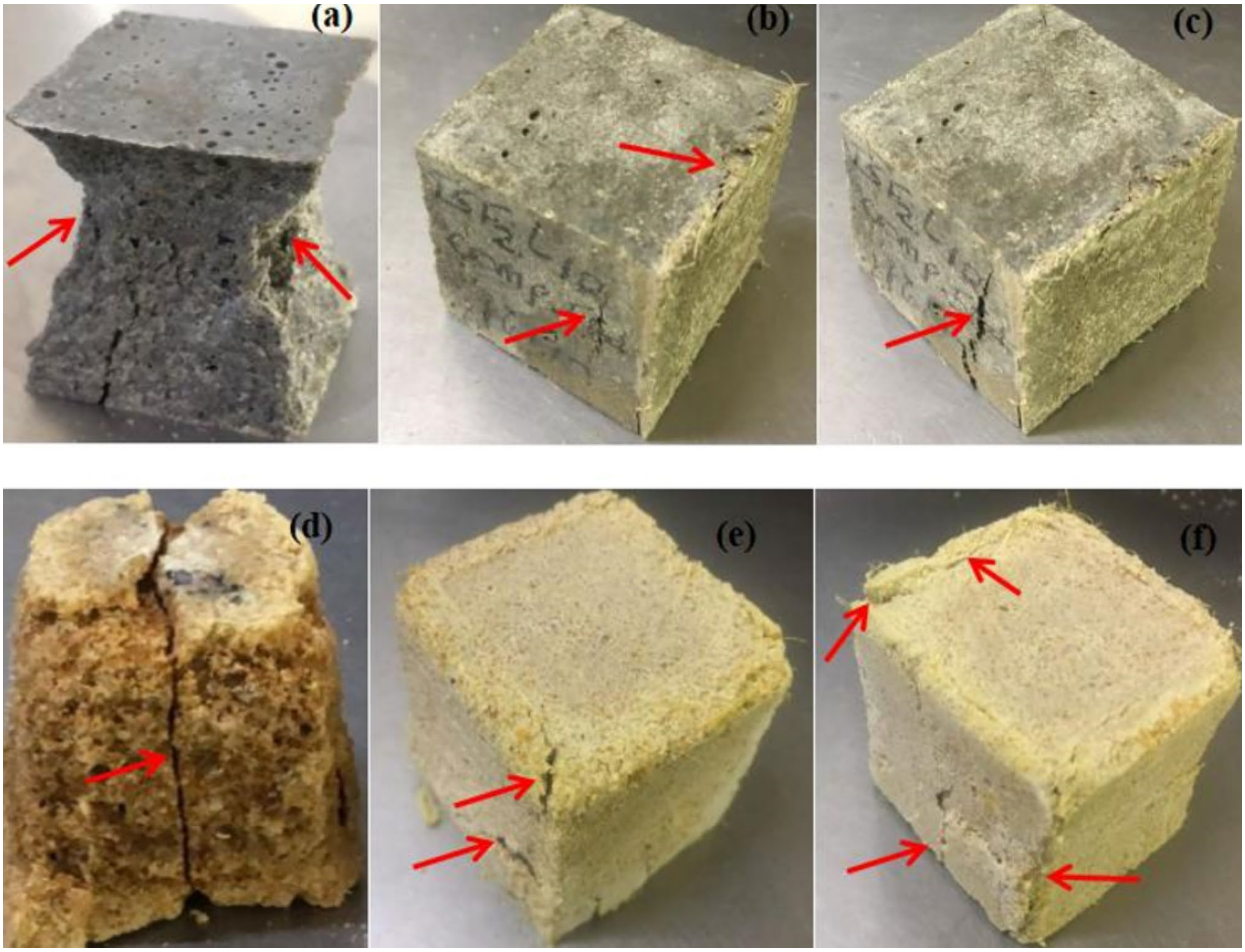

Fig. 18. The residual after compressive strength test at 56 days (a) control mixture, (b) sisal fiber reinforced, (c) second residual of (b), (d) the residual cured in 5% HCl for 56 days, (e) sisal fiber reinforced residual cured in 5% HCl, and (f) the second residual of (e) respectively.

Future prospective

In this study, calcined bentonite was used to treat sisal fiber degradation and moisture sensitivity in cement composite materials. However, the use of different doses of bentonite and many other natural pozzolanas in sisal fiber treatment is still yet to be well unknown. Therefore, it is highly recommended to study the effect of similar materials at different doses, mainly from natural pozzolana, for the sisal fiber degradation treatment to use in concrete reinforcement.

Data availability

All data generated or analyzed during this study are included in this published article.

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References

1. Naraganti, S. R., Pannem, R. M. R. & Putta, J. Impact resistance of hybrid fibre reinforced concrete containing sisal fibres. *Ain Shams Eng. J.* **10**, 297–305 (2019).
2. Long, W. & Wang, Y. Effect of pine needle fibre reinforcement on the mechanical properties of concrete. *Constr. Build. Mater.* **278**, 122333 (2021).
3. Akinyemi, B. A. & Adesina, A. Utilization of polymer chemical admixtures for surface treatment and modification of cellulose fibres in cement-based composites: a review. *Cellulose* **28**, 1241–1266 (2021).
4. Hasan, R. et al. Eco-friendly self-consolidating concrete production with reinforcing jute fiber. *J. Build. Eng.* **63**, 105519 (2023).
5. Ramesh, M. Hemp, jute, banana, kenaf, ramie, sisal fibers. in Handbook of Properties of Textile and Technical Fibres 301–325 (Elsevier Ltd, doi:https://doi.org/10.1016/B978-0-08-101272-7.00009-2. (2018).
6. Shadrach Jeya Sekaran, A., Palani Kumar, K. & Pitchandi, K. Evaluation on mechanical properties of woven aloevera and sisal fibre hybrid reinforced epoxy composites. *Bull. Mater. Sci.* **38**, 1183–1193 (2015).

7. Bheel, N., Ali, M. O. A., Kırgız, M. S., Shafiq, N. & Gobinath, R. Effect of graphene oxide particle as nanomaterial in the production of engineered cementitious composites including superplasticizer, fly ash, and polyvinyl alcohol fiber. *Mater. Today Proc.* (2023). https://doi.org/10.1016/j.matpr.2023.03.010
8. Zhang, P., Han, S., Ng, S. & Wang, X. H. Fiber-Reinforced Concrete with Application in Civil Engineering. *Adv. Civ. Eng.* (2018). (2018).
9. Gao, C., Fu, Q., Huang, L., Yan, L. & Gu, G. Jute Fiber-Reinforced Polymer Tube-Confined Sisal Fiber-Reinforced recycled aggregate concrete Waste. *Polym. (Basel)* **14**, (2022).
10. Fode, T. A., Jande, C., Kivevele, T. & Y. A. & Physical, mechanical, and durability properties of concrete containing different waste synthetic fibers for green environment – a critical review. *Heliyon* **10**, e32950 (2024).
11. Zhou, X. Engineering properties of treated Natural Hemp Fiber-Reinforced. *Front. Built Environ.* **3**, 1–9 (2017).
12. Shah, I. et al. A review on Chemical modification by using Sodium Hydroxide (NaOH) to investigate the Mechanical Properties of Sisal, Coir and Hemp Fiber Reinforced concrete composites. *J. Nat. Fibers*. **19**, 5133–5151 (2021).
13. Mahesh, V., Gobinath, R., Kırgız, M. S., Shekar, R. P. V. & Shewale, M. Global Trends of Research Productivity in Natural Fibre Reinforced composites: Comprehensive Scientometric Analysis. *Nat. Fibers*. https://doi.org/10.1080/15440478.2022.2085227 (2022).
14. Katman, H. Y. B. et al. Fabrication and Characterization of Cement-Based Hybrid Concrete Containing Coir Fiber for Advancing Concrete Construction. *Buildings* 12, (2022).
15. Sridhar, J., Gobinath, R. & Kırgız, M. S. Evaluation of Artificial Neural Network Predicted Mechanical Properties of Jute and Bamboo Fiber Reinforced concrete along with silica fume. *J. Nat. Fibers* **20**, (2023).
16. Bheel, N. et al. Effect of wheat straw ash as cementitious material on the mechanical characteristics and embodied carbon of concrete reinforced with coir fiber. *Heliyon* **10**, e24313 (2024).
17. Singh, S. et al. Preference index of sustainable natural fibers in Stone Matrix Asphalt Mixture using Waste Marble. *Mater. (Basel).* **15**, 1–17 (2022).
18. Ferreira, S. R., Pepe, M., Martinelli, E. & de Andrade Silva, F. Toledo Filho, R. D. Influence of natural fibers characteristics on the interface mechanics with cement based matrices. *Compos. Part. B Eng.* **140**, 183–196 (2018).
19. Liu, Y., Wang, Z., Fan, Z. & Gu, J. Study on properties of sisal fiber modified foamed concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **744**, (2020).
20. Song, H., Liu, J., He, K. & Ahmad, W. A comprehensive overview of jute fiber reinforced cementitious composites. *Case Stud. Constr. Mater.* **15**, e00724 (2021).
21. Alene, T. E., Mohammed, T. A. & Gualu, A. G. Use of sisal fiber and cement to improve load bearing capacity of mud blocks. *Mater. Today Commun.* **33**, 104557 (2022).
22. Iniya, M. & Nirmalkumar, K. A review on Fiber Reinforced concrete using sisal fiber. *IOP Conf. Ser. Mater. Sci. Eng.* **1055**, 012027 (2021).
23. Shadheer Ahamed, M., Ravichandran, P. & Krishnaraja, A. Natural fibers in concrete – A review. *IOP Conf. Ser. Mater. Sci. Eng.* **1055**, 012038 (2021).
24. Ravi, M., Dubey, R. R., Shome, A. & Guha, S. & Anil Kumar, C. Effect of surface treatment on natural fibers composite. *IOP Conf. Ser. Mater. Sci. Eng.* **376**, (2018).
25. Herrera-franco, P. J., Carrillo, J. G. & Li, Q. M. Mechanical properties of Natural Fiber Reinforced Foamed concrete. *Mater. MDPI.* **13**, 1–18 (2020).
26. Dinesh Kumar Raju, S. & Balasubramanian, M. & Arul Jeya Kumar, A. EXPERIMENTALSTUDIES on REPLACEMENT of STEEL STIRRUPS by SISAL FIBER REINFORCED POLYMERS. *IOP Conf. Ser. Mater. Sci. Eng.* **912**, (2020).
27. Dantas, L. G., De Castro Motta, L. A., Pasquini, D. & Vieira, J. G. Surface esterification of sisal fibres for use as reinforcement in cementitious matrix. *Mater. Res.* **22**, (2019).
28. Ferreira, S. R., Silva, F. D. A. & Lima, P. R. L. Toledo Filho, R. D. Effect of fiber treatments on the sisal fiber properties and fiber-matrix bond in cement based systems. *Constr. Build. Mater.* **101**, 730–740 (2015).
29. Wei, J. Degradation behavior and kinetics of sisal fiber in pore solutions of sustainable cementitious composite containing metakaolin. *Polym. Degrad. Stab.* **150**, 1–12 (2018).
30. Veigas, M. G., Najimi, M. & Shafei, B. Cementitious composites made with natural fibers: investigation of uncoated and coated sisal fibers. *Case Stud. Constr. Mater.* **16**, e00788 (2022).
31. Gonzalez-Lopez, L., Claramunt, J., Hsieh, Y., Lo, Ventura, H. & Ardanuy, M. Surface modification of flax nonwovens for the development of sustainable, high performance, and durable calcium aluminate cement composites. *Compos. Part. B Eng.* **191**, (2020).
32. Naik, T. P., Gairola, S., Singh, I. & Sharma, A. K. Microwave-assisted alkali treatment of sisal fiber for fabricating composite as non-structural building materials. *Constr. Build. Mater.* **411**, 134651 (2024).
33. de Azevedo, A. R. G. et al. Technological performance of açaí natural fibre reinforced cement-based mortars. *J. Build. Eng.* **33**, 101675 (2021).
34. Hari, R. & Mini, K. M. Mechanical and durability properties of sisal-Nylon 6 hybrid fibre reinforced high strength SCC. *Constr. Build. Mater.* **204**, 479–491 (2019).
35. Masood, B., Elahi, A., Barbhuiya, S. & Ali, B. Mechanical and durability performance of recycled aggregate concrete incorporating low calcium bentonite. *Constr. Build. Mater.* **237**, 117760 (2020).
36. Rehman, S. U. et al. The influence of Thermo-Mechanical activation of Bentonite on the mechanical and durability performance of concrete. *Appl. Sci. MDPI*. https://doi.org/10.3390/app9245549 (2019).
37. Wei, J. & Meyer, C. Utilization of rice husk ash in green natural fiber-reinforced cement composites: mitigating degradation of sisal fiber. *Cem. Concr Res.* **81**, 94–111 (2016).
38. ASTM C109/C109M-02. Standard test method for compressive strength of hydraulic cement mortars. *Annu. B ASTM Stand.* (2002).
39. Abirami, R. & Sangeetha, S. P. Effect of Surface Modification on the characteristics of Sisal Fiber Reinforced concrete treated with Na2CO3. *Nat. Environ. Pollut Technol.* **21**, 289–295 (2022).
40. Reddy, S. S. & Reddy, M. A. K. Optimization of calcined bentonite caly utilization in cement mortar using response surface methodology. *Int. J. Eng. Trans. Basics*. **34**, 1623–1631 (2021).
41. Wei, J. & Meyer, C. Degradation rate of natural fiber in cement composites exposed to various accelerated aging environment conditions. *Corros. Sci.* **88**, 118–132 (2014).
42. Standard, T. O. ASTM C138M – 17a Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric). in *ASTM Standard* 1–6 (2019). https://doi.org/10.1520/C0138
43. C1437, A. Standard Test Method for Flow of Hydraulic Cement Mortar. in ASTM International vol. i 4–6. (2017).
44. Rai, A. & Joshi, Y. P. Applications and properties of Fibre Reinforced concrete. *J. Eng. Res. Appl. www Ijera com. ISSN*. **4**, 123–131 (2014).
45. C618, A. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolana for Use in Concrete, ASTM International, West Conshohocken, PA, 2012. in ASTM Standard 3–6. (2010). https://doi.org/10.1520/C0618
46. Tayeh, B. A., Hadzima-Nyarko, M., Zeyad, A. M. & Al-Harazin, S. Z. Properties and durability of concrete with olive waste ash as a partial cement replacement. *Adv. Concr Constr.* **11**, (2021).

47. Pachideh, G. & Gholhaki, M. Effect of pozzolanic materials on mechanical properties and water absorption of autoclaved aerated concrete. *J. Build. Eng.* **26**, 100856 (2019).
48. Deboucha, W., Oudjit, M. N., Bouzid, A. & Belagraa, L. Effect of incorporating blast furnace slag and natural pozzolana on compressive strength and capillary water absorption of concrete. *Procedia Eng.* **108**, 254–261 (2015).
49. Chandrasekar, M., Ishak, M. R., Sapuan, S. M., Leman, Z. & Jawaid, M. A review on the characterisation of natural fibres and their composites after alkali treatment and water absorption. *Plast. Rubber Compos.* **46**, 119–136 (2017).
50. Ali-Boucetta, T., Ayat, A., Laifa, W. & Behim, M. Treatment of date palm fibres mesh: influence on the rheological and mechanical properties of fibre-cement composites. *Constr. Build. Mater.* **273**, 121056 (2021).
51. Fode, T. A., Jande, C., Abeid, Y. & Kivevele, T. Modelling and optimization of multiple replacement of supplementary cementitious materials for cement composite by response surface method. *Clean. Eng. Technol.* **19**, 1–18 (2024).
52. Filho, J. D. A. M. & Silva, F. D. A. Toledo Filho, R. D. Degradation Kinetics and aging mechanisms on sisal fiber cement composite systems. *Cem. Concr Compos.* **40**, 30–39 (2013).
53. Wei, J. & Gencturk, B. Cement and Concrete Research Hydration of ternary Portland cement blends containing metakaolin and sodium bentonite. *Cem. Concr Res.* **123**, 105772 (2019).
54. Fode, T. A., Abeid, Y., Jande, C. & Kivevele, T. Effects of raw and different calcined bentonite on durability and mechanical properties of cement composite material. *Case Stud. Constr. Mater.* **20**, 1–17 (2024).
55. Wei, J. & Meyer, C. Sisal fiber-reinforced cement composite with Portland cement substitution by a combination of metakaolin and nanoclay. *J. Mater. Sci.* **49**, 7604–7619 (2014).
56. Snoeck, D., Smetryns, P. A. & De Belie, N. Improved multiple cracking and autogenous healing in cementitious materials by means of chemically-treated natural fibres. *Biosyst Eng.* **139**, 87–99 (2015).
57. Fode, T. A. et al. A review on degradation improvement of Sisal Fiber by Alkali and Pozzolana for Cement Composite materials. *J. Nat. Fibers* **21**, (2024).
58. Hajiha, H., Sain, M. & Mei, L. H. Modification and characterization of hemp and sisal fibers. *J. Nat. Fibers*. **11**, 144–168 (2014).
59. Bahja, B., Elouafi, A., Tizliouine, A. & Omari, L. H. Morphological and structural analysis of treated sisal fibers and their impact on mechanical properties in cementitious composites. *J. Build. Eng.* **34**, (2021).
60. El Refaey, A. Effect of Calcination and Ca-modified on Bentonite and Zeolite, with respect to Phosphorus removal from aqueous solution. *Egypt. J. Soil. Sci.* **0**, 0–0 (2022).
61. Orue, A. et al. The effect of surface modifications on sisal fiber properties and sisal/poly (lactic acid) interface adhesion. *Compos. Part. B Eng.* **73**, 132–138 (2015).
62. Fode, T. A., Jande, C. A. Y. & Kivevele, T. Modeling and optimization of Sisal Fiber Degradation treatment by Calcined Bentonite for Cement Composite materials modeling and optimization of Sisal Fiber Degradation treatment by Calcined Bentonite for Cement Composite materials. *J. Nat. Fibers* **21**, (2024).
63. Orue, A., Eceiza, A. & Arbelaiz, A. *Pretreatments of Natural Fibers for Polymer Composite Materials*. (2018). https://doi.org/10.1007/978-3-319-68696-7_3
64. Shah, I., Li, J., Yang, S., Zhang, Y. & Anwar, A. Experimental investigation on the Mechanical properties of Natural Fiber Reinforced concrete. *J. Renew. Mater.* **10**, 1307–1320 (2022).
65. Barbuta, M. et al. Characterization of polymer concrete with natural fibers. in *IOP Conference Series: Materials Science and Engineering* vol. 246 (2017).
66. Achour, A., Ghomari, F. & Belayachi, N. Properties of cementitious mortars reinforced with natural fibers. *J. Adhes. Sci. Technol.* **31**, 1938–1962 (2017).
67. Ali, M. S., Arsalan, R., Khan, S. & Lo, T. Y. Utilization of Pakistani bentonite as partial replacement of cement in concrete. *Constr. Build. Mater.* **30**, 237–242 (2012).
68. Asaduzzaman, S. M. & Islam, G. M. S. Using jute Fiber to Improve Fresh and Hardened properties of concrete. *J. Nat. Fibers* **20**, (2023).
69. Sridhar, J., Gobinath, R. & Kırgız, M. S. Comparative study for efficacy of chemically treated jute fiber and bamboo fiber on the properties of reinforced concrete beams. *Nat. Fibers* **19**, (2022).
70. Cruz, J. & Fangueiro, R. Surface modification of natural fibers: a review. *Procedia Eng.* **155**, 285–288 (2016).
71. Mármol, G., Ribes, A., Amigó, V. & Savastano, H. Assessment of Sisal Fiber Integrity as a reinforcing element in MgO-Based cement matrices. *Waste Biomass Valoriz.* **11**, 3045–3056 (2020).
72. Ali, A. et al. Hydrophobic treatment of natural fibers and their composites—A review. *J. Ind. Text.* **47**, 2153–2183 (2018).
73. Nasr, M. S., Shubbar, A., Hashim, T. M. & Abadel, A. A. Properties of a Low-Carbon Binder-Based Mortar Made with Waste LCD Glass and Waste Rope (Nylon) Fibers. *Processes* 11, (2023).
74. Barra, B. N. et al. Residual sisal fibers treated by methane cold plasma discharge for potential application in cement based material. *Ind. Crops Prod.* **77**, 691–702 (2015).
75. Mundim, P. B., Ferreira, R. A. R., Motta, L. A. C., Henrique, M. A. & Pasquini, D. Study of the superficial modification of sisal fibres with lignin, and its use as a reinforcement agent in cementitious composites. *J. Renew. Mater.* **8**, 891–903 (2020).
76. Hashemifard, H., Mehranzadeh, M. & Chenari, M. ConCrete Reinforced with Sisal fibers (SSF): overview of Mechanical and Physical properties. *Cr* **6**, 368–375 (2012).
77. Fidelis, M. E. A. et al. The effect of accelerated aging on the interface of jute textile reinforced concrete. *Cem. Concr Compos.* **74**, 7–15 (2016).
78. Huang, J. & Rodrigue, D. Stiffness behavior of Sisal Fiber Reinforced Foam concrete under Flexural Loading. *J. Nat. Fibers*. **19**, 12251–12267 (2022).
79. Panchangam, S. C. Experimental study on effects of Sisal Fiber Experimental. *Int. J. Mag Eng. Technol. Manag Res.* **2**, 388–394 (2015).
80. Tiwari, V., Parate, H. R. & Patil, N. N. Strength and durability studies of waste nylon cable ties concrete. *J. Phys. Conf. Ser.* **1706**, (2020).
81. More, F. M. D. S. & Subramanian, S. S. Impact of Fibres on the Mechanical and Durable Behaviour of Fibre-Reinforced Concrete. *Buildings* 12, (2022).
82. Tonoli, G. H. D. et al. Impact of bleaching pine fibre on the fibre/cement interface. *J. Mater. Sci.* **47**, 4167–4177 (2012).
83. Dilfi, K. F., Balan, A., Bin, A., Xian, H., Thomas, S. & G. & Effect of surface modification of jute fiber on the mechanical properties and durability of jute fiber-reinforced epoxy composites. *Polym. Compos.* **39**, E2519–E2528 (2018).
84. Mohan, T. P. & Kanny, K. Chemical treatment of sisal fiber using alkali and clay method. *Compos. Part. Appl. Sci. Manuf.* **43**, 1989–1998 (2012).
85. Kanny, K. Surface treatment of sisal fiber composites for improved moisture and fatigue properties. *Compos. Interfaces*. **20**, 783–797 (2013).
86. Bao, H., Meng, H., You, W. & Qin, F. Study on the corrosion resistance of sisal fiber concrete in marine environment. *SN Appl. Sci.* **1**, 1–6 (2019).
87. Okeola, A. A., Mwero, J. & Bello, A. Behavior of sisal fiber-reinforced concrete in exterior beam-column joint under monotonic loading. *Asian J. Civ. Eng.* **22**, 627–636 (2021).
88. Gupta, S., Islam, T., Islam Sohag, M. A., Salakin, S. & Hossain, I. Experimental study of concrete using Raw Rice Husk as partial replacement of cement with natural Fiber (jute Fiber) as reinforcing material. *Comput. Eng. Phys. Model.* **4**, 29–42 (2021).

89. Wei, J. & Meyer, C. Degradation of natural fiber in ternary blended cement composites containing metakaolin and montmorillonite. *Corros. Sci.* **120**, 42–60 (2017).

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Declarations

Competing interests
The authors declare no competing interests.

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