



OPEN **Sisal fiber degradation treatment by different methods for cement composite materials**

Tsion Amsalu Fode^{1,2,4}✉, Yusufu Abeid Chande Jande^{1,3}, Thomas Kivevele^{1,3} & Nima Rahbar^{1,4}

Sisal fiber is the most extensively cultivated and strong natural fiber extracted from the Agave-sisalana plant leaf. The use of sisal fiber in concrete or mortar has a lot of benefits, however it degrades due to mineralization from cementitious materials and moisture absorption. Numerous studies have explored surface treatment methods to reduce this deterioration, however the combined effects of different treatment approaches on the performance of sisal fiber in cement composites remain not well known. This study addresses this gap by systematically evaluating the influence of calcined bentonite, varying concentrations of alkaline solutions by 5% and 10% NaOH, additionally, using 150 °C and 200 °C thermal treatments on reducing the degradation of sisal fiber in cement-based materials. The findings reveal that all three treatments—thermal, alkaline, and calcined bentonite—were effective in removing lignin and surface impurities from the fibers. Notably, fibers treated with 5% sodium hydroxide, heated to 150 °C, or treated with calcined bentonite exhibited improved durability after 10 wetting and drying cycles, showing increases in breaking load resistance of 28.95%, 32.11%, and 33.37%, respectively. These treatments also significantly reduced water absorption by 34.89%, 29.27%, and 60.95%, compared to untreated fibers. Moreover, the calcined bentonite-treated fiber showed reduced mass loss by 28.18% at 367 °C and 29.08% at 600 °C when compared to raw sisal fiber. Incorporating the treated fibers into mortar mixtures resulted in reduced fresh density and enhancements in both compressive and flexural strength. Specifically, fibers treated at 150 °C and with calcined bentonite improved the 28 days compressive strength by 23.31% and 23.44%, respectively, compared to mortar with untreated fibers.

Keywords Sisal fiber, Treatment, Heat, Alkaline, Calcined bentonite, Mortar

Concrete is a brittle material; thus, incorporating fibers enhances its ductility, increases its deformation capacity, and significantly reduces the initiation and propagation of cracks^{1–3}. Among various types, natural fibers—such as sisal, jute, hemp, and banana stem fibers—play a crucial role in improving tensile strength, enhancing post-cracking behavior, providing ductility, and effectively bridging cracks by transferring tensile stresses across crack planes, thereby minimizing crack widths. However, the degree of crack width reduction is strongly influenced by the physical properties and dosage of the fibers used^{4–6}. Moreover, natural fiber reinforcement contributes to improved load-bearing capacity and increased mid-span deflection of concrete under ultimate loading conditions^{7–9}. In addition to mechanical benefits, the use of natural fibers offers environmental and economic advantages, being renewable, cost-effective, and contributing to a reduced carbon footprint^{10–13}.

Sisal fiber is a valuable natural reinforcement in cement composite materials, known for enhancing concrete ductility and tensile strength, reducing crack width, and offering an eco-friendly alternative^{14–19}. However, when incorporated into concrete or mortar, sisal fiber is prone to degradation over time due to the mineralization effects of cementitious materials and moisture absorption. To overcome this challenge, numerous studies have explored various surface treatment methods to improve the durability and performance of sisal fiber in cement-based systems^{20–22}. Alkali treatment of natural fibers increases the existence of the hydroxyl group (–OH) to form chemical and physical bonds to the polymer chains, hence in physical bond cellulose fiber of the hydroxyl

¹School of Materials, Energy, Water and Environmental Sciences (MEWES), The Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania. ²Department of Civil Engineering, Wollega University, P.O. Box 395, Nekemte, Ethiopia. ³Water Infrastructure and Sustainable Energy Futures (WISE-Futures), Centre of Excellence, The Nelson Mandela African Institution of Science and Technology, P.O. Box 9124, Arusha, Tanzania. ⁴Department of Civil, Environmental, and Architectural Engineering, Worcester Polytechnic Institute, Worcester, USA. ✉email: fodet@nm-aist.ac.tz

group can form hydrogen bonds, whereas cellulose fiber chemical bond of the hydroxyl group can react with alkali NaOH and form $-O-Na+$ that has potential to bond with cement composite matrix²³. Castoldi et al.²⁴ examined how alkaline treatment influences the physicochemical characteristics of sisal fiber. The study used sodium hydroxide (NaOH) solutions at concentrations of 1%, 5%, and 10% for the treatment. Their findings revealed that the cellulose content of the fibers increased, while hemicellulose and lignin levels decreased. Moreover, treatments with 5% and 10% NaOH notably lowered the water absorption capacity of the sisal fibers and improved their tensile strength relative to untreated samples.

Fode et al.²⁵ explored the degradation treatment of sisal fiber using a slurry made from calcined bentonite. Various types of calcined bentonite were employed for the fiber treatment, yielding promising outcomes. Treated sisal fibers exhibited a 33.37% increase in breaking load, 98% resistance to degradation, and a 60.95% improvement in moisture sensitivity compared to untreated fibers. Additionally, the calcined bentonite surface treatment enhanced the interfacial bonding between the fiber and the cement matrix when compared to raw sisal fiber.

Wei & Meyer,²⁶ examined the enhancement of sisal fiber degradation resistance through thermal surface treatment. The study found no notable changes on the fiber surface after treatment, as the applied temperature of 150 °C was below the threshold at which lignin and hemicellulose begin to degrade—173 °C and 186 °C, respectively. Nevertheless, the thermal treatment led to an improvement in the tensile strength of the fiber when compared to untreated sisal fiber.

The incorporation of sisal fiber into cementitious materials is beneficial for enhancing tensile strength and minimizing crack width in concrete and mortar. However, sisal fiber is highly sensitive to moisture and tends to degrade within the alkaline environment of cement-based materials. Several studies have improved sisal fiber degradation using pozzolanic materials (e.g., silica fume, kaolin, bentonite), alkaline treatments (NaOH), and thermal methods. However, a systematic investigation and direct comparison of these different treatment techniques in terms of their effectiveness against sisal fiber degradation remain limited. This study introduces a novel approach by comparatively evaluating multiple treatment methods—calcined bentonite, different NaOH concentrations, and heat treatments applied to sisal fibers. The treated fibers were then incorporated into mortar to assess how each treatment influences the physical and mechanical properties of cementitious composites.

Materials and methods

Materials

The raw sisal fiber used in the study was sourced from Korogwe, Tanzania, then washed and brushed to obtain an upper-grade fiber type. For the pozzolanic treatment, optimized calcined bentonite from previous work was utilized²⁵. Alkaline treatment was performed using NaOH solutions at concentrations of 5% and 10% for surface modification of the sisal fiber. For thermal treatment, the fibers were exposed to temperatures of 150 °C and 200 °C in laboratory ovens. The study incorporated both raw and variously treated sisal fibers into the mortar mixture, which was made using ordinary Portland cement (32.5 MPa), washed sand, distilled water, and the treated sisal fibers. Detailed properties of the mortar materials, including sand and cement, are shown in Fig. 1; Table 1, respectively from²⁷.

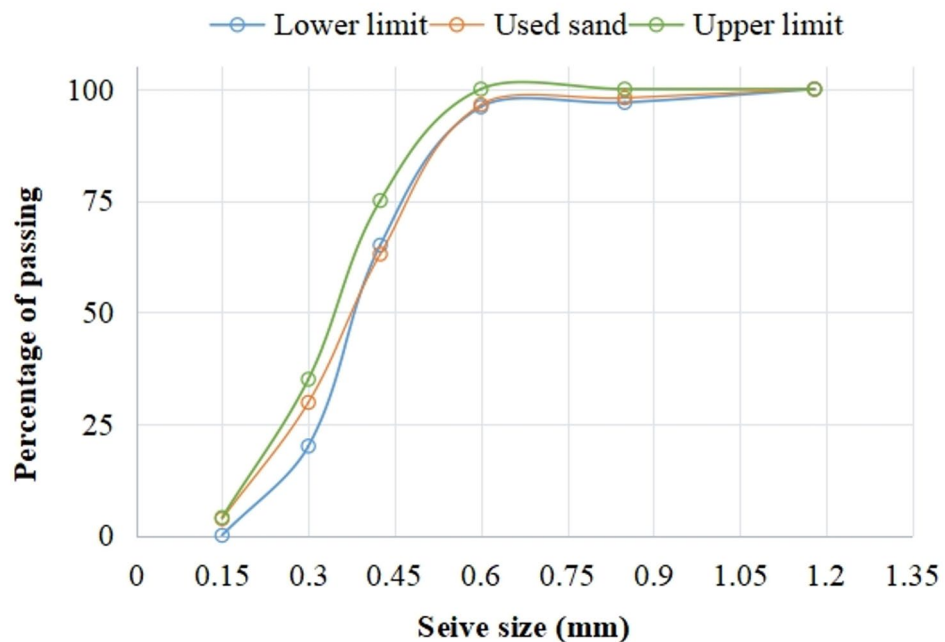


Fig. 1. Gradation of used fine aggregate²⁷.

Composition	OPC	Raw Bentonite	Calcined bentonite
SiO ₂	17.57	50.51	58.30
Al ₂ O ₃	4.07	12.62	10.93
Fe ₂ O ₃	2.63	7.81	8.05
CaO	61.48	1.91	7.75
MgO	0.41	6.38	6.00
SO ₃	1.79	0.13	0.10
K ₂ O	0.11	2.02	2.36
Na ₂ O	0.04	2.88	3.49
TiO ₂	0.29	1.00	0.91
P ₂ O ₅	0.13	0.34	0.21
LOI	10.74	10.74	2.18
Residue at 45 μm	12.49	1.72	0.80

Table 1. Chemical composition of used cement and bentonite²⁷.

Sample name	W/C	Cement (kg/m ³)	Sand (kg/m ³)	Raw (kg/m ³)	Treated sisal fiber				
					Calcined bentonite (kg/m ³)	Heat (°C)		Alkaline	
						150 (kg/m ³)	200 (kg/m ³)	5% NaOH (kg/m ³)	10% NaOH (kg/m ³)
Control	0.5	591.36	1806.93	0	0	0	0	0	0
MRaw1	0.5	591.36	1806.93	5.91	0	0	0	0	0
MRaw2	0.5	591.36	1806.93	11.83	0	0	0	0	0
Mbent1	0.5	591.36	1806.93	0	5.91	0	0	0	0
Mbent2	0.5	591.36	1806.93	0	11.83	0	0	0	0
M150 C1	0.5	591.36	1806.93	0	0	5.91	0	0	0
M150 C2	0.5	591.36	1806.93	0	0	11.83	0	0	0
M200 C1	0.5	591.36	1806.93	0	0	0	5.91	0	0
M200 C2	0.5	591.36	1806.93	0	0	0	11.83	0	0
M5% NaOH1	0.5	591.36	1806.93	0	0	0	0	5.91	0
M5% NaOH2	0.5	591.36	1806.93	0	0	0	0	11.83	0
M10% NaOH1	0.5	591.36	1806.93	0	0	0	0	0	5.91
M10% NaOH2	0.5	591.36	1806.93	0	0	0	0	0	11.83

Table 2. Mortar mix design having raw and different treated sisal fibers.

Sample preparation

For the alkaline treatment of sisal fibers, NaOH (supplied by LOBA CHEMIE PVT.LTD) solutions with concentrations of 5% and 10% were prepared in the laboratory. This selection was based on evidence that a higher NaOH concentration (20%) can damage the fiber structure²⁸, while concentrations lower than 5% may be insufficient to effectively remove lignin, which is highly susceptible to degradation in cement-based materials²⁴. The washed, dried, and brushed sisal fibers were separately immersed in the solutions for one hour. After treatment, the fibers were rinsed with deionized water and dried at ambient temperature. For the pozzolanic treatment, calcined bentonite was used, following the method outlined in²⁵. A slurry was made using the calcined bentonite, ordinary Portland cement, and water with a 0.8 water-to-cement ratio. The sisal fibers were then coated with the slurry as described in²⁵. For thermal treatment, the sisal fibers were placed in an oven at 150 °C and 200 °C for two hours. A graphical representation of the sisal fiber treatment process for all methods is shown in Fig. 2. After heat, alkaline, and calcined bentonite treatments, the fibers were used as reinforcement in mortar, as detailed in Table 2. The raw and treated sisal fibers, cut to 10 mm lengths as recommended in²⁹, were incorporated into the mortar mix at dosages of 1% and 2% by weight of cement which is denoted by 1 and 2 on sample names respectively (Table 2).

Methods

The mineralogical and phase changes in the sisal fiber due to different treatments were analyzed using X-ray diffraction and Fourier transform infrared spectroscopy, respectively. Surface microstructural changes were examined using a scanning electron microscope. The thermal resistance of the treated fibers was assessed through thermal gravimetric analysis (TGA) and differential thermal analysis (DTA). Water absorption of both treated and raw sisal fibers was measured by immersing a known mass of fibers in water for 6 h.

For the mortar mixtures containing raw and treated sisal fibers, the fresh bulk density, compressive strength, and flexural strength were evaluated. The fresh bulk density of the mortar was measured according

to ASTM C138M–17a³⁰ by determining the mass of the fresh mortar and its volume in a 1-liter cylinder. The compressive strength of the mortar, incorporating raw and treated sisal fibers, was tested after 28 days of water curing, using 50 mm³ mortar specimens as per ASTM C618³¹. Additionally, the flexural strength of the mortar, containing raw and treated sisal fibers, was determined using a three-point loading machine on 40 × 40 × 160 mm³ mortar specimens after 28 days.

Results and discussion

Mineral composition of different treatment methods

The mineral composition results for raw and variously treated sisal fibers are shown in Fig. 3. The data reveals peaks at 15–16° which correspond to lignin, pectin, and potential impurities. These peaks are progressively reduced in the raw sisal fiber, 150 °C treated sisal fiber (TSF), 200 °C TSE, 5% NaOH TSE, and 10% NaOH TSE treatments, with the lowest peak observed in the calcined bentonite-treated sisal fiber. This indicates that all treatments effectively reduced the lignin and other impurities. This is significant for cement composite materials because lignin and impurities are the minerals in natural fibers that degrade during the mineralization of cement composites³².

The results also show that the crystalline content of the treated sisal fibers is higher than that of the raw sisal fiber. Notably, the calcined bentonite-treated sisal fibers exhibit a significantly higher crystalline density compared to the other treatments, as the crystalline peaks emerge from both the fiber and the clay compositions. In contrast, the crystalline content of the 10% NaOH-treated sisal fibers is lower than that of the other treated fibers, which may be attributed to the alkaline concentration and soaking time, which could have damaged the cellulose content^{28,33}.

FTIR test results for Raw and different treated Sisal fibers

The phase composition results for raw sisal fiber and those treated with heat, alkaline solutions, and calcined bentonite are shown in Fig. 4. The findings reveal significant differences in the phase composition between the raw and treated sisal fibers. A peak at 1029 cm⁻¹, indicative of C–O stretching in cellulose³⁴, is observed for all raw and treated fibers. However, the amount of cellulose in the heated and alkaline-treated sisal fibers is lower than in the raw and calcined bentonite-treated fibers. Specifically, the 200 °C and 10% NaOH-treated sisal fibers show a significant reduction in cellulose content. This is likely due to the degradation of the cellulose portion of the fiber caused by the heat and the 10% NaOH treatment. Additionally, it was observed that longer soaking times and higher alkaline concentrations can lead to fiber breakage, reduction in fiber area, and most importantly, a decrease in cellulose content^{28,29}.

Additionally, peaks between 1233 and 1720 cm⁻¹, corresponding to the stretching of carboxylic acid or ester, absorbed water, and wagging lignin (C=O, O–H–O, and CH₂), are typically associated with hemicellulose and predominantly lignin^{34,35}. A slight reduction in these peaks was observed in the heat-treated sisal fibers, with a more significant decrease in the calcined bentonite-treated sisal fibers. However, the alkaline-treated sisal fibers show a peak at 1408 cm⁻¹, which may be attributed to the NaOH treatment. For the calcined bentonite-treated sisal fibers, a peak at 1420 cm⁻¹ indicates the presence of quartz SiO₂, originating from the bentonite. The

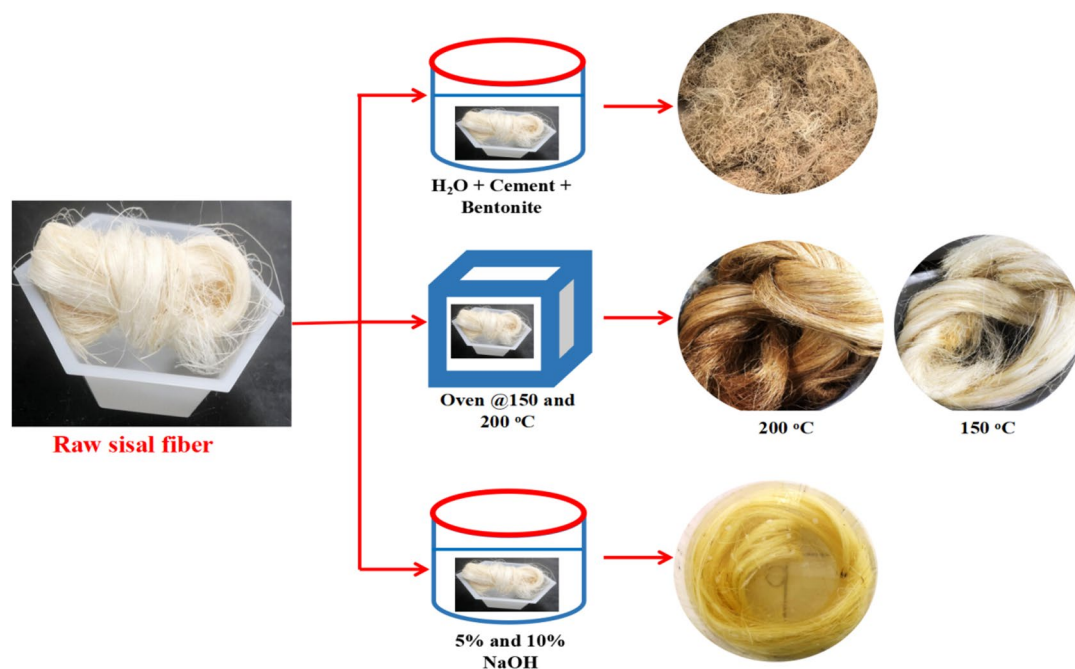


Fig. 2. Different process of sisal fiber treatments.

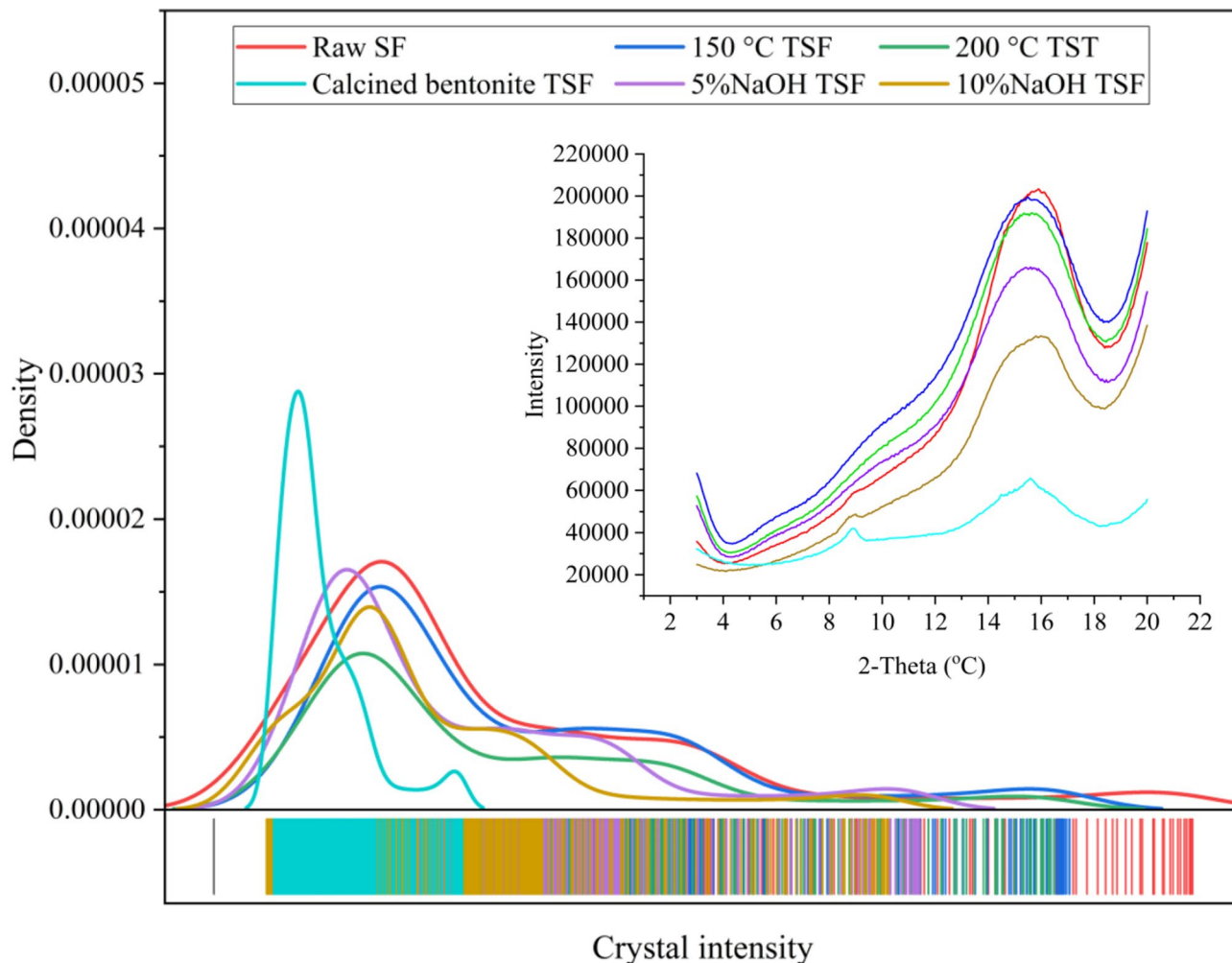


Fig. 3. Crystalline density and mineralogical change of raw and different treated sisal fibers.

presence of SiO_2 is beneficial for consuming free lime, which can degrade sisal fiber and help form additional CHS gel in cement composite materials²⁷.

In addition, a peak at 3343 cm^{-1} —primarily associated with the stretching of the OH group—was observed. This peak was reduced in sisal fibers treated with heat, alkaline solutions, and calcined bentonite. Notably, the calcined bentonite-treated sisal fiber exhibited the smallest peak among all treatments and the raw fiber. This reduction is significant because components such as hemicellulose, lignin, wax, and other impurities are the most susceptible to degradation during the mineralization of sisal fiber. Similar findings were reported by Castoldi et al.²⁴, who observed a decrease in hemicellulose and lignin following 10% NaOH treatment of sisal fibers.

Single fiber breaking load versus extension

Figure 5 presents the results of the single fiber tensile strength test conducted after ten cycles of wetting and drying. The findings show that the various sisal fiber treatments significantly improved resistance to aging under repeated exposure to hot water. Specifically, the 150 °C heat-treated fiber exhibited a higher breaking load than the 200 °C treated fiber, and the 5% NaOH-treated fiber outperformed the 10% NaOH-treated fiber in terms of breaking load. Among all treatments, the calcined bentonite surface coating provided the greatest resistance to aging. In contrast, raw sisal fiber demonstrated the lowest breaking load under the same conditions. Furthermore, the 5% NaOH-treated fiber showed greater extension at break compared to the 10% NaOH-treated fiber, likely because the higher alkaline concentration affected the fiber's outer surface, reducing its ability to elongate. Similarly, the 150 °C heat-treated fiber had a higher extension at break than the 200 °C treated fiber, as the higher temperature may have over-dried the fiber, reducing its flexibility. Overall, sisal fibers treated with 5% NaOH, 150 °C heat, and calcined bentonite exhibited increased breaking loads after ten wetting and drying cycles by 28.95%, 32.11%, and 33.37%, respectively, compared to raw fibers. The calcined bentonite-treated fibers also showed reduced extension at break relative to the raw fibers, likely due to the surface coating restricting fiber elongation²⁵.

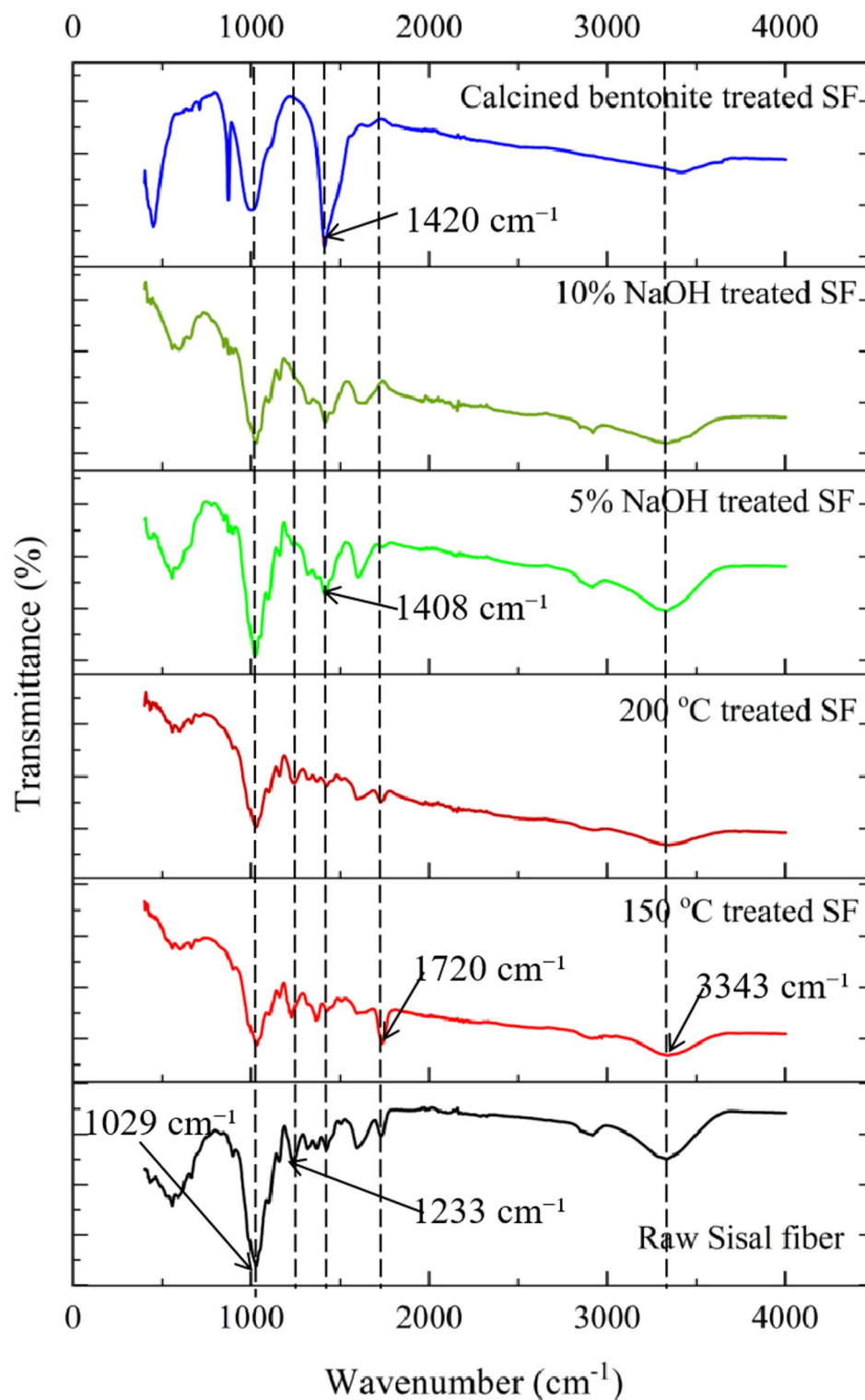


Fig. 4. Mineral phase change for raw and different treated sisal fibers.

Water absorption

Figure 6 illustrates the water absorption results for raw and variously treated sisal fibers. The treatments—heat, alkaline, and calcined bentonite slurry—significantly reduced water absorption compared to untreated sisal fiber, although the extent of reduction varied among the different methods. Notably, the fiber treated with 5% NaOH exhibited lower water absorption than that treated with 10% NaOH, likely due to the higher concentration damaging the cellulose surface, thereby facilitating easier water penetration into the fiber matrix. Similarly, fibers subjected to 150 °C heat for 2 h absorbed less water than those treated at 200 °C, possibly because the higher

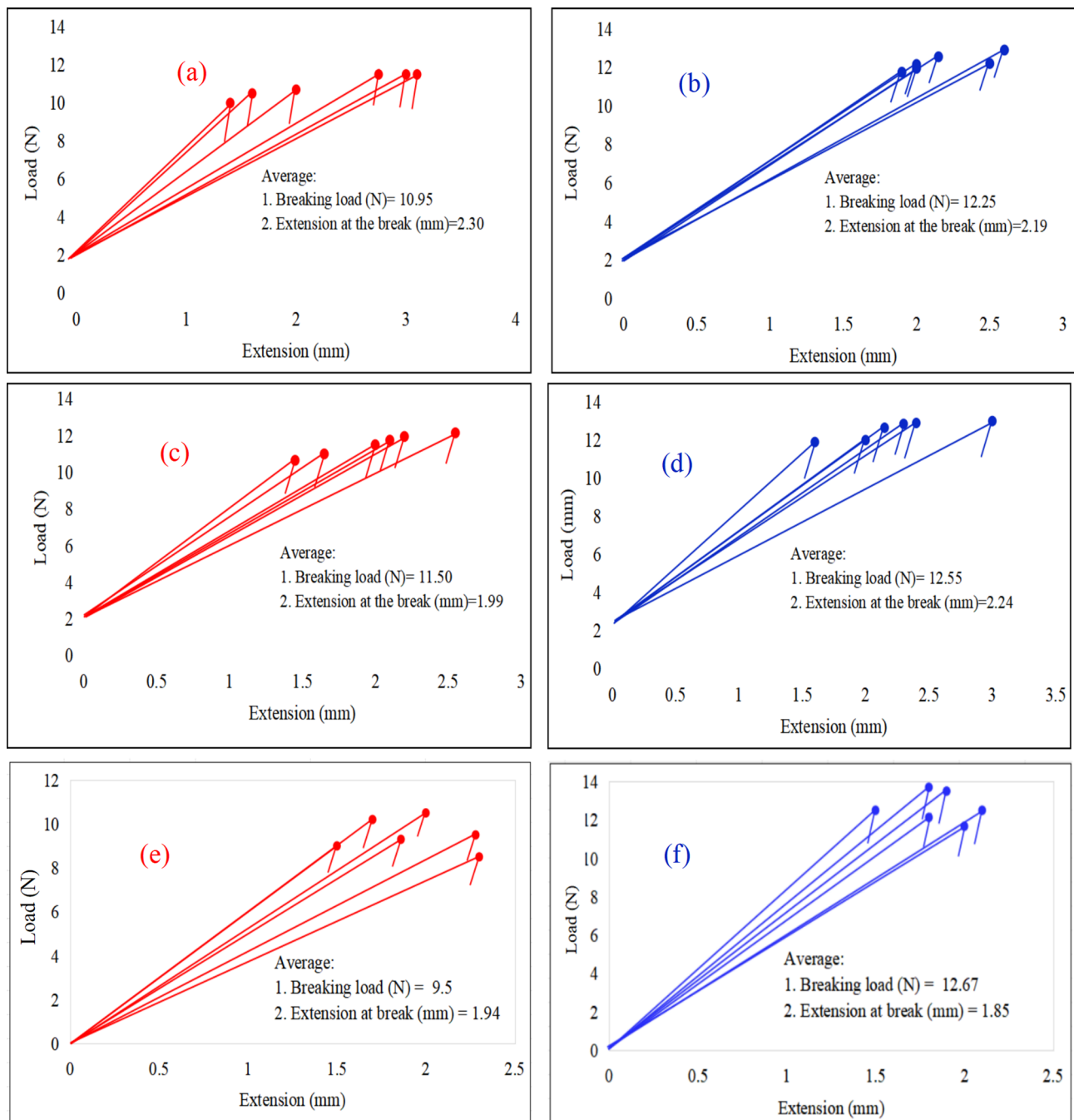


Fig. 5. Single fiber breaking load for 10-times wetting and drying (a) 10% NaOH TSF (b) 5% NaOH TSF (c) 200 °C TSF (d) 150 °C TSE, (e) raw sisal fiber and (f) calcined bentonite TSE (Treated Sisal Fiber).

temperature made the fiber surface more prone to rapid and greater water uptake. Among all treatments, the calcined bentonite slurry was the most effective, significantly minimizing water absorption. This is attributed to the bentonite coating, which covers and fills the surface pores of the fiber, as confirmed by the SEM analysis in “Physical and mechanical properties of mortar consisting of different treated sisal fibers”. Overall, treatments with 150 °C heat, 5% NaOH, and calcined bentonite slurry reduced water absorption by 34.89%, 29.27%, and 60.95%, respectively, compared to raw sisal fiber.

This is a similar result to Ferreira et al.³⁶ observed a decrease in water absorption as a result of treating sisal fibers with an alkaline solution. This treatment was shown to remove lignin and other surface impurities from the fibers, thereby enhancing the interfacial bonding and, in turn, improving the mechanical properties of the cement composite. Additionally, the study noted that an increase in the crystallinity of the cellulose acetyl group chemical bonds contributed to further reduction in water absorption of the treated sisal fibers.

Thermal-resistance

Figure 7 presents the TGA and DTA results for various types of treated sisal fibers. The differential thermal analysis curves for both raw and treated fibers show no significant differences across the samples. Similarly, the thermogravimetric analysis indicates that all fibers, including the raw and treated ones, undergo dehydration around 97.9 °C with negligible variation in mass loss. However, a substantial mass loss occurs for all fiber types between 350 °C and 375 °C. Notably, sisal fiber treated at 200 °C exhibited the highest mass loss at around 372 °C, likely due to increased thermal degradation from the higher heat treatment. At 600 °C, the fiber treated at 150 °C demonstrated greater thermal stability, showing a mass loss of 77.67%, compared to an 80.09% loss for the fiber treated at 200 °C. Despite this, both heat-treated samples displayed better thermal resistance than the raw sisal fiber at this elevated temperature.

Among the alkaline-treated sisal fibers, the sample treated with 10% NaOH demonstrated greater thermal resistance than the one treated with 5% NaOH. This improved performance is likely due to the higher alkaline concentration effectively removing more hemicellulose, lignin, and surface impurities—components located on the fiber's outer layer that are more susceptible to thermal degradation³⁷. In contrast, the sisal fiber treated with calcined bentonite exhibited superior resistance to high temperatures compared to both raw and other treated fibers. This can be attributed to the thermal stability of the clay, particularly calcined bentonite, used in the surface treatment. Unlike organic fiber components, clay does not degrade significantly at high temperatures²⁷. As a result, the calcined bentonite-treated fiber showed reduced mass loss by 28.18% at 367 °C and 29.08% at 600 °C when compared to raw sisal fiber.

Micro-structure of different treated sisal fiber

The microstructural features of sisal fiber surfaces—raw, heat-treated, alkaline-treated, and calcined bentonite-treated—are shown in Fig. 8. In Fig. 8a, the raw sisal fiber displays surface impurities, visible as white spots, which are primarily attributed to the presence of lignin, fats, waxes, and other contaminants. Furthermore, as seen in the magnified view in Fig. 8b, the fiber surface exhibits numerous pores. These pores negatively impact the performance of sisal fiber in cement composite materials by facilitating moisture and water absorption³⁸. This can lead to fiber swelling and shrinkage, ultimately weakening the bond between the fiber and the cement matrix.

As illustrated in Fig. 8c, heat treatment of sisal fiber at 150 °C reduces surface impurities compared to the raw fiber. However, the magnified image in Fig. 8d reveals that some surface pores remain. In contrast, Fig. 8e shows that treatment at 200 °C further decreases surface impurities compared to the 150 °C treatment, although a few pores are still present. Figure 8f demonstrates that sisal fiber treated with 5% NaOH also exhibits fewer surface impurities than the raw fiber. Yet, the magnified view in Fig. 8g shows no visible pores, but a slight surface reduction is apparent—possibly due to mild alkaline damage. Meanwhile, the sisal fiber treated with 10% NaOH, shown in Fig. 8h, displays a significantly altered surface structure, likely due to the higher alkaline concentration and immersion time, as reported in studies^{19,39}. The magnified view in Fig. 8i reveals larger pores and a more deteriorated surface compared to the raw fiber. Such degradation typically starts at the outer layers—composed of lignin, hemicellulose, and other impurities—and gradually progresses toward the cellulose cell walls. This explains how alkaline pore solution infiltration leads to the breakdown of cellulose fibrils and eventually results in premature failure of sisal fibers in cement composite materials⁴⁰.

Additionally, as shown in Fig. 8j, the sisal fiber treated with calcined bentonite slurry exhibits a coated surface, masking the typical structural features seen in raw sisal fiber. This observation is further supported by the magnified image in Fig. 8k, which reveals significantly fewer surface pores compared to both raw and other treated fibers. Overall, among the various treatment methods applied, the 200 °C heat treatment, 5% NaOH

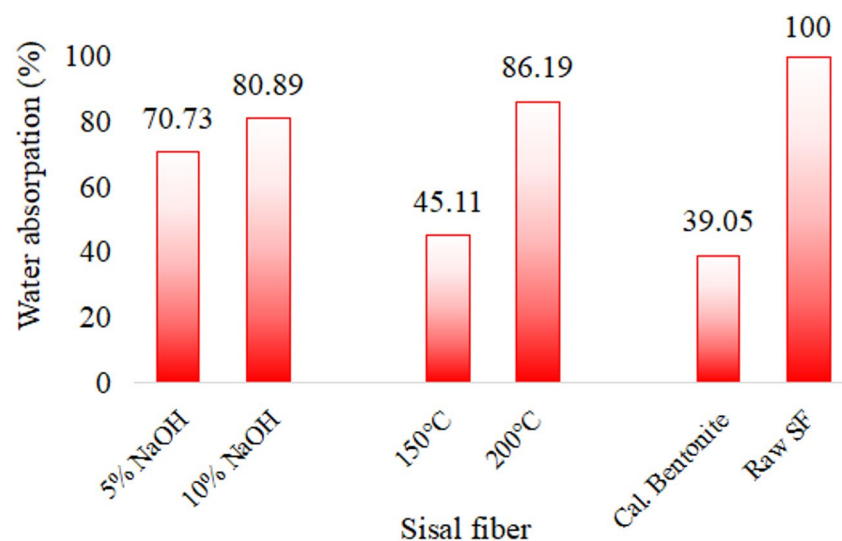


Fig. 6. Water absorption of raw and different treated sisal fibers.

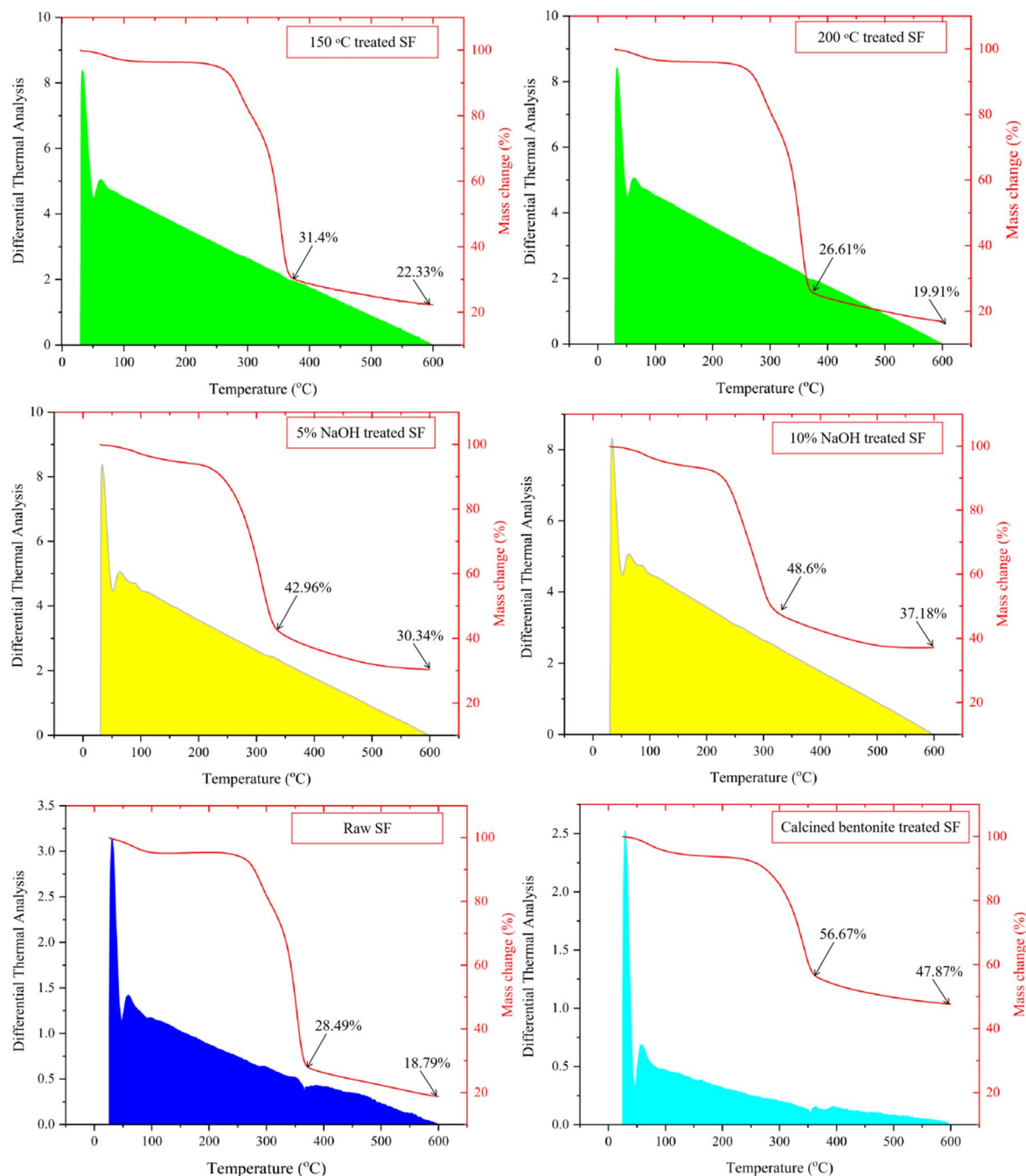


Fig. 7. Thermal resistance of raw sisal fiber and different treated sisal fiber.

treatment, and calcined bentonite slurry treatment were the most effective in reducing surface impurities and minimizing surface porosity. While each method altered the fiber differently, they all contributed to enhancing the surface characteristics of sisal fiber.

The SEM-EDS results presented in Fig. 8 reveal notable differences in the chemical composition between raw and various treated sisal fibers. As shown in Fig. 8m, the raw sisal fiber contains high levels of carbon (C) and oxygen (O), with the oxygen content being particularly elevated. This is primarily attributed to the fiber's moisture-absorbing nature, as the oxygen is largely derived from absorbed water. In contrast, the heat-treated fibers shown in Fig. 8n and p exhibit a slight increase in carbon content and a reduction in oxygen content, indicating that the heat treatment effectively reduces moisture in the fibers. The alkaline-treated sisal fibers, illustrated in Fig. 8q and r, display the presence of a new element—sodium (Na)—which originates from the NaOH solution used in the treatment. Additionally, these fibers show a more significant decrease in oxygen content compared to both raw and heat-treated fibers. Furthermore, the fiber treated with calcined bentonite slurry, shown in Fig. 8s, exhibits the lowest oxygen content along with a noticeably higher calcium (Ca)

concentration. This elevated Ca level is attributed to the calcined bentonite used in the treatment, confirming its strong presence on the fiber surface.

Physical and mechanical properties of mortar consisting of different treated Sisal fibers

Fresh density

Figure 9 illustrates the fresh bulk density of mortars incorporating raw and various treated sisal fibers. The inclusion of both raw and treated sisal fibers significantly reduces the fresh bulk density compared to the control mortar, primarily due to the lower density of sisal fiber relative to the overall mortar composition. Furthermore, an increase in the fiber dosage—regardless of treatment—leads to a further reduction in fresh bulk density. This is attributed to the fibers occupying space that would otherwise be filled by the denser mortar components. While the type of fiber treatment generally does not cause a significant variation in fresh bulk density, the mortar containing 10% NaOH-treated sisal fiber exhibited the lowest density among all samples. This could be due to the more severe surface degradation of the fiber caused by the higher alkaline concentration, potentially affecting its interaction within the mortar mix and leading to further density reduction.

The present result is similar with Almusawi et al.⁴¹, who found that incorporating sisal fiber into cement composite materials reduces the fresh bulk density compared to the control mix. Additionally, it has been reported that increasing the amount of sisal fiber in cement composites further decreases the fresh bulk density of the mortar, as the density of sisal fiber is significantly lower than that of cement particles^{29,42}.

Compressive strength

Table 3 presents the results of the mortar compressive strength at 28 days for mixtures containing raw and various treated sisal fibers. The addition of both raw and treated sisal fibers to the mortar led to improvements in compressive strength. Notably, mortars containing treated sisal fibers exhibited higher compressive strength compared to the control mix. Among the treatments, the mortar with 150 °C heat-treated sisal fiber showed higher compressive strength than the one with 200 °C heat-treated sisal fiber. This difference could be attributed to the surface modifications of the fibers at lower temperatures, which may facilitate better bonding with the cement matrix⁴³. Additionally, the mortar with 5% NaOH-treated sisal fiber outperformed the mortar with 10% NaOH-treated fiber in terms of compressive strength. This is likely because, as discussed in “[Micro-structure of different treated sisal fiber](#)”, the 10% NaOH treatment caused more surface damage to the fibers, impairing their ability to form strong bonds with the cement matrix and consequently reducing the strength of the composite^{28,33}.

Additionally, it was observed that mortar containing bentonite slurry-treated sisal fiber also showed higher compressive strength compared to the control mix. Specifically, the 150 °C heat-treated and calcined bentonite-treated sisal fibers improved the compressive strength at 28 days by 23.31% and 23.44%, respectively, compared to the control mix. However, increasing the fiber content to 2%—whether raw or treated—resulted in a reduction in compressive strength compared to the 1% fiber dosage. This is likely because a higher fiber content reduces the cement-to-sand bonding, leading to a decrease in the mortar’s compressive strength. This finding is consistent with the results of Nasr et al.⁴⁴, who reported significant changes in tensile strength in relation to variations in fiber size and dosage, which also impacted the compressive strength.

According to Fidelis et al.⁴⁵, coating natural fibers with pozzolanic materials reduces the alkalinity of the cement matrix. This occurs due to the pozzolanic reaction, which helps fill the pores of the sisal fiber and creates a strong bond with the matrix. As a result, the mechanical properties of the cement composite are improved, while also reducing the deterioration of the fiber caused by alkalinity and the mineralization of free lime in the cement.

The summary of this results show that incorporating sisal fibers enhances the 28-day compressive strength of mortar, with treated fibers performing better than raw fibers and the control mix. Treatments at 150 °C, 5% NaOH, and calcined bentonite were most effective, achieving about a 23% strength improvement due to improved fiber–matrix bonding. However, increasing the fiber content to 2% reduced compressive strength, indicating that an optimal fiber dosage is essential to maintain cement matrix integrity (Table 3).

Flexural strength

Table 4 presents the results of mortar flexural strength at 28 days for mixtures containing raw and various treated sisal fibers. The results show that the inclusion of both raw and treated sisal fibers significantly improved the flexural strength compared to the control mortar. Notably, the mortar with 150 °C heat-treated sisal fiber exhibited higher flexural strength than the mortar with 200 °C heat-treated sisal fiber. Additionally, mortar containing 5% NaOH-treated sisal fiber demonstrated higher flexural strength than mortar with 10% NaOH-treated fiber. Furthermore, the mortar with calcined bentonite-treated sisal fiber showed superior flexural strength compared to the mortar with raw sisal fiber. This improvement can be attributed to the fiber treatments, which reduce the lignin and impurity content (as discussed in “[Mineral composition of different treatment methods](#)”), thereby enhancing the interaction between the fiber and the cement matrix.

It was also observed that increasing the dosage of raw and treated sisal fibers in mortar resulted in a decrease in flexural strength. This is likely because a higher fiber content reduces the bonding between the cement particles in the mortar. These findings are consistent with the results of Tiwari et al.⁴⁶, who found a decrease in flexural strength with an increase in the fiber doses.

Conclusions

This study investigated the effects of various treatment methods on sisal fiber and evaluated the use of these treated fibers in cement composite materials, specifically in mortar. The following conclusions can be drawn from the findings.

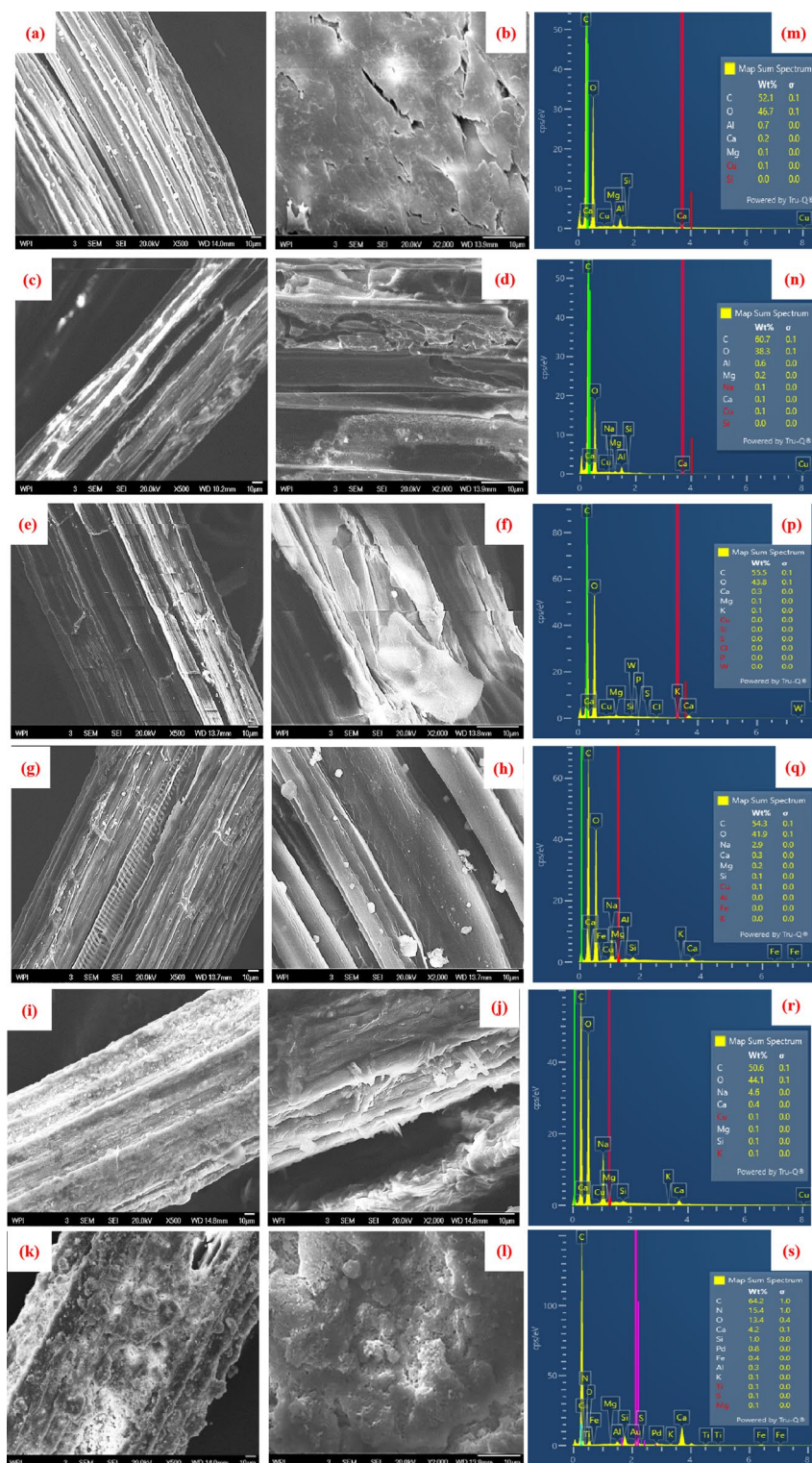


Fig. 8. Microstructural of sisal fiber at 500 magnification (a) raw sisal fiber, (c) 150 °C treated, (e) 200 °C treated, (g) 5% NaOH treated, (i) 10% NaOH treated, (k) calcined bentonite treated, microstructural of sisal fiber at 2000 magnification (b) raw sisal fiber, (d) 150 °C treated, (f) 200 °C treated, (h) 5% NaOH treated, (j) 10% NaOH treated, (l) calcined bentonite treated, and chemical composition change of sisal fiber (m) raw sisal (n) 150 °C treated, (p) 200 °C treated, (q) 5% NaOH treated, (r) 10% NaOH treated, (s) calcined bentonite treated.

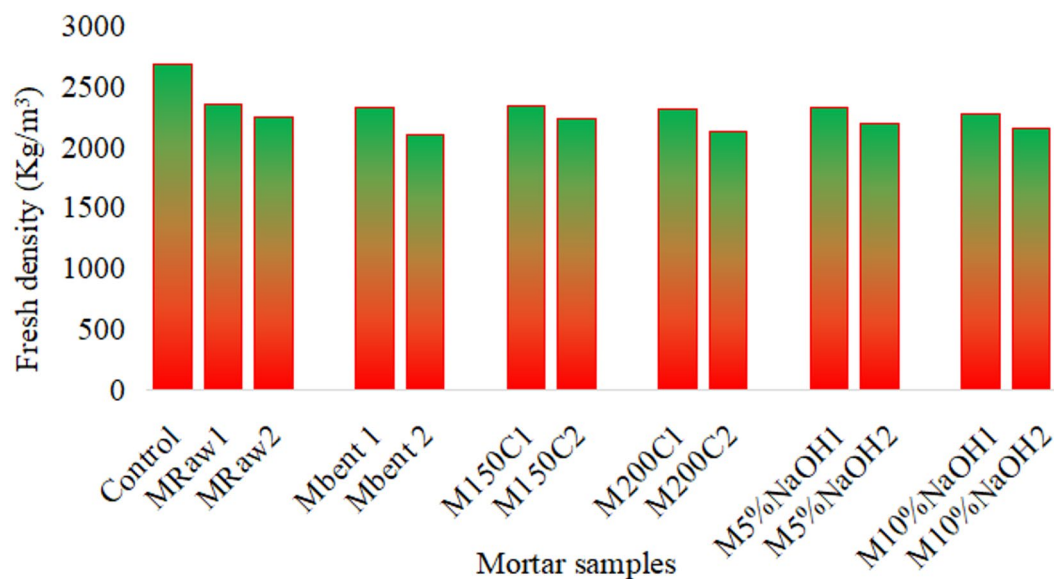


Fig. 9. Mortar fresh bulk density for raw and different treated sisal fibers.

Sample	CS- 1 (Mpa)	CS-2 (Mpa)	CS-3 (Mpa)	Average (MPa)	Standard deviation
Control	36	36.9	37.8	36.9	0.73
MRaw1	45.1	47	43.8	45.3	1.31
MRaw2	36	44.4	39	39.8	3.48
Mbent 1	43.55	47.6	45.5	45.55	1.65
Mbent 2	41.2	47.3	44.25	44.25	2.49
M150C1	45	46	45.5	45.5	0.41
M150C2	41.3	40	42.45	41.25	1.00
M200C1	42.5	47	44	44.5	1.87
M200C2	41	36.15	40	39.05	2.09
M5%NaOH1	40.25	48	47.5	45.25	3.54
M5%NaOH2	41.3	45.5	44	43.6	1.74
M10%NaOH1	40	44.2	42.1	42.1	1.71
M10%NaOH2	37.5	40	41	39.5	1.47

Table 3. Compressive strength (CS) of mortar having raw and different treated sisal fiber at 28 days mortar age.

- (1) All treatments by heat, alkaline, and calcined bentonite reduced lignin and other impurities from sisal fiber.
- (2) All treatments of sisal fiber improved its breaking load resistance under aging conditions. Notably, sisal fibers treated with 5% NaOH, 150 °C heat, and calcined bentonite exhibited increases in breaking load resistance after 10 cycles of wetting and drying, with improvements of 28.95%, 32.11%, and 33.37%, respectively, compared to the raw sisal fiber.
- (3) The treatment of sisal fiber with 150 °C, 5% NaOH, and calcined bentonite slurry respectively reduced water absorption by 34.89%, 29.27%, and 60.95% compared to the raw sisal fiber.
- (4) The inclusion of raw and treated sisal fibers in mortar significantly reduced the fresh bulk density compared to the control mortar.
- (5) The addition of treated sisal fiber in mortar improved the compressive strength compared to the mortar with raw sisal fiber.
- (6) Among all the treatments, mortar containing 150 °C heat-treated and calcined bentonite-treated sisal fibers significantly improved compressive strength at 28 days, with increases of 23.31% and 23.44%, respectively, compared to the control mix.
- (7) The calcined bentonite-treated sisal fiber significantly reduced heat mass loss by 28.18% at 367 °C and 29.08% at 600 °C, compared to raw sisal fiber.
- (8) Mortar having raw and different treated sisal fiber improved flexural strength compared to control mortar.

Sample	FS- 1 (Mpa)	FS-2 (Mpa)	FS-3 (Mpa)	Average (MPa)	Standard deviation
Control	7	9.2	8	8.07	0.90
MRaw1	8	8.75	9.5	8.75	0.61
MRaw2	7.75	7.95	9.2	8.3	0.64
Mbent 1	8.75	8.8	9	8.85	0.11
Mbent 2	8	8.65	8.85	8.5	0.36
M150C1	8.75	8.5	9	8.75	0.20
M150C2	8.5	8.5	8.5	8.5	0.00
M200C1	8	9	8.5	8.5	0.41
M200C2	8	8.2	8.1	8.1	0.08
M5%NaOH1	9.2	8.5	9	8.9	0.29
M5%NaOH2	8.35	8.5	8.95	8.6	0.25
M10%NaOH1	8	7.5	8.5	8	0.41
M10%NaOH2	7.5	8	7.6	7.7	0.22

Table 4. Flexural strength (FS) of mortar employed raw and different treated sisal fibers at 28 days mortar age.

The study concludes that 5% NaOH treatment, 150 °C heat treatment, and calcined bentonite provide the best performance for sisal fibers, and recommends future research focus on optimizing these three treatment techniques through numerical optimization software and experimental validation to achieve the most effective sisal fiber treatment.

Data availability

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

Received: 25 April 2025; Accepted: 6 February 2026

Published online: 15 February 2026

References

- de Lima, T. E. S. et al. Potential of using Amazon natural fibers to reinforce cementitious composites: A review. *Polymers (Basel)*. **14**, 1–20 (2022).
- Latifi, M. R., Biricik, Ö. & Mardani Aghabaglou, A. Effect of the addition of polypropylene fiber on concrete properties. *J. Adhes. Sci. Technol.* **36**, 345–369 (2022).
- Li, H. et al. Synergistic reinforcement of recycled carbon fibers and Biochar in high-performance, low-carbon cement composites: A sustainable pathway for construction materials. *Cem. Concr Compos.* **162**, 106148 (2025).
- Afolayan, J. O., Wilson, U. N. & Zaphaniah, B. Effect of sisal fibre on partially replaced cement with periwinkles shell ash (PSA) concrete. *J. Appl. Sci. Environ. Manag.* **23**, 715 (2019).
- Wu, Z., Shi, C., He, W. & Wu, L. Effects of steel fiber content and shape on mechanical properties of ultra high performance concrete. *Constr. Build. Mater.* **103**, 8–14 (2016).
- Mudadu, A., Tiberti, G., Germano, F., Plizzari, G. A. & Morbi, A. The effect of fiber orientation on the post-cracking behavior of steel fiber reinforced concrete under bending and uniaxial tensile tests. *Cem. Concr Compos.* **93**, 274–288 (2018).
- Yinh, S., Hussain, Q., Joyklad, P. & Chaimahawan, P. Strengthening effect of natural fiber reinforced polymer composites (NFRP) on concrete. *Case Stud. Constr. Mater.* **15**, e00653 (2021).
- Hussain, T. & Ali, M. Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of FRC. *Constr. Build. Mater.* **213**, 592–607 (2019).
- Li, H. et al. Effect of electrophoretic deposition of micro-quartz on the microstructural and mechanical properties of carbon fibers and their bond performance toward cement. *J. Mater. Sci.* **57**, 21885–21900 (2022).
- Silva, D. W. et al. Influence of thermal treatment of eucalyptus fibers on the physical-mechanical properties of extruded fiber-cement composites. *Mater. Today Proc.* **31**, S348–S352 (2019).
- Ivanova, I., Assih, J. & Dontchev, D. Application of natural fiber composite materials in the strengthening of reinforced concrete structures. *IOP Conf. Ser. Mater. Sci. Eng* **951** (2020).
- Batista dos Santos, G. Z., Passos de Oliveira, D. & de Almeida Melo Filho, J. & Marques Da Silva, N. Sustainable geopolymer composite reinforced with Sisal fiber: durability to wetting and drying cycles. *J. Build. Eng* **43** (2021).
- Zakaria, M., Ahmed, M., Hoque, M. & Shaid, A. A. Comparative study of the mechanical properties of jute fiber and yarn reinforced concrete composites. *J. Nat. Fibers.* **17**, 676–687 (2020).
- Yadav, D., Selokar, G. R., Agrawal, A., Mishra, V. & Khan, I. A. Effect of concentration of NaOH treatment on mechanical properties of Epoxy/Sisal fiber composites. *IOP Conf. Ser. Mater. Sci. Eng* **1017** (2021).
- Asim, M. et al. Comparative experimental investigation of natural fibers reinforced light weight concrete as thermally efficient building materials. *J. Build. Eng.* **31**, 101411 (2020).
- Ferreira, D. P., Cruz, J. & Fanguero, R. Surface modification of natural fibers in polymer composites. In *Green Composites for Automotive Applications*. 3–41. <https://doi.org/10.1016/B978-0-08-102177-4.00001-X> (Elsevier Ltd, 2018).
- Thomas, B. C. & Jose, Y. S. Impact of Sisal fiber reinforced concrete and its performance analysis: A review Biju. *Evol. Intell.* **15**, 865–875 (2022).
- Martinelli, F. R. B. et al. A review of the use of coconut fiber in cement composites. *Polym. (Basel)*. **15**, 1–15 (2023).
- 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).
- Gupta, U. S. et al. Surface modification of banana fiber: A review. *Mater. Today Proc.* **43**, 904–915 (2020).
- 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).

22. Ahmad, W. et al. Effect of coconut fiber length and content on properties of high strength concrete. *Materials (Basel)* **13** (2020).
23. Verma, N., Singh, M. K. & Zafar, S. Development of porous bio-nano-composites using microwave processing. *Biofibers Biopolymers Biocomposites: Synthesis Charact. Prop.* https://doi.org/10.1007/978-3-030-40301-0_10 (2020).
24. de Castoldi, R. S. et al. Effect of alkali treatment on physical-chemical properties of sisal fibers and adhesion towards cement-based matrices. *Constr. Build. Mater.* **345** (2022).
25. Fode, T. A., Jande, C. A. Y. & Kivevele, T. Modeling and optimization of Sisal fiber degradation treatment by calcined bentonite for cement composite materials. *J. Nat. Fibers* **21** (2024).
26. Wei, J. & Meyer, C. Improving degradation resistance of sisal fiber in concrete through fiber surface treatment. *Appl. Surf. Sci.* **289**, 511–523 (2014).
27. Fode, T. A., Jande, Y. A. 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).
28. de Klerk, M. D. et al. Durability of chemically modified sisal fibre in cement-based composites. *Constr. Build. Mater.* **241**, 117835 (2020).
29. Fode, T. A., Jande, Y. A. C. & Kivevele, T. A. Review on degradation improvement of Sisal fiber by alkali and Pozzolana for cement composite materials. *J. Nat. Fibers* **21** (2024).
30. ASTM C138M, 17a. Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric). In ASTM Standard 1–6. <https://doi.org/10.1520/C0138> (2019).
31. ASTM C618. *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolana for Use in Concrete*, ASTM International, West Conshohocken, PA. In *ASTM Standard*. 3–6. <https://doi.org/10.1520/C0618> (2012).
32. Hajiha, H., Sain, M. & Mei, L. H. Modification and characterization of hemp and sisal fibers. *J. Nat. Fibers*. **11**, 144–168 (2014).
33. Musanif, I. S. & Thomas, A. Effect of alkali treatments of physical and mechanical properties of coir fiber. *Chem. Mater. Eng.* **3**, 23–28 (2015).
34. Natural fibers and their composites. In *Tribology of Natural Fiber Polymer Composites* 1–58. <https://doi.org/10.1533/9781845695057.1> (2008).
35. 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).
36. Ferreira, S. R., Silva, F., de Lima, A., Toledo Filho, R. D. & P. R. L. & Effect of hornification on the structure, tensile behavior and fiber matrix bond of sisal, jute and curauá fiber cement based composite systems. *Constr. Build. Mater.* **139**, 551–561 (2017).
37. Gudayu, A. D., Steuernagel, L., Meiners, D. & Gideon, R. Effect of surface treatment on moisture absorption, thermal, and mechanical properties of sisal fiber. *J. Ind. Text.* **51**, 1–21 (2020).
38. Zhang, Z., Li, Y., Fu, K. & Li, Q. Determination of interfacial properties of cellulose nanocrystal-modified sisal fibre in epoxy by cyclic single-fibre pull-out. *Compos. Sci. Technol.* **193**, 108142 (2020).
39. 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).
40. 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).
41. Almusawi, M., Hussein, A. S., Shallal, A. & T. & Effect of temperature and sisal fiber content on the properties of plaster of Paris. *Int. J. Eng. Technol.* **7**, 205 (2018).
42. Barbuta, M. et al. Characterization of polymer concrete with natural fibers. In *IOP Conference Series: Materials Science and Engineering*. Vol. 246 (2017).
43. Orue, A., Eceiza, A. & Arbelaz, A. *Pretreatments of Natural Fibers for Polymer Composite Materials*. https://doi.org/10.1007/978-3-319-68696-7_3 (2018).
44. 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).
45. 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).
46. Tiwari, V., Parate, H. R. & Patil, N. N. Strength and durability studies of waste nylon cable ties concrete. *J. Phys. Conf. Ser.* **1706** (2020).

Acknowledgements

The authors are thankful to the Partnership for Applied Sciences, Engineering, and Technology (PASET) - Regional Scholarship and Innovation Fund (RSIF) for their support in this study.

Author contributions

Tsion A. F. Conceptualization, investigation, Original writing. Y. A. CH.J., T.K., and N.R.-Conceptualization, supervision, review and edit writing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to T.A.F.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026