Structural Performance of Sisal Fiber Mat Retrofits for Post-Fire Damaged Reinforced Concrete Beams

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Received: 14 October 2024 | Revised: 30 October 2024 | Accepted: 3 November 2024

 DOI: https://doi.org/10.48084/etasr.9266

ABSTRACT

Concrete experiences degradation in mechanical properties when exposed to high temperatures, leading to spalling, disintegration, and surface damage. Research shows a 26-40% reduction in structure strength under fire. While strengthening and restoring existing structures is a practical solution, a more sustainable approach is needed. This study evaluated the performance of sisal fiber mat retrofits for post-fire damaged beams and investigated natural fiber retrofits as a sustainable solution for fire-damaged structures, addressing challenges like elevated temperatures and moisture sensitivity to restore safety, stability, and functionality. The physical, chemical, and mechanical properties of the constituent materials used to fabricate the reinforced concrete beams and retrofitted material were characterized. The mechanical properties of 150×225×650 mm reinforced concrete beams exposed to 800 °C for 1 hour were assessed. The load-carrying capacity of the concrete beam was determined after it had been repaired with one or two layers of sisal fiber mat. The results indicated that the load-carrying capacity of concrete reinforced beams exposed to fire was reduced by 13.03%. However, the use of two layers of sisal fiber mat retrofits in the beams restored the load-carrying capacity by 33.86% and improved ductility by 43.56%. These findings demonstrate the feasibility of using sisal fiber mat retrofits to repair fire-damaged reinforced concrete beams, as the fiber mat enhances the load-carrying capacity by providing additional tensile strength to the structure.

Keywords-sisal fiber mat; flexural strength; load-carrying capacity; elevated temperature; reinforced concrete beam

I. INTRODUCTION

Structural design ensures stability, safety, and functionality in built environments by withstanding loads without cracking or deforming. Naturally, reinforced concrete structures resist fire better than steel or wood due to the low thermal diffusivity and relatively large size of concrete members [1, 2]. Within the built environment, the structural integrity and safety of a building are critical factors that engineers must carefully consider, especially under elevated temperatures. Fire disasters represent a significant global problem, particularly in developing countries, resulting in substantial damage to buildings and infrastructure due to wear, corrosion, or deterioration over time [3]. For instance, between 2000 and 2001, Taiwan experienced 5,893 residential fires, while Dubai had 5,490 fires between 2008 and 2016, and China reported 132,497 fires in 2010 [4-6], with 52.1% of these incidents being associated with domestic units, commercial stores, manufacturing plants, construction areas, and government institutions. High temperatures in concrete can negatively impact its mechanical properties, leading to deformation and cracking [7, 8].

When exposed to high temperatures, concrete experiences a deterioration of its material properties, such as reduced strength and elastic modulus, as well as the development of spalling and cracks [9]. Studies have shown that when a portion of a structure is affected by fire, it can lose 26-40% of its strength [10]. Strengthening and renovating existing structures is a practical, long-term solution, as it addresses structural deficiencies, ensures stability, and enables the structure to withstand various loads and environmental conditions [10, 11]. When structures face hazards like fire incidents, it is necessary to explore efficient and sustainable retrofitting methods to repair damaged structural elements. Retrofitting involves modifying structures to enhance their performance and durability, considering factors, such as the extent of damage, element shape, repair materials, cost, duration, and component functions before repairing fire-damaged components [9, 12]. Researchers have utilized conventional retrofitting techniques, including shear walls, bracing, concrete jacketing, steel jacketing, fiber-reinforced polymer composites, and fiber-reinforced cementitious matrix, to restore and strengthen damaged structures. For example, investigating the retrofitting of reinforced concrete columns with square or rectangular sections using the steel jacketing method, authors in [13] found that the rectilinear steel jacketing, when partially stiffened, is an effective approach. This technique prevents brittle shear failure and significantly enhances the column's ductility, eventually resulting in an ultimate drift ratio of more than 8%.

Authors in [14] examined the flexural behavior of 2.5×0.15×0.25m reinforced concrete beams subjected to 2-point loading, strengthened with concrete and reinforced concrete jackets applied to their soffit after 2 hours of fire exposure. The fire-damaged section and jacketed section utilized high-strength concrete, 50 MPa, and 500 MPa tensile yield strength steel. The proposed approach estimates the flexural capacity of fire-damaged jacketed beams. It was established that increasing the reinforcement content significantly impacts the moment capacity. A 50 mm concrete jacket increased the fire-damaged beam's maximum moment capacity by 24.84%, and a 0.223% steel jacket increased the moment capacity by 54.73%. The load-deflection response of the reinforced beams suggests that adding a 0.223% steel reinforcement jacket may greatly enhance stiffness and load-bearing capacity. Previous research determined the axial performance of low-strength concrete using external jacketing applied through sprayed Glass Fiber-Reinforced Mortar (GFRM) or basalt textile-reinforced sprayed GFRM, demonstrating that this material and method provided significant gains in compressive strength and energy dissipation [15]. However, it was noted that further research is needed to assess the residual strength and performance of fire-damaged 30 MPa beams retrofitted with sisal fiber mats under service loads and explore their structural performance.

Jacketing with steel or concrete can help retrofit fire-damaged reinforced concrete beams, but it increases the cross-sectional area and weight. Fiber-reinforced composites provide a lighter alternative, as they are less rigid than steel or concrete jackets. Synthetic fiber-reinforced polymer has been used to retrofit concrete elements damaged by high temperatures, encasing them in the polymer sheets and epoxy resin. These sheets provide additional reinforcement and confinement to the beam [16]. In [17], the behavior of reinforced concrete beams retrofitted using Carbon Fiber Reinforced Polymers (CFRP) was examined. The study investigated the impact of simple retrofitting schemes on reinforced concrete beam flexural behavior, aiming to offer economical and effective solutions for ageing infrastructure and catastrophic event damage. The CFRP strips were attached to tension beams using high-strength epoxy, with U-shaped anchorages made of Sika-Wrap 230C. The primary failure mode was the debonding of CFRP from the concrete surface, emphasizing the importance of anchorage systems. The study revealed that CFRP significantly enhanced beam flexural capacity, with a 17.36% higher strength achieved in a retrofitted beam, highlighting the need for effective anchorage systems for load-carrying. Authors in [18] focused on retrofitting post-fire reinforced concrete beams with CFRP to restore their mechanical properties, providing structural engineers with practical information. It was found that applying CFRP increases the post-fire Reinforced Concrete (RC) beams' load-carrying capacity by 27.5-40.9% for 30-60 minutes and recovers the load-carrying capacity for 75 minutes. Additionally, the ultimate load-carrying capacity increased significantly, but the increased level depends on the CFRP retrofit and fire duration. This technique effectively retrofits structural elements by enhancing flexural strength, ductility, and durability. Due to the lack of sustainability, synthetic fibers face elevated manufacturing expenses, environmental concerns, and health hazards. The use of natural fibers, such as sisal, silk, bamboo, kenaf, and jute, as reinforcement in polymeric strengthening materials was investigated in [19]. These natural fiber composites showed promising results in enhancing the load-bearing capacity of post-fire damaged beams. The fibers were compared in terms of density, tensile strength, modulus of elasticity, and elongation at break. Bamboo fibers were less dense and had similar tensile strength to sisal fibers. Sisal fibers exhibited superior modulus of elasticity and elongation at break compared to other natural fibers, demonstrating the highest ductility and ability to control crack formation without rupture.

The potential of sisal and jute fibers in mitigating the brittle shear failure of short RC columns in seismic-prone areas was evaluated in [16]. This investigation examined the seismic performance of shear-critical strengthened RC columns through a quasi-static reversed cyclic loading test. The objective was to explore the feasibility of using natural fibers as an alternative to CFRP. The findings revealed that natural fiber sheets, sisal, and jute, prevented brittle shear failure, thereby enabling the columns to gain sufficient ductility. The ductility attained by sisal and jute-strengthened columns was comparable to that of the CFRP-strengthened column. However, the natural fiber sheets consumed more epoxy due to their greater thickness compared to CFRP. Nevertheless, replacing CFRP with natural fiber sheets reduced the total cost per single column by 35% and 15% for sisal and jute, respectively. The literature review indicates a paucity of studies on the load-bearing capacity of concrete beams exposed to elevated temperatures and retrofitted with a sisal fiber mat.

Sisal fibers, derived from the agave sisalana plant, have garnered significant interest due to their composites' high impact strength and moderate tensile and flexural properties [20]. These natural and renewable fibers provide cost-effective alternatives for strengthening structures in harsh environments, outperforming their synthetic counterparts. Sisal fiber mats have demonstrated potential as sustainable retrofitting materials, capable of enhancing the load-bearing capacity, ductility, and toughness of composites. Previous research has highlighted the promising use of sisal fibers as reinforcements in polymer composites, such as thermoplastics, thermosets, and rubbers. The present study aims to investigate the structural performance of sisal fiber mats as a retrofitting solution for restoring the load-bearing capacity of fire-damaged reinforced concrete beams.

II. MATERIALS AND METHODS

A. Materials

1) Material Acquisition

The material used in this study was Ordinary Portland Cement (OPC) CEM I/42.5 N, coarse and fine aggregates, 10 mm and 6 mm reinforcing bars, water, sisal fiber mat, and epoxy resin, as seen in Figure 1. The OPC, Bamburi Power Plus, was sourced locally from Bamburi Cement Brands. The fine and coarse aggregates were sourced from Warren Concrete Ltd, while the reinforcement bars were obtained from One Step Steel Hardware Limited. The sisal fiber mat was purchased from Fiber Source, and the epoxy resin, specifically Sikadur 32 LP, was purchased from Sika Kenya Limited. Sisal fiber mats were prepared using ASTM D 3822-01 procedures.

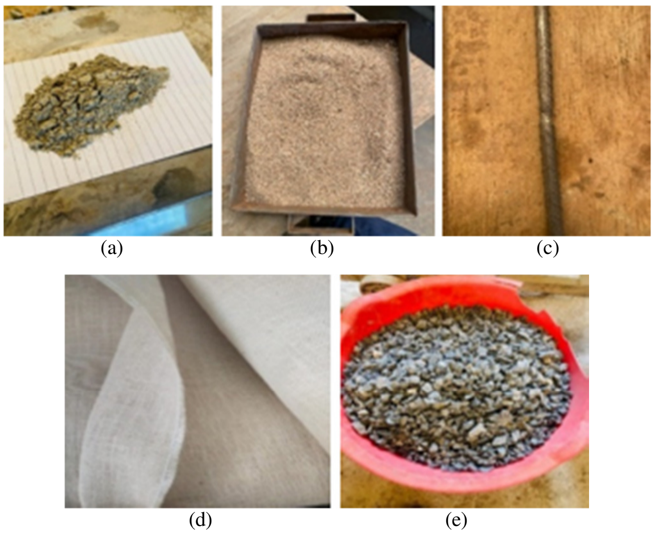


Fig. 1. Images of (a) OPC CEM I 42.5, (b) fine aggregates, (c) reinforcements, (d) sisal fiber, and (e) coarse aggregates.

2) Material Preparation

Prior to the laboratory experiment, the fine aggregates underwent sieving through a 4.75 mm mesh sieve, while the coarse aggregates were sieved using a 20 mm mesh size. The fine and coarse aggregates were then washed to diminish silt content and eliminate unwanted particles, and subsequently air-dried, respectively. Additionally, the steel reinforcement bars were cut into 500 mm segments.

For the epoxy resin, the manufacturer's instructions were followed when blending the two-part epoxy. Five minutes were used to mix the epoxy until a uniform mix was obtained. The stirring of the mixture ensured that no air entered in it to avoid points of weakness. Safety measures, like gloves, were implemented to avoid direct contact with the epoxy.

B. Methods

1) Material Characterisation

The physical characteristics of OPC that were examined included fineness and specific gravity, which were evaluated using the ASTM C 184-94 and ASTM C 188 test methods, respectively. Both the fine and coarse aggregates were further analyzed in terms of particle size distribution, fineness modulus, specific gravity, and water absorption, in accordance with ASTM standards [15, 16]. Additionally, the fine aggregates were assessed for silt content, while the coarse aggregates were evaluated for aggregate crushing value and aggregate impact value, as per the aforementioned standards. The various tests conducted on the fine and coarse aggregates are illustrated in Figure 2.

Fig. 2. Various tests conducted on fine and coarse aggregates. (a) Particle size distribution, (b) specific gravity on coarse aggregates, (c) specific gravity on fine aggregate, and (d) silt content on fine aggregate.

Furthermore, 10 and 6 mm diameter reinforcement bars were tested for tensile strengths until failure, using a Universal Testing Machine (UTM), as per ASTM A370-15. The force, displacement, and elongation were recorded during the test after every failure mode. The tensile strength test on sisal fiber mat was conducted using a SHIMADZU UTM, as shown in Figure 3(a). The chemical properties of sisal fiber assessed were the content of cellulose, hemicelluloses, and lignin. Additionally, the quality of the fibers was analysed using high-resolution images of the fibers captured by Scanning Electron Microscopy (SEM). Figure 3(b) displays the images captured during the test.

(a) (b)

Fig. 3. (a) Tensile test and (b) SEM analysis performed on sisal fiber mat.

2) *Experimental Set-Up and Data Collection Procedure*

a) Tests on Fresh and Hardened Concrete

In this study, the normal concrete of M30 grade was designed according to the Department of Environmental Design Method (DOE) method of concrete mix design. The material properties obtained from the characterisation were used for the constituent materials of the concrete. The design results for the mix proportion by weight of cement, fine aggregate, and coarse aggregate were 1:1.75:3 with a water-cement ratio of 0.5.

Preliminary tests were conducted on concrete cubes and cylinders under different treatments to determine their strengths after curing. The treatments comprised untreated concrete as Control (C), Heated Concrete (HC), and Retrofitted Concrete (RC). For the C and HC, nine cubes of 100×100×100 mm and nine cylinders 200 mm long and with 100 mm diameter for each treatment were tested for compressive strength and split tensile strength, respectively, at 7, 14, and 28 days.

The study examined the workability, compressive strength, and split tensile strength, of fresh and hardened concrete. The workability of freshly mixed 30 MPa concrete was assessed using the ASTM C143/C143M-10 standard slump test procedure. Concrete samples were placed in the mold in three equal layers, and each layer was compacted with 25 uniform strokes of a tamping rod across the mold's cross-section. The tamping penetrated the underlying layers for the subsequent layers. Excess concrete was then removed, and the surface was leveled with a trowel. The mold was slowly raised vertically, and the slump was measured as the difference between the mold height and the height of the tested specimen.

On the other hand, the compressive strength test was carried out using cubes as per ASTM C39. A UTM was utilized while applying pressure at a rate of 140 kg/cm^2 per minute until failure to the concrete cubes. This test was conducted on C and HC. Finally, a split tensile test according to ASTM C 496-04 was conducted on C and HC specimens using a UTM, and the results were recorded.

b) Tests on Reinforced Concrete Beams

Eighteen reinforced concrete beams, each measuring 150×225 mm in cross-section and 650 mm in length, were fabricated and tested for flexural strength after 28 days. The beams were designed using M30 concrete and incorporated two longitudinal steel bars of 10 mm diameter in tension and 10 mm diameter in compression, along with 6 mm diameter stirrups spaced at 100 mm intervals along the span.

The beams were divided into six experimental groups: Control (C), Control Retrofitted with one layer (CR1), Control Retrofitted with two layers (CR2), Heated (H), Heated Retrofitted with one layer (HR1), and Heated Retrofitted with two layers (HR2). H, HR1, and HR2 were subjected to fire to simulate fire damage, with the samples heated in a furnace to a target temperature of 800 °C for one hour. After the heating phase, the beams were allowed to cool at ambient temperature. CR1, CR2, HR1, and HR2 were strengthened using a sisal fiber mat. The retrofitting process required surface preparation to remove concrete dust and spalled concrete, followed by wrapping the sisal fiber mats around the beams using Sikadur 32 Lp. The beams were then subjected to three-point bending, as depicted in Figure 4.

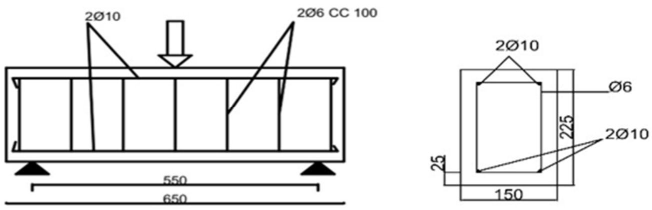
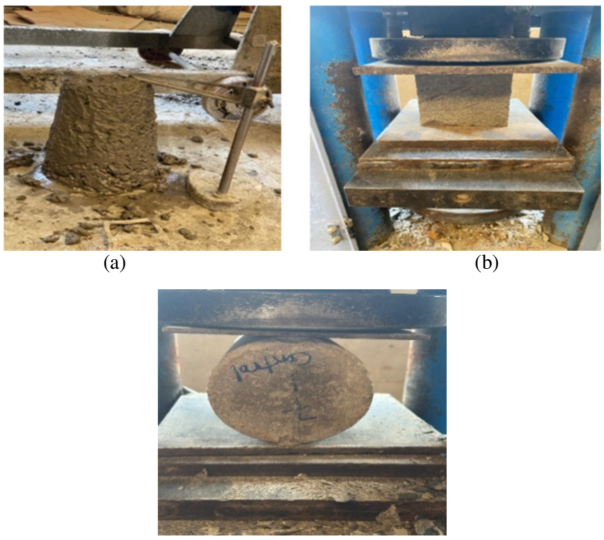


Fig. 4. Test sample setup.

Fig. 5. Concrete beam test set-up.



(a) (b) (c)

Fig. 6. (a) Workability test, (b) compressive strength test, and (c) split tensile strength test on concrete.

Flexural tests were conducted on all samples to evaluate their load-bearing capacity and the effectiveness of using a sisal fiber mat as a natural material to strengthen fire-damaged beams. Linear Variable Differential Transformers (LVDT) and strain gauges were employed to monitor the structural response, and the full test setup is shown in Figure 5.

The flexural performance of the beams was evaluated using a three-point bending test in accordance with ASTM C 293. The beams were supported with simple support. The loading was applied utilizing a hydraulic jack.

III. RESULTS AND DISCUSSION

A. *Characterisation of Constituent Materials*

1) *Cement*

Three samples were employed to determine the fineness of cement, the average value obtained of 98% met the fineness requirement as per ASTM C 184 – 94. The specific gravity of the cement was 2.8, which, according to ASTM C188, falls between 2.8 and 3.1. The mix design, which affects the workability and strength of concrete, may be influenced if the specific gravity of the cement is below or beyond the defined range.

2) *Fine and Coarse Aggregates*

a) *Physical Properties*

The particle size distribution of fine and coarse aggregates is presented in Figure 7. As per ASTM C33, this property is essential in evaluating the quality of aggregates for concrete applications [21]. The fine and coarse aggregates, ranging from 1.18-5 mm and 5-20 mm, respectively, were found to comply with the gradation limits specified by ASTM C33. The fine aggregates had a particle size distribution that met the requirements of ASTM C33, ensuring the proper grading for concrete use. Similarly, the coarse aggregates also fell within the gradation limits set forth by ASTM C33, indicating their suitability for concrete applications. Additionally, the fineness moduli of the fine and coarse aggregates were determined to be 3.78 and 4.9, respectively, further confirming their compliance with industry standards.

The specific gravity and water absorption tests for both fine and coarse aggregates were conducted using the standard ASTM C128-0 and ASTM C127-01 test procedures, respectively. The test results are provided in Table I. The specific gravity values of the fine and coarse aggregates were measured to be 2.69 and 2.50, respectively. Similarly, their corresponding water absorption and moisture content were found to be 1.21% and 2.07%, and 1.20% and 2.03%, respectively. The findings demonstrate that the fine aggregate exhibits a higher specific gravity but lower water absorption compared to the coarse aggregate. This suggests that the fine aggregate is denser and less absorbent than the coarse aggregate. Additionally, the fine aggregate has a lower moisture content than the coarse aggregate. These results imply that the concrete produced using these aggregates is anticipated to be denser, more durable, and easier to mix. In construction projects, it is essential to determine the silt content to understand the suitability of the aggregate. From the test, the silt content was measured to be 5.3%, which falls within the standard range as per ASTM C33.

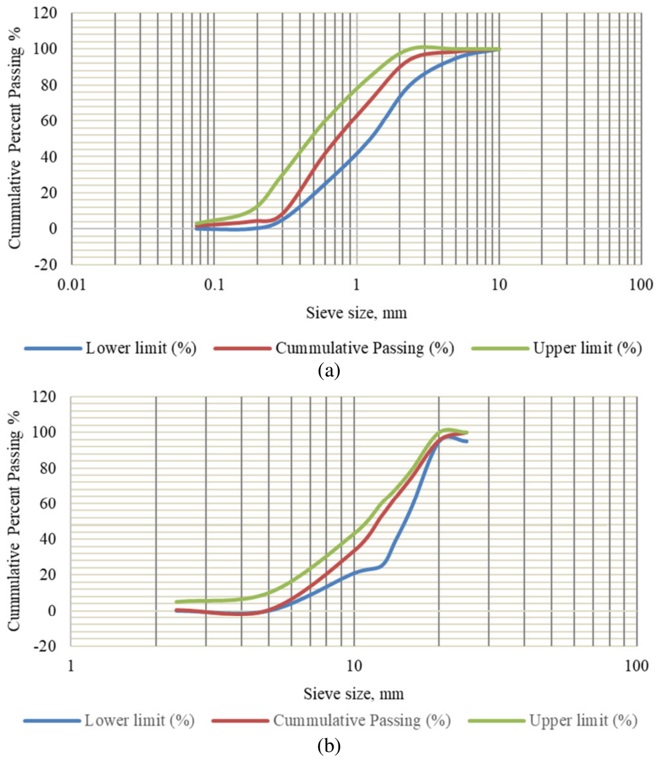


Fig. 7. Particle size distribution for (a) fine aggregates and (b) coarse aggregates.

TABLE I. SPECIFIC GRAVITY OF FINE AND COARSE AGGREGATES

Properties	Fine aggregate	Coarse aggregate
Specific gravity, saturated surface dry	2.69	2.50
Specific gravity, oven-dried basis	2.66	2.45
Water absorption (%)	1.21	2.07
Moisture content (%)	1.20	2.03

b) *Mechanical Properties*

Experiments were conducted on the coarse aggregate to determine Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV). The aggregate crushing value was measured following the guidelines in BS 812 Part 110, while the aggregate impact value was evaluated using ASTM D 58-74. The ACV and AIV of the coarse aggregates were found to be 17.13 and 12.57, respectively. According to BS 812 Part 110, aggregates with ACV values below 30% are deemed suitable for use in concrete intended to withstand heavy loads and high-stress conditions. Moreover, ASTM D 58-74 suggests that an AIV ranging from 10-20 indicates a property of very tough/strong aggregate, implying that the aggregate can resist sudden shocks or impacts. When exposed to high temperatures, concrete undergoes thermal expansion and internal stresses; therefore, aggregates with high ACV and AIV are more susceptible to crushing under these stresses, potentially leading to a loss of concrete strength and cohesion. The crushing value test accurately estimates the aggregate's resistance to crushing under gradually applied compressive loads, while the impact value test provides a comparative measure of the aggregate's resistance to sudden impacts [24]. Based on the experimental findings, it is estimated that the aggregates can better withstand the internal pressure and associated impact, thus reducing the risk of spalling and maintaining structural cohesion, contributing to better concrete residual strength after fire exposure [25]. This suggests that the concrete element can continue to support loads even after being damaged by fire, thereby improving its overall fire resistance.

3) Reinforcing Bars

The present study examined the tensile properties of 10 mm and 6 mm diameter steel rebars used for longitudinal and transverse reinforcement, following BS EN ISO 6892. The UTM was employed to assess the tensile strength of three samples for each rebar type. The mean ultimate strengths were determined to be 548.27 MPa and 677.541 MPa for the T6 and T10 bars, respectively. Similarly, the average yield strengths were found to be 535.471 MPa and 589.934 MPa for the T6 and T10 bars, respectively, indicating that the T10 bars exhibit a higher yield strength, meaning they can withstand more stress before permanent deformation occurs. Furthermore, the ultimate strength of the T10 bars was significantly greater than that of the T6 bars, suggesting that the T10 bars can endure higher stresses before failure. The tensile properties of the rebars were observed to meet the requirements specified in BS EN 10080 for reinforced concrete applications.

4) Sisal Fibers

The tensile test conducted on the sisal fiber mat evaluated three samples, with the average values being presented in Figure 8. The results demonstrate that the mat required a force of 340.406 N and a displacement of 18.0629 mm to reach failure, and the maximum stress endured was 283.672 N/tex. The fiber mat's composite structure effectively distributes the applied load, leading to its significantly higher force at failure. The mat displays excellent ductility and strength, making it a robust material for high load-bearing applications.

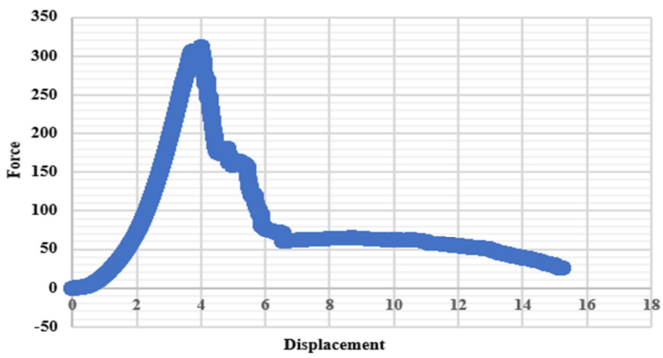


Fig. 8. Tensile results of sisal fiber mat.

The analysis of the sisal fiber mat in terms of chemical composition was obtained from the manufacturer. Table II shows the chemical composition per percentage of cellulose, hemicellulose, and lignin.

TABLE II. CHEMICAL COMPOSITION OF SISAL FIBER MAT

Material	Content (%)
Cellulose	65.0
Hemicellulose	12.0
Lignin	9.9
Waxes	2.0

B. Mechanical Properties of Hardened Concrete

1) Compressive Strength

The compressive strength of the 30 MPa concrete mix was measured at 7, 14, and 28 days, as illustrated in Figure 9. The unheated concrete, which is considered the C, exhibited an initial compressive strength of 29.33 MPa at the early stage of 7 days, which increased to 37.349 MPa by the end of the 28-day curing period. In contrast, the HC samples started with a lower compressive strength of 17.47 MPa and showed a slight decline over time, reaching 16.039 MPa by the 28th day. This decrease can be attributed to the detrimental effects of heat exposure, including thermal cracking, accelerated moisture loss, and alterations in the concrete matrix's chemical structure [26]. These factors compromised the concrete's quality, impeding its normal hydration and strength development. Conversely, the C samples followed a typical strength gain pattern due to the ongoing cement hydration, resulting in a denser microstructure that enabled higher compressive load resistance over time.

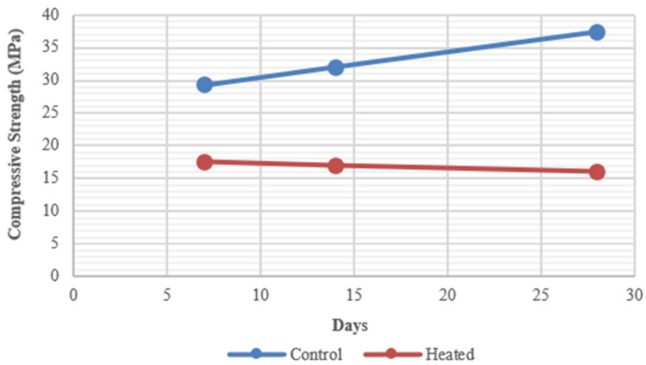


Fig. 9. Compressive strength of concrete.

2) Split Tensile Strength

The split tensile strength tests were conducted on the C and HC cylinders at 7, 14, and 28 days, as evidenced in Figure 10. The results obtained are 2.5, 2.55, and 2.66 at 7, 14, and 28 days, respectively. Those for the heated samples were 0.58, 0.66, and 0.59 at the respective curing period. These findings show that the HC has sustained damage due to the exposure to high temperatures, limiting its ability to recover tensile strength even with continued curing. The results demonstrate that heat exposure significantly reduces the split tensile strength of concrete, and sisal fiber mat retrofits may provide a way to enhance the tensile strength by redistributing the tensile stresses and reducing the likelihood of crack propagation. This highlights the importance of retrofitting as a necessary intervention to restore or enhance the tensile strength of fire-damaged structures.

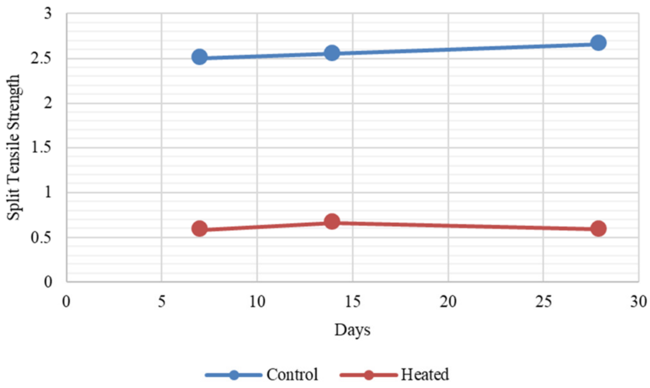


Fig. 10. Split tensile strength.

3) Flexural Strength

The results for flexural strength were obtained after 28 days of curing. The flexural strength was compared for six treatments, C, CR1, CR2, H, HR1, and HR2. CR1, CR2, HR1, and HR2 had higher flexural strength than C and H beams. The load-deflection curves were used to determine the load-carrying capacity and ductility of the beams. The crack patterns were analyzed to know the effectiveness of the sisal fiber mat retrofit in improving the post-fire strength of the beams. The load-deflection responses of the beams; C, CR1, CR2, H, HR1, and HR2 are portrayed in Figure 11.

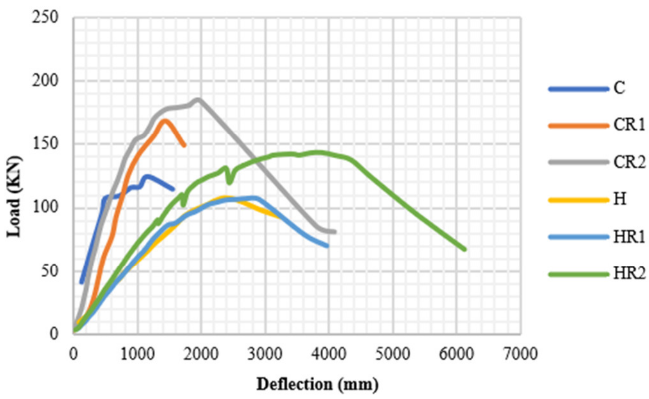


Fig. 11. Load-deflection responses of reinforced concrete beams.

From the results, the unaffected C specimen reaches a maximum load of 120.57 kN before beginning to degrade under increased deflection. This represents the baseline performance of undamaged, unheated concrete. In contrast, the heated specimen reached a lower peak load of 108.34 kN, indicating a reduction in structural capacity due to fire-induced damage. The fire exposure degraded both the compressive and tensile properties of the concrete, leading to lower load-bearing capacity. Interestingly, the CR1, CR2, HR1, HR2 incorporating a sisal fiber mat exhibited a wide range of behavior. Notably, specimens CR2 and HR2 achieved higher peak loads than the C, reaching 184.39 kN and 147.59 kN respectively, while also maintaining significant post-peak load resistance.

The C beam presented moderate deflection capacity, whereas the H beam had a lower deflection capacity, indicating that fire damage makes the concrete more brittle. HR1 and HR2 showed significantly improved deflection capacities, with HR2 exhibiting the highest deflection before failure. This demonstrates that the sisal fiber mat not only restores load-bearing capacity, but also improves ductility and energy absorption. The ability to deform more before failure is crucial in structural applications, as it helps prevent catastrophic failure under excessive loading. CR1 and CR2 beams also demonstrated improved deflection capacity compared to the un-retrofitted C, reinforcing the effectiveness of the retrofit in improving both strength and ductility.

The retrofitted beams in this study demonstrate superior performance compared to the un-retrofitted beams, particularly the CR2 and HR2 samples, in terms of peak load-carrying capacity. This suggests that sisal fiber mat retrofitting is an effective method for restoring or even enhancing the load-carrying ability of concrete beams that have sustained fire damage. The enhanced tensile resistance provided by the sisal fiber mats helps compensate for the degradation in the concrete microstructure caused by fire exposure. Moreover, the increased deflection capacity observed in the retrofitted specimens is particularly significant for the structural safety of post-fire-damaged beams. Fire damage typically leads to a more brittle failure mode in concrete, but the sisal fiber mat retrofit improves the ductility of the structural elements, which is crucial for maintaining their integrity and safety in fire-damaged scenarios.

IV. CONCLUSION

This study evaluated the structural performance of reinforced concrete beams subjected to fire damage and retrofitted with sisal fiber mats. The novelty of the study lies in its focus on a sustainable and eco-friendly material, sisal fiber, which offers a viable alternative to synthetic fibers as a potential retrofit solution for fire-damaged concrete structures. The study demonstrated the effectiveness of sisal fiber mats in restoring the load-carrying capacity and stiffness of the damaged beams. The findings of this research contribute to the growing body of knowledge on sustainable construction materials and practices, particularly in the context of post-disaster recovery and rehabilitation. Compared to similar works using synthetic fibers, sisal fiber mats showed comparable resilience and strength restoration, positioning them as a viable, greener alternative. Based on the experimental results and analysis, the following conclusions can be drawn:

- Fire exposure reduced the load-carrying capacity and increased the stiffness of reinforced concrete beams by 13.03 and 104.138%, respectively, compared to the C beams.
- The sisal fiber mat retrofit restored part of the lost flexural capacity of the fire-damaged beams. The heated retrofitted beams with two layers of sisal fiber mat increased the ultimate load by 33.86% compared to the non-retrofitted fire-damaged beams, though they did not fully recover the original capacity of the C beams. This indicates that sisal fiber mat enhances the load-carrying capacity of fire-

damaged reinforced concrete beams by providing additional tensile strength to the structure.

- Retrofitting the fire-damaged reinforced concrete beams with two layers of sisal fiber mat improved the ductility by 43.56% compared to the heated un-retrofitted beams, as reflected by an increased mid-span deflection at the ultimate load.

FUNDING STATEMENT

The authors extend their sincere gratitude to the African Union Commission for their generous financial support, which made this research and publication possible. Their commitment to advancing knowledge and innovation is greatly appreciated.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI) and Jomo Kenyatta University of Agriculture and Technology (JKUAT) for providing access to their advanced laboratory facilities, which were essential for conducting this research. Their support and contributions are deeply appreciated.

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