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Effect of Increasing Amount of Sisal Fabric on Density, Compressive Strength and Flexural Strength of Sisal Fabric Reinforced Concrete Composite

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Abstract

This study examines the impact of adding plain-woven sisal fibres on the mechanical characteristics of sisal reinforced concrete composites. Analysis of the mechanical strength was done in relation to their density, compressive strength, and flexural strength. The sisal fabric composite matrix contained up to four layers of sisal fabric, which was either NaOH treated or untreated. The properties of sisal fabric reinforced concrete were compared to those of steel reinforced concrete. With addition of layers of sisal fabric, the flexural strength of both NaOH-treated and untreated concrete composites increased to a maximum of 18.2 MPa, which was less than steel reinforced at 20.59 MPa. As the number of fabric layers increased, both NaOH-treated and untreated composites' compressive strength decreased. Although the compressive strength for treated sisal fabric composites decreased by 14.6%, it remained above the desired level of 30 MPa. For untreated sisal fabric composites compressive strength decreased by 18.0% and decreased below the target compressive strength of 30 MPa for up to four layers of fabric added. In comparison to control concrete, the density of concrete with treated sisal fabric decreased to up to 6.05% while for concrete with NaOH treated fabric decreased by 4.90%.

Keywords: Plain woven sisal fabric; Sisal fabric reinforced composite; Mechanical properties; Flexural strength; Density

Introduction

The global crude steel production increased by 3.1% in 2020 which is 1.9% higher than other years (WSA 2021), but the costs of production remain extremely high (Boulamanti and Moya 2016), thus resulting in increased cost of construction. Furthermore, steel production is an energy-intensive process, which results in the release of hazardous substances, particularly from furnaces, such as metal oxides, smoke, fumes, dusts, and gases (Doushanov 2002), all of which are harmful to the environment. The production process also generates huge amounts of CO_2, which contributes towards global warming. On average, 1.83 tons of CO_2 are produced for every ton of steel produced, making the steel industry one of the leading contributors to global warming, accounting for about 3.3 million tons of CO_2 yearly (Pandit et al. 2020).

In lower middle-income countries like Tanzania, the construction industry is not only a significant contributor to GDP, but also one of the most important predictors of economic growth. Construction works in

Tanzania rose by 4.3% in 2021, compared to 9.1% in 2020. This growth was due to construction of classrooms, health centres, residential and commercial buildings, and rehabilitation of road infrastructure, bridges, and airports (Ministry of Finance 2021). The report further states that the construction sector contributed 13% to the GDP in 2021, a slight reduction from 14.1% of the previous year. Increase in construction activities calls for an increase in demand for construction materials, which includes steel reinforcement bars. This fuels the need for more steel in the world market, thus contributing further to global warming.

Replacement of steel reinforcement with other materials in concrete for some of construction activities is a welcoming endeavour as far as reduction of greenhouse gases is concerned. Several researchers have reported using lignocellulosic fibres, such as sisal, reinforcement in cement matrices (Tian et al. 2016, Oriola et al. 2019, Dineshkumar and Bharathimurugan 2021, More and Subramanian 2022, Teixeira et al. 2022). Long Sisal fibres, when used to reinforce concrete, are known to play an important role in post-cracking behaviour, particularly due to their high tensile strength (Filho et al. 1999). When employing natural fibres in cement-based matrices, long-term durability has been a significant challenge due to alkali attack, volume changes brought on by a high water absorption rate, and fibre mineralization (Tian et al. 2016). The durability of sisal fibres in concrete is improved by alkali treatment using a low concentration of sodium hydride or a combination of sodium hydroxide treatment and acetylation (de Klerk et al. 2020).

Sisal as fabric in cementitious composites has received little attention; the majority of the work done so far has focused on sisal as fibres in cement composites. The influence of fabric characteristics on the mechanical behaviour of the composite has also received little attention. Fabric content, bond interphase, and fabric anchorage properties are some of these factors. This study was necessary because natural fabric reinforced concrete will not be widely used in the construction industry until its unique properties have been thoroughly investigated and understood.

Materials and Methods

Materials

Cement

Portland Limestone cement CEM II B-L Class 42.5N supplied by Tanzania Portland Cement PLC under the trade name Twiga Plus was used. The cement conforms to EN 197-1:(2015)

Fine aggregates

The fine aggregate used was river sand that passed a standard sieve of 4.75 mm, conformed to BS 882:1992, and free from dirt. Table 1 summarizes its characteristics and Figure 1 shows the grading curve.

Table 1: Properties of fine aggregates

Property	Units	Value	BS 882:1992 Limit
Specific gravity	-	2.67	2.4-2.9
Bulk density (Loose)	kg/m^3	1469	-
Bulk density (Rodded)	kg/m^3	1580	-
Water absorption	%	1.0	0-4
Organic impurities	colour	Nil	-
Fineness modulus	-	2.66	2.3–3.1
Silt content	%	1.13	≤3.0
Clay lumps & particles	%	0.3	-
Chloride content	%	0.0114	0.03
Sulphate content	%	0.1235	0.4

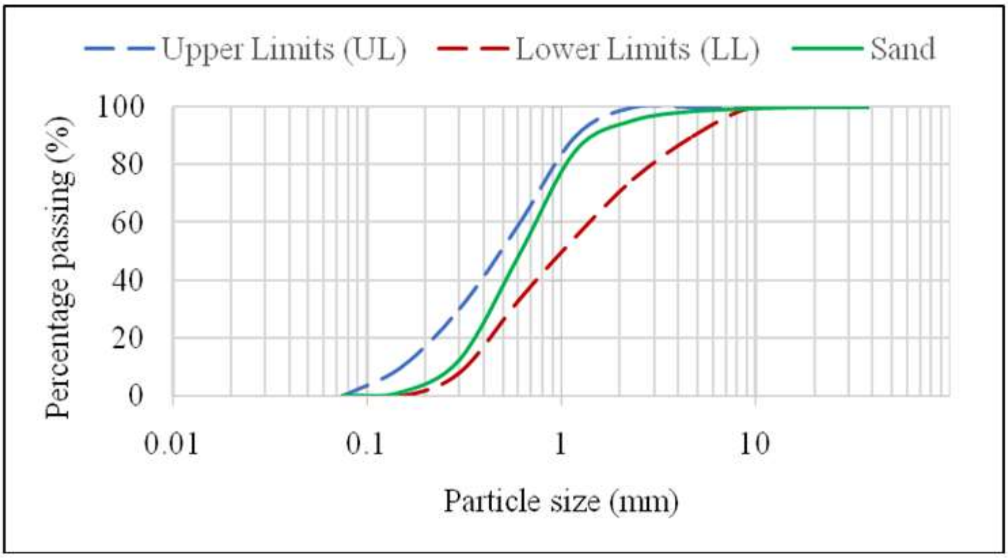

Figure 1: Particle size distribution of fine aggregates

Coarse aggregates

Crushed granite with a nominal size of 9.5–20 mm was used as the coarse aggregate, which was supplied by Gulf aggregate (T) Ltd from Lugoba quarry in Tanzania. As indicated in Figure 2, the grading limitations for coarse aggregate were found to be within the limits of BS 882:1992. Table 2 summarizes its characteristics.

Table 2: Properties of fine aggregates

Property	Units	Value	BS 882:1992 Limit
Specific gravity	-	2.78	2.4-2.9
Bulk Density (Loose)	kg/m^3	1483	
Bulk density (Rodded)	kg/m^3	1576	-
Shape	-	Angular	-
Texture	-	Rough	-
Water absorption	%	0.49	0-4
ACV	-	20.2	-
AIV	-	19.7	-
Chloride content	%	0.0035	≤ 0.01

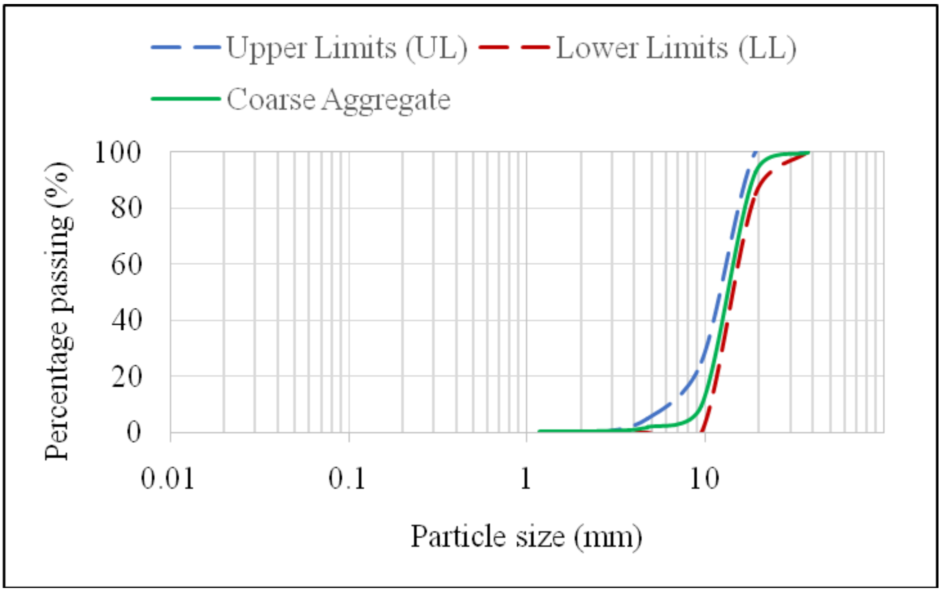

Figure 2: Particle Size Distribution for Coarse Aggregates

Water

For the mixing and curing of concrete mixtures, ordinary potable water from the laboratory that met BS 3148 criteria and had a pH of 8.1 was used. The appropriateness of the water used in the manufacturing of concrete was evaluated according to BS 3148. Table 3 shows the outcomes of the tests. According to BS 3148, water qualified for use in making concrete.

Table 3: Properties of fine aggregates

Parameter	Result	Specification limit	Remarks
Chlorides (CL^-), mg/l	339.34	≤ 1000	Pass
Sulphates (SO_4^{2-}), mg/l	308.17	≤ 1000	Pass
Alkalies, mg/l	298.22	≤ 1000	Pass

Sodium hydroxide

Sodium hydroxide used was supplied in crystal form by LAB EQUIP LTD under the brand name and code of, sodium hydroxide pearls, S0145 respectively.

Steel reinforcement bars

Mild steel with an average yield strength (σ_y) of 250 N/mm^2 was used to fabricate the beam specimens. The steel bars were purchased from a local supplier in Dar es Salaam and tested to confirm conformity with BS 4449:2005 at the Structures and Materials Laboratory of the University of Dar es Salaam.

Plain woven sisal fabric

Sisal fabric was obtained from Mohammed Enterprises (T) Ltd (MeLT), Tanzania, grown at Bamba Estate, Tanga region. The fabric was supplied in dimensions of 5 m x 0.5 m x 2.67 mm, length, width and thickness respectively as shown in Figure 3. The properties of the fabric are shown in in Table 4.

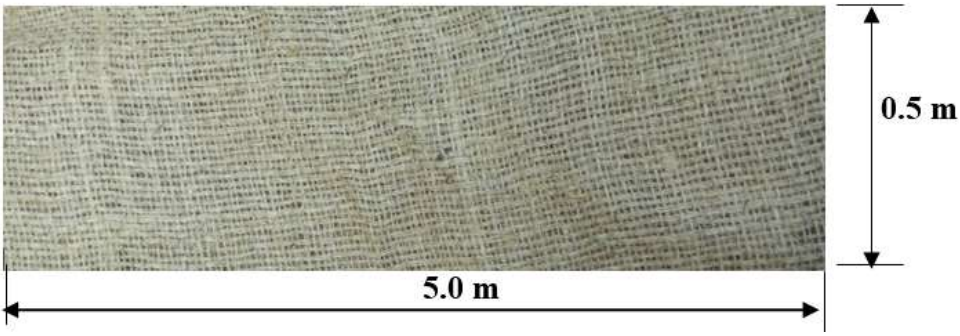

Figure 3: Plain woven sisal fabric

Table 4: Physical and Mechanical properties of plain woven sisal fabric

S/No	Property	Result
1	Colour	Creamy white
2	Diameter of a sisal fibre/ μ m	100 - 200
3	Thickness(mm)	
	Warp	2.82
	Weft	2.67
4	Density (g/m^2)	161.02
5	Water absorption (%)	43.58%
6	**Tensile Strength (N/cm^2)**	
	Untreated	
	Warp	7.345
	Weft	5.280
	Treated	
	Warp	6.299
	Weft	6.255
7	**Young's Modulus (GPa)**	
	Untreated	
	Warp	8,640.80
	Weft	11,866.15
	Treated	
	Warp	10,075.75
	Weft	4,022.4
8	**Elongation (%)**	
	Untreated	
	Warp	9.0 -13.04
	Weft	8.49-10.08
	Treated	
	Warp	8.34 - 29.84
	Weft	12.6 - 13.34

Specimen preparations

Sisal fabric concrete beam prisms

Specimens from untreated sisal fabric were measured to sizes of length, width and thickness of 440 mm x 90 mm x 2.28 mm respectively using a measuring tape, straight rod and cut using a pair of scissors as shown in Figure 4.

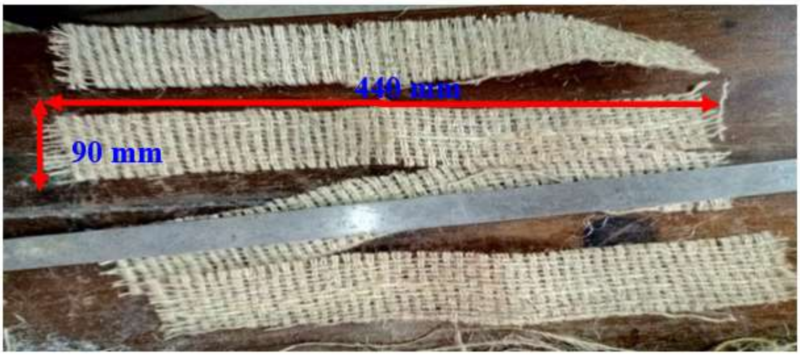

Figure 4: Untreated sisal fabric samples

For specimen treated with 4 % NaOH, 20 mm was added to the length and widths compared to untreated samples, i.e., the length and width used were 460 mm and 110 mm respectively. This was because treatment of fabric with NaOH results in a reduction in length and widths of fabric (Mwaikambo and Ansell 2002). After treatment the required sizes of 440 mm x 90 mm of the fabric was obtained as shown in Figure 5.

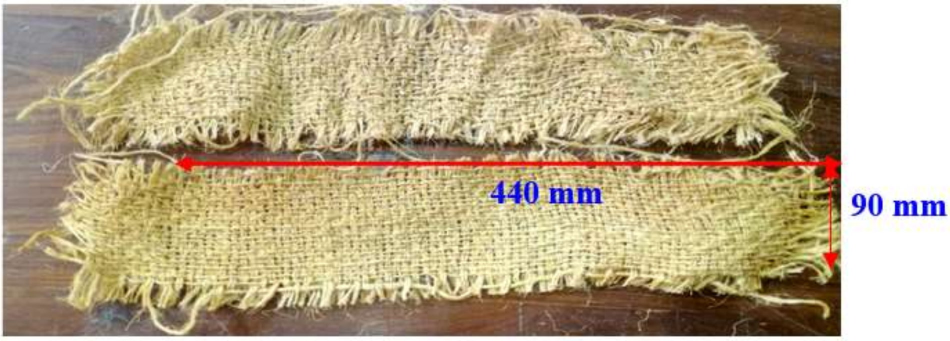

Figure 5: NaOH treated samples used in the study

Steel concrete beam prisms

The reinforcement bars were cut to appropriate lengths using a basic saw and bent to the required shape with a bar bending machine. Binding wires were used to tie two bottom bars of 12 mm diameter and two top reinforcement of 8 mm diameter to the shear stirrups of 6 mm diameter for each beam specimen. Figure 6 shows the resulting steel cage.

Figure 6: Fabricated steel cages/bars used in the study

Mix design

The class 30 concrete mix used to fabricate beam and cube specimens was designed according to BS.5328-3:1990 with reference to Building Research Establishment, second edition, 1997. The concrete mix design was made using a 1:2:3 mix proportion. Each mixture contained 388 kg/m^3 cement, 724 kg/m^3 sand, and 1043 kg/m^3 coarse aggregates by weight. The water–cement ratio was 0.58 for a targeted strength of 30 MPa and slump of 63 mm.

Casting and curing of concrete cubes and beams

Sisal fabric composite beam specimens

A thin layer of grease was applied to the moulds to ensure easy de-moulding. Then, starting from the bottom, one layer of 30 mm thick concrete was poured in the mould, followed by layers of fabric measuring 440 mm x 90 mm, which were then filled with concrete and compacted with a standard electric vibrator, before the surface was finished level as shown in Figure 7(a). Other fabrics were placed in the beam in a similar way. After 24 hours, the specimens were removed from the moulds and continuously cured for 7 and 28 days. (Figure 7(b).


(a) (b)

Figure 7: (Left) Casting of SFRC beam prisms (Right) beam prisms in the curing tank.

Steel reinforced beam specimens (control beams)

Beams containing steel bars (Control beams) measuring 150 mm x 150 mm x 500 mm were produced for concrete grade 30. Casting was done in steel moulds with compaction done by a vibrating table method as shown in Figure 8. The samples were cured in water at ambient temperature for 28 days before testing. All beams were reinforced with two bars of 12 mm diameter as main reinforcement and 8 mm diameter bars at the top. Stirrups with a diameter of 6 mm were used to hold the reinforcements and take up shear loads. After curing of the concrete beam prisms and cubes, various tests were done on the hardened concrete. Their brief details and results are presented in the next sections.

Figure 8: Casting of Steel reinforced concrete beam specimens.

Results and Discussion

Bulk density of concrete

Cube sisal fabric concrete specimens with dimensions of 150 mm ×150 mm × 150 mm were made according to BS EN 12390-7:2019, and after curing they were tested. Three samples for each configuration of sisal fabric concrete were made, and an average density was obtained. Figures 9 and 10 show the bulk densities of hardened concrete specimens at 7 and 28 days for both untreated and NaOH treated concrete specimens respectively. The bulk densities of all hardened concrete specimens marginally increase with prolonged curing days. Among all concrete specimens, the reference concrete (CO) produces the greatest density with average bulk density of 2545 kg/m^3 while concrete with four layers of the fabric has the lowest density of 2391 kg/m^3 and 2420 kg/m^{3}for untreated and treated composite specimens respectively, but all lie within the range for normal weight concrete (ACI CODE-318).

The density of concrete was reduced at percentages of 1.23%, 1.43%, 5.86%, and 9.08% for 1, 2, 3 and 4 layers of fabric respectively as compared with reference concrete at 7 days of curing. At 28 days of curing, the percentage reductions in the density were 1.76%, 2.06%, 4.52%, and 6.05% for 1, 2, 3, and 4 layers respectively for untreated fabric specimens. For treated fabric specimens, the density decreased at percentages of 0.21%, 0.62%, 5.62%, and 8.68% for 1, 2, 3, and 4 layers respectively compared with reference concrete at 7 days of curing. At 28 days of curing, the percentage reductions in the density were respectively 0.94%, 1.09%, 3.76%, and 4.90% for 1, 2, 3, and 4 layers respectively. Because sisal fabric has a lower bulk density than coarse and fine aggregates, which are denser constituents, there is an inverse relationship between the density of concrete and the number of layers of sisal fabric (Hidaya et al. 2017).

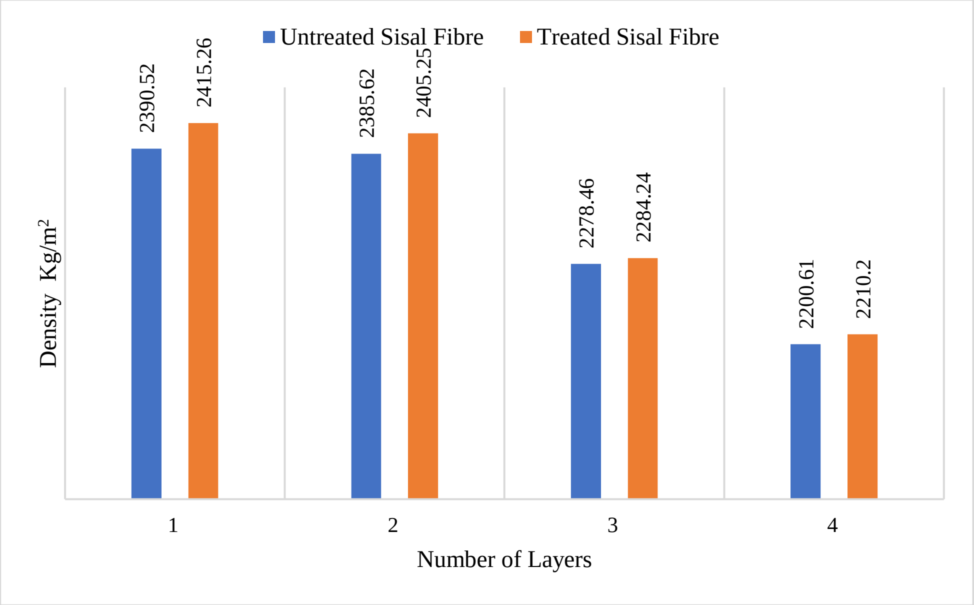

Figure 9: **Density of untreated and NaOH treated plain woven sisal fabric concrete composite cured for 7 days**

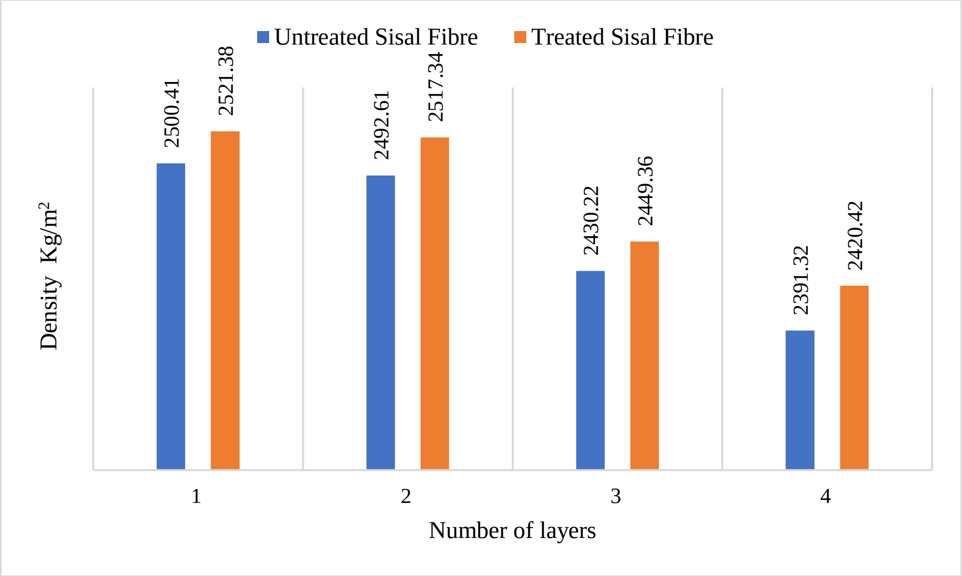

Figure 10 **Density of untreated and NaOH treated plain woven sisal fabric concrete composite cured for 24 days**

Untreated sisal fabric concrete composites have lower density than NaOH treated sisal fabric concrete composites, but not below the acceptable density for normal weight concrete (ACI 216: 2009). Furthermore, the decrease in density is slightly more in untreated sisal fabric than in treated sisal fabric composite. The NaOH treatment on the sisal fabric eliminates impurities like pectin and lignin in the fibres, resulting in a rougher fabric surface (Mwaikambo and Ansell 2002). The removal of impurities through NaOH treatment improves bonding of the sisal fabric with the matrix in the fabricated composites, resulting in a more compact material that is less porous(Rajulu A et al. 2003).

Compressive strength

The compressive strength test of concrete was performed according to BS 1881-116 using a standard compressive testing machine on cubes of size 150 mm x 150 mm x 150 mm. Figure 11 shows the test set-up for the cubes. The results for compressive strength of specimens cured for 7 and 28 days are presented in Figures 12 and 13 for composites with untreated and treated fabric respectively.

Figure 11: Compressive Strength Testing

The results show that increasing the layers of sisal fabric reduces the compressive strength of concrete. This agrees with results reported by (Suryawanshi and Dalvi 2013), that compressive strength reduces with increase in quantity of sisal fibres. However, the reduction is higher in untreated sisal fabric composite compared to NaOH treated fabric composite. At higher fabric content there are more voids in the concrete due to the lack of free rearrangement of concrete matrix as a result of balling effect during vibration and casting of the specimens. The reduction is also due to the reduction in adhesive properties between the surface of the fabric and the cement paste, resulting in the need for higher compacting energy (Ilya and Cheow Chea 2017). Furthermore, sisal is a hydrophobic material, implying that there is a tendency of it leaving behind freer water–cement, impeding strength gain.

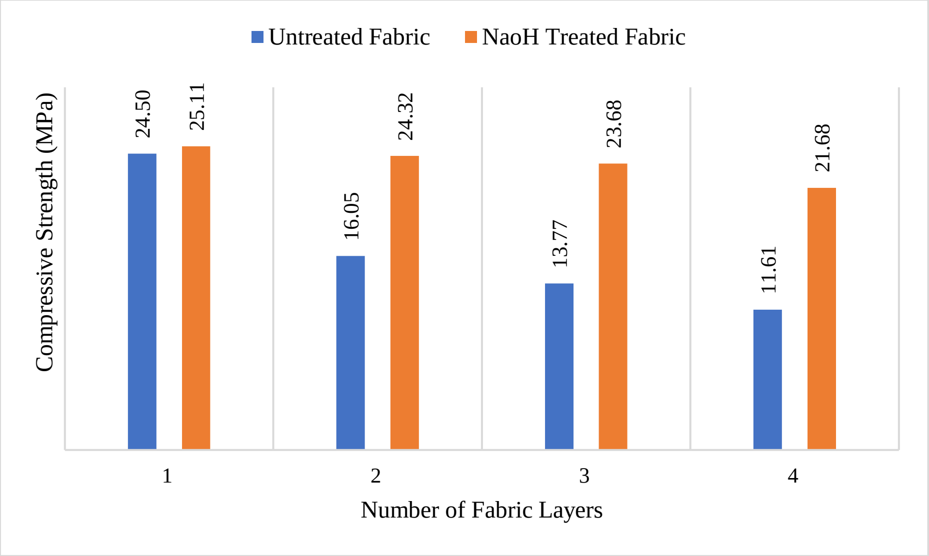

Figure 12: Compressive strength of untreated and NaOH treated SFRC cubes cured for 7 days

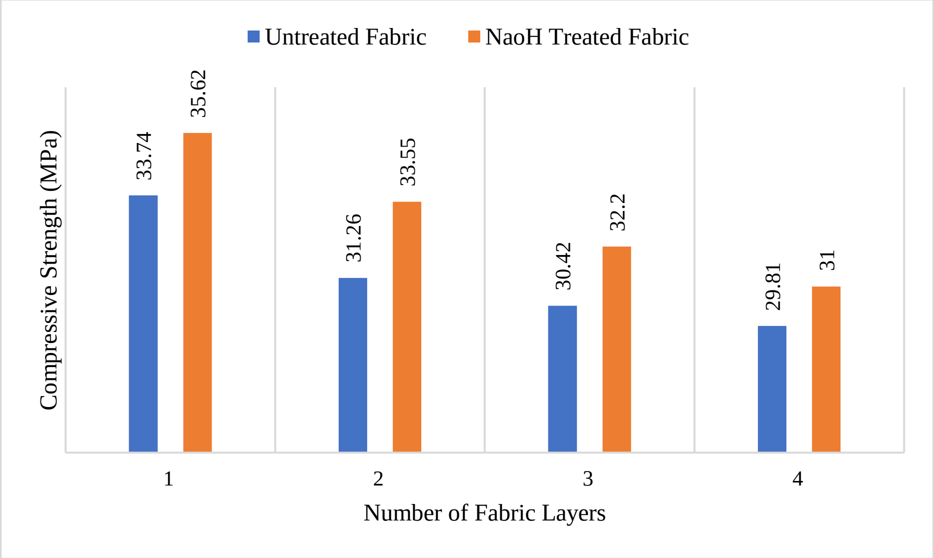

Figure 13: Compressive strength of untreated and NaOH treated SFRC cubes cured for 28 days

Flexural strength

Beam prisms were tested for flexural strength according to BS EN 12390-5:2009. Three-point bending tests were done on simply supported beams of 500 mm x 150 mm x 150 mm. Figure 14 shows the flexural strength testing process.

Figure 14: Three-point flexural strength test

Figure15 shows the flexural strength of the control beam (i.e., beam with reinforcements) and beams reinforced with different layers of sisal fabric at 7 and 28 days. All beam specimens failed in bending, but Sisal fabric composite specimens showed an improvement in flexural strength as the number of layers of sisal fabric was increased. Furthermore, as the curing period was increased, the flexural strength increased. However, when comparing treated plain-woven sisal fabric layers to untreated plain-woven sisal fabric layers, the treated plain-woven sisal fabric layers showed a significant increase in strength.

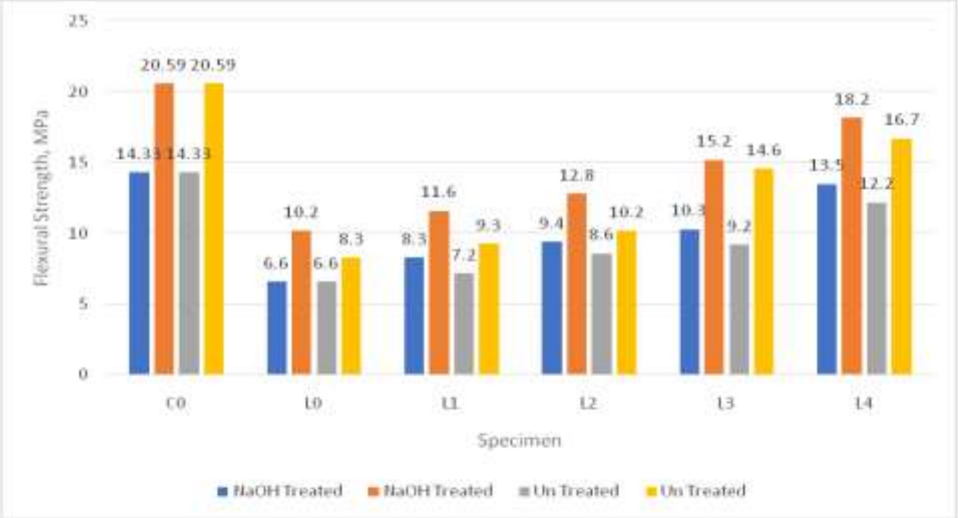

Figure 15: Flexural strength of untreated and NaOH treated sisal fabric reinforced concrete

From Figure 15, it is observed that for the treated Sisal fabric concrete, beam L4 with four layers of fabric, cured for 28 days, has the highest flexural strength of 18.2 MPa, while L_0 which does not have fabric layers, has the lowest flexural strength of 10.2 MPa. When compared to the control beam at 7 days of age, the flexural strength of treated fabric concrete increased by 0.54 %, 0.42 %, 0.34 %, 0.28 %, and 0.06 % for L_0, L_1, L_2, L_3, and L_4 respectively. The percentage increase in flexural strength was 0.51 %, 0.44 %, 0.38 %, 0.26 %, and 0.12 % respectively, at 28 days of age.

For the untreated Sisal fabric concrete beam L4, with four layers of fabric, has the highest flexural strength of 16.7 MPa, while L_0 has the lowest at 8.3 MPa. At 7 days of age, the flexural strengths of the untreated fabric concrete increased by 0.54 %, 0.49 %, 0.39 %, 0.36 %, and 0.15 % for L_0, L_1, L_2, L_3, and L_4 respectively. At 28 days, the percentage increase in flexural strength for beam prisms with untreated sisal fabric reinforcements was 0.59 %, 0.55 %, 0.50 %, 0.29 %, and 0.19 % from L_0, L_1, L_2, L_3, and L_4 respectively. As the number of layers of fabric were added, the flexural strength increased.

Furthermore, when compared to untreated Sisal fabric concrete, treated Sisal fabric concrete showed greater flexural strength values. This was due to the fact that the fabric treated with NaOH solution had a rougher surface and exhibited signs of yarn expansion due to cellulose and lignin breakdown, as well as the removal of surface oils, pectin, wax, dust, and other foreign elements. This enhanced the surface area exposed for bonding with the cement matrix, resulting in a strong bond and increased flexural strength (Rajulu et al. 2003).

The roughness of the fabric surface increases the surface area, which implies that the fabric may connect extremely effectively with the cement matrix, resulting in greater anchoring of the fabric in the cement matrix, resulting in a very strong and compact bond, increasing flexural strength (Rajulu et al. 2003). Furthermore, the nature of fabric geometry partly explains the increase in strength. The fabric's woven "mesh-like" structure forms a unique geometry that enables mechanical anchoring to the concrete matrix, resulting in a stronger bond and a reduced interfacial shear bond between the fabric and the matrix resulting in an increase in flexural strength. As a result, treated composites surpassed their untreated counterparts in terms of strength.

In comparison with the control beams (Beam with reinforcements), sisal fabric reinforced beams show a relatively steady increase in flexural strength as the number of layers of the fabric increased. A maximum flexural strength of 18.2 MPa for composites with four layers of NaOH treated fabric and 16.7 MPa for composites with four layers of untreated Sisal fabric was observed in comparison with 20.59 MPa for composites reinforced with mild steel of 12 mm diameter at the bottom and 8 mm diameter at the top after 28 days of age.

Conclusion

In this investigation, the study on use of plain-woven sisal fabric as replacement for steel bars in a concrete composite was analysed. From the results, the concrete composites prepared with NaOH treated sisal fabric showed a significant increase in all mechanical strength properties, with positive effects being achieved in flexural strength. By increasing the treated sisal fabric layers in the concrete composite, the flexural strength was improved. The NaOH treated concrete composite compared with the untreated cement composite had an increase in flexural strength of 9.0 %. Therefore, four layers of both NaOH woven sisal fabric and untreated fabrics can be used to replace mild 2R 12 mm (bottom) and 2R 8 mm (top) steel reinforcements for a beam of size 500 mm x 150 mm x 150 mm. The addition of more sisal fabric above 1 layer to the concrete composite had a negative influence on the compressive strength, which was dramatically reduced. However, untreated sisal fabric had a far greater decrease in compressive strength than alkali treated sisal fabrics.

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