

Original Article

Investigation of the Mechanical Behavior of Geopolymer Concrete Reinforced with Cellulose Fibres

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Abstract - Geopolymer Concrete (GPC) is a sustainable material that severely threatens the ordinary Portland cement concrete OPC. Further enhancement is required, which cannot be done with GPC. By adding natural cellulose fibres, we can find a likely solution; however, it is not known if Banyan and Sisal cellulose fibres can affect GPC. The study analyses the effect of these fibres on the fresh, mechanical, durability, and thermal properties of M40 grade geopolymer concrete. The binder weight had fiber contents that differed from 0 to 3%. Evaluations incorporated workability, Compressive Strength (CS), split Tensile Strength (TS), Flexural Strength (FS), resistance to sulphate, salt, and acid attack, water absorption, permeability, and high temperature performance. The findings reveal that the optimum dosages of fibre significantly improved CS by a maximum of 11.3%, TS by 76.9% and FS by 9.5%. Results of durability tests showed that the water absorption of the concrete block decreased by more than 48% and permeability by almost 24%. In addition, more significant thermal resistance was noted as Sisal cellulose fibres were used, and at high temperatures, this resulted in more efficiency. High levels of fibre content (>2%) caused agglomeration, affecting performance. All in all, natural cellulose fibres are a good reinforcement for GPC. Two percent of Banyan cellulose fibres is optimized for mechanical strength and permeation levels. One per cent Sisal cellulose fibres provide chemical and thermal resistance. The results indicate that natural cellulose fibres can be a promising alternative for developing eco-friendly high-performance concrete for structural applications in extreme environmental conditions.

Keywords - Geopolymer Concrete, Banyan cellulose fibre, Sisal cellulose fibre, Natural fibre.

1. Introduction

The continuously increasing warranty of sustainable and high-performance construction materials has intensified the study of alternative binder systems that lessen the environmental effects without affecting the mechanical and durability performance [1-4]. Aluminosilicate GPC is produced mainly using aluminosilicate materials such as fly ash and ground Granulated Blast Furnace Slag (GGBS) and is activated by the use of alkaline solutions, resulting in a low-carbon concrete substitute to ordinary Portland cement concrete, as it yields much lower CO₂ emissions and lower energy consumption properties [2, 5-7]. Along with the aspect of sustainability, GPC has a high early strength gain and resistance to hostile environments, which makes it a prospective structural and durability-sensitive resource [8-10].

Although there are these merits, the geopolymer binders have one common drawback with the traditional cementitious systems: these binders are brittle and have low tensile and flexural strengths, thus they cannot be used in structures where tensile stress and impact loads occur [11, 12]. Fibre reinforcement is an established method of enhancing ductility and governing crack propagation, as well as performance after cracking in brittle composites [13-16]. Although synthetic fibres like polypropylene and steel are becoming highly popular in geopolymer matrices,

natural fibres are also becoming more popular with the increasing attention paid to their renewability, biodegradability, low density, and cost-effectiveness. It was found that plant-derived fibres such as sisal, jute, coir, hemp, and bamboo could enhance mechanical characteristics and affect crack propagation in geopolymer composites through crack bridging and retarding other crack propagation. In addition, natural fibres demonstrate favorable sustainability attributes, which comply with the aims of the circular economy when it comes to construction materials [14, 17-21].

The use of natural fibres in geopolymer matrices is a topic that has been examined in several studies. In a thorough assessment of geopolymer concrete with several natural fibres (sisal, jute, coir, and flax), improved impact and mechanical performance were reported owing to the improved crack-bridging mechanism, but the fibre type and aspect ratio had a substantial impact on the outcomes [22]. Also, geopolymer concrete that contains hemp-sisal hybrid fibres had higher compressive, tensile, and flexural strength and better ductility than plain mixes, highlighting the possibilities of hybrid natural fibres reinforced concrete as a long-lasting construction method [23]. Further, studies of the further application of natural fibres to major geopolymer matrices have reported their effect on workability and durability properties, though highlighting the problem of



moisture absorption and bond quality at the interface between the fibre and the matrix [24]. Numerous investigations on sisal cellulose fibre reinforced geopolymer composites have shown enhanced mechanical characteristics and microstructure, which confirms sisal as a reinforcing material based on its tensile properties and extensive availability. It has been demonstrated, however, that research on jute fibre reinforced geopolymer concrete shows that different lengths of the fibres and fraction of volume may have a major influence on workability, compressive strength, and fracture performance, and as such, it is necessary to optimise fibre content to obtain desirable composite properties [25].

Although there is an increasing amount of literature on natural fibre-reinforced geopolymer composites, there is still a gap in the research literature, which is the lack of systematic and comparative studies that can independently determine the impact of various cellulose fibres on the mechanical and durability performance of geopolymer concrete. The majority of current studies concentrating on single fibre types with small dosage variations and mechanical characteristics are overlooked, and elaborate durability tests, which include sulphate and acid resistance, chloride penetration, permeability, water absorption, and thermal stability, are mostly ignored. Moreover, little direct comparative assessment of specific natural cellulose fibres in the same proportions and test conditions has been done to allow a clear picture of the contribution of the individual performance of these fibres.

To fill these gaps, this study involves research on how the banyan cellulose fibre and sisal cellulose fibre affect M40 grade geopolymer concrete when added separately. All the types of fibres are incorporated separately at 0, 1, 2, and 3 % to determine their effects on fresh, mechanical, and durability properties of geopolymer concrete. The experimental program will involve measuring workability, CS, TS, and FS, and also a thorough description of the properties of durability, including sulphate resistance, salt resistance, acid resistance, water absorption, permeability, and thermal resistance. By means of this comparative and systematic study, the paper will find out the optimum fibre content of each type of cellulose fibre, as well as determine their appropriateness in improving structural performance and long-term stability of sustainable geopolymer concrete.

2. Materials and Methods

Geopolymer concrete was designed in the current study based on fly ash, GGBS, fine aggregate, coarse aggregate, alkaline activator solutions consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), and natural cellulose fibres in the guise of banyan cellulose fibre and sisal cellulose fibre. The fibres were added independently in various volume fractions to test their respective influences on the mechanical and durability performance of geopolymer concrete.

The fine aggregate employed in this paper was the natural river sand that met the requirements of the IS

383:2016 (Zone II). The sand did not contain silt or clay, organic matter, or other deleterious elements. It had a Specific Gravity (SG) of 2.43, a fineness modulus of 2.69, and a water absorption of 4.16%. Coarse aggregate was the crushed angular granite of nominal maximum size 20 mm, sourced in a nearby quarry. Before using, the aggregates were carefully washed to get rid of dust and surface impurities. The coarse aggregate met the requirements of IS 383:2016 and had a SG of 3.06, a fine modulus of 7.3, and water absorption of 0.201%.

The primary aluminosilicate source material was Low-calcium Class F fly ash, which is within the requirements of the IS 3812 (Part 1):2013 [26]. The fly ash was obtained in the Tuticorin Thermal Power Plant, Tamil Nadu, India. It was composed of mostly spherical and glassy particles with particle sizes of between 10 and 100 μm , which adds to enhanced workability and reacts pozzolanically. The blast furnace slag GGBS was used to partially replace fly ash to increase early-age strength and general mechanical performance. GGBS was employed with a bulk density of between 1000-1100 kg/m^3 with a specific gravity of 2.87.

NaOH pellets and Na_2SiO_3 solution were used to prepare the alkaline activator solution. The electrolysis of sodium chloride was used to produce sodium hydroxide, which was provided in high-purity form in pellets. Care was taken in preparing NaOH solutions because they were hygroscopic and highly exothermic on dissolution. The alkaline activator was made 24 hours before the mixing of the concrete to ensure that there is full dissolution and stabilization of the temperature of the solution.

The banyan cellulose fibre was obtained by taking the banyan prop roots, pulping them into fine fibres, and then adding them to the geopolymer matrix. Agave sisalana leaves were used to extract sisal cellulose fibre that was then treated mechanically to attain uniformity in length and dispersion of the fibre. Fibres were introduced to the geopolymer concrete individually at volume fractions of 0%, 1%, 2% and 3%. It is hoped that the utilization of these natural cellulose fibres would increase the bridging ability of cracks, enhance the post-cracking behaviour, and the sustainability of geopolymer concrete.

2.1. Banyan Cellulose Fibre

2.1.1. Extraction and Preparation of Banyan Prop Root Fibre

Ficus benghalensis (banyan tree) is very common in India, and it is known to produce strong and durable cellulose fibres. The aerial prop roots of the mature banyan trees gradually transform into trunk-like hard roots and thus are a suitable source of natural fibres found in cellulose. The aerial prop roots of the mature banyan trees were re-retted in a controlled procedure to extract cellulose fibres in the current study.

To extract the prop roots, the collected prop roots were first put in water, where they were exposed to a duration of about 20-30 days to allow the microbes to break down the

non-cellulosic components, as shown in Figures 1 and 2. After retting, the relaxed roots were gently pounded with a splitting maul to loosen the bundles of fibres and further increase fibre separation. The fibres were then scraped with a sharp knife and combed in order to separate individual fibres of the woody matrix. The fibres obtained were dried in the sun, and it took 1 week to dry all the moisture. The fibres were dried and then, using shears, cut to the desired lengths to fit the desired proportions of the concrete mix. In this study, the fibre lengths of 20 mm, 30mm, and 40mm were used to examine the effect of fibre length on fibre-matrix bonding properties, crack-bridging effectiveness, and the mechanical performance of geopolymer concrete in general.

In a bid to improve the purity of the fibres as well as surface properties, the dry banyan cellulose fibres were chemically treated with a sodium chloride (NaCl) solution at a temperature of 70 °C. To stabilize the pH of a solution to approximately 4, acetic acid was added. The fibres were subjected to treatment for 1 hour, and the treatment cycle was repeated until the fibres were whitened, which indicated successful extraction of lignin and hemicellulose constituents. The fibres were then subjected to bleaching with hydrogen peroxide to end up with pure cellulose fibres. Fibres were then treated and washed thoroughly, dried, and then stored to be used again in geopolymer concrete applications, as illustrated in Figure 1. Banyan cellulose fibres offer a sustainable alternative to synthetic fibres, with lower environmental impact and renewable sourcing compared to other natural or man-made reinforcements. Tables 1 and 2 provide a summary of the physicochemical properties of the treated banyan cellulose fibres.



Fig. 1 Banyan cellulose fibre

Table 1. Physical properties of Banyan cellulose fibre

Sl. No	Properties	Banyan cellulose fibre
1	Category	Natural cellulose fibre
2	Fibre form	Chopped fibre
3	GSM	200
4	Average fibre diameter	0.196mm
5	Density	1.69g/cc

Table 2. Chemical properties of Banyan cellulose fibre

Sl. No	Properties	Banyan cellulose fibre (%)
1	Cellulose	70–76
2	Hemicellulose	19.2–21.5
3	Lignin	3.9–5.9
4	Moisture	6.3–12.7
5	Pectin	0.8
6	Wax	0.7

2.1.2. Extraction and Preparation of Sisal Cellulose Fibre

The leaf of the Agave sisalana, which has been extensively grown as a source of natural cellulose fibre, produces strong and tough fibres of cellulose that are used to produce the Sisal cellulose fibre. Adult sisal leaves were harvested and washed with a lot of clean water to eliminate clinging dirt, dust, and surface impurities, and then extracted to extract the fibres.

A mechanical decortication process was used in the extraction of sisal cellulose fibres. In this procedure, the soft part of the leaves was crushed and scraped with the use of mechanical force to separate the bundles of fibres and the non-fibrous tissue.

The fibres extracted were washed repeatedly with water to get rid of the leaf pulp and chlorophyll content. The fibres were then dried under the sun over a span of 5-7 days to decrease the moisture level and improve the stability of the fibres.

The sisal cellulose fibres, after drying, were sheared into predetermined lengths of 20 mm, 30 mm, and 40 mm using shears, in line with the fibre lengths used with the banyan cellulose fibres. The various lengths of the fibres were picked to determine their effect on fibre dispersion, fibre-matrix interfacial bonding, crack bridging behaviour, and the mechanical performance of geopolymer concrete.

The chopped Sisal cellulose fibre was treated by the use of chemicals with an aim of enhancing the balance of fibre surface properties and eliminating the non-cellulosic constituents like lignin, hemicellulose, wax, and pectin. The fibres were placed into a solution of sodium chloride (NaCl) with a temperature of 70 °C, and acetic acid was added to normalize the pH level of the solution to about 4.

This treatment was continued until both the fibres whitened observably and the process was repeated, which meant that cellulose was partially delignified and purified. Subsequently, the fibres were bleached with hydrogen peroxide to get pure sisal cellulose fibres.

The chemical treatment was followed by the thorough washing of the fibres with distilled water to eliminate the traces of the chemicals, after which they were dried in the oven at a regulated temperature and kept in airtight containers to be used later in the preparation of GPC. Tables 3 and 4 give the physicochemical characteristics of the processed sisal cellulose fibres.



Fig. 2 Sisal cellulose fibre

Table 3. Physical properties of sisal cellulose fibre

Sl. No	Properties	Banyan cellulose fibre
1	Category	Natural cellulose fibre
2	Fibre form	Chopped fibre
3	GSM	200
4	Average fibre diameter	0.200mm
5	Density	1.50g/cc

Table 4. Chemical properties of sisal cellulose fibre

Sl. No	Properties	Banyan cellulose fibre (%)
1	Cellulose	65-72
2	Hemicellulose	15-20
3	Lignin	8-12
4	Moisture	6.3-12.7
5	Pectin	0.9
6	Wax	0.7

2.2. Mix Design

The geopolymer concrete mix design has been done according to the technique suggested by N. Subash and S. Adish Kumar in their article “Technique to proportionate industrial wastes-alkaline liquids-aggregates to obtain geopolymer concrete” [27]. In this approach, the percentage of industrial by-products, alkaline activators, and aggregates is taken into account to produce the required grade of concrete.

In the development of M40 grade GPC, the mix design was determined based on the selection of the right binder to aggregate ratio and optimum alkaline activator-binder ratio. The binder system was a mixture of low-calcium Class F fly ash and GGBS, with Na₂SiO₃ and NaOH solutions as alkaline activators. The NaOH solution was made with a molarity of 10 M, and the ratio of Na₂SiO₃ and NaOH was kept at 2.5 so as to achieve proper geopolymerization and the hardening of strength. Tables 5 and 6 display the proportions of the detailed mix and the corresponding amounts of materials needed to have M40 grade geopolymer concrete.

Table 5. Mix proportioning of M40 geopolymer concrete

Fly ash (kg/m ³)	GGBS (kg/m ³)	Sodium hydroxide (kg/m ³)	Sodium silicate (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)
208.33	208.33	57.50	172.50	757.74	1158.06

Table 6. Mix details

Sl. No	Mix	Fibre content %	Fly ash (kg/m ³)	GGBS (kg/m ³)	Fibre content (kg/m ³)	NaOH (kg/m ³)	Na ₂ SiO ₃ (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)
1	Mix 1	0	208.33	208.33	0.00	57.50	172.50	757.74	1158.06
2	Mix 2	1	208.33	208.33	4.17	57.50	172.50	757.74	1158.06
3	Mix 3	2	208.33	208.33	8.33	57.50	172.50	757.74	1158.06
4	Mix 4	3	208.33	208.33	12.50	57.50	172.50	757.74	1158.06

2.3. Methods

The preparation of geopolymer concrete mixes was done using paddle mixers. First, fly ash, GGBS, and other dry materials were blended, and they were mixed properly. Fine and coarse aggregates were then introduced and dry mixed until a homogeneous mix was obtained. The dry materials were then added in an even manner, and the alkaline activator solution was added gradually into the mixer, which contained NaOH and Na₂SiO₃. The mixing was carried out until a homogeneous, unified, and workable geopolymer concrete mix was obtained.

The wet concrete was then poured into pre-oiled moulds in layer after layer and compacted with the help of a vibrating table to get rid of any air trapped in it and also to enable sufficient densification. When the casting was done, the moulds were well closed to avoid loss of moisture in the

initial period of setting. The specimens were demoulded after 24 hours and cured at the ambient room temperature till the required testing age.

2.4. Slump Cone Test

Workability of the fresh GPC was analysed using the slump test as per IS 1199:2000 [28]. The interior of the slump cone (200 mm base, 100 mm top, 300 mm height) was cleaned and lubricated before use and placed on a flat 400 × 400 mm base plate. The newly prepared concrete mix was put into the slump cone in three equal layers, and each layer was compacted by tamping 25 times with a steel rod with a length of 600 mm and a diameter of 16 mm. After the top surface was levelled to ensure uniformity, the cone was carefully withdrawn vertically, and the reduction in height of the concrete specimen was recorded. The slump value was obtained by comparing the mould height with the

specimen height immediately after lifting, as shown in Figure 3.



Fig. 3 Slump cone apparatus

2.5. Hardened Properties Test

The mechanical properties of control and fibre-reinforced geopolymer concrete were evaluated through CS, TS, and FS tests, as represented in Figure 4. CS was measured on $150 \times 150 \times 150$ mm cube specimens in accordance with IS: 516–1959 [29], with a total of 36 specimens tested after 7 and 28 days of curing using a 2000 kN compression testing machine at a loading rate of $140 \text{ kg/cm}^2/\text{min}$ until failure. TS was assessed on cylindrical specimens of 150 mm diameter and 300 mm height following IS: 5816–1999 (Reaffirmed 2013)[30], with 36 specimens tested after 7 and 28 days of curing. Thin wooden bearing strips were placed along the line of contact between the specimen and loading platens to ensure uniform load distribution and prevent local stress concentration. Flexural performance was evaluated on prism specimens measuring $500 \times 100 \times 100$ mm in accordance with IS: 516–1959 [29], with 38 specimens tested after 7 and 28 days of curing under two-point loading using a 600 kN universal testing machine. The tests collectively provided a comprehensive assessment of the mechanical behavior of both control and fibre-reinforced geopolymer concrete.

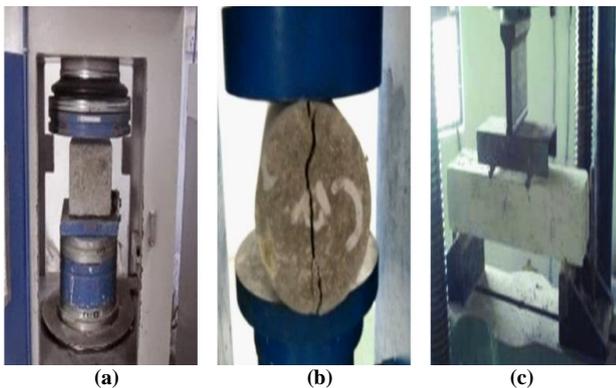


Fig. 4 Hardened properties of concrete: (a) Compressive strength test, (b) Split tensile strength test, and (c) Flexural strength test.

2.6. Durability Tests

The thermal performance and durability of the control geopolymer concrete (CGPC) and cellulose fibre-reinforced geopolymer concrete (CFRGPC) were evaluated systematically using the standard tests. Sulphate resistance

was determined in accordance with ASTM C1012 [31] by determining the change in length of $100 \times 100 \times 100$ mm cubes immersed in a 5% magnesium and sodium sulphate solution at 45 and 90 days after 28 days of curing, with the loss of weight and strength being compared to control specimens. Salt resistance was tested by placing similarly cured cubes in a 3.5% NaCl and MgCl_2 solution under ambient conditions after 45 and 90 days, and then weight loss, strength degradation, and the overall chloride resistance were measured. Acid resistance was calculated by using ASTM C642 [32], in which cured cubes were subjected to a 5% solution of HCl and H_2SO_4 at room temperature over a period of 180 days, where weight and strength losses were recorded at 45 and 90 days. Water absorption was measured per ASTM C642-13 by drying cured specimens at 100°C for 24 hours, immersing them in water for 28 days, and calculating the percentage mass change. Water permeability was assessed according to IS 3085-1965 [33] by subjecting $150 \times 150 \times 150$ mm cubes to 2 N/mm^2 water pressure for 48 hours and measuring penetration depth. Thermal resistance was evaluated by exposing cured specimens to 200°C and 400°C for 2 hours and recording mass loss to compare the performance of fibre-reinforced and control mixes.

3. Results and Discussion

3.1. Slump Tests

The slump values of geopolymer concrete reinforced with banyan and sisal cellulose fibres at 0%, 1%, 2%, and 3% by binder weight are presented in Figure 5. It is observed that the inclusion of natural fibres decreases the workability of the mix compared to the control (0% fibre). For the banyan cellulose fibre series, the slump reduced from 80 mm at 0% to 75 mm at 3%, with a dip to 78.5 mm and 78 mm at 1% and 2%, respectively. Equally, the sisal cellulose fibre series had a greater initial workability at 0% (95 mm) but steeper to 43 mm at 3% fibre content. Such trends point to the fact that the addition of natural fibres reduces slump values in increasing proportions with the percentage content of fibres, more so in the case of sisal than in the case of banyan.

Such reduction of workability may be explained by the fact that the cellulose fibres have a greater surface area and are more hydrophilic, and thus they absorb mixed water and augment friction inside the fresh concrete. As a result, the fibre content of the mix is more flowable and stiffer. This behaviour is in agreement with literature reports, which have demonstrated a linear relationship between slump and sisal cellulose fibre dosage because sisal cellulose fibre increases the water requirement and mix cohesion [34]. The comparative differences between Banyan and Sisal reinforced mixes further reveal that fibres of sisal cellulose of a relatively coarser morphology and greater water absorption capacity disrupt workability much more severely than banyan cellulose fibres at the same volumetric content. This workability decrease also needs to be taken care of in practice by adjusting the content of the paste to get the required consistency without reducing the mechanical performance.

The results clearly demonstrate that banyan cellulose fibre provides better workability retention compared to sisal cellulose fibre at higher fibre contents. Sisal cellulose fibre mixes become stiff and difficult to place beyond 2% fibre dosage, whereas banyan cellulose fibre mixes remain workable even at 3% inclusion.

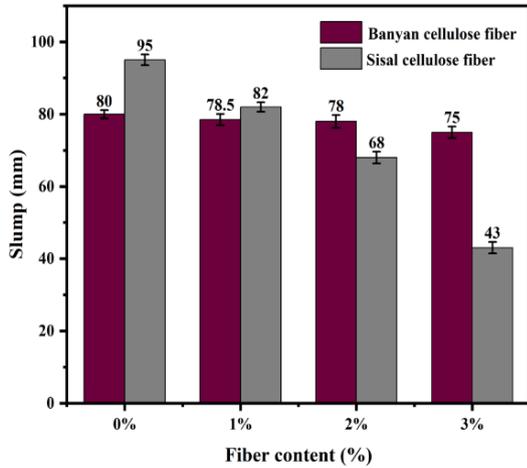


Fig. 5 Comparison of slump values

3.2. Compressive Strength Test

The compressive strength results demonstrate that the inclusion of natural cellulose fibres significantly influences the strength performance of M40 grade geopolymer concrete, with the extent of improvement strongly dependent on fibre type and dosage. In the case of the control composite geopolymer concrete, which had no fibres, the 28-day compressive strength was measured and yielded 42.5 N/mm² and 39.5 N/mm² in the banyan and sisal series, respectively. The CS was gradually gaining strength until a maximum fibre content of 2% was reached, where the highest strength of 46.2 N/mm² was reached after 28 days, which is 8.6% higher than the control mix. At a level that exceeded this, a minor decrease to 43.8 N/mm² was noted with the fibre content at 3%, which signified the start of fibre agglomeration and lowered homogeneity of the matrix depicted in Figure 6. Comparatively, sisal cellulose fibre-reinforced geopolymer concrete performed best with the minimum dosage of fibre of 1% CS of 28 days of 43.9 N/mm² which is an 11.3% improvement compared to the control mix. Additional increases of the sisal cellulose fibre content led to a progressive reduction in CS, indicating that sisal cellulose fibres are sensitive to increasing volume fractions in the geopolymer matrix, as represented in Figure 7.

The differences in the strength development of the banyan and sisal cellulose fibres can be explained by the differences in their physical morphology, surface features, and the interaction mode with the geopolymer binder. Banyan cellulose fibres have a relatively coarser surface texture and finer fibrillar structure, which increases mechanical interlocking and fibre-matrix bonding, and increases the efficiency of stress transfer and crack-bridging with moderate fibre dosages. This has the effect of giving sustained strength enhancement, even to a higher fibre content, as compared to sisal cellulose fibres. Even though the sisal cellulose fibres have higher intrinsic tensile

strength, they are stiffer and coarser, which may obstruct uniform dispersion of the fibre and elevated internal void content when beyond the optimal dosage, resulting in low densification of the matrix.

The existing literature of natural fibre reinforced geopolymer and concrete composite proves that the addition of optimal fibre content increases compressive strength, whereas the addition of fibre content results in a decrease of strength because of the dispersion problem, as well as the porous nature. An example of this is the experimental findings on sisal cellulose fibre-reinforced geopolymer concrete, where compressive strength steadily increases up to a fibre content of about 1%, followed by a decreasing trend as the dosage increases [35]. Equally, the addition of sisal cellulose fibre in regular concrete reflected the increase in compressive strength by 16.6% at 1.0% and 29.7% at 1.5% fibre content, respectively, with a notable decrease in strength at 2% fibre content [36]. Altogether, the outputs confirm that although both types of fibres increase compressive strength compared to the control mix, the highest compressive strength was achieved when there was 2% of banyan cellulose fibre addition which is more efficient at higher doses and the sisal cellulose fibre is more efficient at lower doses, hence, it is essential to optimize the fibre selection and dosage to design a geopolymer concrete.

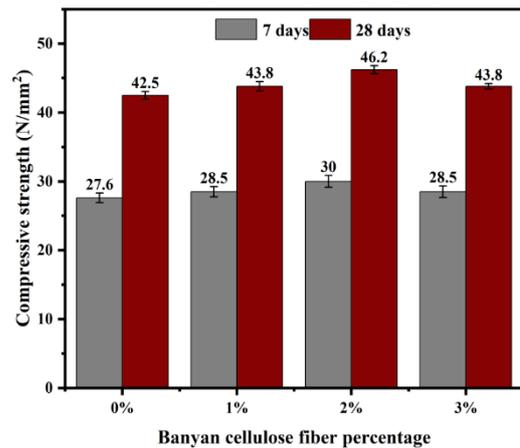


Fig. 6 Compressive strength results of Banyan cellulose fibre-reinforced geopolymer concrete

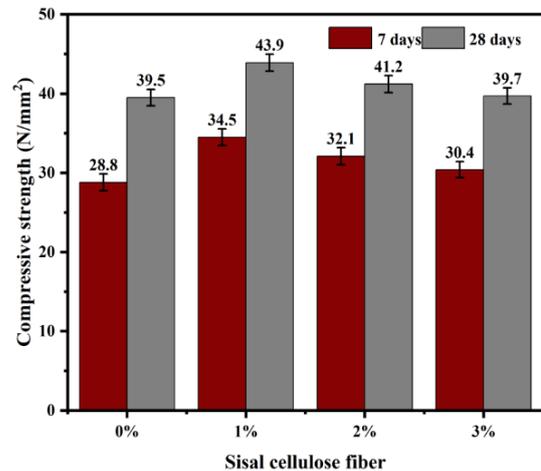


Fig. 7 Compressive strength results of sisal cellulose fibre-reinforced geopolymer concrete

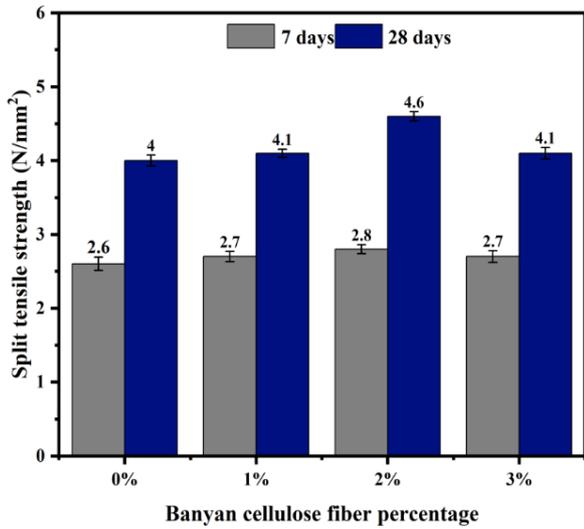


Fig. 8 7-day and 28-day split tensile strength results for banyan cellulose fibre

3.3. Split Tensile Strength Test

These values of split tensile strength of banyan and sisal cellulose fibre-reinforced geopolymer concrete prove that the incorporation of natural fibres yields a substantial improvement in TS compared to the control mixes, with the level of improvement being dependent on the type of fibre and the dosage. In the case of banyan cellulose fibre, 28-day split tensile strength rose above 2.6 N/mm² in the control mix up to an approximate level of 4.6 N/mm² at 2% fibre content, which is an improvement of up to 76.9% before slightly decreasing at 3% because of a possible clustering of the fibres and low density of the matrix, as represented in Figure 8.

Similarly, sisal cellulose fibre increased the tensile strength in 28 days to approximately 3.4 N/mm² in the control to almost 3.9 N/mm² at 1% fibre content, which is a 14.7% increment. An increase in fibre content is shown in Figure 9. The mechanistic explanation of these enhancements is the capacity of cellulose fibres to span microcracks and transmit tensile stresses on the geopolymer matrix, thus delaying crack propagation and enhancing toughness. The measured optimum fibre contents of 2% of banyan and 1% of sisal are in agreement with what the literature has shown with respect to similar natural fibre reinforcements; an optimum fibre volume fraction simultaneously increases tensile characteristics but beyond that point harms workability and performance [37].

Moreover, hybrid systems that use the sisal cellulose fibres have demonstrated tensile strength improvements in the multilayered geopolymer composites; the interaction and alignment of fibres in the fibre-matrix interaction is observed to govern tensile performance, and the importance of optimal dosage optimization in order to achieve maximum performance in sustainable geopolymer concrete applications [23]. The addition of banyan and sisal cellulose fibre increases split tensile strength due to its bridging cracks and toughness, and using banyan (2%) cellulose fibre is better in terms of its enhancement of split tensile strength

than sisal (1%). High fibre content decreases working and matrix densities and reduces gains. Sustainable geopolymer concrete is optimized for tensile performance using proper dosage and hybrid fibre strategies.

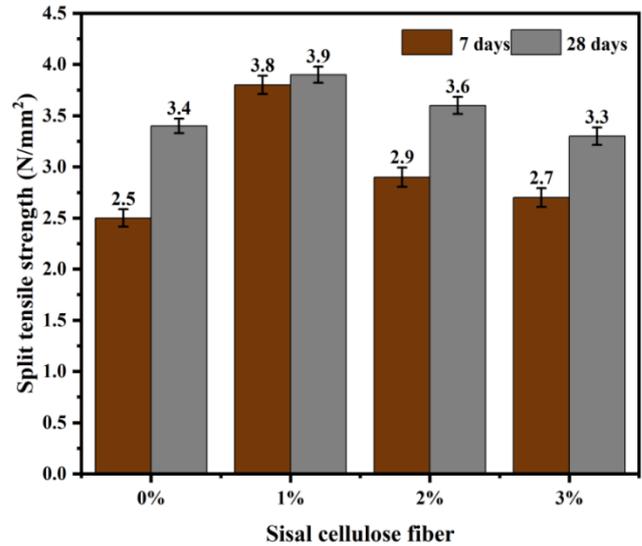


Fig. 9 7 days and 28-day split tensile strength results for sisal cellulose fibre

3.4. Flexural Strength Test

The flexural strength performance of both banyan and sisal cellulose fibre-reinforced geopolymer concrete shows that natural fibre in it enhances flexural performance much better than the control mixes. In the case of banyan cellulose fibre, flexural strength saw a 28-day improvement of 8.8%, augmenting the control mix of 4.43 N/mm² to 4.82 N/mm² at 2% fibre content before slightly falling to 4.57 N/mm² at 3% cellulose fibre content, since there was possibly a clustering of the fibre and less densification of the material, as shown in Figure 10.

The 28-day flexural strength of 4.2 N/mm² in the control was increased to 4.6 N/mm² at a fibre content of 1%, which is a 9.5% increase, and the increase in flexural strength decreased with increases in fibre content, as shown in Figure 11. These enhancements are mechanistically attributed to the fact that cellulose fibres were able to bridge the microcracks, transmit tensile stresses throughout the geopolymer matrix, and retard the crack propagation during bending, hence increasing toughness and energy absorption.

The trends observed are in line with the literature that indicates that moderate levels of fibre addition (1-2 %) maximize flexural performance, whereas high additions negatively influence workability as well as introduce weak areas in the matrix [37, 38]. Compared analysis reveals that the banyan cellulose fibre 2% gives the maximum absolute flexural strength, with the sisal 1% giving the maximum relative enhancement over the control.

Overall, both fibres enhance flexural performance effectively, but banyan at its optimum dosage is marginally better for practical application in sustainable geopolymer concrete.

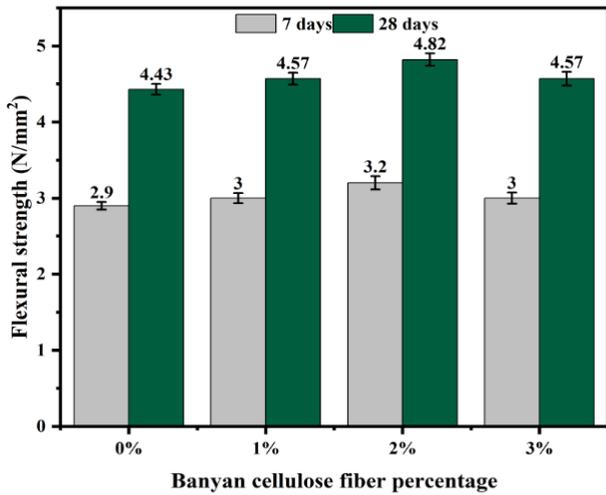


Fig. 10 7 days and 28-day flexural strength results for banyan cellulose fibre

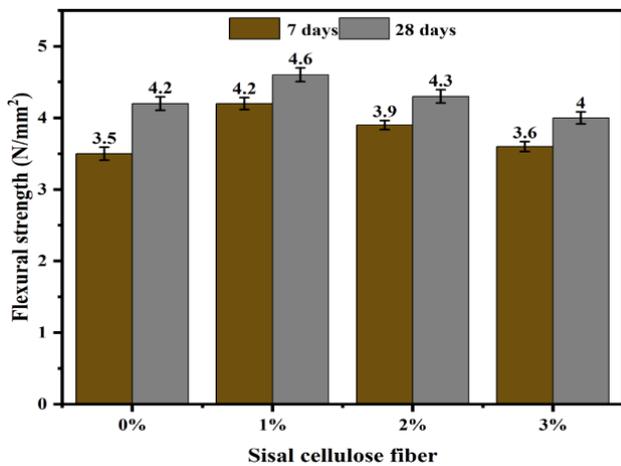


Fig. 11 7 days and 28-day flexural strength results for sisal cellulose fibre

3.5. Sulphate Resistance Test

The sulphate resistance results indicate that both banyan and sisal cellulose fibre-reinforced geopolymer concretes exhibit improved durability against MgSO₄ and Na₂SO₄ exposure compared with the control mix, as reflected in lower weight and strength loss percentages. For banyan cellulose fibres, the weight loss after 90 days in

MgSO₄ decreased from 1.0 % in the control to 0.8 % at 2 % fibre, and the Na₂SO₄ weight loss was also lower at 0.7 % compared with 0.9 % for the control, indicating enhanced resistance represented in Figure 12; similarly, strength loss percentages at 90 days were reduced from 6 % (control) to 4 % at 2 % banyan, representing roughly 33 % lower strength degradation versus the control.

Sisal cellulose fibre mixes showed a comparable trend: weight loss in MgSO₄ decreased from 2.0 % (control) to 1.5 % at 1 % fibre and 1.6 % at 2 %, and Na₂SO₄ weight loss dropped from 1.4 % to 1.0 % at 1 % sisal, while strength loss reduced from 10 % to 7 % at the 1 % sisal mix, equating to about 30 % reduction in strength deterioration relative to the control represented in Figure 13. These trends demonstrate that intermediate levels of fibre content enhance sulphate resistance; however, in higher levels (3 %), weight and strength loss are prone to rise marginally, presumably because of fibre clustering, creating micro-voids, which permit ion ingress. The mechanism of the enhanced performance can be elaborated as fibre bridging and densification of the matrix that inhibits crack formation and retard penetration and growth of deleterious sulphate salts in the geopolymer matrix, and too many fibres may cause heterogeneities that detract from the advantage.

The identified higher durability is in line with recent articles on better sulphate resistance of geopolymer concretes with added fibres or bio-additives that lower the mass and strength loss under severe sulphate conditions compared to plain mixes [39]. The best general sulphate resistance was achieved with 2 % banyan and 1 % sisal cellulose fibre content mixes, and with these mixes, there was the lowest weight and strength loss when compared to the respective controls. Banyan at 2% and sisal at 1% showed a 33% and 30% reduction, respectively, in strength loss compared to the control in a quantitative test, which means that when at the optimum content, banyan provides slightly better durability performance when the sulphate is applied over long periods. In general, moderate amounts of natural fibre reinforcement improve the sulphate attack resistance of geopolymer concrete, with banyan cellulose fibre being better than sisal at their own optimum levels in long-term sustainable durability use.

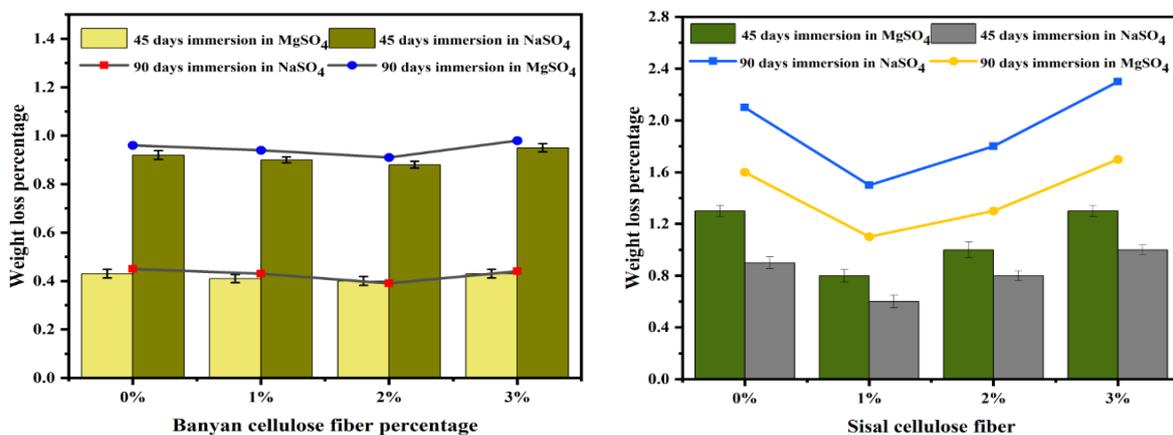


Fig. 12 Weight loss due to sulphate attack

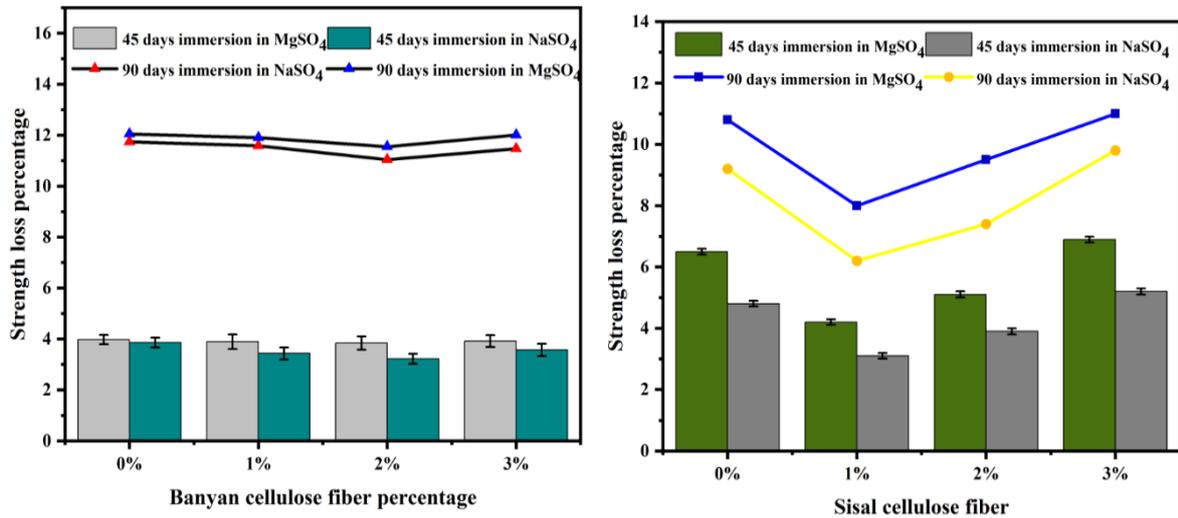


Fig. 13 Strength loss due to sulphate attack

3.6. Salt Resistance Test

The salt resistance behavior of geopolymer concrete with Banyan cellulose fibre and Sisal cellulose fibre was measured using the weight loss and compressive strength remaining after being immersed in MgCl₂ and NaCl solutions for 45 and 90 days. Overall, both natural cellulose fibres contributed to the improvement of the durability performance significantly in comparison to the control mix (0% fibre), and maximum response could be observed at the intermediate fibre dosages.

The weight loss in the case of Banyan cellulose fibre increased gradually with the increase in fibre content to a maximum of 2%, and then increased marginally to 3%. The loss of weight was lessened by 0.85 % in the control mix to 0.78 % at 2 % banyan cellulose fibre, which is an advancement of 9 %. This trend was also realised in the presence of NaCl, with the loss of weight of 2% banyan cellulose fibre being approximated to fall at 8 % compared to the control.

Comparatively, compressive strength retention after 90 days reduced by almost 70 % (control) to 67 % at 2 % banyan cellulose fibre, implying that there was an increase in residual CS of about 5%. Nevertheless, above a fibre concentration of 3%, agglomeration of fibre was probable, causing a slight degradation increase shown in Figure 14.

However, Sisal cellulose fibre exhibited higher performance of salt resistance than Banyan cellulose fibre under all exposure conditions. Loss of weight at 90 days in MgCl₂ decreased 1.30 % (control) to 0.95 % at 1% sisal cellulose fibre, which translates to a significant change of 26%. Exposure to NaCl resulted in a reduction of 22%, which was a good indicator of resistance to chloride ingress.

This tendency was also confirmed by the strength loss at 90 days; the CS loss at 90 days reduced between 58% and 50% in the control mix to that of 1% sisal cellulose fibre, which is an improvement of 15%. Adding the fibre material higher than 1% increased the weight and strength loss,

indicating that the fibre clustered and became more porous with increased sisal cellulose fibre dosages, as represented in Figure 15.

The enhanced crack-bridging effect and pore refinement mechanism explain the enhanced performance in terms of durability when using cellulose fibre. The two fibres inhibit the propagation of microcracks and decrease the connectivity of capillary pores, hence inhibiting the entry of degrading chloride and magnesium ions.

Due to their superior tensile strength, and more coarse surface texture as well as superior fibre-matrix interfacial bonding, sisal cellulose fibres offer better stress transfer and crack-arresting ability than Banyan cellulose fibres. This leads to increased densification of the matrices and increased resistance to chemical attack. Increased fibre contents, however, cause increased local porosity due to poor dispersion and fibre balling, which counteract the positive effects.

According to the comparative analysis, Banyan cellulose fibre and Sisal cellulose fibre were determined to have optimum fibre of 2% and 1%, respectively. Out of the two, both Sisal cellulose fibre at 1% dosage showed the highest overall performance with a maximum weight loss of 25% and strength retention of 15% better than the control mix, and performed consistently better than Banyan cellulose fibre both with MgCl₂ and NaCl exposure.

This result can be compared to the recent literature, which has found increased chloride and sulfate resistance in geopolymer composites reinforced with sisal and other plant-based fibres, as a result of better interfacial bonding and optimization of the microstructure [40, 41]. Generally, the experiment has shown that Sisal cellulose fibre is superior to Banyan cellulose fibre with respect to strengthening salt resistance of geopolymer concrete, particularly when a lower content of fibre is used, hence it is a prospective sustainable reinforcement in a hostile environment.

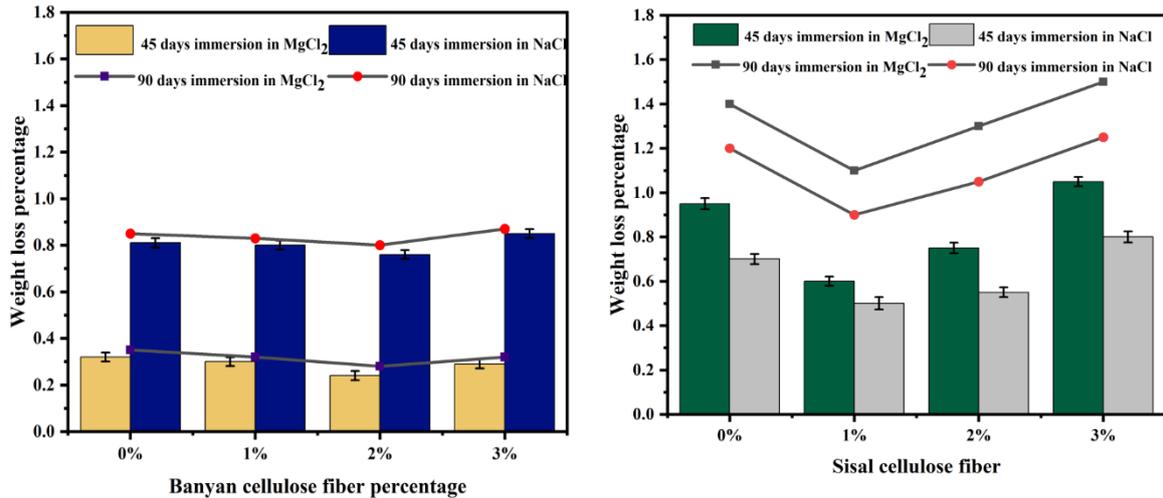


Fig. 14 Weight loss due to salt attack

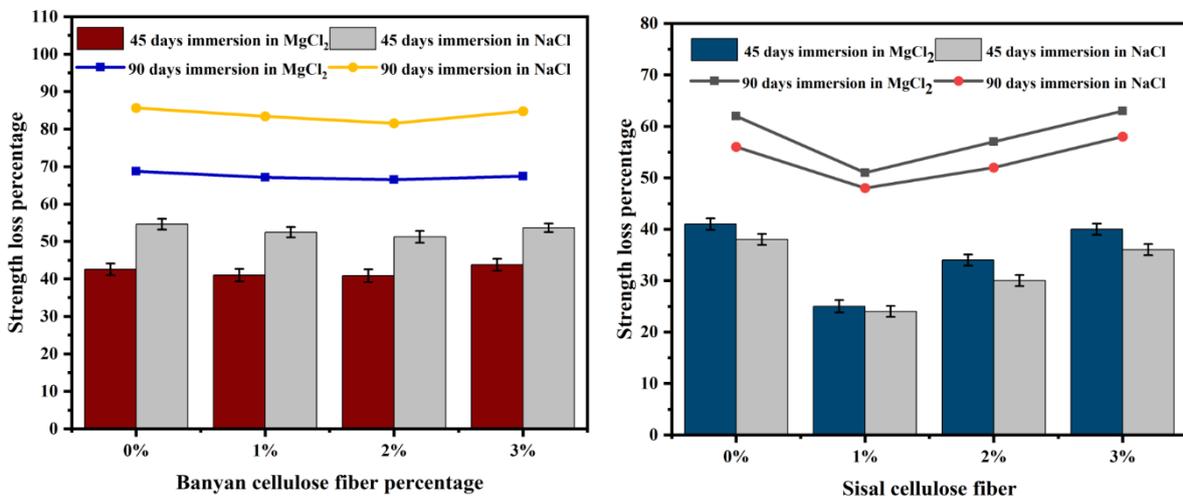


Fig. 15 Strength loss due to salt attack

3.7. Acid Resistance Test

The acid resistance performance of Banyan cellulose fibre and Sisal cellulose fibre reinforced geopolymer concrete was systematically determined in hydrochloric (HCl) and sulphuric (H₂SO₄) environments in terms of weight loss and residual CS at the end of 45 and 90-day immersion. Inclusion of fibre was found to be significantly beneficial in increasing the durability of the mix compared to that of the control mix, where the differences were quite large based on the type of fibre and its dosage.

In the case of the Banyan cellulose fibre mixes, the trends of weight losses showed a decline with an increase in the fibre content to 2% and slightly higher losses at 3%. At the end of 90 days of exposure to H₂SO₄, the control mix experienced a weight loss of 11.5% as compared to the mix with 2% banyan cellulose fibre, which experienced about 10.2%, which is an improvement of 11%. Weight loss decreased by 9.8% (control) to 8.7% at 2% banyan cellulose fibre (11% improvement) on HCl attack. The retention of compressive strength was similar, and the retention of CS was reduced to 68% in the control and 65% in 2% banyan cellulose fibre, which represented a 5% strength increase.

This levelled off at a fibre content of greater than 2%, probably because of fibre agglomeration, weak dispersion, and more local porosity at higher levels of fibre dosage, as represented in Figure 16.

The Sisal cellulose fibre mixes, in contrast, had increased resistance to acid degradation, with the strongest increases observed at 1% sisal cellulose fibre. The weight loss at the end of 90 days in H₂SO₄ was reduced considerably by 28%, with about 6.8% and 4.9% in the control and 1% sisal cellulose fibre, respectively. Equally, the weight loss became 22% less under HCl exposure at 1% sisal cellulose fibre. The loss of strength was also significantly lower than that of almost 58% (control) to 50% (1% sisal cellulose fibre) (13% improvement in strength retention). Sisal cellulose fibre with greater content (3%) was more deteriorative, which was in line with greater fibre aggregation and reduced matrix integrity as shown in Figure 17.

The improved acid resistance incorporation of fibres can be related to a combination of microcrack bridging, pore refinement, and the improved fibre-matrix interface

interactions. Natural fibres inhibit crack propagation and minimise capillary network connectivity, thus restricting the infiltration of aggressive acid ions into the matrix. This process agrees with the observations of Liu and Lv (2022) [37], who indicated that cellulosic fibres enhance the acid stability of geopolymer composites by enhancing the interfacial bond and pore structure, and reducing acidic environments (and in particular, H_2SO_4 and HCl) decreased the mass loss of composites (Supplementary material). Similarly, recent research on sisal-reinforced concrete proved that the use of natural fibres can largely alleviate the effects of acid attacks, since the use of strong fibres leads to the improvement of the cohesion of the matrix and lowers

the accessibility of acid to the fibres, especially in those that are evenly placed in the composite [42].

Using the comparative analysis, the optimal content of the fibre was determined as 2 % Banyan cellulose fibre and 1 % Sisal cellulose fibre. Among the two, Sisal cellulose fibre at 1% dosage has the greatest overall improvement, with up to 30 % obtainable weight loss and 15 % better strength retention than the control mix. Such findings contribute to the conclusion that 1% sisal cellulose fibre is the most suitable acid-resistant one to use in geopolymer concrete, and it is better than Banyan cellulose fibre in terms of resistance to the negative impacts of the long-term interaction with acids.

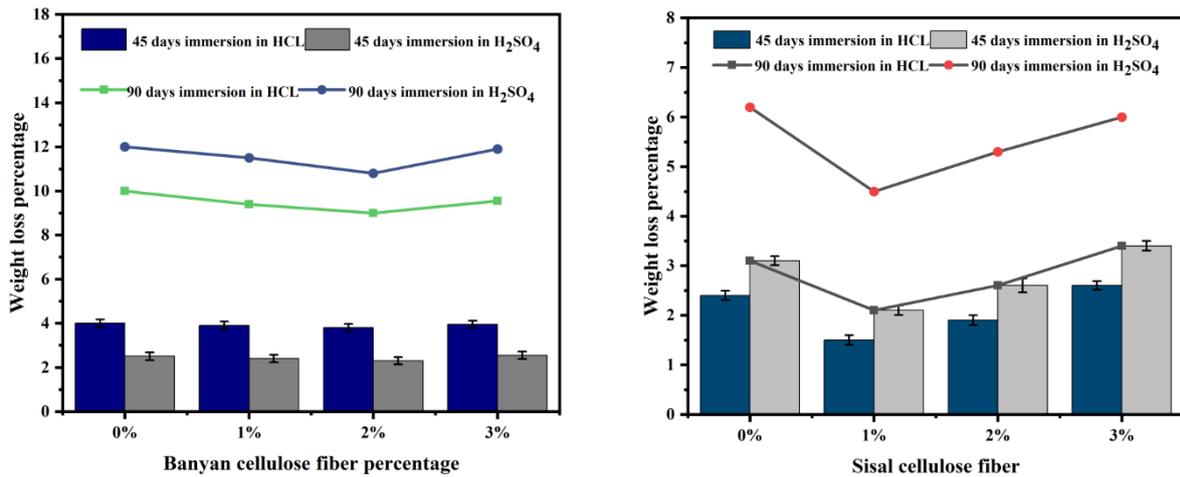


Fig. 16 Weight loss due to acid attack

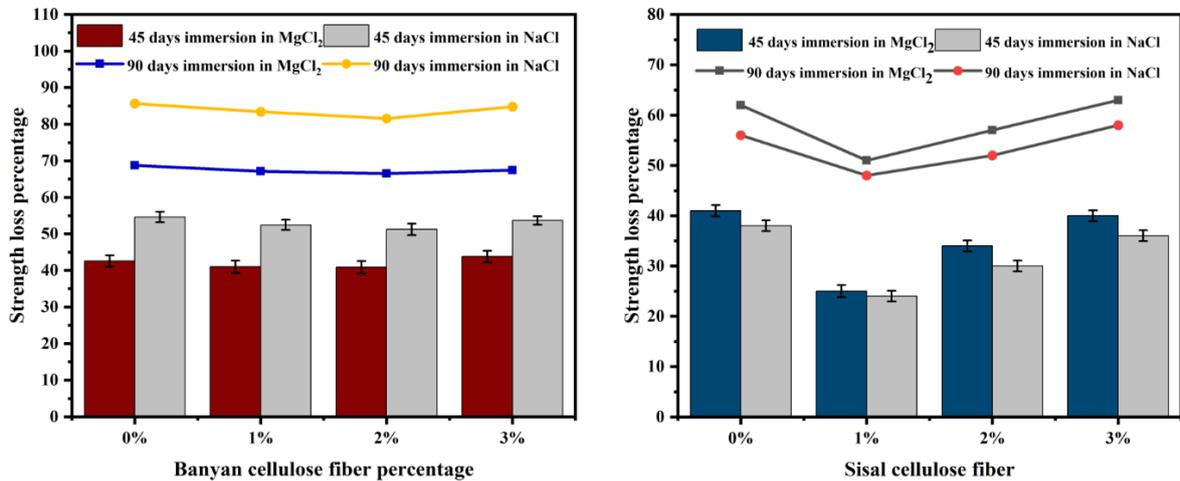


Fig. 17 Strength loss due to an acid attack

3.8. Water Absorption Test

The water absorption characteristics of geopolymer concrete using Banyan cellulose fibre and Sisal cellulose fibre across the fibre content range of 0-3% were determined to determine the effects of natural fibres on the pore structure and permeability of the geopolymer concrete. The findings reveal that the inclusion of fibre greatly lowers the level of water absorption relative to the control mix, and the success of fibre is greatly influenced by the dosage and type of fibre.

In the case of the control mix (0% fibre), the water absorption of the Banyan cellulose fibre mixes and Sisal cellulose fibre mixes were 6.7% and 6.9%, respectively, which means that the geopolymer matrix was relatively porous. A significant decrease in water absorption was noted with the addition of fibre to the optimum content of fibre. When the content of Banyan cellulose fibre was increased to 2%, the amount of water absorbed declined to 3.5%, which is 48 % lower than that of the control mix. The absorption was 3.8% at 1% fibre addition, with a slight rise

to 3.7% at 3% fibre addition, indicating the occurrence of fibre agglomeration and high pore connectivity at high doses.

Likewise, the water absorption of Sisal cellulose fibre showed a negative frequency of increase in the water absorption capacity to a 2 % fibre concentration, but at that level, the tendency was only slight. The lowest value of water absorption (4.2%) was obtained at 2 % sisal cellulose fibre; this was 39 % less than the control mix (6.9 %). With a concentration of 1% sisal cellulose fibre, the water absorption was 3.9%, whereas at 3% it rose slightly to 4.3%, which shows that lower fibre volumes are more effective blockers of the pore, as represented in Figure 18. Even though both of the fibres enhanced resistance to water ingress, Banyan cellulose fibre always had lower absorption values as compared to Sisal cellulose fibre at the same fibre contents.

The dampening effect of the absorption of water can be explained by the microcrack-bridging effect and pore refining mechanism that is offered by cellulose fibres. Distributed fibres limit the microcracks created by shrinkage, and increase matrix continuity, creating fewer interconnected capillary pores that transport water. Banyan cellulose fibres, being smoother, fibrillar, and better dispersed in the geopolymer matrix, seem to prevent pores more effectively than Sisal cellulose fibres, and therefore give lower values of water absorption. Increased fibre contents (greater than 2 %), however, may create voids by fibre clustering and lack of workability, and nullify the positive impact. The observed trends are consistent with recent studies on natural fibre-reinforced geopolymer composites. Tian et al. (2023) [43] demonstrated that plant-based fibres decrease permeability and water uptake in alkali-activated materials due to enhanced crack resistance and reduced capillary porosity. These findings strongly support the experimental observations of reduced water absorption in the present study.

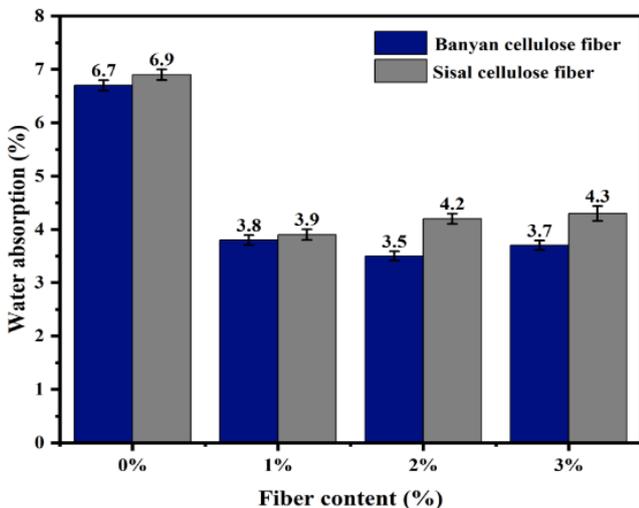


Fig. 18 Water absorption percentage

According to the comparative analysis, the optimum percentage of fibre content of minimum water absorption

was determined as 2% of Banyan cellulose fibres and Sisal cellulose fibres. The two types of cellulose fibre showed the best performance, with the dosage of 2 % Banyan cellulose fibre exhibiting almost 48 % reduction of water absorption as opposed to Sisal cellulose fibre at 2 % dosage. This is a clear indication that Banyan cellulose fibre is better when it comes to strengthening the impermeability of geopolymer concrete.

3.9. Permeability Test

The penetration depth of water shows clearly that the inclusion of natural cellulose fibres enhances geopolymer concrete impermeability considerably, and the performance highly depends on the type of fibres and their dosage. The control mix (0% fibre) had a penetration depth of 33 mm, showing a relatively open pore structure, which is easily penetrated by water. As the Banyan cellulose fibre was added, the depth of penetration decreased to 30mm with the 1% fibre content (9% decrease) and to 28mm with 2% fibre content (maximum improvement of approximately 15%). Nevertheless, when Banyan cellulose fibre was added to the suspension at 3 %, the depth of penetration returned to 32 mm, indicating that the level of addition of a fibre surpassing a certain point reduces the benefit of impermeability associated with fibre aggregation and subsequent internal voids.

Greater enhancement was made when using Sisal cellulose fibre. The penetration depth decreased dramatically at 1% fibre content to 25mm, which would be a 24 % reduction, which is the largest improvement of all mixes studied. The penetration depth at 2% Sisal cellulose fibre was 27 mm (18% reduced), and as the cellulose fibre content was increased further to 3%, the penetration depth was 31 mm, which is a maximum of about 6% improvement shown in Figure 19. These trends suggest that Sisal cellulose fibre is better than Banyan cellulose fibre in refining the pore structure and limiting the movement of water, especially at lower dosages of the fibres.

The permeability drops that are observed are largely attributed to microcrack-bridging and pore-blocking effects of cellulose fibres in the geopolymer matrix. Highly dispersed fibres disrupt continuity of capillary pores, enhance tortuosity of the flow paths, and inhibit microcrack extension through shrinkage and reaction processes. This results in a less permeable and denser matrix at optimal fibre contents. On the other hand, during dosage increases, there is a poor dispersion and clustering of the fibre, which causes extra missing and weak areas, negates the positive results, and causes more water to penetrate.

These results are in line with current literature. Zhang et al. (2022) [44] found that cellulose fibre contents of up to 2% enhanced the permeability of geopolymer concrete to a significant degree, whereas larger dosages raised porosity because of fibre entrapment. The trends and optimum fibre ranges given in these reports are very close to the results given in the current investigation, hence testifying to the reliability of the behaviour observed.

The inclusion of cellulose fibre in geopolymer concrete considerably improves the performance of permeability, and 1% Sisal cellulose fibre was found to be the most optimal mix in this extensive case, as it offers the highest contribution to permeability reduction; other fibre cellulose contents were found to harm impermeability.

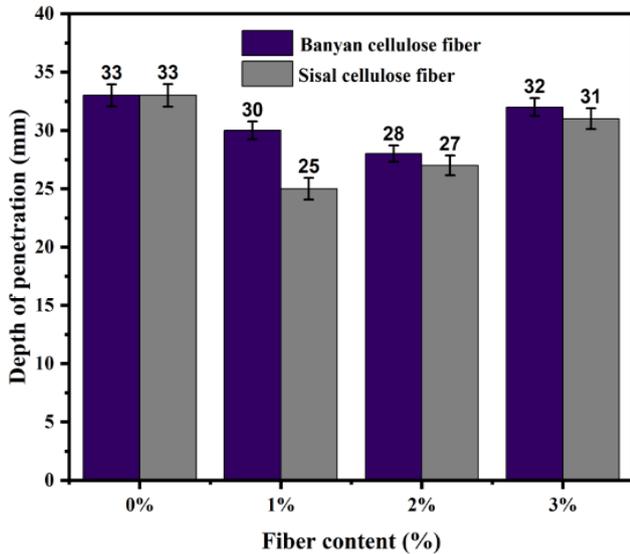


Fig. 19 Depth of water penetration

3.10. Thermal Resistance Test

Thermal resistance of geopolymer reinforced with Banyan and Sisal cellulose fibres was assessed through the loss of weight after being exposed to 200 °C and 400 °C. The two types of fibre had a profound impact on the thermal degradation behaviour of the geopolymer matrix, and unique tendencies were noted in the reduction in weight loss with varying fibre content of 0-3 %.

The control sample (0%) of the Banyan cellulose fibre mixes had a weight loss of 3% and 4% at 200 °C and 400 °C, respectively. The addition of one percentage of banyan cellulose fibre minimized weight loss to 2.9 % (200 °C) and 3.8% (400 °C), which was a 3 % and 5 % enhancement, respectively. Weight loss also increased to 2% banyan cellulose fibre with additional weight loss of 2.8% (200 °C) and 3.7% (400 °C) (improvement of 7 and 8 % compared to control), indicating an increase in thermal stability.

Nevertheless, weight loss attained a low of 3.6% (200 °C) and 3.9% (400 °C) at 3% banyan cellulose fibre, which is a slight improvement and thus reflects the decrease of thermal resistance caused by the clustering of fibres, and at higher banyan cellulose fibre loadings, it is characterized by the increase of microvoids represented in Figure 20.

A greater thermal resistance increase was noted in the case of Sisal cellulose fibre. The control (0%) showed a weight loss of 3.6% and 6.9% at 200 °C and 400 °C, respectively, indicating the greater impact that the increased temperature had on the unreinforced matrix. At 1 % sisal cellulose fibre content, weight losses were reduced to 2.8% (200 °C) and 5.1% (400 °C), giving an increase of 22% and

26% respectively. The weight losses decreased further at 2% sisal cellulose fibre to 2.4% (200 °C) and 5.6% (400 °C), which is 33% and 19 % of weight loss compared to the control, respectively. The 3 % sisal cellulose fibre blend had weight loss of 2.6 % (200 °C) and 5.4% (400 °C), marginally higher but by far better than the control represented in Figure 21.

The noted tendencies can be explained by the thermal reinforcement processes of cellulose fibres, comprising crack bridging, decreasing the microcracks, and enhanced heat dissipation in the geopolymer matrix. Under high temperatures, the formation of char by the cellulose fibres acts as a protective shield, and materials are not wasted. Moreover, the existence of fibres enhances the tortuosity of the heat and mass transfer directions, thereby postponing thermal decomposition.

The results have been in line with the past literature on natural fibre-reinforced geopolymer and alkali-activated systems. Rahman et al. (2023) [45] established that natural fibres reduced thermal degradation in cementitious and alkali-activated binders through facilitating better structural stability and the deterioration of cracks at high temperatures.

Throughout, both types of fibres enhanced thermal resistance, but Sisal cellulose fibre proved to perform the best, especially at a 1-2 % dosage level. Reduction in weight loss with the addition of fibre shows that there is increased thermal stability due to the increase in matrix integrity.

The best cellulose fibre contents (thermal resistance) were found to be 2% Sisal cellulose fibre (optimal performance), 2% Banyan cellulose fibre (moderate performance), and a higher cellulose fibre content (3%) was found to have reduced benefits, probably because of fibre agglomeration and higher internal porosity.

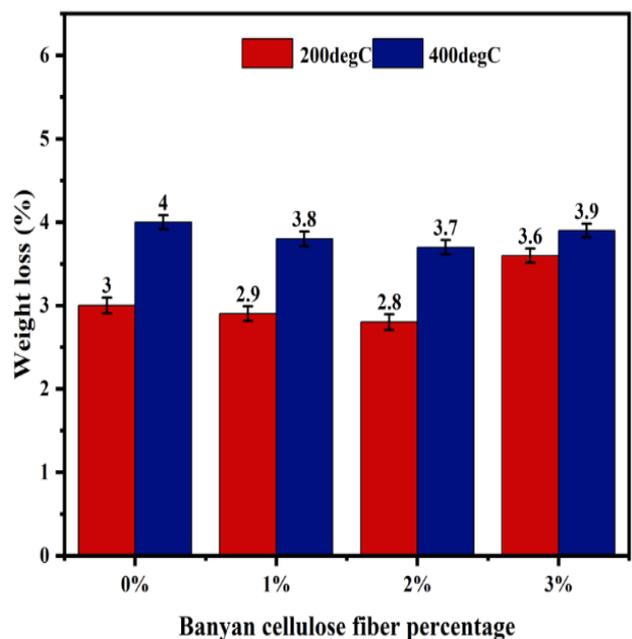


Fig. 20 Weight loss percentage for banyan cellulose fibre

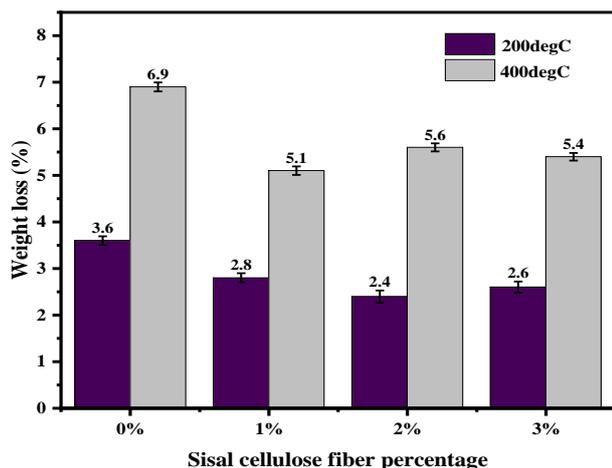


Fig. 21 Weight loss percentage for sisal cellulose fibre

4. Conclusion

This paper has examined the influence of Banyan and Sisal natural cellulose fibres on M40 grade GPC in terms of fresh, mechanical, durability, and thermal properties at fibre content levels of between 0-3 % by binder weight. The study was meant to determine the best type and amount of fibre that will increase the structural performance without affecting the workability and durability. To give insights into the sustainable and high-performance concrete application, the effect of fibre addition to the material on the strength, chemical resistance, and high-temperature behavior was systematically studied with an optimum cellulose fibre content of 2 % of binder weight. Inclusion of fibres reduced workability, with Sisal cellulose fibre causing higher slump loss than Banyan cellulose fibre due to higher water absorption and coarser morphology.

- Mechanical strengths were significantly enhanced at optimum dosages, with compressive, tensile, and

flexural strengths showing maximum improvement at 2% Banyan cellulose fibre and 1% Sisal cellulose fibre.

- Durability performance improved under sulphate, salt, and acid exposure, with reductions in weight and strength losses, and water absorption and permeability were minimized.
- Thermal resistance was enhanced for both fibres, with Sisal cellulose fibre exhibiting superior performance at elevated temperatures.
- Excessive fibre content beyond the optimum (>2%) led to fibre agglomeration, reducing the effectiveness of reinforcement.
- The observed improvements are attributed to microcrack bridging, matrix densification, and enhanced fibre–matrix interaction.

In general, the experiment has shown that natural cellulose fibres are effective and sustainable reinforcements of geopolymer concrete. The ideal combinations of 2% Banyan cellulose fibre, which provides mechanical strength and permeability, and 1% Sisal cellulose fibre, which provides chemical and thermal resistance, are very promising in terms of improvement in performance. These results demonstrate the promise of natural fibres in eco-friendly high-performance concrete to be used in hostile chemical conditions and high-temperature environments.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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