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Engineering properties of natural fibre-reinforced one-part geopolymer concrete

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ABSTRACT

Environmental concerns and the desire for improved performance in building construction have led to a great deal of attention being paid to developing sustainable construction materials. The engineering characteristics of natural fibre-reinforced one-part geopolymer concrete (NFROPGC), a novel material that combines strong mechanical qualities and offers significant environmental advantages, are examined in this work. Activated by a dry alkali source (Sodium meta–Silicate Anhydrous), one-part geopolymer concrete is more sustainable and easier to use than two-part geopolymer concrete. Fibres from kenaf, coconut, and oil palm measuring 25 mm and containing 0 %, 0.75 %, and 1 % were utilised. The chosen fibres were treated with an alkaline solution of 5 % concentration to enhance their performance. The engineering properties of natural fibre-reinforced one-part geopolymer concrete were measured by determining its workability, compressive, flexural, split tensile, impact resistance strengths, MOE, Poisson's ratio, and water absorption. Also, its morphology was studied under the scanning electron microscope. The flexural, splitting tensile strengths and MOE were improved by including 0.75 % natural fibre in one-part geopolymer concrete. Kenaf, coconut, and oil palm fibre-reinforced one-part geopolymer concrete showed increased flexural strengths from 4.93 MPa to 7.87 MPa, 4.11 MPa to 6.04 MPa, and 4.02 MPa to 5.85 MPa, respectively, while splitting tensile strengths of kenaf, coconut, and oil palm fibre-reinforced one-part geopolymer concrete increased from 3.3 MPa to 4.95 MPa, 3.25 MPa to 4.37 MPa, 2.95 MPa to 3.79 MPa, respectively and the MOE of kenaf, coconut, and oil palm fibre-reinforced one-part geopolymer concrete increased from 37.77 GPa to 44.04 GPa, 37.77 GPa to 42.79 GPa, and 37.77 GPa to 39.61 GPa, respectively. The optimum impact resistance strengths of the reinforced geopolymer concrete for kenaf fibre, coconut fibre, and oil palm fibre were obtained at 1 % fibre content with increments of 122.11 %, 98.33 %, and 88.33 %, respectively. However, fibre-reinforced one-part geopolymer concrete's compressive strength and workability reduced slightly as fibre content rose. The SEM results demonstrate how well fibres fill voids and bridge cracks in one-part geopolymer concrete. Future studies will focus on long-term performance evaluations and scaling up for industrial buildings.

1. Introduction

The traditional raw materials used to create concrete are not sustainable due to their high energy consumption during manufacturing and reliance on non-renewable natural resources, including gravel, river sand, and Portland cement. The substantial energy requirements of Portland cement production have led to a growing need for a greener binder that consumes less energy and emits fewer carbon emissions [27]. In recent decades, the building sector has seen a paradigm change towards eco-friendly and sustainable materials to lessen the environmental impact of conventional construction methods [3]. Of these newly developed materials, geopolymer concrete (GPC) is particularly noteworthy as a possible substitute for traditional Portland cement-based concrete because of its enhanced mechanical qualities, smaller carbon footprint, and ability to use industrial waste as raw ingredients [21]. Compared to using OPC as the binder in concrete, previous studies indicated that geopolymer might reduce carbon dioxide emissions by around 75 %. As a result, the advancement of GPC technology offers a long-term way to address the problem of carbon neutrality and lower industrial waste levels to enhance our quality of

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life. Additionally, it has been discovered that GPC has excellent workability, durability, permeability, early strength, and fire safety qualities. Therefore, it is anticipated that GPC will have numerous and widespread uses in the building sector in the future [13].

GPC is a relatively recent kind of green concrete initially documented in 1978. Solid materials rich in aluminosilicate are geopolymerized to create GPC in an alkaline environment. The source materials for GPC might come from a variety of industrial by-products. Some examples are fly ash (FA), red mud, metakaolin, silica fume, glass powder, and ground granulated blast-furnace slag (GGBS) [33]. The alumino-silicate can generate significant volumes of calcium silicate hydrates (C-S-H), calcium aluminate hydrates (C-A-H), calcium aluminosilicate hydrates (C-A-S-H), and sodium aluminosilicate hydrates (N-A-S-H) gels when an alkaline activator activates it. In the interim, these gels can contribute to a strong geopolymer matrix by constructing a rigid, hardened, three-dimensional tetrahedral structure of networks. Due to its excellent performance, ability to use solid waste, and nearly zero carbon emissions, geopolymer is becoming a viral material worldwide [21]. Alkali-activated materials are receiving increased attention because of sustainable advancements in concrete technology. The interaction of aluminosilicate precursors with an alkaline activator gives these materials their hardened characteristics. The activator's alkalinity and the precursors' oxide content determine the ensuing binding phases [11].

Geopolymer concrete (GPC) has been treated with traditional two-part alkali activators, sodium hydroxide and sodium silicate or potassium hydroxide and potassium silicate. Nevertheless, using these alkali-activators presents a problem because sodium silicate in liquid form can be dangerous on construction sites and injure personnel if mismanaged. In GPC research, a one-part alkali activator has gained popularity as a solution to this problem [32]. The "one-part geopolymer" (OPG) method proposes substituting solid alkali activators for liquid alkali solutions that have already been pre-mixed with binder powders. Water addition to the mixture is like standard cement concrete manufacturing. This method offers a more workable substitute using a single powdered alkali-activator, such as sodium metasilicate pentahydrate and sodium metasilicate anhydrous [29]. Examining how natural fibre influences the engineering performance of one-part geopolymer concrete (OPGC) may provide insight into its usefulness in construction industries.

When added at 20 mm and 2 % length and volume, hemp fibre increased the one-part geopolymer concrete's compressive and flexural strengths. SEM images demonstrated that an increase in geopolymeric gels accomplished this. An efficient wetting between the fibre and the geopolymer matrix is shown by the imprints of hemp fibre shape on the surface of the matrix. This implies that the fibres and matrix will come into contact during fracture, dissipating energy and boosting fracture toughness [32]. Adding fibre reinforcement can improve Cement-based composite materials in terms of flexural strength, toughness, and impact resistance. It can also reduce plastic shrinkage, increase heat conductivity, and enhance specific damping. Motivated by the need for low-carbon and environmentally friendly products, there is an urgent need for novel materials that are dependable, affordable, sustainable, and capable of replacing synthetic fibres as an improvement for brittle materials [17]. Furthermore, adding natural fibres to geopolymer concrete matrices presents a cooperative way to improve the material's technical qualities and advance resource efficiency and sustainability. The mechanical characteristics of one-part geopolymer concrete and mortal have been enhanced by the addition of synthetic fibres, including steel, rubber tyre, carbon, PVC, Basalt, and glass fibres [9,11,12,16,22,34]. Nevertheless, it is discovered that these synthetic fibres are pricy, hard to come by, and caustic. Because natural fibres function similarly to synthetic fibres in typical concrete, using natural fibres is therefore preferable. Natural fibres are inexpensive, widely accessible, carbon dioxide neutral, and require less energy and technology. In addition, the two-part geopolymer matrix has been reinforced with natural fibres such as kenaf, bamboo, flax, coconut, sisal, ramie, hemp, graphite, and jute. The output has better tensile and flexural strength, decreased density, and enhanced thermal and acoustic insulation qualities [1,2].

The qualities and latest developments in the production of Geopolymer composites reinforced with natural fibres were evaluated [23]. It was said that to lessen resource depletion, environmental degradation, and greenhouse gas emissions worldwide, sustainable development in the building industry is crucial. Due to their technical similarities to Portland cementitious materials, with significantly fewer CO_2 emissions and a more negligible environmental impact, geopolymer materials have drawn much attention. Natural fibres have good mechanical, thermal, and insulating qualities, and their addition can improve the performance of geopolymer concrete. In addition, natural fibres like jute, hemp, flax, and bamboo can be added to the geopolymer matrix as reinforcement. This has the advantage of improving tensile and flexural strength, lowering density, and improving thermal and acoustic insulation. Furthermore, the fibre's length, orientation, and composition impact its performance in geopolymer concrete [23].

Researchers investigated the effects of adding natural graphite on metakaolin-based geopolymer materials' mechanical and microstructural properties. Various techniques, including compressive strength, setting time, FTIR, TGA, SEM/EDS, and XRD, were used to examine the impact of NG inclusion on the MK-based geopolymer matrix. The findings of the microstructural analysis showed that the graphite sheets are integrated into the geopolymer network and that the densification of the geopolymer composites is significantly influenced by the amount of carbon, which increases with the gradual addition of NG. Based on the exceptional mechanical qualities of graphite, the elaborated geopolymer composite's mechanical parameters showed that 30 wt percent of NG is the ideal amount to use, increasing the composite's compressive strength by 49 % over that of the reference material. When NG was used to get the ideal mix proportion, the geopolymer composite paste took 663 minutes longer to set than the reference geopolymer paste. These results proved that the created geopolymer composite has potential in many fields, both economically and environmentally [24].

The behavior of a high calcium fly ash geopolymer mortar reinforced with natural fibres was examined. Two natural fibres, namely sisal and coconut, were added to the geopolymer mortar with varied quantities at 0 %, 0.5 %, 0.75 %, and 1.0 % volume fractions. The mechanical, thermal, and physical properties of geopolymer mortar reinforced with fibres were compared with those of glass fibre (synthetic fibre) and control (0 % fibre) geopolymer mortars. The results showed that similar to the use of glass fibre, adding natural fibre (sisal and coconut fibres) as reinforcing materials significantly improved tensile and flexural strength performances. Concurrently, there was a tendency for compressive strength, workability, dry density, and ultrasonic pulse velocity to decrease [30].

A study examined the behavior of geopolymers reinforced with natural fibres that contained waste-based sands and industrial by-products. In the case of geopolymer mortars reinforced with natural fibres (1 % coir, ramie, sisal, hemp, jute, and bamboo fibres, as well as 2 % ramie fibre by volume fraction of fine aggregates), industrial by-products fly ash (FA) and ground granulated blast furnace slag (GGBS) were used as binders, and waste-based sands lead smelter slag (LSS) and waste glass sand (WGS) were utilized as fine aggregates. The study involves flowability, durability (water absorption), mechanical (compressive strength and direct tensile strength), and drying shrinkage of the mortars. The findings show that geopolymers, including WGS, exhibit greater stability and less water absorption than those containing LSS and natural river sand (NS) for a given binder and fibre type. Compared to geopolymers made with WGS and NS, those with LSS show less drying shrinkage. Additionally, it is discovered that, compared to unreinforced geopolymers, geopolymers containing 1 %, 2 %, and hemp and bamboo fibres have higher compressive and tensile strengths and lower drying shrinkage. The geopolymers containing 1 % ramie fibres show the highest strength and lowest drying shrinkage. These results are encouraging and hold great promise for the use of natural fibres in the development of structural-grade building materials, where waste-based

and industrial by-products are used in place of aggregate and binder [14]

Noor Abbas et al. [25] conducted a statistical analysis and experimental evaluation of geopolymer concrete reinforced with kenaf fibres. This work presents Kenaf Fibre-Reinforced Geopolymer Concrete (KFRGC), a potentially sustainable building material investigated through statistical modeling and experimental testing. Measurements were made on the impact of kenaf fibre lengths ranging from 20 to 40 mm and volume fractions ranging from 0.75 % to 1.5 % on the engineering attributes of KFRGC. KFRGC's splitting tensile and flexural strengths improved without a discernible rise in compressive strength. Comparing KFRGC produced with 30 mm of length and 1.25 per cent volume fraction of fibre to plain geopolymer after 28 days of curing age; the former demonstrated a 27 % and 20 % increase in splitting tensile strength and flexural strength, respectively. Furthermore, there was less than 5 % error between the model's prediction and the experimental results. It concludes that natural concrete with KF incorporated can be a sustainable and environmentally beneficial building material [25].

Two-part geopolymer concrete's hazardous nature has restricted its use in construction. Hence, the construction industry searches for new materials, such as one-part geopolymer concrete, which is safe, economical, environmentally friendly, and safe for people. Even though natural fibre-reinforced one-part geopolymer concrete (NFROPGC) is becoming increasingly popular as a sustainable substitute for Portland cement concrete and two-part geopolymer concrete, several unanswered research questions remain. Limited research has been done on the effects of various natural fibre types (such as coconut, kenaf, and oil palm) on the engineering characteristics of one-part geopolymer concrete. To maximize the fibre-matrix bond and prevent deterioration, more research is needed to determine how fibre treatments, such as alkali treatment, affect NFROPGC's performance. The combined effects of fibre kinds and content on the mechanical properties (impact resistance strength, density, MOE, Poisson's ratio, UPV, flexural, compressive, and split tensile strengths, as well as SEM) of natural fibre-reinforced one-part geopolymer concrete remain largely unexplored. Therefore, this research aims to investigate and comprehend how adding natural fibres affects the mechanical properties and morphology of this environmentally friendly building material (one-part geopolymer concrete). By utilising natural fibres and reducing the reliance on traditional Portland cement, this research aims to promote sustainability while improving the performance of one-part geopolymer concrete, particularly its strength, toughness, and resistance to cracking. This will lessen the environmental impact of construction practices. The research hypothesis of the study is how adding natural fibres to one-part geopolymer concrete affects the material's engineering qualities while preserving its sustainability. These qualities include compressive strength, flexural strength, tensile strength, modulus of elasticity, Poisson's ratio, impact resistance, UPV, density, and water absorption. The kind and volume percentage of natural fibres also significantly impact the mechanical properties and microstructural features of one-part geopolymer concrete.

2. Materials and methods

2.1. Materials

Kenaf fibre, coconut fibre, oil palm fibre, class C fly ash, sodium metasilicate anhydrous (SMA) (53.00 % SiO_2 and 46.00 % Na_2O_3), granite, ground granulated blast-furnace slag (GGBS), and river sand were the primary materials used in this investigation. The study's oil palm and kenaf fibres originated from the Ladang Alaf Oil farm in Kota Tinggi, Johor, Malaysia, and the Faculty of Civil Engineering, UTM, Malaysia, respectively. Coconut fibre was simultaneously obtained through Malaysian Planting Media. These natural fibres were selected due to their light weight, good corrosion resistance, low cost of production, availability, and capacity to absorb carbon dioxide (CO_2) (Kumar Jagarapu & Eluru, 2020; Elbehiry et al., 2021). To clean them up and improve their functionality in concrete, the fibres were treated with 5 % NaOH. Tables 1 and 2 show the oxide compositions of FA, GGBS and SMA and the physical properties of fibres, respectively. Fig. 1 shows the raw materials for OPGC. while Fig. 2 displays the attributes of fibres. OPGC was selected due to its ability to prevent the problems associated with two-part geopolymer concrete. The fibres were chopped into 25 mm lengths since this was the optimum length from the literature. The percentage of fibres utilised was 0.75 % and 1 % as optimum volume ranges from existing literature. Both fly ash (FA) and ground granulated blast-furnace slag (GGBS) functioned as the source materials in a ratio of 1:1. From the Meridian Maplestar SDN BHD and Tanjung Bin Energy Power Plant Johor, Malaysia, ground granulated blast-furnace slag (GGBS) and the Class C fly ash was gathered, respectively. According to ASTM C618–15, its high amount of CaO (14.5 %) and total oxides of Al_2O_3, SiO_2, and Fe_2O_3 (71.1 %) led to its classification as Class C pozzolanic material. Fly ash with a median particle size of 32.6 mm and a specific gravity of 2.27, with a range of 1.88–76 μm, was found to have a 59 % passing fineness using a 45 lm sieve. UTM's Faculty of Civil Engineering in Malaysia obtained granite and river sand. Quartz makes up most of the river sand, with a SiO_2 concentration of 96.60 %. Fig. 3 illustrates the well-graded particle size distributions of granite, river sand, fly ash, and slag. All geopolymer concrete aggregates had a specific gravity of 2.60 and a fineness modulus 2.9 from river sand. Granite comes in particle sizes ranging from 2.36 to 10 mm. For river sand, the particle sizes varied from 0.075 to 4.75 mm. During mixing, distilled water was added to the admixtures of natural fibre-reinforced one-part geopolymer concrete (NFROPGC) to reduce contaminants.

2.2. Mix proportions

Seven different geopolymer concrete mixtures were made to examine the effects of different fibre types and the amount on the characteristics of the material. Table 3 displays the proportions of the mixtures. OPGC represents the control mixture. While KFROPGC-0.75 %, KFROPGC-1 %, CFROPGC-0.75 %, CFROPGC-1 %, OPFROPGC-0.75 %, and OPFROPGC-1 % represented one-part geopolymer concrete mixtures reinforced with kenaf, coconut, and oil palm fibres at 0.75 % and 1 %. The granite, river sand, fly ash, GGBS, SMA dosages, and water were fixed in all the mix designs at 835, 730, 265, 265, 75, and 195 kg/m^3, respectively. The DOE method of determining conventional concrete variables was utilised to establish the values of granite, river sand, fly ash, slag, SMA, and water because there is no design standard for a geopolymer concrete mix. 40 MPa was the design strength. The first step in manufacturing the one-part geopolymer combination involved the thorough dry mixture of granite, river sand, fly ash, and GGBS for three minutes. After the dry blending procedure, the material was homogenised for five minutes before adding SMA and water. The resultant mixture was mixed with fibre for five minutes to achieve homogeneity and an even fibre distribution. This resulted in a fibre-reinforced one-part geopolymer concrete (FROPGC). When using OPGC (control mix), the SMA is mixed into the dry mixture first, and then water is added

Table 1
Chemical properties of fly ash, sodium metasilicate anhydrous, and slag [27].

Oxides	FA	GGBS	SMA
AL_2O_3	19.60	14.00	0.19
SiO_2	41.00	27.42	53.00
Na_2O	2.10	0.52	46.00
MgO	3.82	5.64	-
P_2O_5	0.259	-	-
SO_3	1.56	1.73	0.01
K_2O	0.964	0.89	0.13
CaO	20.70	44.27	0.02
TiO_2	1.16	2.48	0.01
Fe_2O_3	8.29	1.00	0.05

Table 2
Physical properties of fibres.

Properties	Kenaf fibre	Coconut fibre	Oil palm fibre
Length (mm)	25	25	25
Volume (%)	0.75	0.75	0.75
	1	1	1

gradually while mixing. This thorough process is continued until the mixture is homogeneous. To evaluate compressive strength, UPV, water absorption, split tensile strength, flexural strength, impact resistance strength, modulus of elasticity (MOE), Poisson's ratio, and SEM, the prepared wet mixes were used to cast cubes, cylinders, beams, and impact resistance samples. All samples were cured and tested at 28 days. Fig. 4 illustrates the thorough mixing stages of the materials used.

2.3. Test methods

SEM imaging was used to analyse the fibre morphology using a JEOL JSM-1T300LV at a working voltage of 20 kV. To guarantee that every surface scanned was conductive, fibre samples were placed flat on double-sided carbon tape, gold coated, rotated, and recoated. There was a working distance of 15 mm and an accelerator voltage of 20 kV. Gellar Microanalytical dPICT software was used to capture the images digitally.

The freshly mixed concrete's workability was assessed as soon as it was mixed. This step involved filling a conventional slump cone with unconsolidated concrete samples, lifting the cone to allow the concrete to spread, and then measuring the slump cone's height following BS EN 12390 part 4 (2009) specifications.

Twelve cube specimens measuring 100 mm were tested for each concrete group to evaluate the compressive strength. As per BS EN 12390 part 9 (2009), the loading rates used to measure compressive strength were 6 kN/s and universal testing equipment with a maximum capacity of 3000 kN was utilised. The compressive strengths were measured at maturity on days 3, 7, 14, and 28. At 28 days, tests were conducted for the splitting tensile (BS EN 12390, part 6, 2009) and flexural (BS EN 12390, part 5, 2009). While cylindrical samples of 100 mm in diameter and 200 mm in height were constructed to evaluate splitting tensile strengths, prisms measuring 100 ×100 x 500 mm were made to measure flexural strength. The flexural and split tensile strengths were tested at loading rates of 0.13 kN/s and 1.25 kN/s, respectively. ACI 544 (2004) was utilised to ascertain the strength of impact resistance. The impact resistance strength was measured at 28 days of curing using cylindrical samples with an 80 mm diameter and 160 mm height. The standard falling hammer weight was 4.5 kg from a height of 1 m mm. The impact resistance strength is the product of the number of blows, the mass of the failing hammer, the height of fall and acceleration due to gravity [28].

Concrete strain gauges were affixed to the cylindrical sample in vertical and horizontal orientations to measure the vertical and horizontal strain after the sample was cured for 28 days. The sample was then tested using a 2000 kN Tinius Olsen Super L400 Universal testing apparatus. The corresponding vertical and horizontal strains were obtained at each loading, and the stress was calculated. The MOE was determined from the slope of the stress-vertical strain graph, as shown in Eq. 1, while the Poisson ratio was obtained from the slope of the vertical strain-horizontal strain graph, as shown in Eq. 2 (ASTM C469, 2009).

$$MOE = \frac{\text{Stress}}{\text{Vertical Strain}} \tag{1}$$

$$Poisson\ ratio = \frac{\text{Vertical strain}}{\text{Horizontal strain}} \tag{2}$$

In addition, the UPV test was carried out through ASTM C597 (2009) to examine concrete's integrity. The UPV value was calculated using Eq. 3

$$UPV = \frac{\text{Length}}{\text{Time}} \tag{3}$$

Each mix's water absorption rate was also calculated using ASTM D570 (1998) as shown in Eq. 4. This method evaluates the amount of water a substance absorbs in a given situation. Understanding the behaviour of a material in moist settings is crucial, as water absorption can impact its mechanical and electrical properties and, in turn, offers vital information to make sure the substance will function as planned in various environments.



Fig. 1. Materials for OPGC: (a) SMA (b) FA (c) Granite (d) River Sand (e) GGBS.



Fig. 2. Fibres (a) untreated kenaf (b) treated kenaf (c) untreated coconut (d) treated coconut (e) untreated oil palm (f) treated oil palm.

$$Water\ Absorption = \left(\frac{\text{wet weight} - \text{dry weight}}{\text{dry weigth}}\right) x100 \quad (4)$$

Finally, the JOEL JSM-IT300LV device was used to analyse the morphology of the natural fibre-reinforced one-part geopolymer concrete samples. Samples are manufactured at about $12\times12\ mm^2$ and coated with platinum before analysis. Following their introduction into a scanning electron microscope's chamber, these coated samples are examined under vacuum at a voltage of 20 kV. The SEM uses a small magnetic field external to the objective lens. It can magnify objects up to 900,000 times and operate at 1–50 mm, among other things.

3. Results and discussion

3.1. Effects of treatment on morphology of fibres

Utilising a variable-pressure scanning electron microscope, the untreated and alkaline-treated kenaf fibre morphology was examined under 3000 magnifications. Using VPSEM, the effects of the alkaline treatment on the fibre surface were investigated. The morphologies of

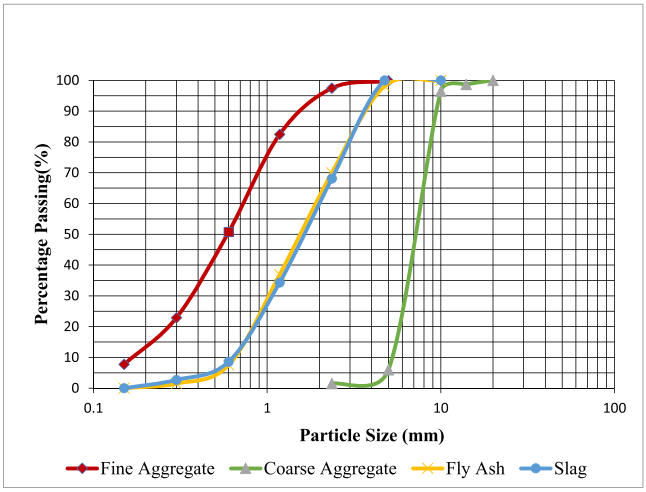


Fig. 3. Particle size distribution curves.

oil palm, coconut, and kenaf fibres treated and untreated are displayed in Fig. 5. A rougher and cleaner fibre morphology results from treatment procedures (such as alkaline treatments) that eliminate contaminants from the fibre surface, such as lignin, oils, waxes, and hemicellulose. The network of cellulose, wax, and oil covering the untreated fibre's flat surface is visible. Increased hydrogen bonding between cellulose chains is made possible by eliminating non-cellulosic components, which can enhance the mechanical qualities of the fibres. As a result of treatment, fibres become more flexible or even stretchable because of the breakdown or modification of the cell wall structure. A rougher fibre surface for composite materials is advantageous because it enhances the adhesion between the fibre and the matrix, improving load transmission and material strength overall. In conclusion, untreated fibres often have smooth surfaces, robust, undamaged cell walls, and impurity-caused hydrogen bonding obstructions. Increased hydrogen bonding, rougher surfaces, and altered cell wall structures in treated fibres lead to superior mechanical qualities and composite matrix compatibility.

3.2. Effects of fibres types and volumes on the workability of OPGC

The slump values of one-part geopolymer concrete reinforced with natural fibres (Kenaf, Coconut, and Oil palm fibres) show a declining pattern when the fibre content increases, as shown in Fig. 6. It showed that adding fibres) considerably reduced the workability of the concrete. This resulted from the fibre's uneven stripes, rough surface, and porosity texture [30]. When the fibre content rose from 0 % to 0.75 %, kenaf fibre, coconut fibre, and oil palm fibre concrete slump values decreased by 8.14 %, 10.47 %, and 13.95 %, respectively. Furthermore, the slump values of kenaf fibre, coconut fibre, and oil palm fibre concrete decreased by 17.72 %, 18.18 %, and 20.27 %, respectively, when the fibre content was raised from 0.75 % to 1 %. The workability difference expressed as a percentage shows how including fibres lessens the concrete slump, affecting workability [34]. The one-part geopolymer concrete augmented with oil palm fibres shows the most significant decrease in workability with increasing fibre volume. This resulted from the fibres' uneven stripes, porous texture, and rough surface. As the fibre content increased, the fresh geopolymer concrete became rigid. Thus, it can be said that the workability of fresh geopolymer concrete was decreased when kenaf fibre, coconut fibre, and oil palm fibre were added to one-part geopolymer concrete. This data is essential for determining the right fibre volume to provide concrete workability in different applications. This result supports the existing literature that fibres generally reduce the workability of concrete (conventional or geopolymer) and that workability always shows an inverse relationship with fibre content [31].

3.3. Effects of fibre types and volumes on water absorption of OPGC

The water absorption behaviour of one-part geopolymer concrete reinforced with natural fibres is depicted in Fig. 7. The findings demonstrated that introducing fibres enhanced the water absorption property of the geopolymer [25]. The water absorption of kenaf fibre, coconut fibre, and oil palm fibre concrete increased by 2.34 %, 3.32 %, and 6.93 %, respectively, when the fibre content increased from 0.75 % to 1 %. In contrast to Kenaf (6.02 %) and Coconut (6.4 %), Oil palm fibre-reinforced one-part geopolymer concrete has the highest water absorption (6.64 %) at 0.75 % fibre volume, whereas the control sample had 4.95 % water absorption. Furthermore, one-part geopolymer concrete reinforced with oil palm fibres at 1 % fibre volume has the maximum water absorption (7.1 %), followed by coconut (6.55 %) and kenaf (6.22 %). The Figure shows that one-part geopolymer concrete absorbs more water with increased fibre content. Considering the types of fibres, oil palm fibres exhibit the most significant increase in water absorption, followed by coconut and kenaf fibres. It shows that both fibre types and contents affect water absorption. Due to their hydrophilic structure, natural fibres increase the water absorption capacity of one-part geopolymer concrete [4]. These fibres' large surface area and abundance of microfibrils boost the concrete's overall porosity and ability to absorb water. Higher permeability may result from natural fibres' increased capacity to absorb water. The fibrous network's additional paths for water to enter the material may compromise the concrete's ability to function as a barrier to moisture and other fluids. An increased permeability brought about by introducing natural fibres may compromise the durability of geopolymer concrete. However, it's crucial to remember that these issues can be lessened with alkaline-based fibre treatments [5]. This strategy, with its potential to

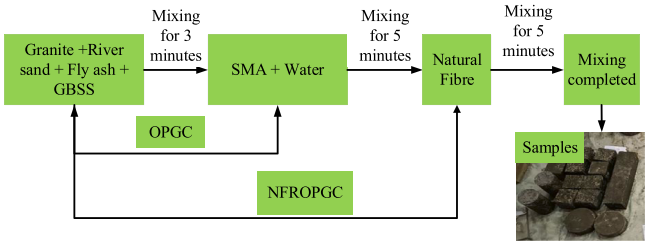


Fig. 4. Mixing stages.

Table 3
Mix combination (kg/m^3).

Mixture ID	Granite	River Sand	Fly Ash	GGBS	SMA	Water	Fibre
OPGC	835	730	265	265	75	195	-
KFROPGC−0.75 %	835	730	265	265	75	195	18
KFROPGC−1 %	835	730	265	265	75	195	25
CFROPGC−0.75 %	835	730	265	265	75	195	18
CFROPGC−1 %	835	730	265	265	75	195	25
OPFROPGC−0.75 %	835	730	265	265	75	195	18
OPFROPGC−1 %	835	730	265	265	75	195	25

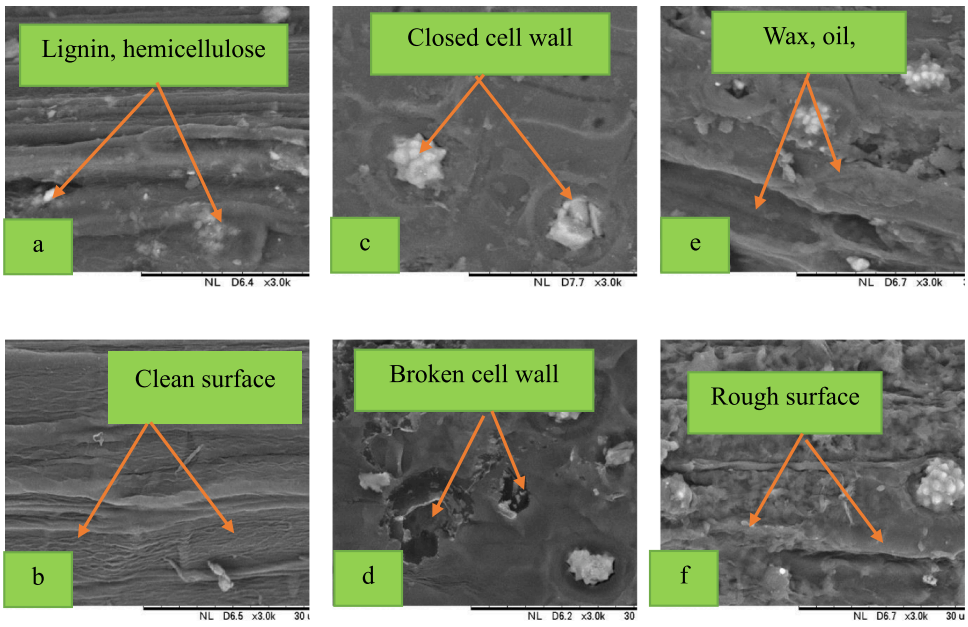


Fig. 5. Fibre Morphology (a) untreated kenaf (b) treated kenaf (c) untreated coconut (d) treated coconut (e) untreated oil palm (f) treated oil palm.

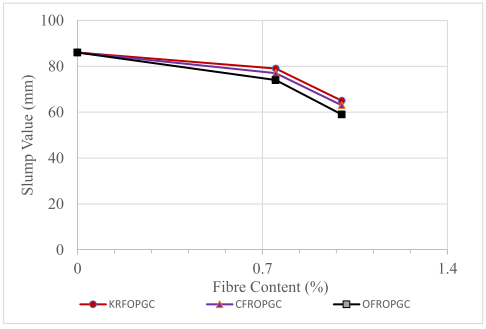


Fig. 6. Slump Values of Nature Fibre-reinforced One-Part Geopolymer Concrete.

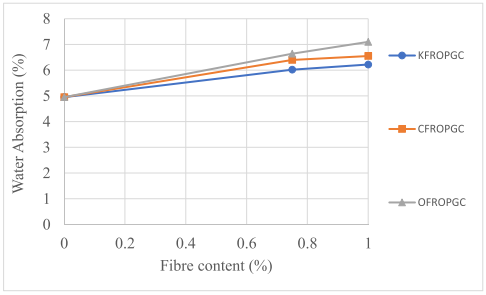


Fig. 7. Water absorption of natural fibre-reinforced one-part geopolymer concrete.

improve flexural strength and crack resistance, offers hope for enhancing the durability of geopolymer concrete [15].

3.4. *Effects of fibre types and volumes on compressive strength of OPGC*

The compressive strength of one-part geopolymer concrete supplemented with natural fibres is shown in Fig. 8. The compressive strength values for each specimen rose as the curing period increased from 7 to 28 days. The compressive strength decreased with increasing fibre volume

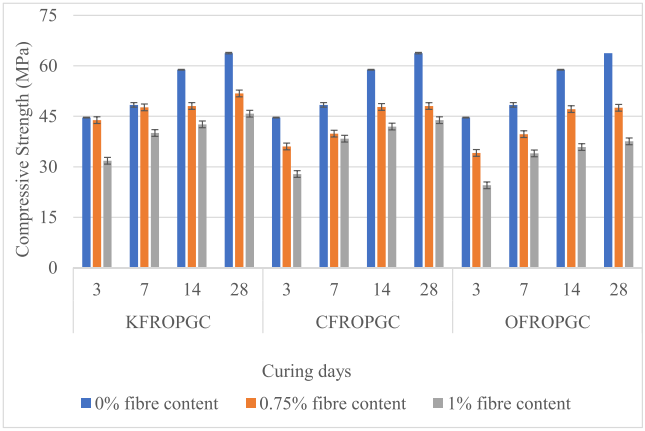


Fig. 8. Compressive strength of natural fibre-reinforced one-part geopolymer concrete.

at each curing period for every one-part geopolymer concrete sample tested [11]. Compared to CFROPGC and OFROPGC, KFROPGC had the maximum compressive strength at 0.75 % fibre volume throughout all curing durations. KFROPGC exhibits the maximum compressive strength at 1 % fibre volume, followed by CFROPGC and OFROPGC. The compressive strength of kenaf fibre, coconut fibre, and oil palm fibre concrete dropped by 18.79 %, 23.21 %, and 25.47 %, respectively, when the fibre content increased from 0 % to 0.75 %. Additionally, when the fibre content was increased from 0.75 % to 1 %, the compressive strengths of kenaf fibre, coconut fibre, and oil palm fibre concrete fell by 28.22 %, 31.24 %, and 41.13 %, respectively. Also, the specimens with a higher volume fraction of fibre are more challenging to prepare, which results in more voids or high porosity in the matrix, leading to a lower compressive strength. Nevertheless, after 28 days of curing, one-part geopolymer concrete samples reinforced with kenaf and coconut fibre gave higher compressive strength than the intended strength of 40 MPa. The Figure also illustrates the most notable reduction in oil palm fibre-reinforced geopolymer concrete. The fracture surfaces of samples after the compressive strength test are shown in Fig. 9. One-part geopolymer concrete with visible fissures and spalling

following testing is depicted in Fig. 9(a). On the other hand, fibre-reinforced one-part geopolymer concrete with improved cracking and concrete spalling resistance is shown in Fig. 9(b). It is impossible to overstate the benefits of adding fibre to one-part geopolymer concrete since it increases the material's resistance to fractures, deformation, and spalling. These findings are consistent with existing findings that natural fibre could not enhance the compressive strength of concrete [1,25]. This data is essential for choosing the right fibre volume in various applications to get the required compressive strength [23]. Lastly, the chart includes the standard deviation error bar, which indicates the degree of variation that may be anticipated between a sample estimate and the actual value in the samples. The standard deviation errors varied between 0.11 and 0.98, suggesting that the estimated value is precisely the genuine value because the smaller the standard deviation error, the better.

3.5. Effects of fibres types and volumes on flexural strength of OPGC

Concerning the fibre quantities, Fig. 10 illustrates that for all three types of concrete, the flexural strength increases at 0.75 % fibre volume compared to 0 % fibre volume. Fibres added to geopolymer concrete significantly improved the flexural strength performance [1]. When the fibre content rose from 0 % to 0.75 %, the flexural strengths of kenaf fibre, coconut fibre, and oil palm fibre concrete increased by 54.62 %, 18.66 %, and 14.93 %, respectively. Furthermore, the flexural strengths of kenaf fibre, coconut fibre, and oil palm fibre concrete decreased by 3.14 %, 19.25 %, and 21.02 %, respectively, when the fibre content was raised from 0.75 % to 1 %. The binder matrix surrounding the fibres at higher fibre content did not contain enough activator solution for geopolymerization, which caused a decrease in the bonding between the fibres and the matrix, affecting the flexural strength. When considering the different fibre types, kenaf fibre exhibits the most gain in flexural strength at 0.75 % fibre content, but it considerably declines at 1 % fibre volume. In contrast, although their magnitudes differ, oil palm fibre and coconut fibre exhibit similar tendencies. Coconut fibre exhibits a comparatively higher flexural strength of 0.75 % compared to oil palm fibre. The failure modes of OPGC and NFROPGC are shown in Fig. 11. The OPGC sample was ultimately damaged into two parts, while in the NFROPGC sample, fibre prevented complete damage under flexure. These results support related research findings that fibres tend to improve the flexural strength of concrete. This is achieved due to the capacity of fibre to delay crack formation and propagation in concrete [23,35]. This behaviour may result from a deterioration in structural integrity caused by exceeding the ideal interaction between the fibres and the geopolymer matrix at greater fibre concentrations. Finally, for optimal performance of natural fibre-reinforced one-part geopolymer concrete to flexural strength, the fibre content is limited to 0.75 %.

3.6. Effects of fibres types and volumes on split tensile strength of OPGC

Fig. 12 shows the effect of varying fibre quantities and types on the split tensile strength of several fibre-reinforced one-part geopolymer concrete types. At first, the split tensile strength is improved by adding up to 0.75 % of fibres. When 0.75 % of kenaf fibre, coconut fibre, and oil palm fibre are added to one-part geopolymer concrete, increments of 32 %, 16.53 %, and 1.07 %. Nevertheless, for kenaf fibre, coconut fibre, and oil palm fibre, respectively, additional addition (up to 1 % decreases the split tensile strength by 12 %, 13.37 %, and 21.33 %. This behaviour may result from exceeding the ideal fibre-geopolymer matrix interaction at greater fibre concentrations, which lowers the bonding strength of the composite. Fig. 13 reveals the crack propagation in OPGC and NFROPGC. The OPGC sample shows a wide crack, while the NFROPGC sample shows a microcrack. It was mentioned that adding natural fibres to the geopolymer matrix as reinforcement could have additional advantages like increased tensile strength [23]. In addition, Gholampour et al. [14] it was concluded that natural fibre improved the tensile strength of geopolymer. This resulted from the fibre's high tensile strength and elasticity modulus and the ability of the specimens' interaction with the geopolymer matrix to transfer stress to the fibre [30]. Finally, for optimal performance of natural fibre-reinforced one-part

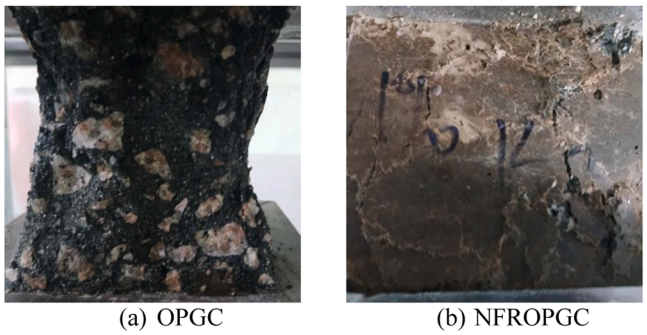


Fig. 9. Fracture surfaces of samples after compressive strength test.

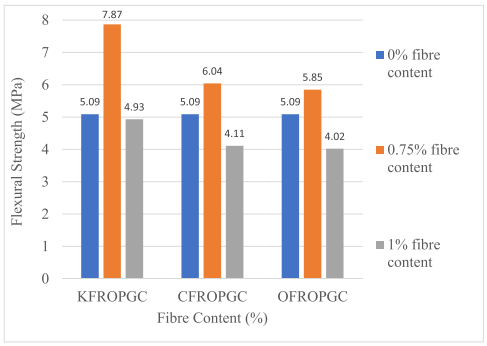


Fig. 10. Flexural strength of natural fibre-reinforced one-part geopolymer concrete.

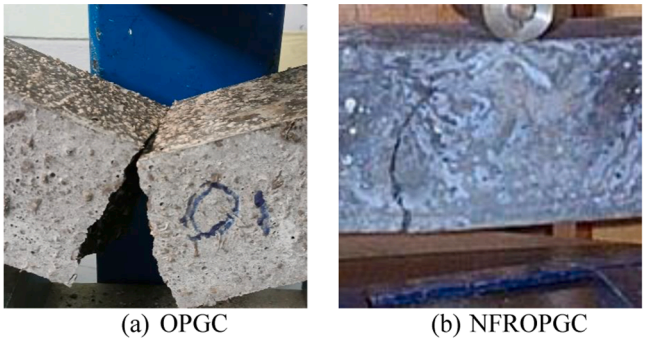


Fig. 11. Failure mode of the beam in flexure.

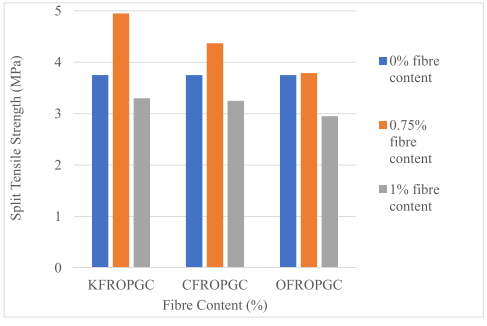


Fig. 12. Split Tensile Strength of natural fibre-reinforced One-Part Geopolymer Concrete.



Fig. 13. Crack pattern in OPGC and NFROPGC after split tensile strength test.

geopolymer concrete with split tensile strength, the fibre content is limited to 0.75 %.

3.7. Relationship between compressive, flexural, and split tensile strength of NFROPGC

Since compressive strength, flexural strength and split tensile strength are different types of stresses, there is no direct theoretical link between them. However, for design purposes, empirical methods estimate flexural strength and split tensile strength based on compressive strength. Alternatively, flexural strength is 10–20 % of compressive strength, while split tensile strength is about 8–12 %. Also, flexural strength is empirically obtained from split tensile strength. For most concrete mixtures, the flexural strength is roughly 1.8–2.2, or 1.5–2 times the split tensile strength. The empirical relationship developed in this research agreed with fundamental empirical relationships.

In this research, empirical relationships were developed to help estimate the mechanical properties of natural fibre-reinforced one-part geopolymer concrete. The empirical relationship between compressive strength and flexural strength is depicted in Fig. 14. The relationship between these values was determined, and this relationship is given in Eqs. 1, 2, and 3. In these Equations, $fc1$, $fc2$, and $fc3$ represent compressive strengths for KFROPGC, CFROPGC, and OFROPGC, respectively, and ft is their corresponding flexural strength with correlation coefficients of 0.89, 0.90, and 0.93, respectively.

$$fc1 = 8.54ft \tag{5}$$

$$fc2 = 2.2717ft + 40.353 \tag{6}$$

$$fc3 = 6.6945ft + 16.24 \tag{7}$$

Also, the relationship between compressive strength and split tensile strength is shown in Fig. 15. This relationship is expressed in Eqs. 4, 5, and 6. In these Equations $fc1$, $fc2$, and $fc3$ represent compressive strength for KFROPGC, CFROPGC, and OFROPGC, respectively, and st is their corresponding split tensile strength with correlation coefficients of 0.86, 0.81, and 0.89, respectively.

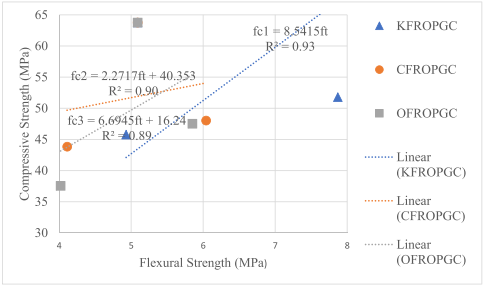


Fig. 14. Relationship between compressive strength and flexural strength of NFROPGC.

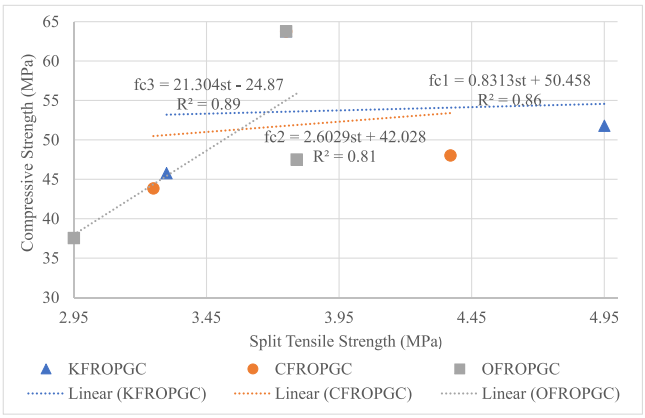


Fig. 15. Relationship between compressive strength and split tensile strength of NFROPGC.

$$fc1 = 0.8313st + 50.45854 \tag{8}$$

$$fc2 = 2.6029st + 42.028 \tag{9}$$

$$fc3 = 21.304st - 24.87 \tag{10}$$

Furthermore, the relationship between flexural strength and split tensile strength is shown in Fig. 16. This relationship is expressed in Eqs. 7, 8, and 9. In these Equations, $ft1$, $ft2$, and $ft3$ represent flexural strengths for KFROPGC, CFROPGC, and OFROPGC, respectively, and st their corresponding split tensile strength is 0.95, 0.99, and 0.86 correlation coefficients, respectively.

$$ft1 = 1.8921st - 1.6051 \tag{11}$$

$$ft2 = 1.7157st - 1.4225 \tag{12}$$

$$ft3 = 1.799st - 1.3038 \tag{13}$$

Also, the experimental and empirical results for flexural and split tensile strengths were 5.09 and 7.46 MPa, 3.75 and 4.08 MPa, respectively. They are relatively close to each other. The empirical results were obtained through the equations.

3.8. Effects of fibre types and volumes on impact resistance strength of OPGC

In Fig. 17, the effects of fibre types and volumes are displayed. The impact resistance strength and fibre volume of one-part geopolymer concrete reinforced with natural fibres are directly correlated. The impact resistance strength of kenaf fibre, coconut fibre, and oil palm

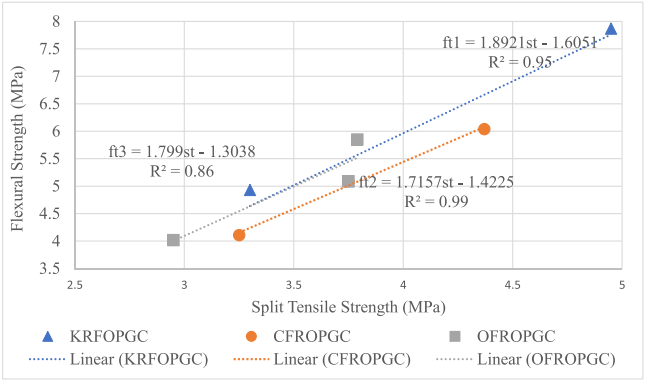


Fig. 16. Relationship between flexural strength and split tensile strength of NFROPGC.

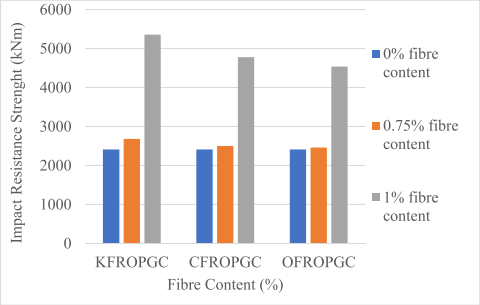


Fig. 17. Impact Resistance Strength of One-Part Geopolymer Concrete.

fibre reinforced geopolymer concrete increased by 11.35 %, 3.77 %, and 2.09 %, respectively, when the fibre volume increased from 0 % to 0.75 %. Additionally, the impact resistance strength of kenaf fibre, coconut fibre, and oil palm fibre reinforced geopolymer concrete improved by 122.11 %, 98.33 %, and 88.33 %, respectively, when the fibre volume increased from 0.75 % to 1 %. Consequently, including natural fibres enhances the improvement of impact resistance strengths. It should also be mentioned that the strength enhancement will increase proportionately with the quantity of natural fibres added. In addition, kenaf fibre is the most effective type of concrete in increasing impact resistance among the three, with coconut fibre and oil palm fibre following similar trends but with smaller increases in impact resistance than kenaf fibre. The kenaf fibre consistently demonstrates the highest impact resistance strength among the three types at all fibre volumes.

Lastly, one-part geopolymer concrete significantly strengthens its impact resistance strength when natural fibres are added up to 1 % of the total volume; this volume is appropriate for best performance. The primary source of OPGC fibre's toughening mechanism, especially in impact resistance, is the energy needed to de-bond, stretch, and pull out of fibres. Usually, this procedure starts and continues when concrete cracks appear. When randomly oriented fibres inside the concrete inhibit a microcracking process and limit the propagation of cracks, the strength and ductility of the concrete are immediately increased. Apart from analysing the internal mechanical action, comparing the failure mode of OPGC discs to that of NFROPGC discs sheds light on the effectiveness of natural fibres in OPGC. The OPGC discs were mainly damaged by the three-piece break, whereas the NFROPGC discs failed due to the formation of micro-cracks shown in Fig. 18. According to a report, unreinforced geopolymer concrete did not exhibit as much impact resistance as fibre-reinforced geopolymer concrete. This was brought about by fibre's ability to lessen crater damage, penetration depth, and crack propagation in geopolymer concrete [18]. In like manner, compared to ordinary two-part geopolymer concrete, Rayapudi & Rao [26] found that adding 2 % steel fibre increased the impact resistance strength of the steel fibre-reinforced two-part geopolymer concrete. Generally, two-part and one-part geopolymer concrete have enhanced impact resistance strength by incorporating fibre compared to plain geopolymer concrete, principally attributable to superior matrix-fibre bonding and a denser microstructure. However, one-part geopolymer concrete is safer and less harmful to work with than two-part geopolymer concrete [32].

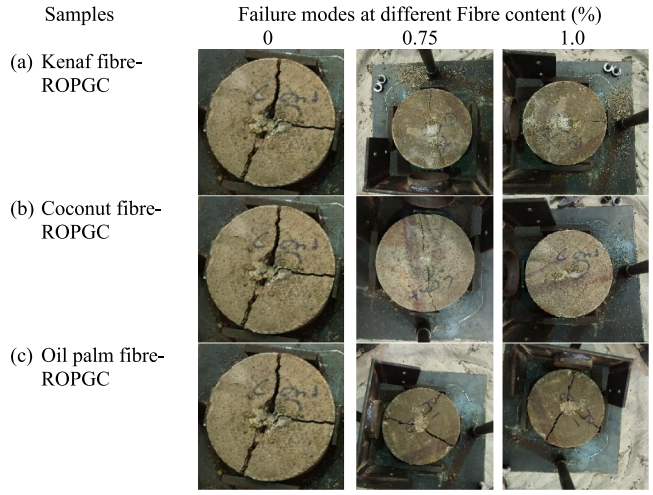


Fig. 18. Failure modes of samples after the impact resistance strength.

3.9. Effects of fibre types and volumes on MOE, Poisson's Ratio, UPV, and density of OPGC

The existing literature revealed that fibre increases the modulus of elasticity and lowers the Poisson ratio of concrete [10,19].The MOE increased from 37.77 GPa to 44.04 GPa, 37.77 GPa to 42.79 GPa, and 37.77 GPa to 39.61 GPa when 0.75 % of kenaf, coconut and oil palm fibres were added to one-part geopolymer concrete, respectively. However, when the fibre content was increased to 1 %, there were percentage reductions of 0.21 %, 5.53 %, and 23.25 in MOE for kenaf, coconut, and oil palm fibres, respectively. This is shown in Fig. 19. This is because the fibre addition lowers the transverse strain of the concrete. Notably, the proper amount and length of fibre used could reduce the strain on concrete [20]. It has been demonstrated that adding fibre very slightly improves the elastic modulus, with hybrid fibre samples showing the most significant gains [6].

In addition, the concrete Poisson's ratio is the lateral strain to axial strain ratio when an axial load is applied to a concrete specimen. It measures the amount the material expands or contracts transversely in reaction to a force. Fig. 20 shows a declining trend in the Poisson ratio of NFROPGC as the fibre content increased. When the fibre content rose from 0 % to 0.75 %, the Poisson ratio for KFROPGC, CFROPGC, and OFROPGC reduced by 16 %, 28 %, and 40 %, respectively. However, a higher reduction was observed when the fibre content increased from0.75 % to1 %. The Poisson's ratios for all the samples tested range from 0.13 to 0.25, however, the Poisson's ration for a typical concrete varied between 0.1 and 0.2, for a normal concrete 0.15 and 0.2, while for a high strength concrete 0.1 and 0.15. Previous research indicates that fibre decreased concrete's Poisson ratio [19].

Furthermore, the density and UPV of NFROPGC compared to the density of OPGC (control), the densities of KFROPGC, CFROPGC, and OFROPGC showed insignificant percentage reductions of 0.21 %, 1.92 %, and 2.96 % at 0.75 % and 2.14 %, 2.78 %, and 3.85 % at 1 % fibre inclusion, respectively. The total decrease in the dead load of concrete is the benefit of this. However, compared to CFROPGC and OFROPGC, KFROPGC preserves its properties over the specified range, indicating better material stability. Furthermore, at 0.75 % and 1 % fibre contents, KFROPGC outperformed CFROPGC and OFROPGC regarding UPV. It was observed that fibre inclusion reduces the UPV and density of geopolymer concrete [1].

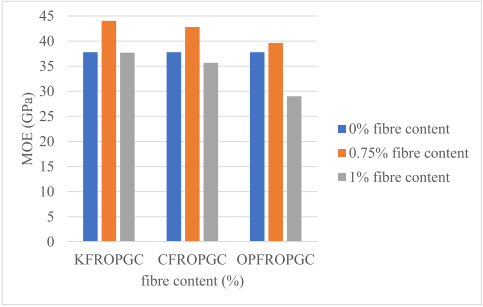


Fig. 19. MOE of geopolymer concrete of One-Part Geopolymer Concrete.

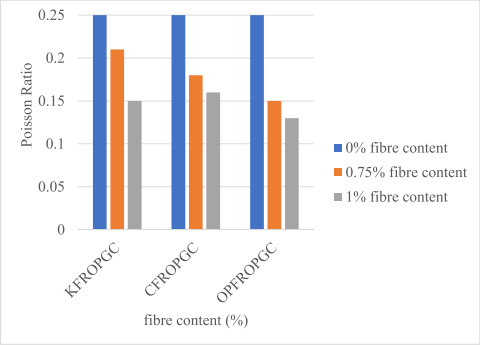


Fig. 20. Poisson ratio of one-part geopolymer concrete.

3.10. Empirical relationship between impact resistance strength, density and UPV of OPGC and NFROPGC

The UPV of concrete is directly correlated with its density. As the density of concrete increases, UPV likewise tends to increase. This is true because fewer voids, cracks, or discontinuities in denser concrete can slow down the ultrasonic pulse. The relationship between density and UPV is depicted in Fig. 21. The relationship between these values was determined, and this relationship is given in Eqs. 10, 11, and 12. In these Equations, *D*1, *D*2, and *D*3 represent densities for KFROPGC, CFROPGC, and OFROPGC, respectively, and *upv* is their ultrasonic pulse velocity with 0.9, 0.98, and 0.94 correlation coefficients, respectively.

$$D1 = 235.69upv + 1320.78.54 \quad (14)$$

$$D2 = 243.17upv + 1279.6 \quad (15)$$

$$D3 = 273.99upv + 1141.5 \quad (16)$$

Also, Density and impact resistance strength often have a positive connection, with higher density resulting in stronger impact resistance. Nevertheless, mix design, fibre content, and aggregate type affect the precise relationship. Therefore, it is crucial to experimentally ascertain the empirical constants for each unique situation. The relationship between impact resistance strength and density is shown in Fig. 22. This relationship is expressed in Eqs. 13, 14, and 15. In these Equations, *IRS*1, *IRS*2, and *IRS*3 represent impact resistance strength for KFROPGC, CFROPGC, and OFROPGC, respectively, and *d* is their corresponding density with 0.99, 0.58, and 0.51 correlation coefficients, respectively.

$$IRS1 = -59.104d + 140703 \quad (17)$$

$$IRS2 = -30.641d + 73807 \quad (18)$$

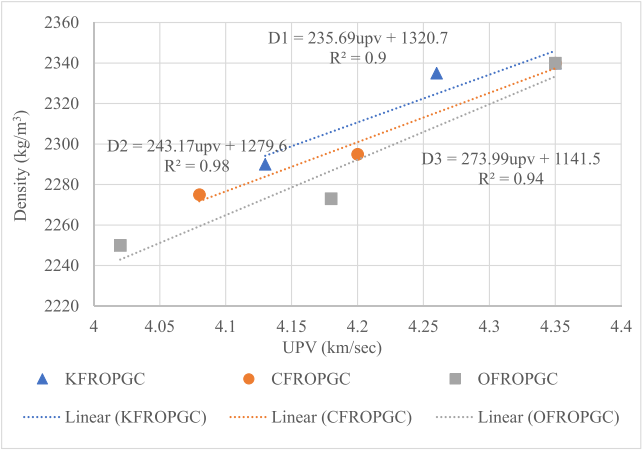


Fig. 21. Relationship between density and UPV of NFROPGC.

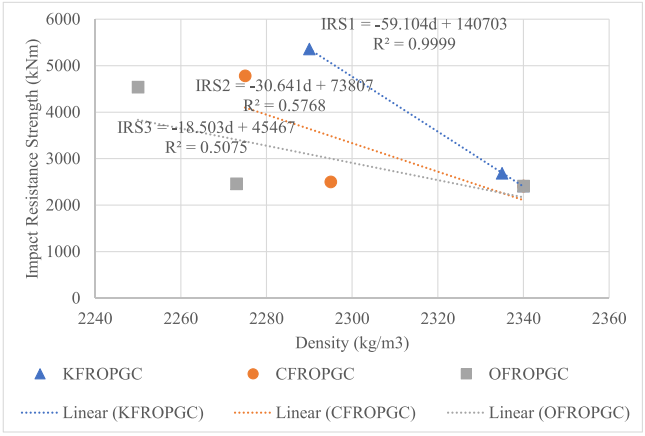


Fig. 22. Relationship between impact resistance strength and density of NFROPGC.

$$IRS3 = -18.503d + 45467 \quad (19)$$

Also, the experimental and empirical results for density and impact resistance strength were 2340 and 2345.25 kg/m^3, 2410.82 and 2399.64 kNm, respectively. They are relatively close to each other. The empirical results were obtained through the equations.

3.11. Scanning electron microscopy (SEM) on OPGC and NFROPGC

The images from the SEM of OPGC, KFROPGC, CFROPGC, and OFROPGC at 3000 magnifications were obtained at a working voltage of 20 kV. The production of dense homogeneous geopolymerization is confirmed by the microstructure of OPGC and NFROPGC, as examined by SEM examination and displayed in Fig. 23(a-e). The bonding between the components of geopolymer concrete is depicted in Fig. 23(a). Microvoids were found on the surface of OPGC, whereas well-bounded surfaces were found in KFROPGC, CFROPGC, and OFROPGC. These differences can be attributed to the fibres' presence and capacity to mix well with the geopolymer matrix. Zhao et al., [34]. Moreover, Fig. 23(b) depicts the OPGC surface's abundant voids and cracks. In this instance, fibres functioned as a crack bridge, stopping cracks from spreading in the geopolymer concrete. Aluko et al., [7]. The matrix's two source components needed to initiate the geopolymerization process are also visible in Fig. 23(c and d). Since no unreacted portions were visible, it is evident that the two elements interacted favourably within the matrix. Lastly, voids were visible on the surface of OPGC, whereas KFROPGC, CFROPGC, and OFROPGC had spaces filled with fibres, as shown in Fig. 23(e). In conclusion, as demonstrated by the SEM data, the significance of fibre inclusion in one-part geopolymer concrete cannot be overstated because it aids in halting the spread of cracks and filling voids [8]. The microstructures of fibre-reinforced one-part and two-part geopolymer concrete exhibit a denser and more cohesive composition, improving the link between fibres and the geopolymer matrix compared to the plain geopolymer matrix. On the other hand, working with one-part geopolymer concrete is less hazardous and safer than working with two-part geopolymer concrete [32].

4. Conclusions

The experimental investigation is conducted in this work to examine the engineering properties of one-part geopolymer concrete reinforced with natural fibres. One-part geopolymer concrete reinforced with natural fibres shows great promise as a mechanically improved and environmentally friendly building material. Several engineering qualities are enhanced by adding natural fibres, especially impact resistance, tensile strength, and flexural strength. Natural fibre-reinforced one-part

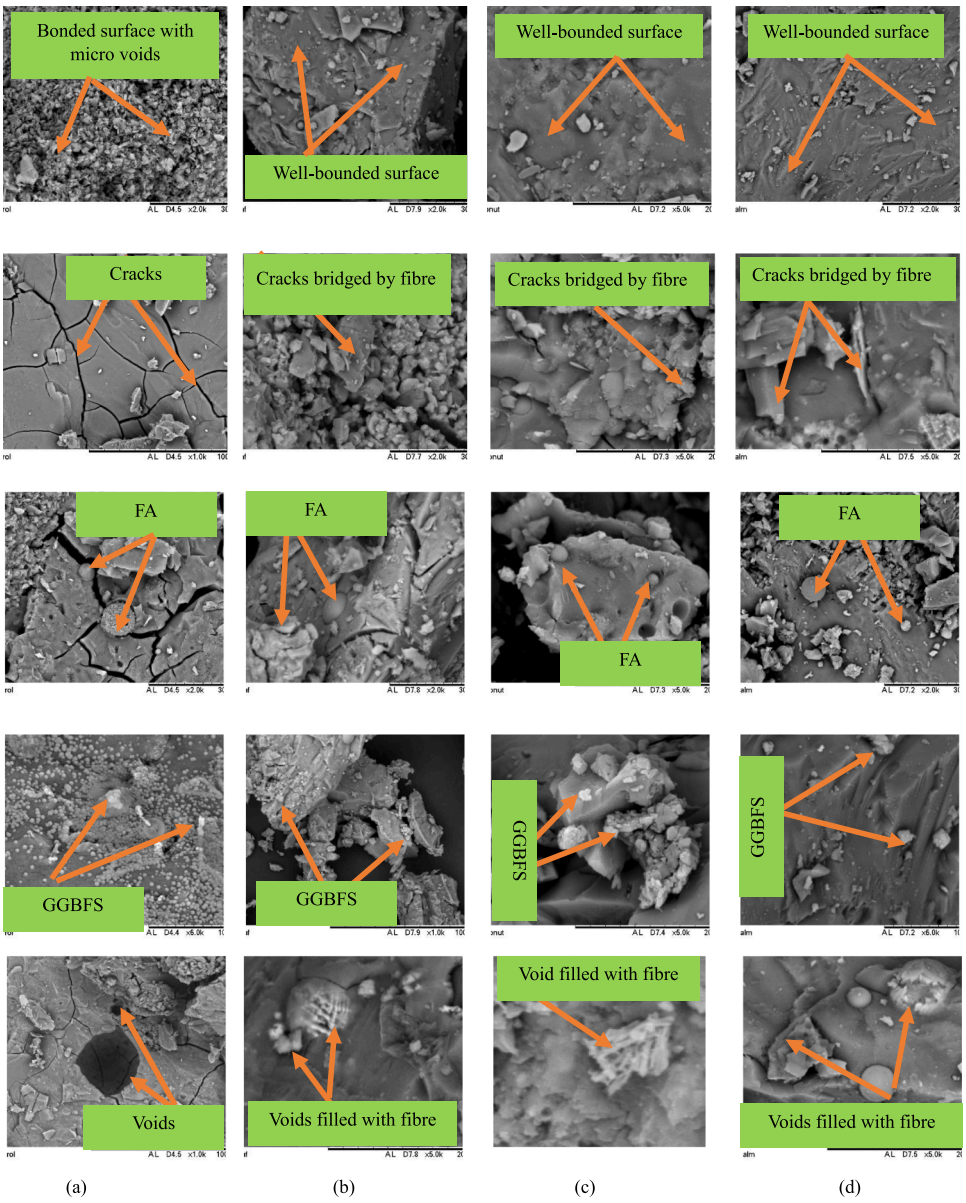


Fig. 23. OPGC/NFROPGC Morphology (a) OPGC (b) KFROPGC (c) CFROPGC (d) OFROPGC.

geopolymer concrete has the potential to be a competitive alternative for sustainable construction applications, offering improved performance and environmental advantages. From the analysis provided in this paper, the following conclusions can be made:

- It has been demonstrated that adding natural fibres to one-part geopolymer concrete enhances its mechanical qualities. In particular, because of the fibres' enhanced capacity for energy absorption and crack-bridging, adding fibres improves tensile strength, flexural strength, modulus of elasticity, and impact resistance strength. These improvements result in a less brittle geopolymer matrix and more ductile failure behaviour.
- Depending on the fibre's kind, length, and volume percentage, one-part geopolymer concrete reinforced with natural fibres may have different compressive strength, Poisson's ratio and workability. Although introducing fibres into the matrix causes a little drop in compressive strength, Poisson's ratio and workability, this effect can be minimized and, in some cases, even somewhat improved by improving fibre-matrix bonding through optimal selection and proportioning of fibres.
- One-part geopolymer concrete reinforced with natural fibres performs best when optimised fibre parameters such as length, type, and volume fraction. According to this study, 1 % fibre content produced the maximum impact resistance strength, whereas a moderate fibre content of 0.75 % produced the best flexural, split tensile strength, and MOE. Regarding fibre types, kenaf fibre produced the best results, followed by coconut and oil palm fibre.
- Furthermore, the production of dense homogeneous geopolymerization is confirmed by the microstructure of OPGC and NFROPGC, as examined by SEM examination. The SEM pictures demonstrate how well fibres fill voids and bridge cracks in one-part geopolymer concrete. Additionally, it demonstrates how well the fibre and geopolymer matrix are bonded.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr HASANAH reports financial support and equipment, drugs, or supplies were provided by University of Technology Malaysia. DR

HASANAH AND DR AYENI reports a relationship with University of Technology Malaysia that includes: employment. The authors state that no known competing financial interest or personal relationship may have influenced any work disclosed in this study.

If there are other authors, they 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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Authors' Contribution Statement

Nor Hasanah Abdul Shukor Lim, Ige Samuel Ayeni and Mostafa Samad conceptualized the study. Nor Hasanah Abdul Shukor Lim, Ige Samuel Ayeni and Mostafa Samad conducted the laboratory experiments. Ige Samuel Ayeni wrote the manuscript and conducted the data analysis, while Nor Hasanah Abdul Shukor Lim and Mostafa Samad handled the formatting, editing, and oversight. The authors concurred that the manuscript would be submitted.

Data availability

No data was used for the research described in the article.

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