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Fresh and Hardened Properties of Different Percentages of Hybrid Kenaf-Glass Fibres Reinforced Geopolymer Concrete under Ambient Curing Condition

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ABSTRACT

Geopolymer concrete (GPC) has become one of the alternative green materials to normal concrete due to its inherent advantages in minimizing carbon emissions for a sustainable environment. However, geopolymers have a brittle nature, hence integration of hybrid fibres in geopolymer concrete enhances its strength and ductility, mitigating fracture propagation. In this research, two types of fibres namely kenaf (KF) and glass fibres (GF) are hybrid to 1% of the total volume fraction added in fly Ash and GGBFS-based geopolymer concrete known as hybrid fibre-reinforced geopolymer concrete (HFGPC) with different percentages to identify the optimal percentage of the fibre mixture. The composite fresh and hard properties are determined from eight mixes to determine the workability, density, compressive strength and crack patterns. ANOVA was used to analyse the compressive strength results, indicating statistically significant enhancements in performance. The experimental results showed that the optimum HFGPC is 0.3KF-0.7GF mix achieved higher compressive strength characteristics around 51.2 MPa by 27% and 10.8% improvement compared with single KFs or GFs inclusion respectively. Moreover, increasing density and reducing crack propagation have been observed for the optimum hybrid mixture. This work provides insight into the performance of HFGPC, Promoting the utilization of sustainable construction materials in practical engineering.

1. Introduction

The term “Geopolymer” was introduced in 1978 by French Professor Davidovits. Davidovits suggested that waste materials like fly ash and slag that consist of aluminium (Al) and silicon (Si) as source materials can react with an alkaline to produce binder [1]. Geopolymer concrete (GPC) is a

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modern concrete that does not use any Portland cement as a binder. The total energy needed to produce FA-based GPC is around 60% less than that required to produce OPC and it releases at least 80% less CO2 [2]. Geopolymer is an eco-friendly material, fire-resistant, high strength, solves disposal problems, is a very economical material and is an alternative to Portland cement [3]. Despite all these features, geopolymers suffer from a brittle nature. Embedding fibres can reduce the brittleness of geopolymers by increasing the toughness of composites [4]. The concept of adding fibres to improve the brittle nature of geopolymer behaviour is one of the interesting topics.

Many researchers impart natural fibre into geopolymer concrete to improve the mechanical and other properties of the composite and prevent cracks from taking place in the matrix [5]. Several types of fibre, like synthetic and natural fibres, are commonly utilized in geopolymer technology [6,7]. Synthetic fibre possesses notable characteristics, including high tensile strength, a superior strength-to-weight ratio and fatigue stability [8]. Natural fibres are abundant in many nations and are renewable, inexpensive and biodegradable materials. Numerous efforts have been devoted to enhancing the ductility and toughness of GPC through the implementation of various types of short fibres [9].

Usually, fibre-reinforced geopolymer concrete uses a single type of fibre. Single fibres are only useful within a limited range of strain and crack spreading. Consequently, certain kinds of fibre can enhance either the strength or ductility of the composite. Steel, glass, polyvinyl alcohol and carbon fibres are examples of high-modulus and high-strength fibres that can effectively enhance the strength of geopolymer [10]. Nevertheless, their inherent brittleness limits the potential for significant enhancement in ductility. Fibres with low tensile strength, such as polypropylene, nylon and acrylic fibres, are more effective in enhancing ductility and minimizing cracking [11]. Therefore, mixing fibres with various chemical and mechanical characteristics is necessary for producing GPC that has greater strength and ductility. Incorporating more than one type of fibre in the right proportions can lead to enhancements in both the overall properties of concrete and the synergistic performance [12]. The integration of different types of fibres is often called hybridization [13].

Hence, in recent years, much investigation has focused on using various kinds of fibre in a geopolymer matrix to produce hybrid composites where the superior engineering characteristics of one fibre promote the flaws in the other type of fibre in the composite [12]. Hybridization enhances the mechanical characteristics of concrete and provides superior crack prevention compared to concrete reinforced with a single type of fibre. The combination of two distinguished fibres results in the formation of materials with unique characteristics [14,15].

Alwesabi *et al.,* [14] conducted research on steel-polypropylene hybrid fibre by incorporating different percentages of macro steel fibre (0%, 0.75, 0.825,0.9% and 1.0%) mixed with different percentages of polypropylene fibre (0%, 0.1%, 0.175, 0.25% and 1.0%) to determine the optimum hybrid mix. The results showed that the hybrid mixture of 0.1% PF-0.9% MSF has shown the most notable enhancement in compressive strength as density increases and water absorption and voids decrease compared with other mixes. Another study was conducted by Arunkumar *et al.,* [16] on HFGPC by using polypropylene and rubber fibres with the incorporation of different percentages of 0, 0.5%, 1%, 1.5% and 2% of volume fractions. The study reveals that the hybrid mixes of 0.5% PP and 0.5% rubber showed optimal performance in terms of mechanical strength and durability compared to other mixes. Hybrid fibres enhanced the workability and residual compressive and flexural strength properties of GPC mortars in compression for their single use. Another study reported that the inclusion of hybrid fibre Steel and basalt fibres in a geopolymer matrix with the appropriate percentage can improve the compressive strength, tensile strength and flexural properties. This is due to the implication of hybrid fibres, which prevent the diffusion of cracks. Moreover, the chopped basalt fibre's great strengthening capability with concrete [17].

Despite existing reviews on hybrid fibre-reinforced geopolymer concrete, there is a noticeable absence of incorporating different percentages of hybrid natural kenaf with synthetic glass fibre into geopolymer composites. Kenaf Fibres (KF) gained popularity among natural fibres, resulting in the adoption of kenaf as an industrial crop all over the world [18]. Kenaf fibre is extracted from the bast of the annual fast-growing plant called Hibiscus cannabinus [19]. Kenaf fibre possesses exceptional characteristics. The kenaf plant exhibits rapid growth, with a maturity period of 4-5 months enabling it to yield a substantial quantity within a short timeframe and low cost [20]. Abbas *et al.*, [21] carried out research on the incorporation of kenaf fibre within geopolymer composite with different lengths and volumes. It has been found that KF-incorporated geopolymer concrete can be used as an eco-friendly and sustainable building material. Despite the numerous advantages of using KF, they have a high-water demand and moisture absorption capacity, which must be addressed before they can be used in cementitious composites. Synthetic fibres worked along with natural fibres to overcome the obstacles faced by geopolymers. Generally, synthetic fibres are known to have higher tensile strength and modulus than natural fibres [22].

Most of the studies are on the hybridization of natural fibres with glass fibres (GF) to improve their properties [23]. Hence, the hybridization of natural fibre like kenaf with synthetic fibre like glass produces a method to improve the kenaf fibre composite and reduce the water absorption of kenaf fibre [24]. Glass fibre has distinguished properties such as high strength, low cost, control of shrinkage and cracking easily [25].

Incorporation of a 1% total volume fraction of hybrid glass fibre with steel fibre within geopolymer concrete. Great improvement in the achieved compressive, indirect tensile and flexural strength when compared to concrete without fibre [26]. However, the hybrid kenaf-glass fibre-reinforced geopolymer concrete with different percentages has not been studied previously. Therefore, this paper aims to determine the optimum hybrid kenaf-glass fibres-reinforced geopolymer concrete mix that can improve the properties of geopolymer concrete compared to individual fibres in terms of workability test, hard density and compressive strength with crack patterns of different percentages of HFGPC. ANOVA was used to analyse the compressive strength indicating statistically significant enhancements in performance.

2. Methodology

2.1 Materials

HFGPC mixes consist of binders like Fly ash class F (FA) and Ground granulated blast slag (GGBS), alkaline solution, fine and coarse aggregate, kenaf and glass fibres. Low calcium fly ash was obtained from (Green Cement Company, Malaysia) and occupied 60% of the total binder, which satisfied the ASTM C618 [27] requirements, while GGBS was obtained from YTL Cement and utilized as 40% of the binder [28]. The alkaline solution consists of sodium silicate and sodium hydroxide (97-98% purity) with 14 M construction and is prepared before 24 hours of mixing to be cool and obtained from the company BT Science Sdn. Bhd. Malaysia. Coarse and fine aggregates are used in producing geopolymer concrete. The river sand was tested for water absorption and specific gravity according to ASTM C128-07 [29] and sieved by ASTM C33-03 [30] to the standard specifications. The specific gravity is 2.52, with an average of 1.68 water absorption for fine aggregate. While the specific gravity is 2.65 with an average of 0.88 water absorption for coarse aggregate, the aggregates had a saturated, dry condition.

2.2 Fibres

Natural kenaf fibre (KF) and synthetic glass fibre (GF) were used as hybrid fibres in this research. KF were supplied from Lembaga Kenaf Dan Tembakau Negara (LKTN), Malaysia. The fibres were subjected to an alkaline treatment to enhance their properties before being used in the GPC. The fibres were immersed in 6% NaOH solution for 3 hours, then washed with water and immersed in the water for 24 hours. After 24 hours, the fibres were kept drying for 6 hours at the ambient temperature. The treatment was conducted by Ganesh *et al.,* [25]. After the treatment, the fibres were cut to a length of 30mm and added to the GPC mixtures [21,31]. GF was obtained from Chemrex Corporation Sdn Bhd Selangor, Malaysia, in length, cutting to 12 mm [32]. The diameter, tensile strength and density of KF and GF were measured and the results are shown in Table 1.

Table 1
Specification of the fibre

Fibre type	KF	GF
Colour	Light yellow	White
Length (mm)	30	12
Density (g/cm3)	1.4	2.6
Fibre diameter (mm)	0.056	0.03
Elastic modulus (GPa)	29	76
Tensile strength (MPa)	574	1273

2.3 Mix Proportion

The GPC mix proportions are shown in Table 2 and designed with optimum length and volume fractions of kenaf fibre (KF) according to Abbas *et al.,* [21] and optimum percentages of glass fibre according to Sathish Kumar *et al.,* [33]. Eight different HFGPC mixes were prepared. The optimum length of KF added to the GPC matrix was 30 mm with different percentages in hybrid composite and 12 mm length of GF with different percentages and 1% by volume with total volume fraction 1% to evaluate the optimum hybrid kenaf-glass percentages within geopolymer concrete mix. For all mixtures, the sodium silicate (SS) to sodium hydroxide (SH) ratio was set at 2.5.

Table 2
Mix proportions (Kg/m3)

Mix NO.	Mix ID	FA	GGBS	Aggregates		Solutions		SS/SH	M	KF	GF
				Sand	Gravel	SS	SH				
1	GPC-Control	216	174	704.7	1065.7	170.8	68.3	0.55	14	0	0
2	1KF	216	174	704.7	1065.7	170.8	68.3	0.55	14	14	0
3	1GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	0	26
4	0.9KF-0.1GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	12.6	2.6
5	0.7KF-0.3GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	9.8	7.8
6	0.5KF-0.5GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	7	13
7	0.3KF-0.7GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	4.2	18.2
8	0.1KF-0.9GF	216	174	704.7	1065.7	170.8	68.3	0.55	14	1.4	23.4

2.4 Mixing, Casting and Curing

In this work, the following steps must be followed before starting the casting process: To obtain a homogeneous mix, an alkaline solution should be prepared one day before the cast.

Firstly, the dry compounds, coarse and fine aggregates, were mixed for 3 minutes after selecting their proportion in the lab and then the fly ash and GGBS were added and mixed for another 3 minutes by using an electric mixer at a slow speed to prevent clumping. The alkaline solution should be added gradually to the dry compounds, then the hybrid fibres (kenaf and glass fibres) are added to the mixture in small batches after its treatment and cut to the appropriate lengths. The compounds were combined and mixed for five minutes, resulting in a homogeneous mixture of the geopolymer concrete and the Fibres. The moulds are Prepared by cleaning them and applying oil to the inner surfaces to prevent sticking. Finally, the mould was filled with the fresh mixture in three layers. To eliminate any air pockets within the mixture Each layer was compacted using a vibration table for 50 seconds. Three samples were prepared for each mix. The samples were cured for one day at ambient temperature (27 ± 1.5) ◦C and 75% relative humidity. The moulds were removed after a day and the specimens were left in the ambient condition until the test day. As illustrated in Figure 1.

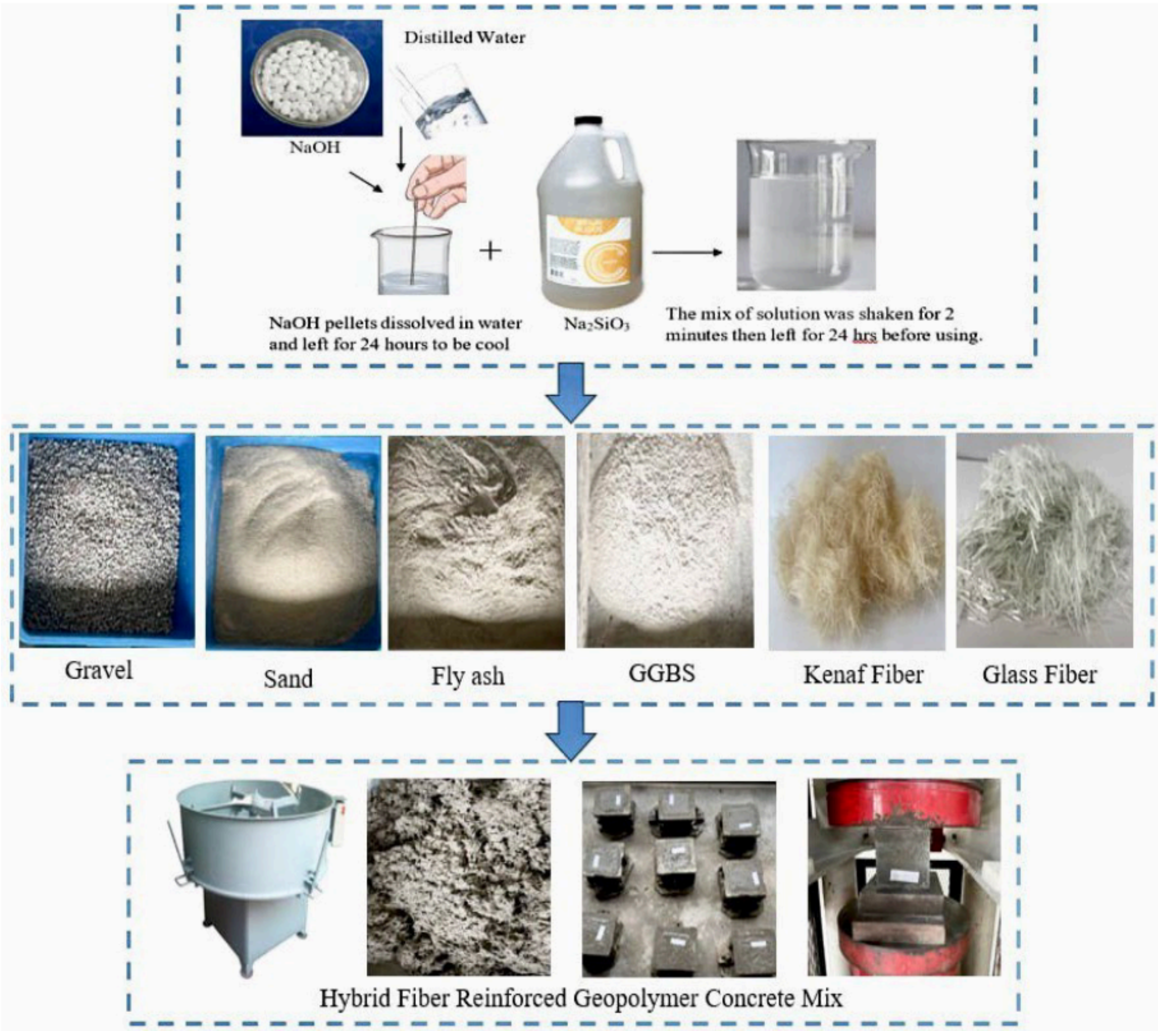

Fig. 1. Mixing procedure of HFGPC

3. Results

3.1 Fresh Properties (Workability)

The effect of different percentages of hybrid kenaf-glass fibre on the workability of geopolymer concrete was evaluated by the slump height. A total of 8 concrete mixes, including geopolymer concrete (GPC) without fibres as a control and seven others with a 1% volume fraction for single fibres and hybrid fibres as explained in Table 2. The slump attained of all mixes is shown in Figure 2. The addition of fibres has highly affected workability regardless of different fibre types, fibre geometry and fibre volume fraction [32]. The results showed that kenaf fibre has a greater effect on workability than glass fibre, with a slump height of around 35 mm for kenaf fibre and 48mm for glass fibre incorporated by 1% fibre content in geopolymer concrete. The HFGPC on the other hand, shows almost insignificant changes with different percentages of glass and kenaf fibres. All HFGPC attained approximately 28mm slump height. This low workability effect is due to the high surface area and the hydrophilic nature of kenaf fibre [21] and the poor water bonding strength of glass fibres. Besides, different fibre lengths in the hybrid lead to a balling of fibre-matrix in the composite, which allows a higher amount of air pockets to form inside the mixtures. The outcome of this study is in line with the findings of other studies by Bakthavatchalam *et al.,* [17], Guler *et al.,* [35] and Al-Baldawi *et al.,* [36]. The standard deviation of the slump presented in Figure 2 and Table 3 ranges from 1.41 to 4.25, indicating an acceptable level of variation within the dataset [37].

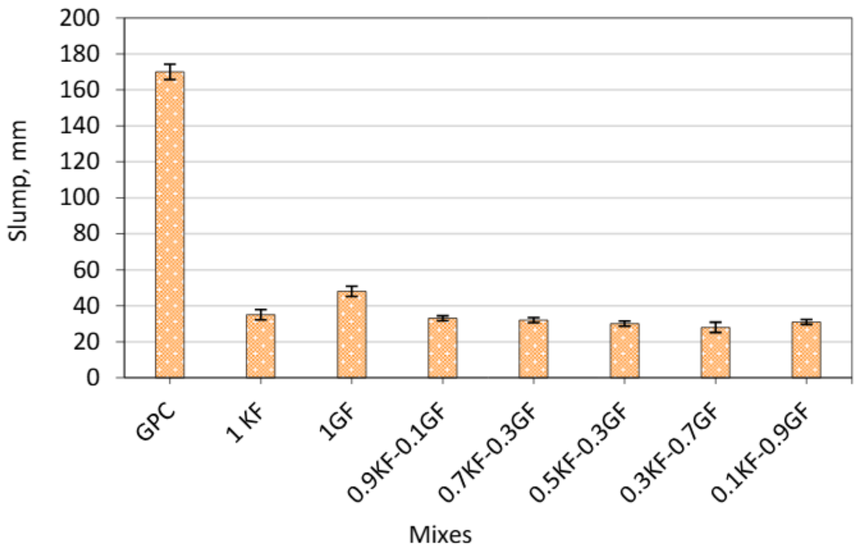

Fig. 2. The slump of HFGPC and standard deviation

3.2 Hard Density

The dry densities of geopolymer concrete with different percentages of HFGPC are shown in Figure 3 and in Table 3, where all mixes achieved normal concrete density. All mixes attained lower densities than control GPC and decreased with the incorporation of single and hybrid fibres due to an increase in porosity. Similar to workability, the addition of fibre increases air pockets in the composite and decreases the unit weight. However, by lowering percentages of kenaf fibre from 90% to 30%, the density increases to the maximum density of 2350kg/m^3. This is due to the better packing effect of glass fibres (2.6 g/cm^3) as its density is higher than kenaf fibres (1.4 g/cm^3). The standard deviation of the hard density presented in Figure 3 and Table 3 ranges from 2.65 to 6.08, indicating an acceptable level of variation within the dataset [37].

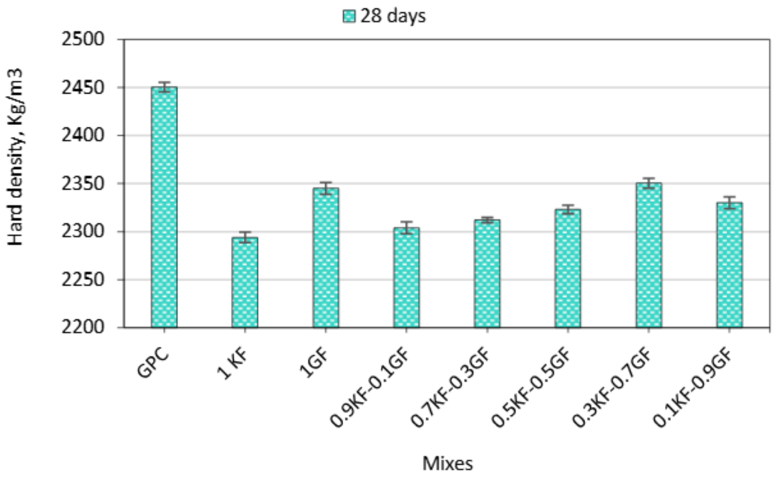

Fig. 3. Hard density of HFGPC and standard deviation

3.3 Compressive Strength

Compressive strength indicates the ability of concrete to restrain the load during its lifespan and is an indicator of the durability performance of concrete. The compressive strength at 7 and 28 days of eight mixes are shown in Table 3.

Table 3
Fresh and hard properties of HFGPC

Mix No.	Mix ID	Slump (mm± SD)	Hard density (Kg/m^3 ± SD)	Compressive strength (MPa ± SD)	
			28 days	7 days	28 days
1	GPC-Control	170 ± 4.24	2450 ± 5.03	42.9 ± 3.14	56.5 ± 1.61
2	1KF	35 ± 2.83	2294 ± 5.56	30 ± 2.29	40.3 ± 1.61
3	1GF	48 ± 2.83	2345 ± 6.08	37.7 ± 1.48	46.2 ± 1.25
4	0.9KF-0.1GF	33 ± 1.41	2304 ± 6.08	31.4 ± 1.8	41.5 ± 1.32
5	0.7KF-0.3GF	32 ± 1.41	2312 ± 2.65	31.9 ± 0.53	42.8 ± 0.87
6	0.5KF-0.5GF	30 ± 1.41	2323 ± 4.36	33.2 ± 1.3	43.7 ± 1.4
7	0.3KF-0.7GF	28 ± 2.83	2350 ± 5.13	38.7 ± 2.07	51.2 ± 2.8
8	0.1KF-0.9GF	31 ± 1.42	2330 ± 6.08	37.5 ± 3.13	45.9 ± 2.72

SD: Standard deviation

This is the average result of three repetitive samples. From the results, Figure 4 is drawn to ease the analysis. All mixes achieved the target strength of this study, which is 40 MPa at 28 days. Similar to concrete, the strength at 7 days is about 70-80% of 28 days. For single fibre, kenaf attained lesser strength than glass GPC due to its hydrophilic nature, which tends to absorb more water, causing more weak bonds and water saturated material within the composite [21]. Moreover, the ability of glass fibre to distribute homogeneously in the concrete mix and to be less agglomerated leads to better control of cracking and less void than kenaf fibre GPC. Similar to the density and workability, the HFGPC shows increasing strength as the percentages of Kenaf fibres decrease to 30%, but oppositely when it reaches 10%. The Incorporating fibres into geopolymer composites transforms the material from brittle to ductile due to the formation of bridges, leading to increased internal bonding in the composite [34]. The standard deviation of compressive strength illustrates in Figure 4 and Table 3, ranging from 0.87-2.8 MPa at 28 days and it considered in an acceptable range, the low standard deviation values recorded throughout testing indicated minimal variance in outcomes, hence demonstrating the reliability of the findings [38].

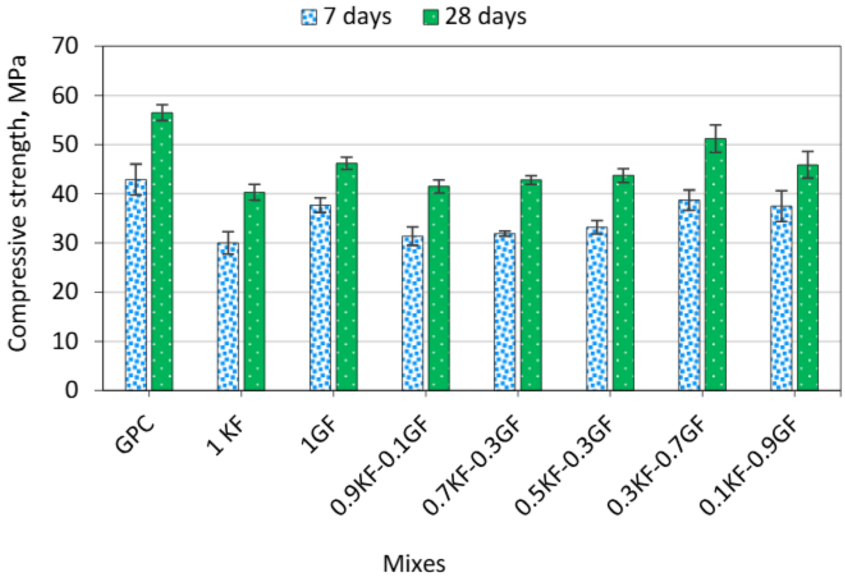

Fig. 4. Compressive strength of HFGPC and standard deviation

The hybrid mixes of 0.3KF-0.7GF exhibits the highest compressive strength among other hybrid mixes, which is less than the control sample by 10.4% and higher by 27% and 10.8% than single kenaf fibre and glass fibre, respectively, which is considered the optimum hybrid mix. Using different lengths of fibres in the composite provides a positive effect on the strength since the short length of glass fibre (12 mm) forms bridges, which increases bonding strength in the composite better against micro-cracks and prevents its diffusion at the initial loading stages, while the long length (30 mm) of kenaf fibre provides a better effect against macro-cracks at the final stage of loading [35]. This effect may be attributed to using more than one type of fibre at an appropriate length and percentages provide better results than using one type of fibre due to the stresses that transfer from one type to another and each fibre supports the obstacle of another type of fibre that provides better strength to the total composite [36].

Figure 5 illustrates a strong positive correlation ($R2$=0.8993) between compressive strength and density in hybrid fibre geopolymer concrete (HFGPC), indicating that 89.93% of the variance in density is accounted for by compressive strength. The regression equation (y=8.5699x+1944.2) indicates that for each 1 MPa increment in compressive strength, the density rises by approximately 8.57 kg/m^3. This tendency illustrates the significance of density in attaining elevated compressive strength, as denser mixtures generally exhibit fewer voids and superior particle packing. The little dispersion of data points indicates uniform behaviour, with the 0.3KF-0.7GF combination likely attaining the optimal balance of density and strength among fibre-reinforced mixtures. This highlights the function of hybrid fibres in improving both qualities, nearing the performance of the GPC control mix.

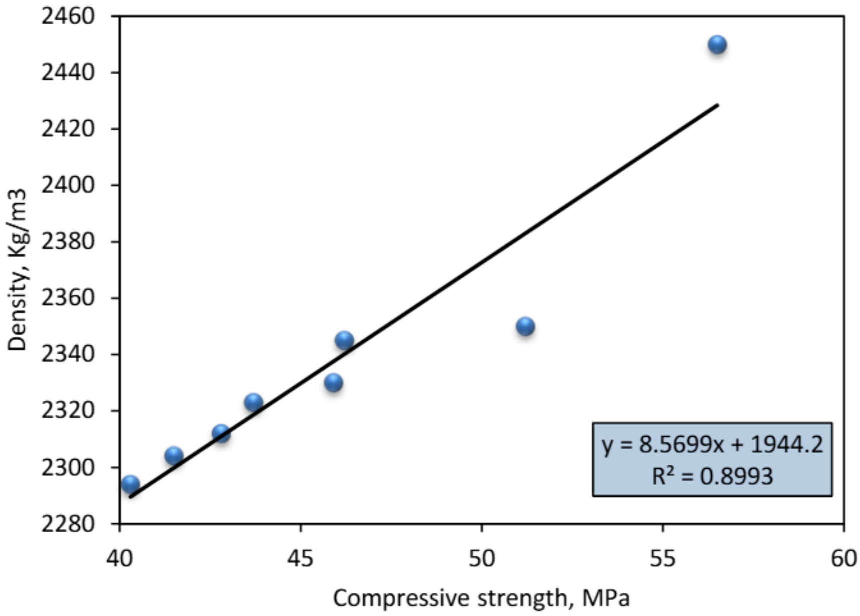

Fig. 1. Correlation between compressive strength and density of HFGPC

3.4 Crack Patterns

The crack pattern for HFGPC mixes is illustrated in Figure 6. The geopolymer concrete mix showed higher cracks compared with other mixes due to the brittle nature of the geopolymer compound. Incorporating single and hybrid fibre showed better effects against cracks compared to control. The incorporation of single kenaf and single glass fibre improved the brittle nature of geopolymer concrete and effectively decreased the cracks that happened under loading stages. The single kenaf and glass fibre decrease cracks, but only to a limited level. The hybrid fibres mix showed better crack control with fewer crack patterns with the least shown by HFGPC of 0.3 KF-0.7 GF. This witnesses the best composition of hybrid fibre mixes due to the short length of glass fibre (12 mm) effective in micro-cracks at early stage loading while the long length of kenaf fibre (30 mm) effective in macro-cracks at final stage loading.

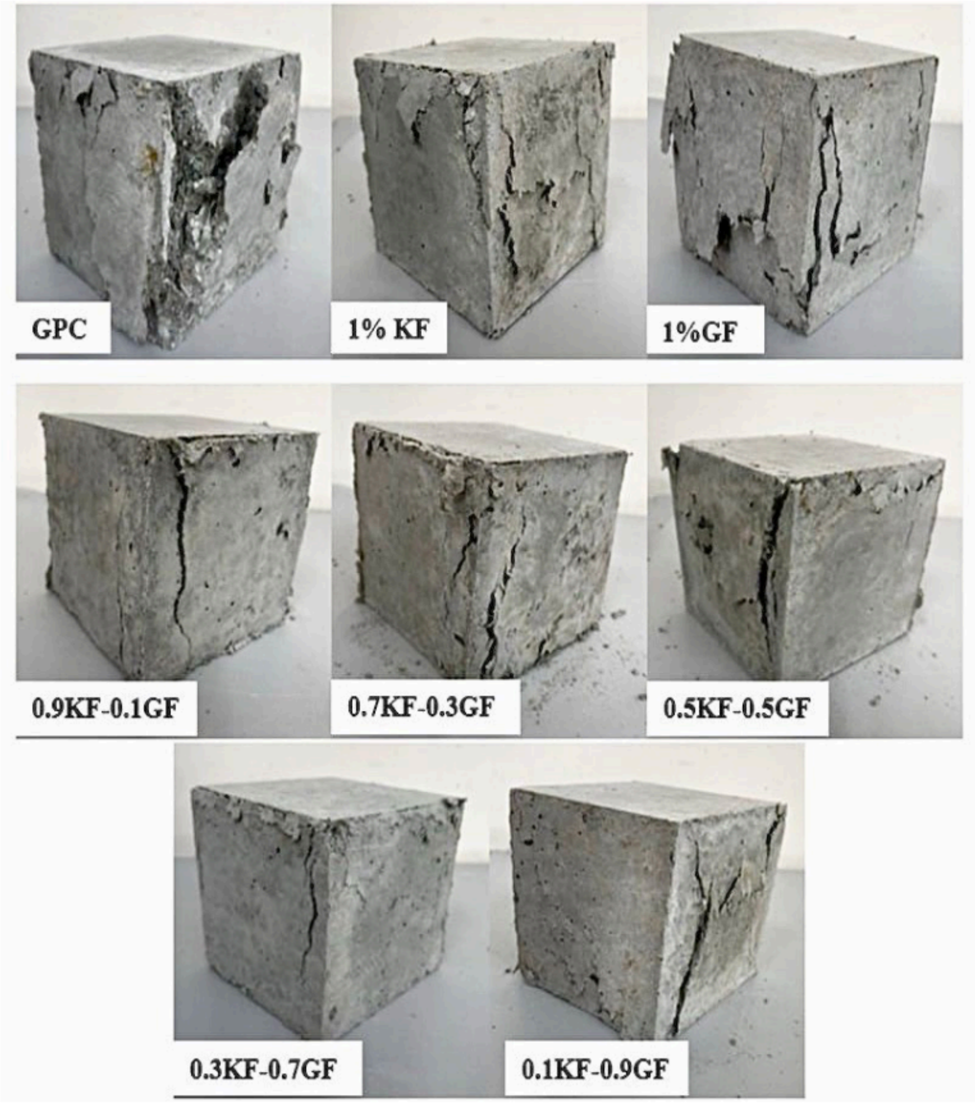

Fig. 6. Cracks pattern of different percentages of HFGPC

3.5 One-Way ANOVA Analysis

The analysis of variance (ANOVA) was performed to assess the significance of variations in the compressive strength characteristics of HFGPC mixtures at 28 days. The significance level was established at 95%, corresponding to a p-value of 0.05. Seven groups of HFGPC were evaluated. The results determined by ANOVA analysis of the compressive strength are illustrated in Table 4. In the ANOVA statistical test, if the P-value is below 5% within a 95% confidence range and the F-value is high, the differences among the results are considered very significant [39]. The P-value achieved in this study was 0.001 below 0.05, while the F value (F = 11.69719) was greater than the critical F value (Fcrit =2.84772)., signifying the test's substantial relevance. The created model effectively demonstrated its ability to elucidate the association between the significant components and responses.

Table 4
One way ANOVA results for compressive strength of HFGPC at 28-days

Groups	Count	Sum	Average	Variance		
1 KF	3	120.9	40.3	2.59		
1GF	3	138.6	46.2	1.57		
0.9KF-0.1GF	3	124.5	41.5	1.75		
0.7KF-0.3GF	3	128.4	42.8	0.76		
0.5KF-0.5GF	3	131.1	43.7	1.96		
0.3KF-0.7GF	3	153.6	51.2	7.87		
0.1KF-0.9GF	3	137.7	45.9	7.41		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	239.7257	6	39.95429	11.6972	0.0001	2.847726
Within Groups	47.82	14	3.415714			
Total	287.5457	20				

4. Conclusions

In conclusion, the incorporation of fibres in the geopolymer matrix decreased the workability properties of the composite to about four times the plain geopolymer concrete. This shows the fibre factors like fibre type, fibre length and fibre percentages are very critical in the workability of the mixture. On the other hand, even the density of HFGPC attained the normal concrete of about 2300kg/m3, it decreased with the incorporation of fibres due to an increase in the porosity of the composite due to fibre balling and bridging. The best compressive strength of HFGPC is obtained in 0.3KF-0.7GF mix of 51.2 MPa. This is higher by 27% and 10.8% than single kenaf fibre and glass fibre, respectively. The optimum 0.3KF-0.7GF mix also exhibits the least and the smallest cracks line on the sample. Furthermore, the one-way ANOVA analysis concludes that there are statistically significant differences in compressive strength among the seven groups. This is supported by the F-statistic (11.69719) being higher than the critical value (2.847726) and a p-value (0.0001) below the 0.05 significance level, signifying the test's substantial relevance. This optimization not only improves the performance of the material but also expands its usability in the construction industry, promoting the growth of more durable and sustainable buildings.

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