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Article

Effect of Hybrid Fibres on the Durability Characteristics of Ternary Blend Geopolymer Concrete

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Abstract: The need to develop sustainable concrete in the civil infrastructure industry increases day by day, resulting in new eco-friendly materials such as geopolymer concrete. Geopolymer concrete is one of the eminent alternatives to conventional concrete for sustainable development by reducing the carbon footprint. Ternary blend geopolymer concrete (TGPC) is a sustainable and environmentally friendly concrete produced with three different source materials to form a binder. The main advantage of TGPC is that it possesses densely packed particles of different shapes and sizes, which results in improved properties. This paper deals with the experimental investigations to evaluate the durability properties of plain and hybrid fibre reinforced TGPC. The durability of concrete is defined as the ability to withstand a safe level of serviceability and different environmental exposure conditions without any significant repair and rehabilitation throughout the service life. Conventional concrete is vulnerable to cracking due to its low tensile and durability properties. The TGPC considered in this work consists of fly ash, GGBS and metakaolin as source materials, selected mainly based on the material's silica and alumina content, shape, size, and availability. The grade of concrete considered was M55. The main variables considered in this study were the proportions of crimped steel fibres (V_f), viz., 0.5% and 1% and proportions of polypropylene fibres (V_p)viz., 0.1%, 0.15%, 0.20% and 0.25%. The durability properties like water absorption, sorptivity, resistance to marine attack, acid attack, sulphate attack, and abrasion were studied in this investigation. The experimental test results were compared with the requirements provided in the standard/literature and found to be well within limits. The study also indicates that the inclusion of fibres in a hybrid form significantly improves the durability parameters of TGPC. The TGPC with 1% steel fibre and 0.15% polypropylene fibre performs better than the other combination of fibres considered in this experimental investigation.

Keywords: abrasion resistance; acid attack; durability; geopolymer concrete; hybrid fibre; ternary blend; sorptivity

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1. Introduction

The main component of conventional concrete is ordinary Portland cement (OPC) and its production consumes a high amount of energy. In addition, during the cement manufacturing process, a large amount of greenhouse gases are released into the atmosphere that contributes to global warming [1–3]. In the future, geopolymer materials may be used as the best alternative for traditional cementitious concrete to reduce the carbon impact on the environment. The main component of the geopolymer concrete (GPC) is the source material rich in alumina and silica. The crust of the earth consists of more than 65% alumina and silica elements [4]. So, to reduce the emission of carbon dioxide due to cement production, it is essential to study how these elements can be effectively used as a binder to produce concrete. Nodehi and Taghvaee [5] carried out a detailed literature review about the challenges in finding OPC substitution. They reviewed different types, mechanisms, curing techniques, and results of mechanical and durability properties of GPC available in the literature. The properties of GPC are very much comparable to conventional concrete. The design standards available for the reinforced cement concrete can also be used for reinforced geopolymer concrete members [6]. GPC manufactured with industrial by-products such as fly ash, GGBS, silica fumes, etc., can result in high early strength, more significant economic benefits, less carbon dioxide emission, and improved service life [7,8]. Fly ash GPC possess high early strength and enhanced durability properties like reduced permeability, especially against aggressive environments [9]. Fly ash/GGBS based GPC has lower strength loss and mass loss than conventional cement concrete when exposed to an acidic environment and exhibits excellent freeze-thaw resistance and high-temperature resistance [10]. GPC produced with lightweight aggregates and recycled rubber or plastics using foaming techniques can result in better durability properties such as lower thermal conductivity and better mechanical properties for lightweight aggregate-based geopolymer [11]. Recent studies on the ultra-high performance and high-strength geopolymer concrete incorporating admixtures like silica fume, quartz sand, steel fibre, etc., exhibit better thermo-mechanical and durability properties than conventional concrete [12].

Durability is one of the critical parameters that directly relate to the service life of the structure. Concrete structures must ensure that they can withstand physical, mechanical, and chemical impact during their expected service life [13]. Even though plain concrete possesses many advantages, it still lacks essential characteristics like tensile strength. Fibre-reinforced concrete (FRC) has gained more importance in the last few decades to improve the tensile strength of concrete [14]. Many types of fibres and their effect on the mechanical properties of different types of concrete have been studied earlier [15–17]. The incorporation of fibres in hybrid form in concrete improves the performance of FRC to a great extent, controlling cracking at different levels of loading [18–23].

The feasibility of utilising three different waste materials, namely fly ash, GGBS, and metakaolin for the manufacturing of ternary blend geopolymer concrete (TGPC) and the effect of hybrid fibres on TGPC have been previously studied in terms of strength [8,24–26]. The GPC in this study consists of fly ash, GGBS, and metakaolin as raw materials to produce the ternary blend geopolymer-based binder. The ternary blend can result in denser concrete due to the different particle sizes of the source material, resulting in better durability life of the concrete. In this paper, the essential aspects of the durability of TGPC under different environmental conditions have been reported. The effect of hybrid fibres on the durability parameters of TGPC are also reported in this experimental investigation.

2. Experimental Programme

2.1. Materials and Mix Proportion

Low calcium Class F fly ash complying with IS 3812:2003 [27] collected from Mettur Thermal Power Station, Tamil Nadu, was used as the primary source material for the TGPC binder. The properties of fly ash are given in Table 1. GGBS conforming to BS 6699:1992 [28] procured from the local supplier was also included as source material. Table 1 shows the properties of GGBS. Metakaolin (MK) from a local supplier was also added for preparing the ternary blend source material. The MK properties are provided in Table 1. Crushed stone (M-sand) conforming to Zone II of IS 383:1970 (reaffirmed 2002) [29] was used as fine aggregate obtained from a local supplier with a maximum particle size of 4.75 mm. Crushed natural stone having a maximum size of 12.5 mm was used as a coarse aggregate. The properties of fine and coarse aggregate are given in Table 2. The alkaline activator with a combination of sodium hydroxide (NaOH) in pellet-form and sodium silicate solution (Na_2SiO_3) consists of 8% of Na_2O, 28% of SiO_2, and 64% of water by mass was used in this study. Conplast SP 430, a naphthalene-based admixture, was used for better workability. For the hybrid combination of fibres, crimped steel and polypropylene fibres were used in different volume proportions to find the effect in the durability characteristics of TGPC. The properties of fibres are shown in Table 3.

Table 1. Properties of fly ash, GGBS and metakaolin.

Oxides%/Properties	Fly Ash	GGBS	Metakaolin
Alumina, Al_2O_3	27.75	20.86	42.38
Silica, SiO_2	55.36	32.49	56.64
Iron oxide, Fe_2O_3	9.74	0.68	0.42
Titanium dioxide, TiO_2	3.54	-	0.1
Potassium oxide, K_2O	2.55	-	0.04
Calcium oxide, CaO	1.07	37.04	0.1
Magnesium oxide, MgO	-	7.82	0.2
Sulphur, S	-	0.98	-
Manganese, Mn	-	0.11	-
Chloride, Cl	-	0.012	-
Sodium oxide, NaO	-	-	0.11
Specific gravity	2.3	2.88	2.56
Average particle size	75 microns	30 microns	2–3 microns
Colour	Dark grey	Off-white	Creamish ivory

Table 2. Properties of aggregates.

Properties	Fine Aggregate	Coarse Aggregate
Specific gravity	2.39	2.79
Fineness modulus	2.92	6.79
Bulk density	1840 kg/m^3	1610 kg/m^3
Loose density	1720 kg/m^3	1450 kg/m^3
Water absorption	6.5%	1.67%
Percentage of voids	30.30%	32.30%

Table 3. Properties of fibres.

Properties	Steel Fibre	Polypropylene Fibre
Length	30 mm	12 mm
Diameter	0.45 mm	40 micron
Aspect ratio	66	300
Tensile strength	800 MPa	550–600 MPa
Density	7950 kg/m^3	950 kg/m^3

In the present investigation, the TGPC mix proportion was arrived at based on the recommendations given by Rangan [30]. The grade of concrete used in this study was M55. The optimum mix proportion for the present study was selected based on the variables like molarity of NaOH, alkaline activator to binder ratio, fly ash, GGBS, and metakaolin contents. The detailed analysis about the mix proportion carried out by the authors is presented elsewhere [24,25]. Thus, the TGPC with 60% fly ash, 25% GGBS and 15% MK with NaOH molarity of 14M. The alkaline activator to binder ratio was fixed at 0.3. For better workability, Superplasticizer dosage was considered as 1.5% of the weight of the binder and the additional water-to-binder ratio was kept constant at 0.2 for all the samples. The fibres were added to the mix in the hybrid form at different volume fractions. Table 4 shows the details of the mix proportions for TGPC.

Table 4. Mix proportions of Ternary blend geopolymer concrete.

Materials	Quantity (kg/m^3)
Fly ash	237.47
GGBS	122.61
Metakaolin	64.53
Coarse aggregate	1293.60
Fine aggregate	554.40
NaOH solution	36.40
Na_2SiO_3	90.99
Superplasticizer	6.37
Water	84.92

2.2. Mixing, Casting, and Curing Procedures

The dry ternary blend source materials were mixed in the laboratory using a drum-type horizontal mixer with the aggregates in saturated surface-dry condition [25]. The NaOH pellets were dissolved in water to make a 14M solution and added with Na_2SiO_3 solution to prepare the alkaline activator [24]. It is advised to prepare the alkaline activator solution 24 h prior to casting to ensure the reactivity of the activator [31]. The superplasticiser, water and the alkaline activator were added to the dry mix. The steel and polypropylene fibres were added at regular intervals as per the designed volume fractions [8]. The fresh concrete was poured into the mould in three layers and vibrated using a table vibrator. The moulds were then covered with a polythene sheet to avoid moisture loss. After 24 h, the test samples were shifted to the steam curing chamber and cured for another 24 h at 60 °C. The moulds were then removed, and the samples were left at ambient conditions for 28 days. The samples were prepared to study the durability properties like water absorption, sorptivity, abrasion resistance, acid attack, marine attack, and sulphate attack. The details of the samples for each test are given in Table 5. Three samples were tested for each mix proportion, and the average results were considered for the study.

Table 5. Details of samples.

Tests	Type of Samples	Size
Water absorption	Cube	100 mm
Sorptivity	Cylinder	150 mm dia × 50 mm
Abrasion resistance	Tiles	70.7 × 70.7 × 25 mm
Acid attack	Cube	100 mm
Marine attack	Cube	100 mm
Sulphate attack	Cube	100 mm

2.3. Test Methods

2.3.1. Water Absorption Test

Water absorption testing was carried out for the TGPC and hybrid fibre-reinforced ternary blend geopolymer concrete (TGPC) samples as per IS 2185 (Part 1):2005 [32]. The cubes were completely immersed in water for 24 h and weighed after wiping the excess water (W_1). Then the cubes were oven-dried at 100 °C for at least 24 h after which they were weighed two times successively at 2 h intervals and were found to be no more than 0.2 percent of their previous weight. This weight was taken as W_2. The water absorption is calculated using Equation (1).

$$\%\text{Water absorption} = \frac{W_1 - W_2}{W_2} \times 100 \tag{1}$$

2.3.2. Sorptivity Test

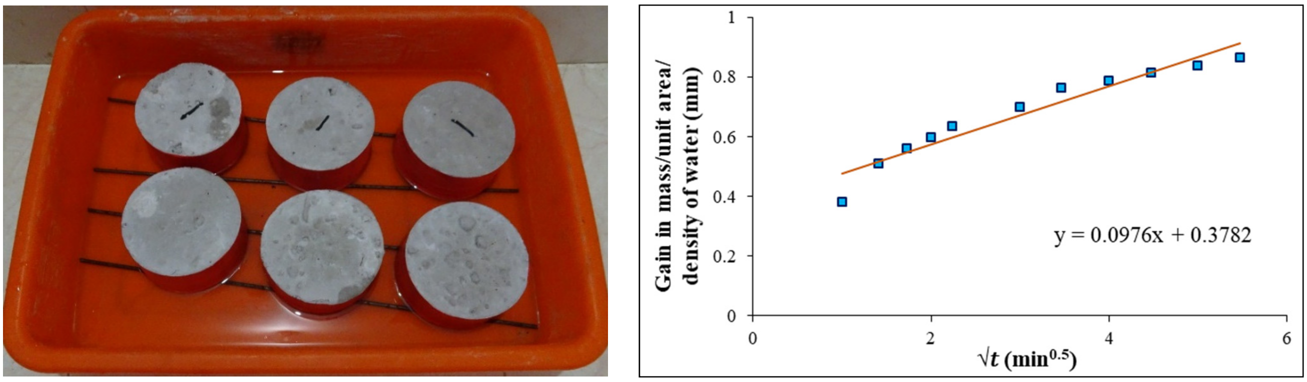
Sorptivity is a quantity that measures the capillary force exerted by the core structure in a concrete, causing fluid to be drawn into the body of the material. It is calculated as the rate of capillary rise absorption by a concrete sample with 2 to 5 mm submerged in water [33]. The relation between absorption and sorptivity for one-dimensional flow is given as,

$$i = S\sqrt{t} \tag{2}$$

where:

i—Cumulative water absorption per unit area of inflow surface
S—Sorptivity
t—elapsed time

The test was carried out on the samples according to ASTM C1585-2004 [34]. The samples were preconditioned at 50 °C in an oven for 7 days. After that, the samples were taken out and cooled to room temperature. The sides of the samples were sealed completely using insulation tape. The initial weight of the sample was noted and then placed in a tray such that 5–10 mm depth was immersed in water. The samples were placed over steel rods to ensure the unidirectional water flow, as shown in Figure 1a. At selected intervals (1, 2, 3, 4, 5, 9, 12, 16, 20, and 25 min), the samples were taken out from the water and weighed after the excess water was blotted off. Then the samples were again placed in the water. The gain in mass per unit area over the density of water versus the square root of time was plotted, as shown in Figure 1b. The slope of the line of best fit of these points (ignoring the origin) was reported as the sorptivity.



(**a**) (**b**)

Figure 1. (**a**) Sorptivity test setup; (**b**) Typical plots for sorptivity test.

2.3.3. Abrasion Resistance Test

The test was carried out according to IS 1237:2012 [35] to determine the effectiveness of TGPC and HTGPC in resisting abrasion. The tile samples were initially oven-dried for 24 h, weighed to the nearest 0.1 gm (W_3) using an electronic balance, and tested in an abrasion testing machine, shown in Figure 2. The grinding path of the testing machine was evenly strewn with 20 gm of abrasive powder. The tile was fixed in the holding device with the surface to be ground facing the disc and loaded at the centre with 30 kg weight. The grinding disc was then set into motion at a speed of 30 rpm. After every 22 revolutions, the disc was stopped, and the abraded powder was removed and replaced with fresh abrasive powder of 20 g. The sample was also turned about the vertical axis through an angle of 90° in a clockwise direction for every 22 revolutions. The process was repeated until 220 revolutions. After that, the specimens were weighed to the nearest 0.1 gm (W_4), and the average loss in thickness was calculated using Equation (3).

$$\text{Average loss in thickness} = \frac{W_3 - W_4}{W_3\ A} \times V_1 \tag{3}$$

where:

V_1—Initial volume of the sample
A—Surface area of the sample

Figure 2. Abrasion testing machine.

2.3.4. Acid Attack Test

The samples were tested to determine their effectiveness in an acidic environment. The samples were immersed in 3% Sulphuric acid (H_2SO_4) solution for 90 days [36,37]. The pH value of the acid solution was maintained at 0.3 throughout the test. After 90 days, the specimens were taken out of the solution, washed in running water, and kept in the atmosphere for two days to attain constant weight (W_6). The control specimens were immersed in ordinary tap water for 90 days and weighed after wiping the excess water (W_5). The percentage loss in weight and compressive strength were calculated using Equations (4) and (5).

$$\%\text{Loss in weight} = \frac{W_5 - W_6}{W_5} \times 100 \tag{4}$$

$$\%\text{Loss in compressive strength} = \frac{C_1 - C_2}{C_1} \times 100 \tag{5}$$

where:

C_1—Compressive strength of cube immersed in water
C_2—Compressive strength of cube immersed in sulphuric acid

2.3.5. Marine Attack Test

This test was conducted to study the effect of seawater on the durability of TGPC and HTGPC as per ASTM D1141-1998 (reapproved 2013) [38]. The samples were immersed in artificial marine water prepared in the laboratory for 90 days. After 90 days, the samples were taken out and dried for 24 h and the percentage reduction in compressive strength and mass were evaluated. The composition of marine water as per ASTM D1141-1998 (2013) [38] is given in Table 6. The chemicals in the required quantity given in Table 6 were dissolved in water and mixed thoroughly till all the chemicals were completely dissolved to simulate the artificial marine water.

Table 6. Composition of artificial marine water.

Composition	Concentration (g/lit)
Sodium chloride	24.53
Magnesium chloride	5.2
Sodium sulphate	4.09
Calcium chloride	1.16
Potassium chloride	0.695

2.3.6. Sulphate Attack Test

The cube samples were immersed in 3% Sodium sulphate (Na_2SO_4) solution for 90 days, and the pH value of the solution was maintained at 7.0 throughout the test [13]. After 90 days of immersion in sulphate solution, the samples were taken out, washed in running water, and kept for 2 days for constant weight. Then the specimens were weighed, and the percentage of loss in compressive strength and mass were calculated.

3. Test Results and Discussions

3.1. Water Absorption

The test results and the details of the samples are provided in Table 7. Figure 3 shows the results of the water absorption test. The figure shows that the maximum water absorption limit of TGPC is less than 2%, which is well below the permissible value of 10% for good concrete [33]. It can also be noted that the addition of hybrid fibres decreases water absorption in HTGPC samples. The water absorption property of the concrete was reduced gradually with the addition of hybrid fibres from 1.97% to 0.94%. The property was enhanced to the extent of 53% with the incorporation of hybrid fibres, and this shows that hybrid fibres reduced the capillary water absorption of the concrete [39,40]. The ability of highly fine particles of fly ash, GGBS, and MK to be located in close proximity to other ingredients, including fibres, makes the resultant matrix extremely dense. It is clear from the figure that the water absorption decreased with the increase in the fibre content up to 0.15% polypropylene and increased further with the addition of polypropylene fibres [41]. This may be due to the low degree of compaction at a higher level of fibre contents in the mixture [42]. The high fineness of the source materials also reduces the bleeding; therefore, no bleed-water was trapped beneath the coarse aggregate particle, and porosity gets reduced [43].

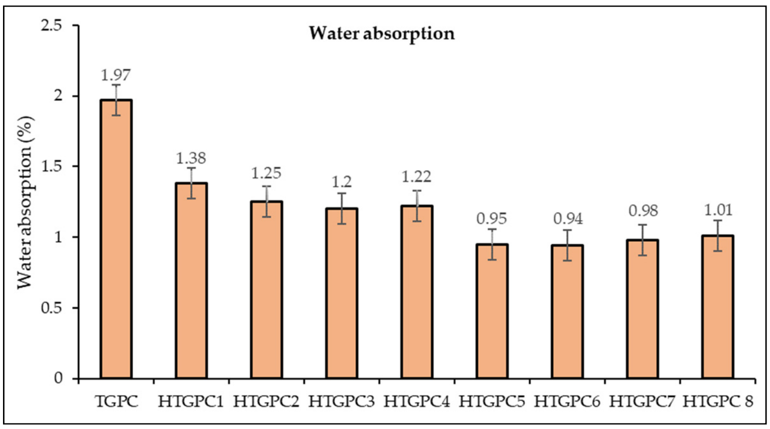


Figure 3. Water absorption test results.

3.2. Sorptivity

The results of the sorptivity test are given in Figure 4. It is clear from the figure that the values are well within the limits of 0.09–0.17 mm/min$^{0.5}$ for concrete [33]. The results clearly explain that the incorporation of hybrid fibres reduced the sorptivity value, which shows the improvement in the quality of the concrete [44]. In comparison with

TGPC samples, HTGPC gives lower sorptivity cofficients. This trend is in agreement with earlier studies using fibres to reduce concrete porosity [45,46]. The concrete samples containing 1% steel fibres and 0.15% polypropylene fibres gives the lowest sorptivity coefficient. The improvement of sorptivity is around 11% over the TGPC samples. The sorptivity value increases with the polypropylene content increase to 0.2%, which shows that the polypropylene fibres were not uniformly dispersed when more than 0.15% with a combination of 1% steel fibres were added [18,21,23]. From this test, it can be noted that the incorporation of hybrid fibres in TGPC exhibited a significant improvement in reducing the sorptivity coefficient.

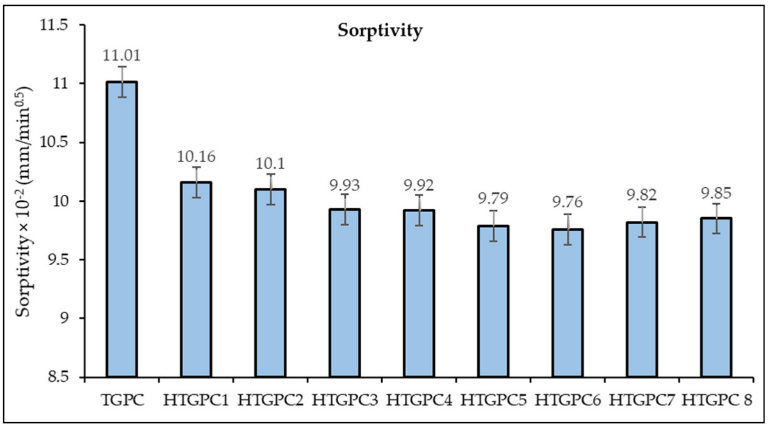


Figure 4. Sorptivity test results.

3.3. Abrasion Resistance

The test results are shown in Figure 5. The abrasion resistance of TGPC and HTGPC is less than the standard value of 2 mm for heavy-duty tiles [35]. This may be due to the uniform microstructure of the concrete and the excellent bond between the coarse aggregate and the matrix, which prevents the differential wear of the surface. Figure 6 shows the concrete surface of the sample tested in the abrasion testing machine. From the test results, it may be noted that the addition of hybrid fibres can strengthen the surface of HTGPC. It can be noted from Figure 5 that the wear value of HTGPC was reduced around 50% in comparison with concrete samples without fibres. The value of the wear is highly influenced by the steel fibres rather than the polypropylene fibres. This may be because the abrasive surface is not sufficiently high to wear the steel fibres in the concrete. The higher dosage of fibres results in the degradation of abrasion resistance due to the removal of fibres from the surface of the concrete [47,48]. The results also agree with the significant effect of the Na_2SiO_3 as an alkaline activator which improves abrasion resistance over that of conventional concrete [49,50].

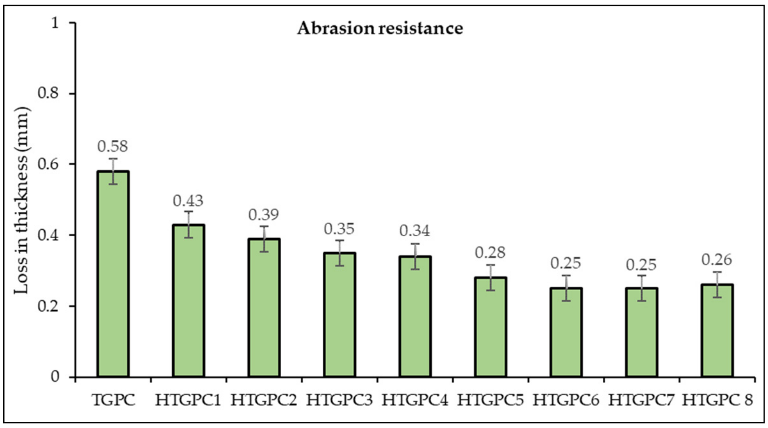


Figure 5. Abrasion resistance test results.

Figure 6. Concrete surface after abrasion resistance testing.

3.4. Acid Attack

Figure 7 shows the samples immersed in sulphuric acid. The initial stage to measure the deterioration due to acid attack is done by visual assessment through analysing the change in colour, deposition of additional components on the surface, surface cracks and spalling of samples [51]. The Samples were seen to remain structurally intact. The surface of the specimens became a little softer but could not be easily scratched with fingernails.

Figure 7. Samples immersed in sulphuric acid.

The loss in weight of the samples due to sulphuric acid attack is shown in Figure 8. The loss in mass of the HTGPC sample was lower than the TGPC. The rate of deterioration is comparatively high for the TGPC without fibres in the acid solution but well within limits. This may be due to the lower concentration of reactive compounds, which slow down the degradation process more than with conventional concrete [51]. The samples with minimal weight reduction values were those with 1% steel fibre and 0.2% polypropylene fibres, indicating that fibre hybridisation is possible for all environment exposure conditions. The samples without fibres exhibit the highest weight reduction, proving that fibres contribute to the durability of concrete in an acidic environment [52].

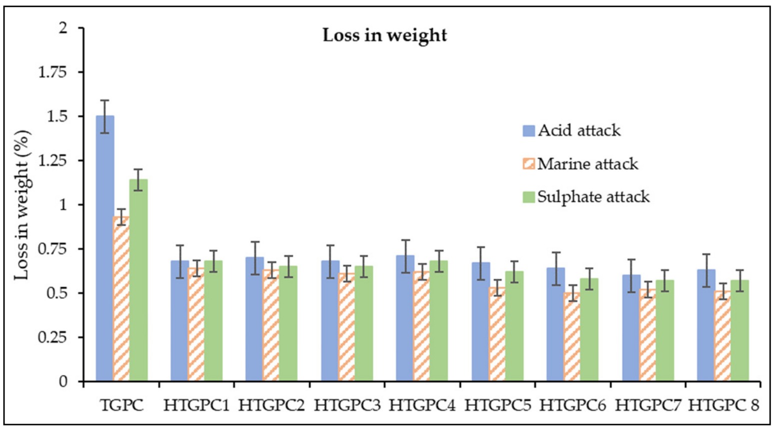


Figure 8. %Loss in weight of concrete samples.

Figure 9 shows the loss in compressive strength due to acid attack. The immersion in the acid medium results in the strength reduction for all the concrete samples. It was observed that as the hybrid fibre content increases, the loss in compressive strength reduces significantly. However, the rate of strength degradation was high in the case of TGPC samples without fibres. When comparing with TGPC samples, the HTGPC samples with 0.5% steel fibres shows around 25% less strength degradation, while the samples with 1% steel fibres show around 35% less degradation. The improvement in the strength loss may be due to the combined effect of the hybrid fibres and source materials with different particle sizes resulted in a denser concrete medium [53].

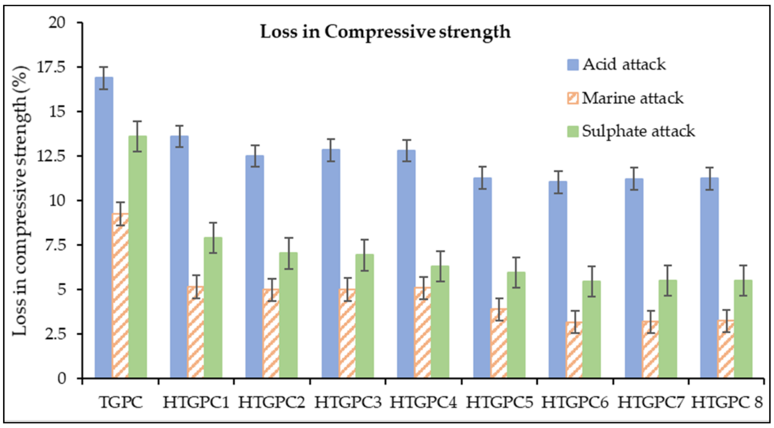


Figure 9. %Loss in compressive strength of concrete samples.

3.5. Marine Attack

The samples immersed in artificial marine water are shown in Figure 10. The percentage of loss was lower when compared with the acid attack test results, which may occur due to the reactive nature of the acidic environment over the chloride environment. It may be noted from Figure 10 that the specimens did not show any changes in shape and remained structurally intact without visible cracks. White precipitates were visible on the exposed surface. Figures 8 and 9 show the loss in weight and compressive strength for the TGPC and HTGPC samples in the marine environment. The loss of weight due to the marine water was improved up to 47% with the incorporation of hybrid fibres, whereas the loss in compressive strength was improved by 66%. The loss in mass and compressive strength of HTGPC was lower than the TGPC, which is similar to the sample treated in the acid environment [44,52].

Figure 10. Samples immersed in artificial marine water.

3.6. Sulphate Attack

Figure 11 shows the samples immersed in a sulphate solution. From the figure, it is clear that the samples remained structurally intact and did not exhibit any noticeable sign of deterioration. This may be due to the low calcium content in the source material, which causes the disintegration of concrete [54]. The loss in weight and compressive strength results are shown in Table 7. As observed earlier, the loss in weight and compressive strength was much lower than the TGPC without fibres. The trend in the loss is similar to the concrete samples immersed in acid and marine environments. The loss in mass and compressive strength of HTGPC was lowered by 50% and 60% compare with TGPC samples.

Figure 11. Samples immersed in sulphate solution.

From the test results, it is clear that incorporating hybrid fibres highly controls the durability characteristics of TGPC. The cracking process of HTGPC is entirely different from the samples without fibres, so the deterioration process is also not the same [55,56]. This shows that the durability properties of TGPC are mainly influenced by the presence of cracks. The ability of the hybrid fibres to arrest the micro-cracks in the concrete and fibre-matrix interface may play a vital role in the durability of TGPC.

Table 7. Durability test results.

Sample	V_f	V_p	Water Absorpt.	Sorptivity $\times 10^{-2}$	Loss in Thickness	Acid Attack		Marine Attack		Sulphate Attack	
	(%)	(%)	(%)	(mm/min$^{0.5}$)	(mm)	%Wt. Loss	%Loss in Strength	%Wt. Loss	%Loss in Strength	%Wt. Loss	%Loss in Strength
TGPC	0	0	1.97	11.01	0.58	1.50	16.9	0.93	9.27	1.14	13.61
HTGPC1	0	0.1	1.38	10.16	0.43	0.68	13.62	0.64	5.17	0.68	7.93
HTGPC2		0.15	1.25	10.10	0.39	0.70	12.52	0.63	5.00	0.65	7.04
HTGPC3		0.2	1.20	9.93	0.35	0.68	12.84	0.61	5.02	0.65	6.94
HTGPC4		0.25	1.22	9.92	0.34	0.71	12.82	0.62	5.10	0.68	6.30
HTGPC5	1	0.1	0.95	9.79	0.28	0.67	11.28	0.53	3.89	0.62	5.98
HTGPC6		0.15	0.94	9.76	0.25	0.64	11.05	0.50	3.18	0.58	5.48
HTGPC7		0.2	0.98	9.82	0.25	0.60	11.23	0.52	3.20	0.57	5.50
HTGPC8		0.25	1.01	9.85	0.26	0.63	11.25	0.51	3.25	0.57	5.52

4. Conclusions

Based on the experimental results, the following conclusions may be derived on the durability characteristics of hybrid fibre-reinforced ternary blend geopolymer concrete.

1. The water absorption values of TGPC and HTGPC were less than 10%, which is well below the mentioned value in the standards. The water absorption property was improved by 53% with the addition of hybrid fibres.
2. Sorptivity test results of TGPC and HTGPC indicate that the capillary pressure exerted by the pore structure is considerably less. The maximum improvement in the sorptivity was around 11% with the addition of hybrid fibres.
3. The abrasion resistance of TGPC and HTGPC is less than the limiting value of 2 mm for heavy-duty floor tiles, and hence the concrete can be used for highways, runways, etc. The abrasion resistance was improved by 55% with the addition of 1% steel fibres and 40% with 0.5% steel fibres.
4. The results for the chemical attack show that HTGPC samples were more resistant than the TGPC. Results of loss in weight and compressive strength imply that HTGPC with 1% steel fibres performed better in all the cases.
5. The TGPC samples with and without hybrid fibres convincingly met all the durability expectations considered in this study. The combination of 1% steel fibres and 0.15% polypropylene fibres exhibits better durability behaviour than the other mix

proportions considered in this study. The results also confirmed that the durability properties are highly significant with the steel fibres rather than the polypropylene fibres used in this study.

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