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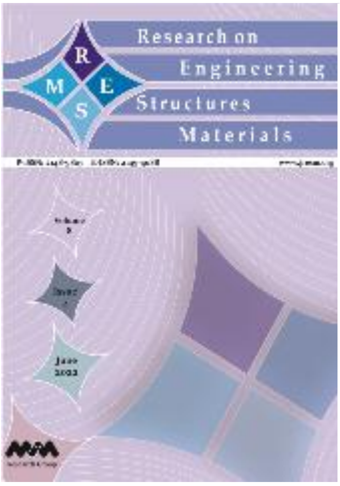

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Research Article

Optimization of hybrid fibre reinforced geopolymer concrete using hardened and durability properties

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Abstract

Geopolymer concrete is the finest replacement to ordinary portland cement concrete, reducing greenhouse gas emissions in cement production. Most of the binders used in geopolymer concrete require high alkaline solution, high-temperature curing, and a prolonged time for setting. In this study, wood ash, which has an alkaline compound in its composition, is used to replace fly ash. The binder ratio is fixed as 70 percent of fly ash and 30 percent of wood ash. Meanwhile, geopolymer concrete lacks brittleness, energy absorption, and impact strength. The addition of fibres is helped in improving the above-mentioned properties. This study has made an effort to incorporate waste rubber as fibre combined with polypropylene fibre. The various dosage of polypropylene and rubber fibre hybridization such as 0/1, 0.75/0.25, 0.5/0.5, 0.25/0.75, 1/0, and 1/1 is optimized. The impact of various fibre dosages on fresh and hardened characteristics of geopolymer concrete is assessed. Further, the impact of various hybrid fibre dosages on durability was also investigated in this study. As a result, the hybrid fibre dosage of 0.5 percent of PP and 0.5 percent of rubber attained significant performance in all hardened properties. The optimum mix also showed better resistance against all durability properties. The mix with 0.5PP/0.5R gained the maximum compressive strength of 47.30Mpa, which is sufficient to design the paver block for medium traffic conditions as per IS15658-2006.

1. Introduction

Climate change [1,2] due to cement production and energy utilization for production has increased every day. Geopolymer concrete is the growing trend in the construction field, which could help for sustainable development by eliminating cement utilization in concrete and mitigating climate change [3–7]. Geopolymer concrete is made by the chemical reaction of precursors from the aluminosilicate binder with the aid of alkalines and the formation of monomers to develop polymerization, which could create polymerized gel structure for binding [8]. Various industries are producing different waste by-products such as metakaolin, silica fume, granulated blast furnace slag, fly ash, pulverized fuel ash, etc., [9], which can be used in the geopolymer concrete as an aluminosilicate binder [10–15]. The GGBS is a very good precursor. In the alkaline environment, pozzolanic powders (GGBS, metakaolin, silica fume, fly ash, etc.) enter into a chemical reaction [16]. Alkaline activators played a vital role in the chemical reaction of the precursors from the by-products and developing monomers [17,18]. Both hydroxide-based activators and silicate-based activators are needed to promote polymerization. The formation of gel structures has based on the compositions of the aluminosilicate binders and the type of the activator used, such

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as sodium-based activators and potassium-based activators. The waste byproduct which contains less calcium has developed Na-S-H (Sodium Silicate Hydrate) gel, and the high calcium source material produces both the Na-S-H gel and C-A-S-H (Calcium Alumino Silicate Hydrate) gel [19–21]. At the same time, the utilization of potassium-based activators leads to the formation of Potassium Silicate Hydrate (K-S-H) gel [22,23]. The various modes of gel formation are the reasons for achieving strength in geopolymer concrete. However, the geopolymer concrete made with any source material lacked brittleness, impact strength, and energy absorption capacity. Hence, the inclusion of fiber is required to expand the brittle, energy absorption, and impact behavior of geopolymer.

The various studies [24–28] on geopolymer concrete by incorporating different types of fibres and their impact on the strength properties are considered in this study. The utilization of coir fiber in geopolymer concrete enhanced the compressive strength and reduced the flexural strength. The incorporation of raffia fibers in geopolymer concrete decreased both the compressive and flexural strength. The addition of cotton and sisal fibers in geopolymer concrete increased the compressive strength to 28.42 MPa and 25.56 MPa from 24.78 MPa of the control specimen. The bond between fibers (cotton, coir, raffia) and the matrix is weak without any cohesiveness, causing negative impacts over the mechanical properties and inducing the failure pattern [29]. The utilization of steel fibre in geopolymer concrete reduces the workability and provides less crack propagation resistance [26]. Steel fibre addition leads to corrosion failure. Glass fibre decreases workability and provides less crack propagation resistance. Polypropylene fibre increases the first crack load and gives more bonding effect in the concrete structure due to its high aspect ratio and the surface texture [30]. The addition of polypropylene fibre does not influence in increasing the compressive strength. However, polypropylene increases the flexural strength (13 to 36.1 percent) and toughness, and it helps in limiting shrinkage deformation. Capillary pores are reduced by increasing the polypropylene content in geopolymer concrete [31]. Polypropylene fibre increases the ductility of geopolymer concrete and reduces the degree of compressibility and shrinkage ratio. Crack width expansion and propagation resistance is increased with the addition of polypropylene fibres [32,33]. PP fibre addition reduced the ITZ width. However, the improvement in energy absorption and impact energy due to the polypropylene fibre incorporation is insufficient to design the structural member as impact resistance and heavy load members.

Various studies [34–37] were done on the various properties of rubberized geopolymer concrete. The addition of rubber fibre decreased the compressive strength due to lesser bonding between rubber particles and increased the flexural strength and splitting tensile strength. In contrast, an increase in rubber fibre increases the ductility of concrete and reduces the brittleness of concrete [38]. The rubber fibre increases the impact strength and energy absorption capacity of concrete due to its retaining effect on the plastic state [39]. The rubber fibres are incorporated as a replacement for fine aggregate only. A smaller volume fraction of rubber fibre helps limit the decrease in compressive strength [40]. The addition of rubber as a fibre with a smaller volume fraction in GPC has not been carried out. Incorporation of individual fibre led to enlarge the convenient characterstics of concrete to certain limit. Hybridization of two or more fibres exhibits improvements in all properties of concrete due to the fact that each fibre has its own properties [32]. The novelty of the study is to utilize the waste rubber as a fibre in smaller volume fractions and hybridization of both the fibres. Hence, an effort has been made by hybridizing polypropylene and rubber fibres to the effects of hybrid fibre on the properties of geopolymer concrete is studied.

In this study, the optimization of hybrid fibre dosage of polypropylene fibre and rubber fibre is done by mechanical and durability properties. Further, the effect of various hybrid fibre dosages on the mechanical and durability properties of geopolymer concrete is investigated.

2. Materials and Methodology

This study uses the smooth, ultra-fine and spherical shape Fly Ash (FA) as a primary binder [41]. The fly ash is obtained from the Tuticorin thermal power station. The FA used in this study has a specific gravity of 2.82, a loss of ignition (LOI) of 1.79 percent, and a surface area of 325 m^2/kg. Wood Ash is a secondary binder, a waste by-product collected from small-scale industries and hotels [42]. The wood ash is sieved through 90μm to remove large agglomerate fragments and carbonaceous components. The surface area and specific gravity of wood ash are determined as 567 m^2/kg and 2.43. The sodium-based activators such as sodium hydroxide and sodium silicate are used in this study as alkaline activators. Natural river sand having a specific gravity of 2.62, and the particles passing on a 4.75mm sieve are used in this study. Local quarry coarse aggregate having a specific gravity of 2.89 and the size of 10mm is used. The fineness modulus of fine and coarse aggregates are 2.91 and 7.6. The short and discontinuous polypropylene fibre having a length of 24 mm and diameter of 0.3 mm is used in this study. The waste rubber tire is collected from the mechanical workshops and cut into pieces of size 20 mm in length and 0.3 mm in diameter. Table 1 represents the chemical compounds present in the fly ash and wood ash which is found using SEM-EDX analyzer.

Table 1**.** Chemical compositions of binders

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	C	Others
Fly Ash	45.2	31.8	12.4	2.84	0.83	0.45	-	-	1.01
Wood Ash	47.56	20.32	2.22	3.61	3.02	14.49	1.01	10.22	3.98

Table 2. Mix proportions for various hybrid dosages

MIX ID	FA (kg/ m^3)	WA (kg/ m^3)	NaOH (kg/m^3)	Na_2SiO_3 (kg/m^3)	Sand (kg/m^3)	CA (kg/m^3)	PPF (kg/ m^3)	RF (kg/m^3)
GW30M10C	385	96.3	61.9	154.7	666.5	993.7	0	0
GW30M10CP2	385	96.3	61.9	154.7	666.5	993.7	4.82	0
GW30M10CHy1	385	96.3	61.9	154.7	666.5	993.7	3.61	1.21
GW30M10CHy2	385	96.3	61.9	154.7	666.5	993.7	2.41	2.41
GW30M10CHy3	385	96.3	61.9	154.7	666.5	993.7	1.21	3.61
GW30M10CHy4	385	96.3	61.9	154.7	666.5	993.7	4.82	4.82
GW30M10CR2	385	96.3	61.9	154.7	666.5	993.7	0	4.82

*FA-Fly Ash, WA-Wood Ash, CA-Coarse Aggregate, PPF-Polypropylene Fibre, RF-Rubber Fibre

The mix design is done using the modified guidelines for geopolymer concrete mix design as per IS 10262-2009 [43]. From the mix design, the material quantities are calculated and listed in Table 2. The optimization of binder ratio was already done in the author's previous study [44], hence the optimum binder ratio was taken as 70 percent of fly ash and 30 percent of wood ash. The molarity of the sodium hydroxide, NaOH to Na_2SiO_3 ratio, and the Alkaline solution to Binder ratio are taken from the author's previous study [10] as 10M, 1:2.5, and 0.45. For the hybridization of fibres, both the fibres are varied by 0, 0.75,0.5, 0.75, and 1 of volume fractions. The polypropylene fibers and rubber fibers are added in various proportions, such as 0/1, 0.25/0.75, 0.5/0.5, 0.75/0.25, and 1/0. The mix ID and the quantity of materials are tabulated in Table 2.

3. Experimental Testing Methods

All the specimens are cured at room temperature in this study, not exceeding 28oC. The mechanical properties are measured at the ages of 3, 7, 28, 56, and 90 days of curing. The mechanical properties such as compressive strength, splitting tensile strength, flexural strength, and hardened properties such as ductility factor and impact strength tests are performed in this study. The compressive strength is determined as per IS: 516-1959 [45] by testing 150mm size cube specimens. The splitting tensile strength test is executed at the age of 3, 7, 28, 56, and 90 days on the cylindrical specimen of size 150 mm x 300 mm, as per the standard procedure given in IS: 5816- 1999. A flexural strength test is performed as per the IS: 516-1959 [45] procedures over the prism specimen of size 500 mm x 100 mm x 100 mm at 3, 7, 28, 56, and 90 days. The measurement of ultimate and yield deflections is done by fixing the dial gauges at the center point while applying flexural load on the prism specimen to find the ductility factor as per IS: 516- 1959. In accordance with ACI committee 544 [46], the impact test is performed with the specimen in a cylindrical shape of size 150 mm x 60 mm. The impact strength is calculated based on the number of blows required to initiate the first crack, the mass of the hammer, and the height of the fall. The durability properties like water absorption, sorptivity, chloride penetration, acid attack, sulphate attack, and marine water-resistance are investigated in this study. The water absorption and sorptivity tests are accomplished as per the procedure given in ASTM C642- 2005 and ASTM-C1585-04. As per the ASTM C1202-2012, the rapid chloride penetration test is performed to find the chloride penetration. In accordance with ASTM C267-1998 [47], the concrete resistance when exposed to 0.8 N for HCl and 1.2 N for H2SO4 solutions is performed. The cube specimens are soaked in acid solutions (HCL-5 percent and H2SO4-5 percent) for 28 days and 56 days. In accordance with ASTM C1012-2015 [48], the concrete resistance when exposed to Na2SO4 (Sodium Sulphate) solutions is tested with a cube specimen. As per ASTM C1012-2015 [48] standards, the concentration of Na2SO4 was maintained at 50g/L, and the samples were soaked in Na2SO4 solutions for 28 days and 56 days, respectively. The concrete resistance when exposed to marine water is tested cube specimen, as per ASTM D1141-1998 [49]. As per ASTM D1141-1998 [49] standards, the marine water was prepared in laboratory and the salinity of marine water was maintained at 37g/L , and the samples were soaked in the marine water container for 28 days and 56 days, respectively.

4. Results and Discussion

4.1. Compressive Strength

This impact of various hybrid dosages on the compressive strength of geopolymer concrete at the ages of 3, 7, 28, 56 and 90 days is assessed. The test results showed that the specimens GW30M10CHy1, GW30M10CHy2, and GW30M10CHy3 exhibited a 20.4, 22.0, and 16.1 percent enhancement in 90 days compressive strength than the control specimen GW30M10C. Meanwhile, the specimens GW30M10CR2 and GW30M10CHy4 exhibit a 10 percent and 0.7 percent enhancement in 28 days compressive strength compared to the control mix GW30M10C. However, the specimens GW30M10CR2 and GW30M10CHy4 show a 20.1 and 32.4 percent decrease in 28 days compressive strength compared to the specimen GW30M10CP2. The enhancement in compressive strength at all ages of concrete is gradual for all the specimens. Figure 1 exhibits that the slight enhancement of compressive strength is noted with various hybrid fibre dosages. The specimen with 0.5 percent PP fibre and 0.5 percent rubber fibre (GW30M10CHy2) has shown maximum performance in all ages of compressive strength. Figure 1 shows that the specimen GW30M10CHy2 exhibits a 43.2, 24.4, 26.8, 26.5, and 22.0 percent enhancement in compressive strength at 3, 7, 28, 56, and 90 days of concrete ages compared to the specimen without fibre (GW30M10C). The specimen GW30M10CHy2 enhanced the 28 days and 90 days compressive strength by 2.4 and 2.3 percent compared to the specimen with 1 percent of PP fibre (GW30M10CP2).

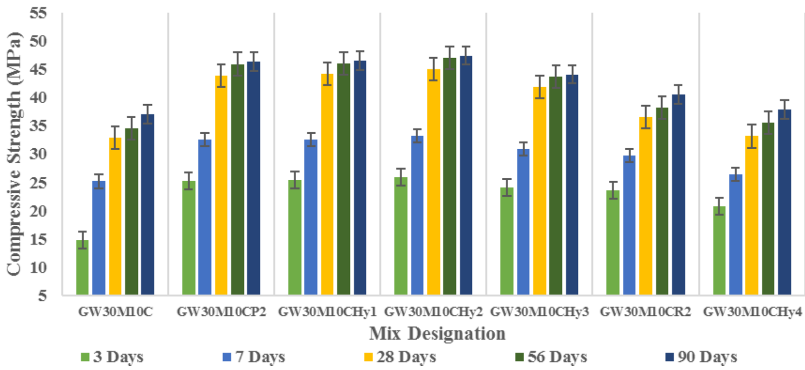

Fig. 1 Compressive strength test results of various hybrid proportions

Meanwhile, the compressive strength of the Hybrid Fibre Reinforced Geopolymer Concrete (HFRGPC) specimen decreases with increasing the rubber fibre content up to 0.5 percent. At the same time, the rubber fibre content exceeding 0.5 percent in fibre hybridization results in a major reduction in the compressive strength. The specimens GW30M10CHy3, GW30M10CR2, and GW30M10CHy4, show a 5.1, 14.2, and 22.4 percent decrease in 90 days compressive strength than the mix with 1 percent PP (GW30M10CP2). The lower degree of compressibility of polypropylene fibre also helped to enhance the strength [50]. The excess quantity of rubber fibre beyond 0.5 percent reduces the strength, due to which develops an unstiffened fibre matrix in the concrete medium. Exceeding the addition of both fibre beyond 1 percent results in a reduction of compressive strength and does not induce any effect than the control mix. In addition, the perfect proportion of low modulus and high modulus fibres showed strength increment [32,51,52]. There has been a considerable increase in the compressive strength with the utilization of both low modulus and high modulus fibers in the matrix.

4.2. Splitting Tensile Strength

The test results show that the specimens GW30M10CHy1, GW30M10CHy2, and GW30M10CHy3 exhibit 26.4, 30.8, and 26.1 percent increase in 28 days splitting tensile strength and 22.0, 26.7, and 21.6 percent increase in 90 days splitting tensile strength than the mix without fibres (GW30M10C). Meanwhile, the mix GW30M10CR2 and GW30M10CHy4 exhibit a 21.4 percent and 14.2 percent increase in splitting tensile strength compared to the control mix GW30M10C. However, the specimens GW30M10CR2 and GW30M10CHy4 show a 1.4 and 10.7 percent decrease in 28 days splitting tensile strength than the specimen GW30M10CP2.

From Figure 2, it can be observed that the hybrid percentage of rubber plays a important role in the enhancement of splitting tensile strength. The specimen with 0.5 percent PP fibre and 0.5 percent rubber fibre (GW30M10CHy2) has shown maximum performance in all ages of splitting tensile strength. Figure 2 shows that the specimen GW30M10CHy2 exhibits a 12.2, 9.7, 10.8, 9.2, and 10.3 percent increase in splitting tensile strength after 3, 7, 28, 56, and 90 days of curing compared to the specimen with 1 percent PP fibre (GW30M10CP2). The specimen GW30M10CHy2 has enhanced the 28 days and 90 days splitting tensile strength by 30.8 and 26.7 percent compared to the specimen without fibre (GW30M10C). Hence, the optimum specimen GW30M10CHy2 has achieved maximum splitting tensile strength compared to all other proportions of hybridization.

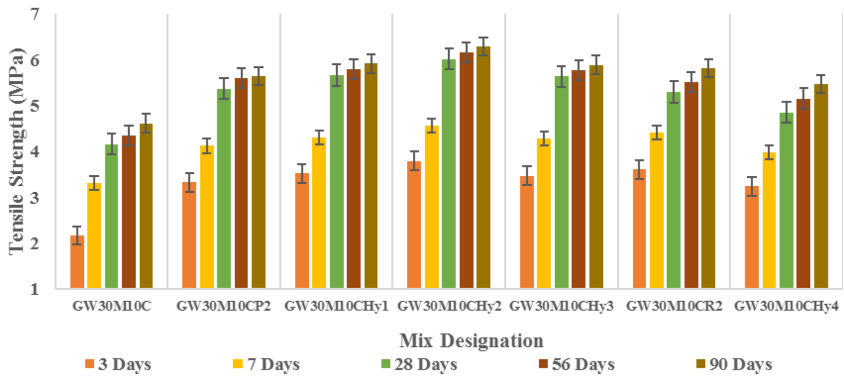

Fig. 2 Splitting tensile strength test results for various hybrid fibre proportions

Meanwhile, the splitting tensile strength of the HFRGPC specimen increases with increasing the rubber fibre content up to 0.5 percent. At the same time, the rubber fibre content exceeds 0.5 percent in fibre hybridization, resulting in reducing the splitting tensile strength. The specimen GW30M10CHy3 showed a decrease in splitting tensile strength compared to specimen GW30M10CHy2. The increase in splitting tensile strength was due to the perfect dispersion of fibres and created a stiffened fibre matrix [32]. The decrease in splitting tensile strength was due to the augmentation of fibres. When the percentage of rubber exceeds 0.5 percent, it develops an unstiffened fibre matrix in the concrete medium. Exceeding the addition of both fibre beyond 1 percent results in reducing splitting tensile strength and does not induce any effect than the control mix. In addition, the perfect proportion of low modulus and high modulus fibres showed strength increment [51,53,54]. It is also observed that there is a considerable increase in the splitting tensile strength with the utilization of both low modulus and high modulus fibers in the matrix.

4.3. Flexural Strength

The test results show that the specimens GW30M10CHy1, GW30M10CHy2, and GW30M10CHy3 exhibit 27.3, 31.7, and 26.9 percent increase in 28 days flexural strength and 22.6, 27.4, and 22.3 percent increase in 90 days flexural strength than the mix without fibre (GW30M10C). Meanwhile, the specimens GW30M10CR2 and GW30M10CHy4 exhibit a 17.5 percent and 0.7 percent increase in flexural strength compared to the control mix GW30M10C. However, the specimens GW30M10CR2 and GW30M10CHy4 showed a 7.4 and 29.4 percent decrease in 28 days flexural strength compared to the specimen GW30M10CP2.

From Figure 3, it is observed that the hybrid percentage of rubber plays a important part in the enhancement of flexural strength. The specimen with 0.5 percent PP and 0.5 percent rubber (GW30M10CHy2) exhibits maximum strength in all age of concrete. Figure 3 shows that the specimen GW30M10CHy2 exhibits a 12.8, 10.0, 11.1, 9.5, and 10.6 percent increase in flexural strength after the respective days of curing, compared to the specimen with 1 percent PP fibre (GW30M10CP2). The specimen GW30M10CHy2 enhanced the 28 days and 90 days flexural strength by 31.7 and 27.4 percent compared to the specimen without fibre (GW30M10C). Hence, the optimum specimen GW30M10CHy2 achieved maximum flexural strength compared to all other proportions of hybridization. The increase in flexural strength was due to the perfect dispersion of fibres and created a stiffened fibre matrix [55]. The strength reduction was by the augmentation of fibres. An unstiffened fibre matrix in the concrete medium is developed when the percentage of rubber exceeds 0.5 percent. Exceeding the addition of both fibre beyond 1 percent results in a reduction of flexural strength and does not induce any effect than the control mix. In addition, the perfect proportion of low modulus and high modulus fibres showed strength increment [32,52,56]. It is also observed that there is a considerable increase in the flexural strength with the utilization of both low modulus and high modulus fibers in the matrix.

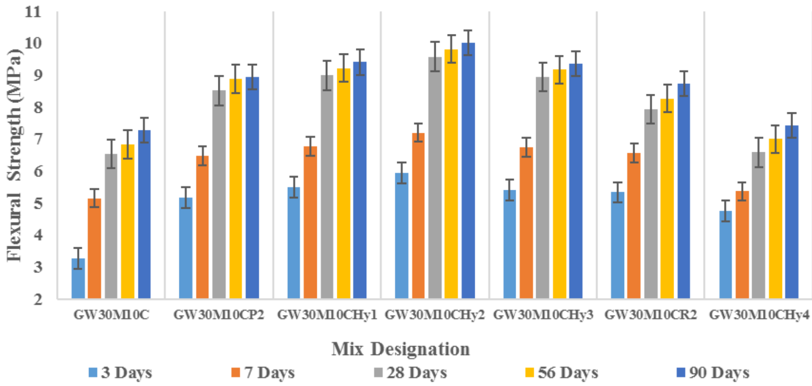

Fig. 3 Flexural strength test results for various hybrid fibre proportions

4.4. Ductility Factor

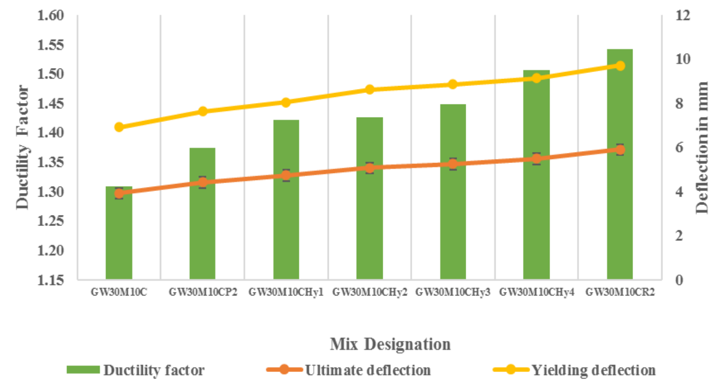

Fig. 4 Ductility factor for various hybrid fibre proportions

The results showed that the specimens GW30M10CP2, GW30M10CHy1, GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 obtained the ductility factor values of 1.37, 1.42, 1.43, 1.45, 1.51 and 1.54. The specimen with 1 percent rubber fibre (GW30M10CR2) showed a maximum ductility factor value compared to other specimens.

From Figure 4, it can be observed that the utilization of rubber fiber increases the ultimate deflection and yield deflection. The specimen GW30M10CR2 exhibits a maximum increase in ductility due to the rubber fibers, which helps in improving the strength properties [35]. The specimens GW30M10CP2 and GW30M10CHy1 suffer from the least ductility with the higher percentage polypropylene fiber affecting the stability of the mix. The specimen GW30M10CHy2 and GW30M10CHy3 obtained a significant ductility factor than the control specimen GW30M10C. Hence, the ductility is improved with perfect proportion of both the fibers.

4.5. Impact Strength

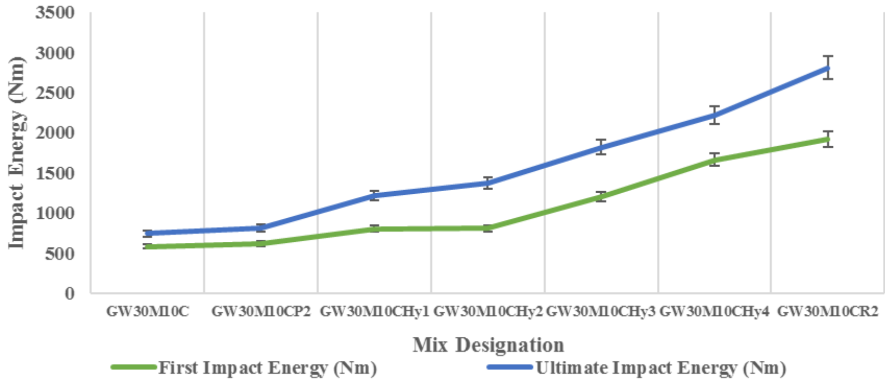

Fig. 5 Impact strength for various hybrid fibre proportions

The result shows that the specimens GW30M10CHy1, GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 observe the ultimate impact energy of 1212.8, 1370.12, 1815.23, 2223.56 and 2809.12 Nm, respectively. Meanwhile, the number of blows required to obtain ultimate failure was observed by the specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 as 60, 75, 82, and 128. The specimen with 1 percent rubber fibre (GW30M10CR2) obtained maximum values in ultimate impact energy of 2809.12 Nm. The specimens GW30M10CHy1 and GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 exhibit 49.30, 68.67, 123.47, 173.73, and 245.82 percent increase in energy absorption compared to the specimen GW30M10CP2.

From Figure 5, it is inferred that the number of blows required to initiate the first crack and ultimate failure increases with the increase in the rubber fiber content and decrease in polypropylene fiber content. Specimen GW30M10CR2 yields maximum impact energy because the rubber fiber increases the energy absorption capacity. The energy-absorbing property of the rubber fibers is higher than the polypropylene fibers [38]. The test results evident that the number of blows for the ultimate crack is enhanced by the higher amount rubber fiber [57]. The maximum enhancement in impact strength is related to the presence of high modulus fibers in a hybrid fiber medium [58]. The specimen GW30M10CP2 yields the least impact energy owing to the poor structural integrity caused by the polypropylene fibers that affect the adhesion between the fiber and the matrix.

4.6. Water Absorption Test

The test results show that the specimens GW30M10CP2, GW30M10CHy1, GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 have obtained a water absorption percentage of 3.21, 3.11, 3.02, 3.05, 3.30 and 3.32 at 90 days. While increasing the concrete age, the water absorption percentage will increase gradually. However, the increase in water absorption of all the HFRGPC specimens after 90 days is lower than the increase in water absorption at 28 and 56 days. The weight of specimen GW30M10CHy2 at 28 days of water immersion increases by 29.7 g from the initial weight. At the same time, the weight of the specimen GW30M10CHy2 after 56 days of water immersion is increased by 23 g from the weight of the specimen at 28 days. The weight of the specimen GW30M10CHy2 after 90 days of water immersion is increased by 21.6 g from the weight of the specimen at 56 days. Hence, the increase in specimen weight was decreased by increasing the immersion period.

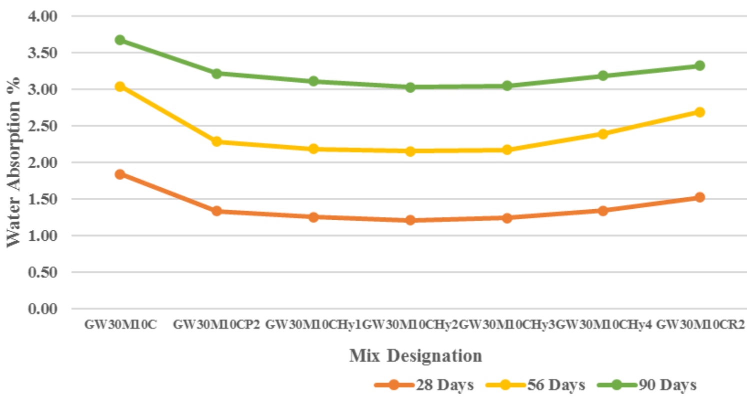

Fig. 6 Water absorption of various HFRGPC specimens

The test results showed that all the HFRGPC specimens exhibit excellent durability in terms of water absorption. The specimen GW30M10CHy2 grasps the minimum water absorption capacity. The specimen GW30M10CHy2 has obtained water absorption percentages of 1.21, 2.17, and 3.05 after 28, 56, and 90 days of water immersion. The porosity of the concrete is significantly reduced, resulting in enhanced resistance to water absorption and minimum water absorption capacity due to the blending effect of both the fibers [59,60].

From Figure 6, it is observed that the water absorption value is maximum in the specimens GW30M10CHy4 and GW30M10CR2. The specimen with higher polypropylene fibres results in lower water absorption than specimens with a high percentage of rubber fibre. However, all HFRGPC specimens observed less water absorption capacity than the specimen without fibres (GW30M10C). The test results show that polypropylene fibre does not influence the geopolymer concrete to absorb more water. Due to its hydrophobic nature [61], polypropylene fibre helped limit the water absorption capacity of HFRGPC specimens.

4.7. Sorptivity

From the results, it can be observed that all the HFRGPC specimens obtained the minimum sorptivity values than the specimen without fibres. Figure 7 represents the sorptivity values of each HFRGPC specimen. From Figure 7, it is inferred that the specimen with a higher percentage of polypropylene fibre obtained the higher sorptivity values. The sorptivity values decrease with increasing the rubber fibre percentage [62]. The observed readings are in agreement with the water absorption test values.

The specimen GW30M10CHy2 has the lowest sorptivity values because polypropylene fibers are hydrophobic and absorb the least water. The specimen GW30M10CP2 exhibits comparatively more sorptivity value due to porosity. However, all HFRGPC specimens observed less sorptivity than those without fibres (GW30M10C). The test results show that rubber fibre does not influence the geopolymer concrete to absorb more water. Due to its elasto-plastic nature, rubber fibre helped limit the sorptivity of HFRGPC specimens.

4.8. Rapid Chloride Penetration Test

RCPT (Rapid Chloride Penetration Test) test results exhibit that the specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 obtained the minimum values of charges passed through concrete compared to other specimens. When the age of concrete increases, the charge passed increases gradually. The specimen GW30M10CR2 obtained the charge passed are 1980, 2163, 2002, and 2283 after 28, 56, and 90 days of testing, which is the least value compared to other specimens. The charge passed through the specimen GW30M10CR2 at 56 days of testing increases by 183 coulombs from the charge passed at 28 days. The charge passed through the specimen GW30M10CR2 after 90 days of testing is increased by 120 coulombs from the charge passed through the specimen at 56 days. The porosity of the concrete is greatly reduced, resulting in enhanced resistance to electrical conductivity due to the blending effect of both fibers.

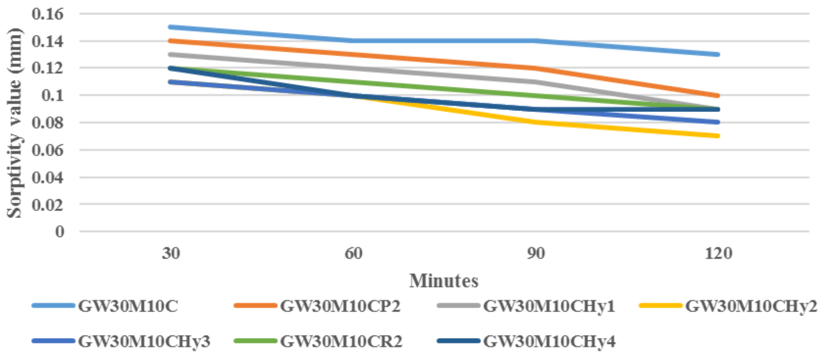

Fig. 7 Sorptivity value of various HFRGPC specimens

The mix with 1 percent PP (GW30M10CP2) displays the minimum resistance for chloride penetration, and the specimen GW30M10CR2 possesses the maximum resistance for chloride penetration. The results showed that the presence of rubber fibers increases the resistance to the flow of chloride ions into the concrete. Due to the high modulus of elasticity, the rubber fibre possesses resistance against the penetration of chloride ions [38]. Ranjith et al. [63] claimed an increase in chloride penetration with increased polypropylene fiber content. Chithambar [55] reported that the penetration of chloride ions in oven-cured samples is slightly more than the charges passed on the ambient cured samples. Hence, the ambient curing of all the specimens gives an excess advantage in resisting the chloride penetration. All the hybrid specimens were in the moderate range as per ASTM standards.

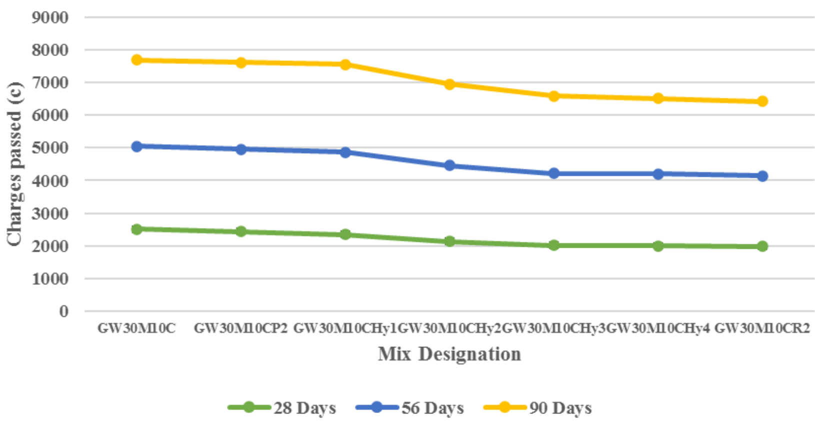

Fig. 8 Electrical resistivity value of various HFRGPC specimens

4.9. Acid Resistance Test

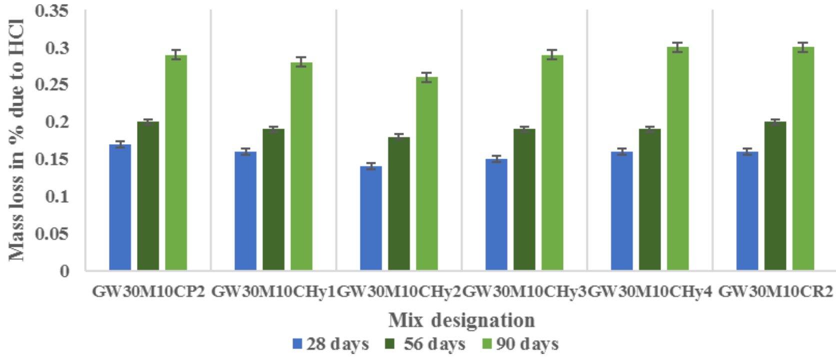

Fig. 9 Mass loss percentage of various HFRGPC specimens under HCL

The test results showed that the specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 obtained the minimum percentages of mass loss compared to other specimens. The percentages of mass loss increase gradually with the increase in concrete age. From Figure 9 and Figure 10, it is clear that the specimens with various hybrid fibre dosages possesses similar and improved resistance to both the acidic solutions. There is no considerable change in the performance of different fibers in resisting the acid attack. However, it is found that specimen GW30M10CHy2 reported the highest acid resistance due to the blended effect of hybrid fibers matrix in contributing to the less porous structure than other specimens.

From Figure 9 and Figure 10, it is observed that all the specimens have exhibited good acid resistance due to the perfect microstructure of optimized geopolymer concrete. The test results show that all the samples resist the acid attack better than the specimen without fibres (GW30M10C). However, the influence of various proportions of hybrid fibres on the sulphate resistance of the hybrid fibre reinforced geopolymer concrete has to be investigated.

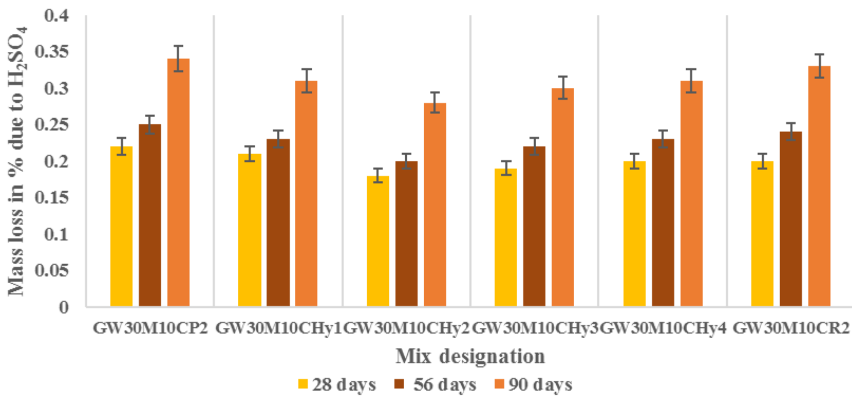

Fig. 10 Mass loss percentage of various HFRGPC specimens under H_2SO_4

4.10. Sulphate Resistance Test

Figure 11 clearly shows the variation in the mass of various HFRGPC specimens under the Na_2SO_4 acid exposures. The results show that the specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 have obtained the minimum percentages of mass loss compared to other specimens. The percentages of mass loss increase gradually with the age of concrete increases [64].

All the mix with various hybrid fibre dosages possesses similar and improved resistance against sodium silicate solution. The specimen GW30M10CHy2 reported the highest sulphate resistance due to the blended effect of hybrid fibers matrix in contributing to the less porous structure than other specimens. The test results showed that all the specimens exhibited good sulphate resistance due to the perfect microstructure of optimized geopolymer concrete. The specimen GW30M10CP2 exhibits lower sulfate attack resistance than other HFRGPC specimens. The test results evident that resistance against the sulphate attack is enhanced with the higher percentage of rubber fiber content and reduced with the hugher percentage of the polypropylene fiber content. The presence of polypropylene fibers reduces the resistance to sulphate attack [39,65,66]. The test results show that all the samples resist the sulphate attack better than the specimen without fibres (GW30M10C).

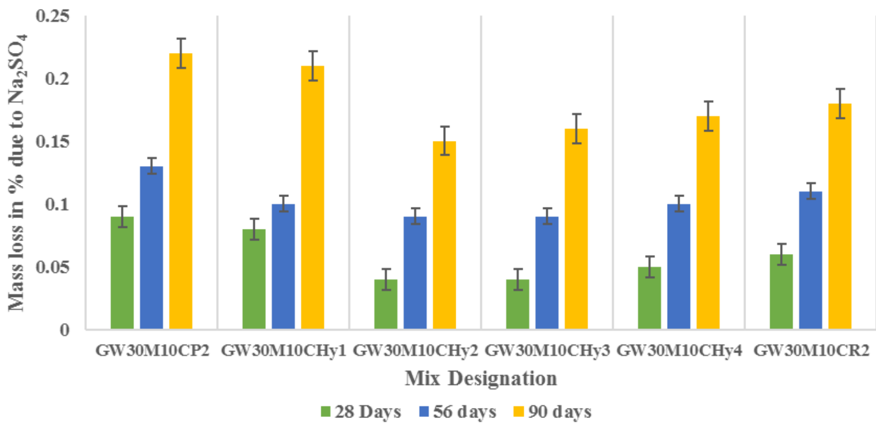

Fig. 11 Mass loss percentage of various HFRGPC specimens under Na_2SO_4

4.11. Marine Water Resistance Test

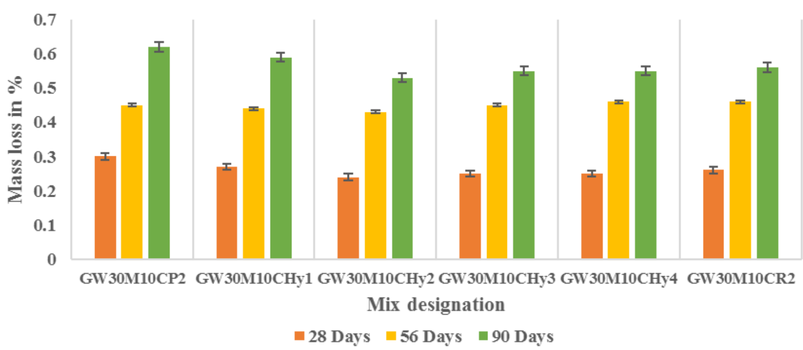

Fig. 12 Mass loss percentage of various HFRGPC specimens under Na_2SO_4

From Figure 12, it is evident that the specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 have obtained the minimum mass loss percentages compared to other specimens. The percentages of mass loss increase gradually with the age of concrete increases. The entire hybrid fiber specimen possesses similar and better resistance to marine water. The specimen GW30M10CHy2 reported the highest marine water resistance due to the blended effect of hybrid fibers in a perfect matrix contributing to the less porous structure than other specimens. The high resistance exhibited by the hybrid fiber reinforced concrete specimens GW30M10CHy2, GW30M10CHy3, GW30M10CHy4, and GW30M10CR2 is attributed to the good microstructure induced by the better adhesion between the fibers and the matrix.

The test results showed that all the specimens exhibited good resistance against marine water attacks due to the perfect microstructure of optimized geopolymer concrete. The specimen GW30M10CP2 exhibits lower marine water attack resistance than all other HFRGPC specimens. The test results exhibit that the resistance offered to the marine water attack increases with the rubber fiber content and decreases with the increase in the polypropylene fiber content. The presence of polypropylene fibers reduces the resistance to a marine water attack. The test results show that all the samples resist the attack against marine water better than the specimen without fibres (GW30M10C).

5. Conclusion

This study examines the impact of various hybrid fibre dosages on the hardened and durability characteristics of geopolymer concrete. The specimen with 0.5 percent PP fibre and 0.5 percent rubber fibre exhibits a 26.9 percent, 30.8 percent, and 31.7 percent enhancement in compressive, splitting tensile and flexural strength compared to the specimen without fibre. The utilization of 0.5 percent of polypropylene fibre and 0.5 percent of rubber fibre (GW30M10CHy2) exhibits maximum performance in compressive, splitting tensile and flexural strength. The specimen with 1 percent rubber fibre (GW30M10CR2) observed maximum performance in impact strength and ductility due to the fact of high modulus of rubber fibre; however, the specimen doesn't show a significant effect in hardened properties. The hybrid fibre dosage of 0.5 percent of PP and 0.5 percent of rubber attained significant performance in all hardened properties. The specimen with 0.5 percent polypropylene and 0.5 percent rubber showed less water absorption and sorptivity values. Hybrid fiber reinforced geopolymer concrete with 0.5/0.5- rubber fiber/polypropylene fiber resisted the acid attack, sulphate attack, and marine water attack better than the other hybrid reinforced geopolymer concrete specimens due to the excellent microstructure contributed by the blended action of both the fibers inside the matrix. Hence, it has been chosen as an optimum mix for developing the hybrid fibre reinforced geopolymer concrete. The study developed a hybrid fibre reinforced geopolymer concrete combined with polypropylene fibre and rubber fibre. Moreover, the geopolymer concrete made up of waste materials such as fly ash and wood ash could be sustainable concrete used in cast-in-situ applications. Meanwhile, the maximum compressive strength of the optimum hybrid fibre reinforced geopolymer concrete specimen is about 47.39Mpa. It is sufficient to design the paver block for medium traffic conditions as per IS 15658-2006.

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References

[1] Loganathan P., and A.B. Mahindrakar. 2020. "Evaluation of surface temperatureand prediction of changes in future projections using quantile to quantile change factor methodologyover cauvery river basin-peninsular India." Indian Journal of Ecology. 47 (2): 312–5.

[2] Loganathan P., and A.B. Mahindrakar. 2020. "Assessment of changes in observed rainfall and prediction of future conditions using quantile delta mapping bias correction technique over cauvery River Basin, India." Indian Journal of Ecology. 47 (3): 708–11.

[3] Mikulčić H., J.J. Klemeš, M. Vujanović, K. Urbaniec, and N. Duić. 2016. "Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process." Journal of Cleaner Production. 136 119–32. https://doi.org/10.1016/j.jclepro.2016.04.145
[4] Loganathan P., and A.B. Mahindrakar. 2021. "Statistical downscaling using principal component regression for climate change impact assessment at the Cauvery river basin." Journal of Water and Climate Change. 12 (6): 2314–24. https://doi.org/10.2166/wcc.2021.223
[5] Turner L.K., and F.G. Collins. 2013. "Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete." Construction and Building Materials. 43 125–30. https://doi.org/10.1016/j.conbuildmat.2013.01.023
[6] Loganathan P., and A.B. Mahindrakar. 2021. "Intercomparing the robustness of machine learning models in simulation and forecasting of streamflow." Journal of Water and Climate Change. 12 (5): 1824–37. https://doi.org/10.2166/wcc.2020.365
[7] Loganathan P., and A.B. Mahindrakar. 2020. "Assessment and ranking of CMIP5 GCMs performance based on observed statistics over Cauvery river basin – Peninsular India." Arabian Journal of Geosciences. 13 (22): 1200. https://doi.org/10.1007/s12517-020-06217-6
[8] Davidovits J. 1991. "Geopolymers: inorganic polymeric new materials." Journal of Thermal Analysis. 37 (8): 1633–56. https://doi.org/10.1007/BF01912193
[9] Gundupalli Bhanu Prakash, and V Prem Kumar. 2017. "Carbonation Resistance of SCC." International Journal of Engineering Research and. V6 (10): 140–4. https://doi.org/10.17577/ijertv6is100087
[10] Arunkumar K., M. Muthukannan, A.S. Kumar, A.C. Ganesh, and R.K. Devi. 2022. "Cleaner Environment Approach by the Utilization of Low Calcium Wood Ash in Geopolymer Concrete." Applied Science and Engineering Progress. 15 (1): 1–13. https://doi.org/10.14416/j.asep.2021.06.005
[11] Zhang P., Z. Gao, J. Wang, J. Guo, S. Hu, and Y. Ling. 2020. "Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review." Journal of Cleaner Production. 270 122389. https://doi.org/10.1016/j.jclepro.2020.122389
[12] Suresh Kumar A., M. Muthukannan, and I. Sri Krishna. 2020. "Optimisation of bio medical waste ash in GGBS based of geopolymer concrete." IOP Conference Series: Materials Science and Engineering. 872 12163. https://doi.org/10.1088/1757-899X/872/1/012163
[13] Okoye F.N., S. Prakash, and N.B. Singh. 2017. "Durability of fly ash based geopolymer concrete in the presence of silica fume." Journal of Cleaner Production. 149 1062–7. https://doi.org/10.1016/J.JCLEPRO.2017.02.176
[14] Kabir S.M.A., U.J. Alengaram, M.Z. Jumaat, S. Yusoff, A. Sharmin, and I.I. Bashar. 2017. "Performance evaluation and some durability characteristics of environmental friendly palm oil clinker based geopolymer concrete." Journal of Cleaner Production. 161 477–92. https://doi.org/10.1016/j.jclepro.2017.05.002
[15] Arunachalam S.K., M. Muthiah, K.D. Rangaswamy, A. Kadarkarai, and C.G. Arunasankar. 2021. "Improving the structural performance of reinforced geopolymer concrete incorporated with hazardous heavy metal waste ash." World Journal of Engineering. ahead-of-p (ahead-of-print): https://doi.org/10.1108/WJE-01-2021-0055
[16] Corbu O., A.M. Ioani, A.M.M. Al Bakri, V. Meiţă, H. Szilagyi, and A.V. Sandu. 2015. "The Pozzoolanic Activity Level of Powder Waste Glass in Comparisons with other Powders." Key Engineering Materials. 660 237–43. https://doi.org/10.4028/www.scientific.net/KEM.660.237
[17] Malkawi A.B., M.F. Nuruddin, A. Fauzi, H. Almattarneh, and B.S. Mohammed. 2016. "Effects of Alkaline Solution on Properties of the HCFA Geopolymer Mortars." Procedia Engineering. 148 710–7. https://doi.org/10.1016/j.proeng.2016.06.581

[18] Suresh kumar A., M. Muthukannan, R. Kanniga Devi, K. Arunkumar, and A. Chithambar Ganesh. 2022. "Improving the Performance of Structural Members by Incorporating Incinerated Bio-Medical Waste Ash in Reinforced Geopolymer Concrete." Materials Science Forum. 1048 321–32. https://doi.org/10.4028/www.scientific.net/MSF.1048.321

[19] Yip C.K., G.C. Lukey, and J.S.J. Van Deventer. 2005. "The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation." Cement and Concrete Research. 35 (9): 1688–97. https://doi.org/10.1016/j.cemconres.2004.10.042

[20] Suresh Kumar A., M. Muthukannan, A.D.K.B. Irene, K. Arunkumar, and A. Chithambar Ganesh. 2022. "Flexural Behaviour of Reinforced Geopolymer Concrete Incorporated with Hazardous Heavy Metal Waste Ash and Glass Powder." Materials Science Forum. 1048 345–58. https://doi.org/10.4028/www.scientific.net/MSF.1048.345

[21] Kadarkarai Arunkumar, Muthiah Muthukannan, Arunachalam Sureh Kumar A.C.G. n.d. "Mechanical characterisation of waste wood ash-based green geopolymer concrete incorporated with waste rubber and polypropylene fibre." Int J Environment and Waste Management. XX (XX): (Accepted).

[22] Arunkumar K., M. Muthukannan, A.S. Kumar, A.C. Ganesh, and R.K. Devi. 2021. "Invention of sustainable geopolymer concrete made with low calcium waste wood ash." World Journal of Engineering. https://doi.org/10.1108/WJE-03-2021-0162

[23] Kadarkarai Arunkumar, Muthiah Muthukannan, Arunachalam Sureh Kumar A.C.G., and R.K. Devi. 2022. "Influence of Hybrid Fibres on the Mechanical Characterization of Low Calcium Geopolymer Concrete." Journal of Technology. 37 (4): (Accepted).

[24] Li W., E.D. Shumuye, T. Shiying, Z. Wang, and K. Zerfu. 2022. "Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties." Case Studies in Construction Materials. 16 e00894 (10 pages). https://doi.org/10.1016/j.cscm.2022.e00894

[25] Arunkumar K., M. Muthukannan, A. Suresh Kumar, A.C. Ganesh, and R.K. Devi. 2022. "Hybrid fibre reinforced eco-friendly geopolymer concrete made with waste wood ash: A mechanical characterization study." Engineering and Applied Science Research. 49 (2): 235–47. https://doi.org/10.14456/easr.2022.26

[26] Koenig A., A. Wuestemann, F. Gatti, L. Rossi, F. Fuchs, D. Fessel, et al. 2019. "Flexural behaviour of steel and macro-PP fibre reinforced concretes based on alkali-activated binders." Construction and Building Materials. 211 583–93. https://doi.org/10.1016/j.conbuildmat.2019.03.227

[27] Chithambar Ganesh A., M. Muthukannan, R. Malathy, and C. Ramesh Babu. 2019. "An Experimental Study on Effects of Bacterial Strain Combination in Fibre Concrete and Self-Healing Efficiency." KSCE Journal of Civil Engineering. 23 (10): 4368–77. https://doi.org/10.1007/s12205-019-1661-2

[28] Güneyisi E., Y.R. Atewi, and M.F. Hasan. 2019. "Fresh and rheological properties of glass fiber reinforced self-compacting concrete with nanosilica and fly ash blended." Construction and Building Materials. 211 349–62. https://doi.org/10.1016/J.CONBUILDMAT.2019.03.087

[29] Korniejenko K., E. Frączek, E. Pytlak, and M. Adamski. 2016. "Mechanical Properties of Geopolymer Composites Reinforced with Natural Fibers." Procedia Engineering. 151 388–93. https://doi.org/10.1016/j.proeng.2016.07.395

[30] Zhang Z., X. Yao, H. Zhu, S. Hua, and Y. Chen. 2009. "Preparation and mechanical properties of polypropylene fiber reinforced calcined kaolin-fly ash based geopolymer." Journal of Central South University of Technology. 16 (1): 49–52. https://doi.org/10.1007/s11771-009-0008-4

[31] Arunkumar K., M. Muthukannan, A. Dinesh Babu, A.L. Hariharan, and T. Muthuramalingam. 2020. "Effect on addition of Polypropylene fibers in wood ash-fly ash based geopolymer concrete." IOP Conference Series: Materials Science and Engineering. 872 12162. https://doi.org/10.1088/1757-899X/872/1/012162

[32] Sukontasukkul P., P. Pongsopha, P. Chindaprasirt, and S. Songpiriyakij. 2018. "Flexural performance and toughness of hybrid steel and polypropylene fibre reinforced geopolymer." Construction and Building Materials. 161 37–44. https://doi.org/10.1016/j.conbuildmat.2017.11.122
[33] Arunkumar K., A. Suresh kumar, A. Chithambar Ganesh, L. Parthiban, and V. Premkumar. 2022. "Incorporation of Waste Wood Ash and Polypropylene Fibre on the Production of Sustainable GPC." Lecture Notes in Civil Engineering. (Accepted). https://doi.org/10.1007/978-981-19-4040-8
[34] Park Y., A. Abolmaali, Y.H. Kim, and M. Ghahremannejad. 2016. "Compressive strength of fly ash-based geopolymer concrete with crumb rubber partially replacing sand." Construction and Building Materials. 118 43–51. https://doi.org/10.1016/j.conbuildmat.2016.05.001
[35] Luhar S., S. Chaudhary, and I. Luhar. 2019. "Development of rubberized geopolymer concrete : Strength and durability studies." Construction and Building Materials. 204 740–53. https://doi.org/10.1016/j.conbuildmat.2019.01.185
[36] Sreesha S., P. Esakkiraj, V. Sreevidya, and P. Ash. 2020. "Development of Self Curing Geopolymer Concrete Incorporating Expanded Polystyrene, Recycled Coarse Aggregate and Rubber Crumbs." International Journal of Recent Technology and Engineering. 9 (2): 292–6. https://doi.org/10.35940/ijrte.b3489.079220
[37] Charkhtab Moghaddam S., R. Madandoust, M. Jamshidi, and I.M. Nikbin. 2021. "Mechanical properties of fly ash-based geopolymer concrete with crumb rubber and steel fiber under ambient and sulfuric acid conditions." Construction and Building Materials. 281 122571 (11 pages). https://doi.org/10.1016/j.conbuildmat.2021.122571
[38] Gupta T., S. Chaudhary, and R.K. Sharma. 2016. "Mechanical and durability properties of waste rubber fi ber concrete with and without silica fume." Journal of Cleaner Production. 112 702–11. https://doi.org/10.1016/j.jclepro.2015.07.081
[39] Mhaya A.M., M.H. Baghban, I. Faridmehr, G.F. Huseien, A.R.Z. Abidin, and M. Ismail. 2021. "Performance evaluation of modified rubberized concrete exposed to aggressive environments." Materials. 14 (8): 1–25. https://doi.org/10.3390/ma14081900
[40] Arunkumar., M. Muthukannan, A. Suresh kumar, and A. Chithambar Ganesh. 2021. "Mitigation of waste rubber tire and waste wood ash by the production of rubberized low calcium waste wood ash based geopolymer concrete and influence of waste rubber fibre in setting properties and mechanical behavior." Environmental Research. 194 110661. https://doi.org/10.1016/J.ENVRES.2020.110661
[41] Arunkumar K., M. Muthukannan, K. Sureshkumar, A. Chithambar Ganesh, and R. Kanniga Devi. 2021. "Mathematical Formulation for Prediction of Structural Performance of Green Geopolymer Concrete Beams and Columns." Turkish Journal of Computer and Mathematics Education. 12 (10): 3806–15.
[42] ArunKumar K., M. Muthukannan, R. Raja Abinaya, and A. Suresh Kumar. 2022. "Structural Behaviour of Green Geopolymer Concrete Beams and Columns Made with Waste Wood Ash a Partial Substitution Binder." Materials Science Forum. 1048 333–44. https://doi.org/10.4028/www.scientific.net/MSF.1048.333
[43] Anuradha R., and B.V. Sreevidyaa, V. Venkatasubramania, R. and Rangan. 2011. "Modified Guidelines for Geopolymer Concrete Mix Design using Indian Standard." Asian Journal of Civil Engineering (Building and Housing). 13 (3): 357–68.
[44] Arunkumar K., M. Muthukannan, A. Suresh Kumar, A.C. Ganesh, and R.K. Devi. 2021. "Production of Eco-Friendly Geopolymer Concrete by using Waste Wood Ash for a Sustainable Environment." Pollution. 7 (4): 993–1006. https://doi.org/10.22059/POLL.2021.320857.1039
[45] IS 516-1959. 1959. "Method of Tests for Strength of Concrete." Bureau of Indian Standards. 1–30.

[46] ACI Commitee 544-1988. 1988. "Measurement of Properties of Fiber Reinforced Concrete." ACI Materials Journal. 85 583–93.
[47] ASTM-C267-98. 1998. "Standard Test Methods for Chemical Resistance of Mortars, Grouts and Monolithic Surfacings and Polymer Concretes." ASTM International. 4 1–6.
[48] ASTM C1012/C1012M-15. 2015. "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution." ASTM International. (C): 1–5.
[49] ASTM D1141-99. 1999. "Standard for the Preparation of Substitute Ocean Water." ASTM International. 98 98–100.
[50] Al-mashhadani M.M., O. Canpolat, Y. Aygörmez, M. Uysal, and S. Erdem. 2018. "Mechanical and microstructural characterization of fiber reinforced fly ash based geopolymer composites." Construction and Building Materials. 167 505–13. https://doi.org/10.1016/j.conbuildmat.2018.02.061
[51] Sivakumar A., and M. Santhanam. 2007. "A quantitative study on the plastic shrinkage cracking in high strength hybrid fibre reinforced concrete." Cement and Concrete Composites. 29 (7): 575–81. https://doi.org/10.1016/j.cemconcomp.2007.03.005
[52] Ganesh C., J. Sivasubramanaian, M.S. Seshamahalingam, J. Millar, and V.J. Kumar. 2021. "Investigation on the Performance of Hybrid Fiber Reinforced Geopolymer Concrete Made of M-Sand under Heat Curing." Materials Science Forum. 1019 73–81. https://doi.org/10.4028/www.scientific.net/MSF.1019.73
[53] Chithambar Ganesh A., and M. Muthukannan. 2019. "Experimental Study on the Behaviour of Hybrid Fiber Reinforced Geopolymer Concrete under Ambient Curing Condition." IOP Conference Series: Materials Science and Engineering. 561 012014 (9 pages). https://doi.org/10.1088/1757-899X/561/1/012014
[54] Alrefaei Y., and J.G. Dai. 2018. "Tensile behavior and microstructure of hybrid fiber ambient cured one-part engineered geopolymer composites." Construction and Building Materials. 184 419–31. https://doi.org/10.1016/J.CONBUILDMAT.2018.07.012
[55] Chithambar Ganesh A. 2020. Experimental Study on the Behaviour of Hybrid Fiber Reinforced Geopolymer Concrete Made of M Sand. Kalasaliingam Academy of Research and Education, 2020.
[56] de Alencar Monteiro V.M., L.R. Lima, and F. de Andrade Silva. 2018. "On the mechanical behavior of polypropylene, steel and hybrid fiber reinforced self-consolidating concrete." Construction and Building Materials. 188 280–91. https://doi.org/10.1016/J.CONBUILDMAT.2018.08.103
[57] Gupta T., R.K. Sharma, and S. Chaudhary. 2015. "Impact resistance of concrete containing waste rubber fiber and silica fume Trilok." International Journal of Impact Engineering. 83 76–87. https://doi.org/10.1016/j.ijimpeng.2015.05.002
[58] Murugan R.B., C. Natarajan, and S.E. Chen. 2016. "Material development for a sustainable precast concrete block pavement." Journal of Traffic and Transportation Engineering (English Edition). 3 (5): 483–91. https://doi.org/10.1016/j.jtte.2016.09.001
[59] Alomayri T., H. Assaedi, F.U.A. Shaikh, and I.M. Low. 2014. "Effect of water absorption on the mechanical properties of cotton fabric-reinforced geopolymer composites." Journal of Asian Ceramic Societies. 2 (3): 223–30. https://doi.org/10.1016/j.jascer.2014.05.005
[60] Karahan O., and C.D. Atiş. 2011. "The durability properties of polypropylene fiber reinforced fly ash concrete." Materials & Design. 32 (2): 1044–9.
[61] Saloni, Parveen, T.M. Pham, Y.Y. Lim, and M. Malekzadeh. 2021. "Effect of pre-treatment methods of crumb rubber on strength, permeability and acid attack resistance of rubberised geopolymer concrete." Journal of Building Engineering. 41 102448 (10 pages). https://doi.org/10.1016/j.jobe.2021.102448
[62] Luhar S., and U. Khandelwal. 2015. "A Study on Water Absorption and Sorptivity of Geopolymer Concrete." International Journal of Civil Engineering. 2 (8): 1–9. https://doi.org/10.14445/23488352/ijce-v2i8p101

[63] Ranjith S., R. Venkatasubramani, and V. Sreevidya. 2017. "Comparative Study on Durability Properties of Engineered Cementitious Composites with Polypropylene Fiber and Glass Fiber." Archives of Civil Engineering. 63 (4): 83–101. https://doi.org/10.1515/ace-2017-0042
[64] Arunkumar K., M. Muthukannan, A. Sureshkumar, A. Chithambarganesh, and R.K.D. R. 2021. "Mechanical and durability characterization of hybrid fibre reinforced green geopolymer concrete." Research on Engineering Structures and Materials. https://doi.org/10.17515/resm2021.280ma1604
[65] Veronie J., and V. Sreevidya. 2020. "Experimental investigation and comparison on structural behaviour of Ferro-Geopolymer concrete and mortar cubes with conventional cubes." Materials Today: Proceedings. 21 (1): 531–6. https://doi.org/10.1016/j.matpr.2019.06.693
[66] Wasim M., T.D. Ngo, and D. Law. 2021. "A state-of-the-art review on the durability of geopolymer concrete for sustainable structures and infrastructure." Construction and Building Materials. 291 123381 (12 pages). https://doi.org/10.1016/j.conbuildmat.2021.123381.