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Exploring the Effectiveness of Polypropylene Fiber-Reinforced Geo-Polymer Concrete

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Abstract

This research explored the effectiveness of Polypropylene Fibers (PPF) in Industrial Fly Ash (IFA) based Geopolymer Concrete (GPC). The GPC of M40 grade was incorporated with different PPF capacities (0.2%, 0.4%, and 0.6% by weight of concrete) and assessed its performance involved mechanical and durability properties and compared with Conventional Concrete (CC) of the same grade. Mechanical properties like Compressive Strength (CS), Split Tensile Strength (STS), and Modulus of Elasticity (MOE), were assessed. Also, Rapid Chloride Penetration Test (RCPT), water permeability, and carbonation tests were directed to assess the durability features of GPC. The study demonstrated that PPF-reinforced GPC exhibited higher CS, STS, better resistance to chloride penetration, lower water permeability, and reduced carbonation compared to CC of the same grade making it a promising alternative to CC with certain advantages and disadvantages. Also, the obtained experimental results and behaviour of GPC with PPF examine the influence of different dosages of PPF on the mechanical and durability characteristics.

Major Findings: *Compared to CC, GPC exhibited notable enhancements in mechanical properties. Compressive strength increased by 4.34-10.20 %, split tensile strength by 13.04-21.56 %, and modulus of elasticity by 24.27-31.73 % after 28 days of curing.*

Keywords: Carbonation, Conventional Concrete, Geopolymer Concrete, Polypropylene Fibers, Rapid Chloride Penetration Test, Water Permeability

1.0 Introduction

The process of producing Ordinary Portland Cement (OPC) results in the release of a substantial quantity of Carbon Dioxide (CO_2) into the atmosphere. These CO_2 emissions stemming from cement production play a role in global warming and the alteration of climate patterns[1–5]. Regarding this issue, the geopolymer technology introduced by Davidovits exhibits significant potential for implementation in the concrete sector as a substitute binding agent for OPC. This innovation can substantially diminish the release of CO_2 into the atmosphere, reducing it by approximately 80%[6]. GPC stands as the most advanced variation of concrete after OPC. Also, GPC brings forth multiple benefits, encompassing enhanced robustness and endurance characteristics. It has the capability for swift initial strength development and curing in ambient conditions and aids in diminishing construction duration[7]. By substituting CC with IFA-based GPC, a viable solution can be found for the environmental and land disposal issues. Additionally, GPC exhibits a lower carbon footprint in comparison to CC[8]. GPC exhibits a comprehensive set of mechanical and structural characteristics, rendering it an optimal selection for the construction sector. The analysis of GPC regarding the strength and durability attributes confirms

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its exceptional performance in terms of chemical and fire resistance when compared to CC[9]. Buildings and infrastructures made by GPC offer environmentally friendly alternatives to CC construction by reducing CO_2 emissions, embodied energy, and the potential for global warming. The increased longevity of these materials also contributes to notable enhancements in design lifespan, thereby reinforcing the principles of sustainable development[10]. Geo-polymers, formed by alkali activation of alumina and silica-rich materials, are eco-friendly, requiring less energy and producing fewer emissions during production[11–14]. The use of alkaline activators notably improves strength development, especially in the early stages[15]. As per the findings of Hamdy K. Shehab *et al.* geopolymer derived from 50% IFA led to increased compressive, splitting tensile, flexural, and bond strengths of concrete[16]. Also, green GPC is both cost-effective and sustainable, making it a versatile choice for various construction projects and exhibiting superior durability using diverse activators with varying concentrations compared to CC[17]. The extended durability characteristics of GPC made from F-class IFA, activated with Na_2SiO_3 and NaOH, exhibited similar outcomes compared to CC[18]. N. Ganesan's[19] research shows that steel fiber-reinforced GPC outperforms CC of similar grade in durability metrics. Steel fibers improve their resistance to cracking, shrinkage, and deformation, leading to enhanced durability, toughness, and resistance to environmental and chemical aggressions. Long-term durability tests reveal increased service life compared to CC, making it a promising alternative for applications where durability is critical[19]. The addition of nanomaterials to geopolymer mortar improves its strength properties. However, it may also reduce the workability and durability parameters, due to modifications in the pore structure and porosity of the mortar. Therefore, careful consideration and optimization of nanomaterials are required to ensure optimal performance for the intended application[20,21]. Furthermore, the amalgamation of silica fume with IFA in GPC enhances mechanical and durability characteristics, while demonstrating favorable performance in challenging environmental conditions[22]. Incorporating PPF into GPC grants the ability to withstand abrasion and erosion, while also enabling it to endure flexure and distortion when subjected to external forces. This indicates that the addition of PPF effectively boosts the material's properties, enhancing its resilience for a wide range of applications[2]. The utilization of a geopolymer earth blend in brick production enhances the robustness and longevity of the bricks, leading to the modernization of earthen architecture. Consequently, this elevates both the strength and durability of the bricks[23]. GPC is an indisputably eco-conscious and sustainable construction material. It substitutes cement with industrial by-products like IFA and slag, incorporating a small amount of alkali activator for the geo-polymerization process. Also, structural elements constructed with GPC outperform those made with OPC when faced with corrosive surroundings[24]. The durability results of fly ash-based GPC reveal that GPC incorporating silica fume exhibits significantly greater resistance to sulfuric acid and chloride solution when compared to the CC[25]. The GPC created by activating F-Class IFA and GGBFS with an alkaline solution demonstrated preferable properties when cured under ambient conditions in comparison to CC. The GPC offers several dominances and can be utilized as a high-performance alternative for structural applications[26]. The GPC formed from IFA and incorporated with the inclusion of higher proportions of silica fume through the application of $NaOH/Na_2SiO_3$, demonstrated enhanced CS, STS, and flexural strength[27]. The analysis indicates that GPC can serve as a substitute for CC due to its superior mechanical properties, enhanced durability, and more favorable structural performance in comparison to CC[28]. Geo-polymer materials present environmental and economic advantages by utilizing waste materials from diverse industries. The durability of concrete is crucial since structures need to withstand a variety of mechanical, physical, and chemical stresses. Ensuring concrete structures possess adequate strength and resilience to maintain their structural integrity and meet service life requirements is crucial. Despite its benefits, the practical application of GPC is significantly restricted. Nevertheless, there is limited and conflicting literature on the durability of PPF reinforcement in different types of GPC compared to OPC. This study aims to examine the strength and durability characteristics of GPC incorporating PPF and compare them to CC.

2.0 Experimental Program

The experimental program and research methodology are explained in Figure 1.

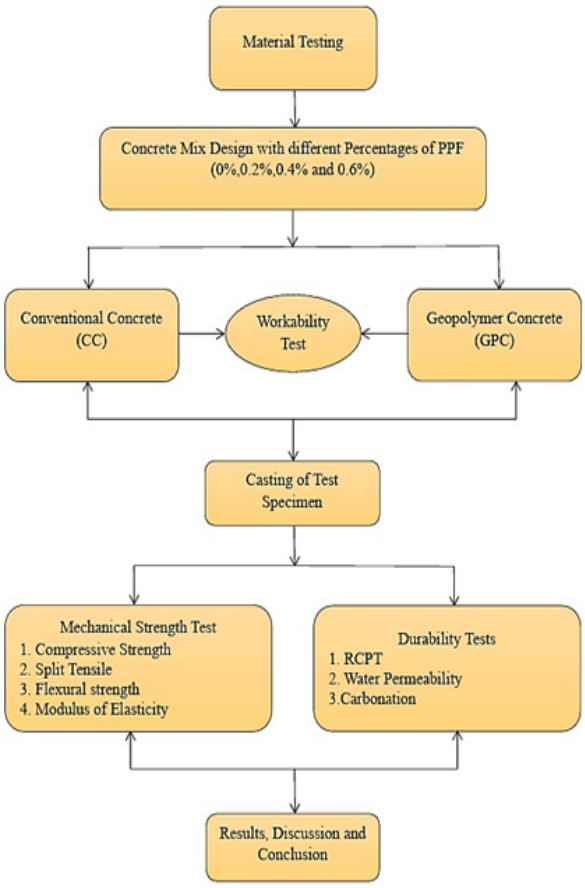


Figure 1. Research Methodology.

2.1 Constituent Components

2.1.1 Cement

The concrete was made using OPC (Ordinary Portland Cement) from Ultratech Cement Ltd., India. The OPC was of 43 grade.

2.1.2 Fly Ash

The study used IFA collected from the Nashik Thermal Power Station in Maharashtra, India. The IFA met all relevant standards for physical properties, as detailed in Table 1.

Table 1. Properties of IFA

Chemical components	Fly-ash %
$SiO_2 + Al_2O_3 + Fe_2O_3$ (min)	90
SiO_2	56
Al_2O_3	30.7
Fe_2O_3	3.3
CaO (max)	5.0
MgO (max)	4.0
SO_3 (max)	2.0
Na_2O (max)	1.5
Physical Properties	
Bulk Weight	The estimated density is 1.0 metric tons per cu m
Specific density	The approximate density is 2.3 metric tons per cu m
Particle size	The maximum amount of residue on a 45-micron sieve is 18%.

2.1.3 Fine and Coarse Aggregates

The qualities of the Fine Aggregate (FA) used in the research were verified following the guidelines specified in the IS2386 code[29]. The FA obtained for the study was

Table 2. Aggregate qualities

Sr. No	Property	CA (20mm)	CA (10mm)	FA
1	Specific gravity	2.63	2.63	2.56
2	Water absorption	0.48%	0.48%	1.20%
3	Fineness modulus	7.54	5.66	3.13
4	Bulk density (kg/m^3)	1560	1478	1675
5	Source	Basalt	Basalt	Basalt

readily accessible and met the grading requirements as per IS 383:2016[30]. Similarly, the Coarse Aggregate (CA) used in the experiment had dimensions of 10mm and 20mm and was easily procured. The qualities and properties of the aggregates are shown in Table 2.

2.1.4 Sodium hydroxide (NaOH)

The NaOH that was used in this work has a high quality with a purity level of 97% in pellet form. The color of the pellets is white, and it has a value of 2.13 specific gravity. The pH is highly alkaline, measuring 14.

2.1.5 Sodium silicate (NA_2SiO_3)

The chemical components of the NA_2SiO_3 solution consist of Na_2O = 13.72%, SiO_2 = 34.16%, and H_2O =52.12%.

2.1.6 Superplasticizer

The Super-Plasticizer (SP) employed in this study is Auramix 500, a high-performance polycarboxylic-based admixture designed for use in the reliability strength of concrete where a low w/c ratio and prolonged workability detention are crucial. The details of the superplasticizer are given in Table 3.

Table 3. Superplasticizer properties

Properties	Description
Appearance	The liquid exhibits a light-yellow hue
pH	Min 6.0
Volumetric mass 20 degrees Celsius	1.100 ± 0.02 kg/liter
Content of alkali	Less than 1.5 g Na_2O equivalent / L of admixture.

2.1.7 Polypropylene Fibers (PPF)

For this experiment, PPF measuring 12 mm in length was utilized. The qualities of the PPF employed are outlined in Table 4.

2.2 Mix Design

The alkaline liquid used for the activation of the IFA was a solution of NA_2SiO_3 and NaOH. The NaOH used was in the form of 97% pure dry pellets of NaOH. In the laboratory, H_2O was added to the NaOH dry pellets to create an 8-molar solution, that consisted of 74% water and approximately 26% NaOH pellets. The CA with 20 mm and 10 mm nominal sizes were used in the investigation. FA was obtained from river sand which was used for the preparation of both CC and GPC. To improve the mixture's workability, an SP with a polycarboxylic base (polycarboxylic-based high-performance superplasticizer) was added. PPF with an aspect ratio of 80 and a length of 12 mm were chosen and sourced locally. OPC (OPC-53 grade) that complies with IS 12269:2013[31] and is produced by Dalmia was used in the investigation. The GPC of grade M40 was formulated based on the guideline given by Rangan[6]. Also, the mix design for M40 grade CC was formulated with the specifications defined in IS 10262-2019[32]. The PPF reinforced GPC by varying the percentage of PPF, SP dosage, and water content. The volume percentages of PPF used were 0.2%, 0.4%, and 0.6%, respectively. Table 5 displays the mix



Figure 2. Casting of specimens.

Table 4. Properties of PPF

Properties	Length	Diameter	Unit weight	Specific gravity	Tensile strength	Modulus of elasticity
Value	12 mm	0.04 mm	9.1 (kN/m^3)	0.9 (g/cm^3)	310 MPa	3.5 GPa

Table 5. Mix Proportions (kg/ (Kg/m^3))

Mix	PPF (%)	IFA	Na_2SiO_3 sol	NaOH sol	CA	FA	Water	SP	Cement
CC	0.00	0.00	0.00	0.00	1068	876	156	0.00	400
GPC1	0.2	408	103	41	1008	840	84.02	8.16	0.00
GPC2	0.4	408	103	41	1008	840	84.02	8.16	0.00
GPC3	0.6	408	103	41	1008	840	84.02	8.16	0.00

proportions for GPC and CC. The samples cast is shown in Figure 2.

2.3 Workability Test

The standard slump cone test as per IS: 7320[33] reaffirmed in 2008 was used to measure the workability of the fresh concrete. Adding PPF slightly decreases the slump value, which is consistent with past studies[34–36]. This reduction is potentially attributed to the phenomenon of fiber balling, where fibers clump together instead of dispersing evenly, hindering their interaction with the cement matrix. Moreover, Excessive PPF content can hinder concrete compaction, negatively impacting its compressive strength. Adding a 1% superplasticizer improves workability and ensures proper compaction.

3.0 Mechanical Tests, Results and Discussion

3.1 CS Test Results

A compression machine was used for CS test. The strength analysis is conducted on standard cube-sized molds after a curing period of 28 days. Compared to CC, GPC1, GPC2, and GPC3 exhibited significant increases in CS of 4.34%, 8.33%, and 10.20%, respectively, after 28 days of curing. This improvement is attributed to the bridging and confinement effect of PPF, which reduces cracking, enhances stiffness, and prevents multiscale crack formation, ultimately leading to higher strength. The CS test setup is shown in Figure 3.



Figure 3. Compressive strength testing.

3.2 STS Test Results

Following IS: 5816-1959[37], individual and average Split Tensile Strength (STS) were measured for cylinders containing varying PPF percentages. Compared to Conventional Concrete (CC) after 28 days, GPC1, GPC2, and GPC3 exhibited significant increases in STS by 13.04%, 18.36%, and 21.56%, respectively. This improvement is attributed to PPF bridging micro-cracks and hindering macro-crack propagation, leading to higher tensile strength at failure.

3.3 MOE Test Results

Stress-strain diagrams generated from compression tests on cylinders yielded the Modulus of Elasticity (MOE) for

Table 6. Fresh Properties (Slump in mm) and hardened Properties (N/mm^2)

Mix	Slump	*CS*	*STS*	*MOE*
CC	125	44	4.00	2.56 x
GPC1	100	46	4.60	3.49 x
GPC2	90	48	4.90	3.52 x
GPC3	80	49	5.10	3.75 x

each specimen, as shown in Table 6. GPC1, GPC2, and GPC3 exhibited MOE increases of 26.64%, 24.27%, and 31.73%, respectively, compared to CC at 28 days. This improvement is attributed to the ability of fibers to bridge and reinforce cracks, enhancing tensile strength and ultimately boosting MOE.

4.0 Durability Tests, Results and Discussion

The durability characteristics of the material were assessed through several tests. In this study, RCPT, water permeability, and carbonation test were performed. The RCPT evaluates the resistance of concrete to chloride ion penetration, which is a common cause of concrete deterioration. The water permeability test assessed the ability of concrete to resist water penetration, which is crucial for ensuring long-term durability. Similarly, the carbonation test examined the resistance of the material to carbonation, which is a chemical process that can lead to concrete degradation. These tests were conducted to evaluate the durability of concrete and provide valuable insights into its performance under various environmental conditions.

4.1 Rapid Chloride Penetrability Test (RCPT) Results

The RCPT was performed by following the ASTM C1202[38] standard. The cylindrical concrete specimens with a diameter of 100 mm and a thickness of 50 mm were taken from the same batch of concrete by cutting with the help of a core cutter. A pair of rubber gaskets with embedded electrodes are used to apply an electrical current to the concrete on each end of the specimen. The



Figure 4. Specimens after core cutting.

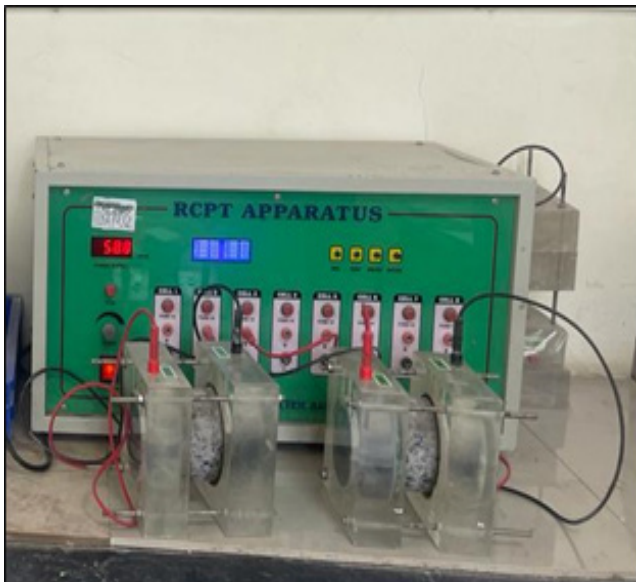


Figure 5. RCPT test.

Table 7. Results of RCPT

Mix	Chloride Penetration depth (cm)	The charge passed (C)	The penetrability of Chloride ion as per ASTM
CC	2.40	1750	Low
GPC1	2.50	1450	Low
GPC2	2.58	1399	Low
GPC3	2.62	1550	Low

specimens after core cutting and the RCPT test setup are illustrated in Figures 4 and 5 respectively. From each mix, three specimens were prepared, with varying percentages of PPF (0.2%, 0.4%, and 0.6%). A 3% NaCl solution was exposed to one face of each specimen, while a 0.3 M NaOH solution was exposed to the other face. The Sealen was used at the ends and sides of the specimens with an appropriate epoxy-based material to prevent any lateral moisture movement during the test. The Total time of the experiment was 6 hours, during which at 30-minute intervals the current between the electrodes was observed. The charge passed during the test is used as an indicator of the concrete's permeability to chloride ions. Lower values of charge indicate lower permeability, while higher values indicate higher permeability. It was observed from Table 7 that the chloride ion penetrability of both GPC and CC was graded as low, following ASTM C1202[38]. This indicates that the inclusion of fibers did not have an unfavorable effect on the chloride resistance of GPC and CC.



Figure 6. Water Permeability Test.

4.2 Water Permeability Test Results

The water permeability test was conducted following the guidelines of IS:516[39] and DIN1048[40] standards. Test specimens of dimension 150x150x150 mm were cured for 28 days and thoroughly dried before the testing. The top surface of each cube was carefully brushed off to ensure a clean and smooth surface for accurate measurements. The specimens were coated with epoxy resin to seal the sides and prevent water penetration. The specimens were subjected to a pressure of 0.5 N/mm^2 for a duration of 72±2 hours. A water tank was connected to the apparatus to maintain the continuous supply of water during the entire duration of the test. After 72 hours, the test specimens were split in a plane perpendicular to the face on which the pressure was applied. The depth of water penetration on each specimen was accurately measured as an indication of the water permeability. The test was conducted at a temperature of 27°C. Considering the potential effect of temperature on the coefficient of permeability, an approximate adjustment was made. It was assumed that the coefficient of permeability increases

Table 8. Results of water permeability.

Mixture no	WPC (x m/s)	Void content (%)
CC	4.10	9.50
GPC1	3.9	12.50
GPC2	2.85	11.30
GPC3	2.45	10.25

Table 9. Results of the carbonation test

Carbonation	PPF	Depth of Carbonation			The average depth of carbonation (mm)
		Cube 1	Cube 2	Cube 3	
CC	0.0%	2.2	2.3	2.3	2.27
GPC1	0.2%	2.1	2.1	2.0	2.07
GPC2	0.4%	1.9	1.9	1.8	1.87
GPC3	0.6%	1.8	1.7	1.8	1.77

by 10% for every 5°C increase in temperature above the standard temperature, and vice versa. The water permeability test results, including the Water Permeability Coefficient (WPC) are presented in Table 8. The water permeability test setup is shown in Figure 6.

4.3 Carbonation Test Results

All samples had been cured for 28 days before the carbonation test. The concrete is exposed to 1% CO_2 for 28 days in a carbonation chamber allowing carbonation to take place. After the carbonation period, the specimen is split by mechanical method to expose the interior and phenolphthalein indicator spray on the interior part of the freshly broken specimen to determine the carbonation depth of each cube specimen. The phenolphthalein solution will turn pink in the presence of uncarbonated concrete (calcium hydroxide) and the uncolored area, which represents the carbonated zone. The carbonation depth of colorless areas of each cube on the interior part was measured with the help of a caliper. The carbonated samples are shown in Figure 7. The average depth value of three cubes is calculated and shown in Table 9. The average carbonation depth of GPC1, GPC2, and GPC3 decreased by 8.81, 17.62, and 22.01 % respectively as compared to CC. The PPF acts as a physical barrier within the concrete, reducing its permeability. As a result, the movement of CO_2 through the concrete is impeded, slowing down the carbonation process. Also, the presence of PPF increases the surface area of the concrete, providing more sites for CO_2 absorption. This can contribute to reducing the concentration of CO_2 that reaches deeper into the concrete.

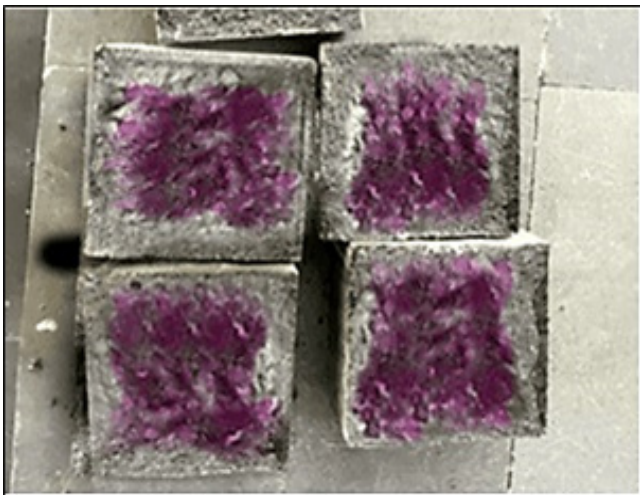


Figure 7. Application of phenolphthalein indicator

5.0 Conclusion

The engineering features of fly ash-based GPC with PPF were evaluated and compared with CC. The mechanical properties of GPC with PPF were evaluated and compared with CC through CS, STS, and MOE. Also, the durability properties of GPC with PPF were evaluated and compared to CC through RCPT, water permeability, and carbonation assessments. Based on the outcomes of the test, the following observations were made.

- PPF significantly enhances the concrete's CS, STS, and MOE through a combined effect of crack bridging, confinement, and improved stiffness. This translates to increased strength and reduced deformation underload. Additionally, PPF minimizes multiscale cracking at various stress levels, further contributing to the overall strength improvement.

- PPF acts as reinforcement and creates a network or framework that hinders the movement of chloride ions through the concrete. This network acts as a physical barrier and restricts the penetration of chlorides, improving the overall resistance to chloride penetration, and resulting in lower charge passed values. In the RCPT test, the penetrability of chloride ions in both GPC and CC are nearly identical.
- The water permeability value decreases with the addition of fibers as well as the void content. The presence of PPF in GPC enhances the overall structure and integrity of the matrix. The PPF creates a network that reinforces the concrete, reducing the size and number of interconnected pores and capillary voids. This improved matrix structure reduces the pathways available for water to flow through, resulting in decreased water permeability.
- The addition of PPF in GPC improves durability by reducing the loss of harmful substances, enhancing crack resistance, increasing strength, and cohesion, and improving resistance to degradation. These factors collectively contribute to a decrease in water permeability, ensuring the long-term durability and performance of the concrete.
- The addition of PPF in GPC leads to a decrease in the depth of carbonation. PPF fibers possess hydrophobic properties, indicating their ability to repel moisture. Moisture plays a significant role in the carbonation process, as it assists in the transportation of carbon dioxide into the concrete. The presence of PPF fibers in GPC helps in enhancing the microstructure of the material.
- Overall, the incorporation of PPF in GPC improves the microstructure, acts as a physical barrier, mitigates cracking, and reduces moisture absorption. These combined effects result in a decreased depth of carbonation, enhancing the durability and long-term performance of the concrete.

Based on the investigation, it can be inferred that GPC with PPF exhibits superior durability and mechanical properties compared to CC of equivalent grade. Furthermore, including PPF enhances the durability attributes of GPC to a greater extent.

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7.0 References

1. Wagale M, Dandin S, Bokil S, Sathe S. Potential use of fly ash in structural fill application: a review. Environ Sci Pollut Res. 2023; 31:90-108. https://doi.org/10.1007/s11356-023-30968-w
2. Sathe S, Patil V. An experimentation on properties of geo-polymer concrete with fibres. Turkish Journal of Computer and Mathematics Education. 2021; 12.
3. Dhalape P, Sathe S, Dekhane C. An experimental study on cement concrete with industrial fly ash and *phosphogypsum*. Mater Today Proc. 2022; 77. https://doi.org/10.1016/j.matpr.2022.11.365
4. Sathe S, Zain Kangda M, Dandin S. An experimental study on rice husk ash concrete. Mater Today Proc. 2023; 77. https://doi.org/10.1016/j.matpr.2022.11.366
5. Dandin S, Kulkarni M, Wagale M, Sathe S. A review on the geotechnical response of fly ash-colliery spoil blend and stability of coal mine dump. Clean Waste Syst. 2022; 3:100040. https://doi.org/10.1016/j.clwas.2022.100040
6. Wallah SE, Rangan BV. Low-calcium fly ash-based geopolymer concrete: long-term properties; 2006. http://hdl.handle.net/20.500.11937/34322
7. Parathi S, Nagarajan P, Pallikkara SA. Ecofriendly geopolymer concrete: a comprehensive review. Clean Technol Environ Policy. 2021; 23(6):1701-13. https://doi.org/10.1007/s10098-021-02085-0
8. Ojha A, Aggarwal P. Fly ash-based geopolymer concrete: a comprehensive review. Silicon. 2022; 14(6):2453-72. https://doi.org/10.1007/s12633-021-01044-0
9. Hassan A, Arif M, Shariq M. A review of properties and behaviour of reinforced geopolymer concrete structural elements: a clean technology option for sustainable development. J Clean Prod. 2020; 245. https://doi.org/10.1016/j.jclepro.2019.118762
10. Ng TS, Voo YL, Foster SJ. Sustainability with ultra-high performance and geopolymer concrete construction. In: Innovative materials and techniques in concrete construction. Springer Netherlands. 2012; 81-100. https://doi.org/10.1007/978-94-007-1997-2_5
11. Shete AM, Patil DSP, Sathe SS. Seismic analysis and design of Pune metro tunnel. Int Res J Eng Technol. 2020. www.irjet.net

12. Rajshekhar G Rathod, Sathe S. The impact of the Golden Quadrilateral project for the location and performance of Indian manufacturing. Int J Eng Res Mech Civ Eng. 2017; 122-9.
13. Kolapkar S, Sathe S. Effect of Sasobit® as a WMA additive on mix design parameters. Mater Today Proc. 2023. https://doi.org/10.1016/j.matpr.2023.03.253
14. Sathe S, Kangda Z, Mate N, Chandraprakash K. Experimental investigation of scouring around circular piers with different opening ratios. Int J Performability Eng. 2022; 18(2):101-7. https://doi.org/10.23940/ijpe.22.02.p4.101107
15. Ryu GS, Lee YB, Koh KT, Chung YS. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. Constr Build Mater. 2013; 47:409-18. https://doi.org/10.1016/j.conbuildmat.2013.05.069
16. Shehab HK, Eisa AS, Wahba AM. Mechanical properties of fly ash-based geopolymer concrete with full and partial cement replacement. Constr Build Mater. 2016; 126:560-5. https://doi.org/10.1016/j.conbuildmat.2016.09.059
17. Indian Standards. IS 2386-4 (1963): Methods of test for aggregates for concrete, Part 4: Mechanical properties; 1963.
18. Indian Standards. IS 383 (2016): Coarse and fine aggregate for concrete—specification. BIS, New Delhi, India; 2016.
19. Indian Standards. IS 12269 (2013): 53 grade ordinary Portland cement; 2013. https://doi.org/10.1016/j.cemconres.2013.06.004
20. Indian Standards. IS 10262 (2019): Concrete mix proportioning—guidelines (second revision); 2019. Available from: www.standardsbis.in
21. Indian Standards. IS 7320 (1974): Specification for concrete slump test apparatus; 1974.
22. American Standards. ASTM C1202-12: Standard test method for electrical indication of concrete's ability to resist chloride ion penetration; 2012. https://doi.org/10.1520/C1202-12
23. Indian Standards. IS 516 (1959): Method of tests for strength of concrete; 1959.
24. German Standards. DIN 1048-5:1991: Testing concrete; testing of hardened concrete; 1991.
25. Okoye FN, Prakash S, Singh NB. Durability of fly ash-based geopolymer concrete in the presence of silica fume. *J Clean Prod.* 2017; 149:1062-7. https://doi.org/10.1016/j.jclepro.2017.02.176
26. Manjunatha GS, Radhakrishna, Venugopal K, Maruthi SV. Strength characteristics of open air cured geopolymer concrete. *Trans Indian Ceram Soc.* 2014; 73(2):149-56. https://doi.org/10.1080/0371750X.2014.923330
27. Okoye FN, Durgaprasad J, Singh NB. Effect of silica fume on the mechanical properties of fly ash-based geopolymer concrete. *Ceram Int.* 2016; 42(2):3000-6. https://doi.org/10.1016/j.ceramint.2015.10.084
28. Ma CK, Awang AZ, Omar W. Structural and material performance of geopolymer concrete: A review. *Constr Build Mater.* 2018; 186:90-102. https://doi.org/10.1016/j.conbuildmat.2018.07.111
29. Indian Standards. *IS 2386-4: Methods of test for aggregates for concrete, Part 4: Mechanical properties;* 1963.
30. Indian Standards. *IS 383: Coarse and fine aggregate for concrete—specification.* Bureau of Indian Standard, BIS, New Delhi, India; 2016.
31. Indian Standards. *IS 12269: 53 Grade Ordinary Portland Cement.* 2013. https://doi.org/10.1016/j.cemconres.2013.06.004
32. Indian Standards. *IS 10262: Concrete mix proportioning—guidelines (Second Revision).* 2019. Available from: www.standardsbis.in
33. Indian Standards. *IS 7320: Specification for concrete slump test apparatus.* 1974.
34. Iyer P, Kenno SY, Das S. Mechanical properties of fiber-reinforced concrete made with basalt filament fibers. *J Mater Civ Eng.* 2015; 27(11). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001272
35. Ayub T, Shafiq N, Nuruddin MF. Effect of chopped basalt fibers on the mechanical properties and microstructure of high-performance fiber-reinforced concrete. *Adv Mater Sci Eng.* 2014; 2014:1-14. https://doi.org/10.1155/2014/587686
36. Wang X, He J, Mosallam AS, Li C, Xin H. The effects of fiber length and volume on material properties and crack resistance of basalt fiber reinforced concrete (BFRC). *Adv Mater Sci Eng.* 2019; 2019:1-17. https://doi.org/10.1155/2019/7520549
37. Indian Standards. *IS 5816: Method of test—splitting tensile strength of concrete.* 1999.
38. American Standards. *ASTM C1202-12: Standard test method for electrical indication of concrete's ability to resist chloride ion penetration.* 2012. https://doi.org/10.1520/C1202-12
39. Indian Standards. *IS 516 (1959): Method of tests for strength of concrete;* 1959.
40. German Standards. *DIN 1048-5: Testing concrete—testing of hardened concrete;* 1991.