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Investigating the Structural Performance of Precast Concrete Pipes with Steel Fiber-Reinforced Geopolymer Concrete

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Abstract

Recent developments in materials science have identified geopolymer as a promising substitute for Ordinary Portland Cement (OPC), with industrial byproducts serving as its primary ingredients. Studies on geopolymer concrete have revealed notable improvements in early strength development and superior resistance to chemical reactions, in contrast to OPC. These properties of geopolymer prefer its use in precast concrete pipes production. This study recognizes the need to interpret the structural response of geopolymer concrete under load-deflection behavior of geopolymer concrete pipes. In collaboration with "Allah Ho Yasir" precast pipe factory located in Lahore, Punjab, Pakistan. R.C.C pipes of 450mm diameter using OPC and GPC were manufactured at industrial scale. For the geopolymer concrete (GPC) locally produced steel fibers are added with the dosage of 30 kg/m³ along with conventional steel cage. These pipes were manufactured by conventional methodology. For structural analysis performed destructive and non-destructive test, were performed. Destructive testing includes compressive strength test, core cutter compressive test, and three-edge bearing test which provided critical insights regarding maximum load-bearing capacity and failure characteristics. The core cutter compressive test was particularly valuable in assessing the in-situ compressive strength of the concrete within the pipes. Additionally, bond strength tests were performed to assess the adhesion between the steel bars and the concrete matrix, which is essential for structural strength of the pipes. Non-destructive testing such as ultrasonic pulse velocity and rebound/Schmidt hammer test, were performed to assess the quality and uniformity of the concrete without causing damage. These combined testing approaches ensured a comprehensive understanding of the mechanical properties, bond strength, and structural strength of the geopolymer concrete pipes, providing its potential application in R.C.C projects.

Index Terms

Unconfined Precast Pipe, Steel Fiber-Reinforced, Geopolymer Concrete.

I. INTRODUCTION

Geopolymer is a cement-free binder made by blending aluminosilicate substances with an alkali, a material is created that closely resembles the hardened form of Ordinary Portland Cement (OPC) but with an 80% lower carbon footprint (Shayan et al., 2014). Aluminosilicate sources include industrial waste products such as ground granulated blast furnace slag (GGBFS), fly ash, clay, and metakaolin. Due to its environmental benefits, extensive research has explored geopolymer's Production techniques, curing parameters, and structural characteristics. Studies highlight its superior compressive and flexural strength and enhanced bonding with steel compared to OPC concrete (Shayan et al., 2014). It also exhibits resistance to sulfate attacks, chloride penetration, and fire, making it suitable for aggressive environments, including precast concrete pipes (Albitar et al., 2017).

Heat curing accelerates polymerization in geopolymer concrete, leading to higher early-age compressive strength, enabling quick formwork removal and increased production efficiency (Shayan et al., 2014). However, traditional geopolymer activation methods require highly concentrated alkali solutions, posing handling challenges. To address this, fly ash/GGBFS-based powder geopolymer binding agent, like geocem, provide more manageable substitute by pre-mixing alkali components in powder form (Zheng et al., 2023).

Several studies focus on reinforced concrete pipes, particularly their behavior under three-edge bearing (TEB) tests. Design parameters like reinforcement configuration, pipe wall thickness, steel, and synthetic fibers have been analyzed. Findings indicate that rotational misorientation of reinforcement cages affects flexural capacity, steel fibers enhance load-bearing capacity and crack resistance, and PVA fibers allow thinner pipe walls for improved flexural performance (Faisal et al., 2023). Despite extensive research on reinforced, synthetic fiber-reinforced, and steel pipes, geopolymer concrete pipes remain underexplored (Ferrado et al., 2016; Kataoka et al., 2017; Mohamed & Nehdi, 2016; Ramadan et al., 2020b).

The use of steel fiber-reinforced geopolymer concrete (SFRGPC) in precast pipe offers an environmentally sustainable, high-strength alternative to conventional pipes. The addition of steel fibers improves Tensile resistance, cracking resistance, and structural robustness, addressing key performance concerns in precast pipes.

This study aims to evaluate the structural characteristics of SFRGPC pipes, particularly their load-bearing capacity, stress distribution, and resistance to cracking under different loading conditions. With increasing infrastructure demands, innovative materials that exceed traditional performance standards are essential, particularly in pipeline systems. The research will analyze the manufacturing process, focusing on steel fiber incorporation and geopolymer mix design. By optimizing geopolymer composition with steel fibers, this study aims to enhance precast pipe performance, contributing to the development of sustainable and durable infrastructure solutions.

II. RESEARCH SIGNIFICANCE AND OBJECTIVES

The objective of this study is to minimize the environmental impact by using geopolymer-based concrete for precast pipes as a sustainable alternative to traditional concrete. Geopolymer concrete, which is derived from industrial by-products like fly ash, offers a greener solution by reducing the reliance on conventional cement, known for its high carbon emissions. The research aims to thoroughly investigate the mechanical properties of geopolymer-based concrete pipes using both destructive and non-destructive testing methods. This will help assess the material's strength, durability, and overall performance in real-world conditions. Furthermore, the inclusion of fly ash in the concrete mix not only improves the material's properties but also plays a vital role in recycling waste from industrial processes, making it an environmentally beneficial choice. By adopting geopolymer concrete for industrial products, there is potential for significant economic advantages, as it lowers production costs while contributing to a more sustainable construction industry. Ultimately, the shift to geopolymer-based concrete has the potential to reduce the environmental

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footprint of construction projects, foster waste management, and support economic growth through more efficient and eco-friendly practices in the building sector.

III. METHODOLOGY

This section discusses the development and evaluation of precast pipes using steel fiber-reinforced geopolymer concrete (SFGPC), covering raw material selection, manufacturing, curing, and transportation. It also details destructive (core cutting, three-edge bearing) and non-destructive (Schmidt hammer, ultrasonic pulse velocity) tests to assess structural integrity, ensuring compliance with sustainable construction standards, as shown in the Figure 1.

IV. MATERIALS

The study will be comprised of using two different comparisons based conventional concrete precast pipes & GPC based steel fiber precast pipes. Fly ash shown in Figure 2 is the raw material selected for the current study, collected from Sahiwal Coal Power Plant, Pakistan. The hub of fly ash production in Pakistan. Sodium Silicate will be purchased from local market, Abkari Road Lahore. This will be preserve in containers to store liquid. Plain Steel Fiber shown in Figure 3 will be procured from local steel market Badami Bagh Lahore, having length of 25mm. Steel Cage will be developed on ASTM Standards (bar size D2) having in diameter 0.160inches. Alkaline activators initiate the geopolymerization process, forming a strong and stable binder. All materials were carefully sourced and stored to maintain consistency and quality in the mix design.

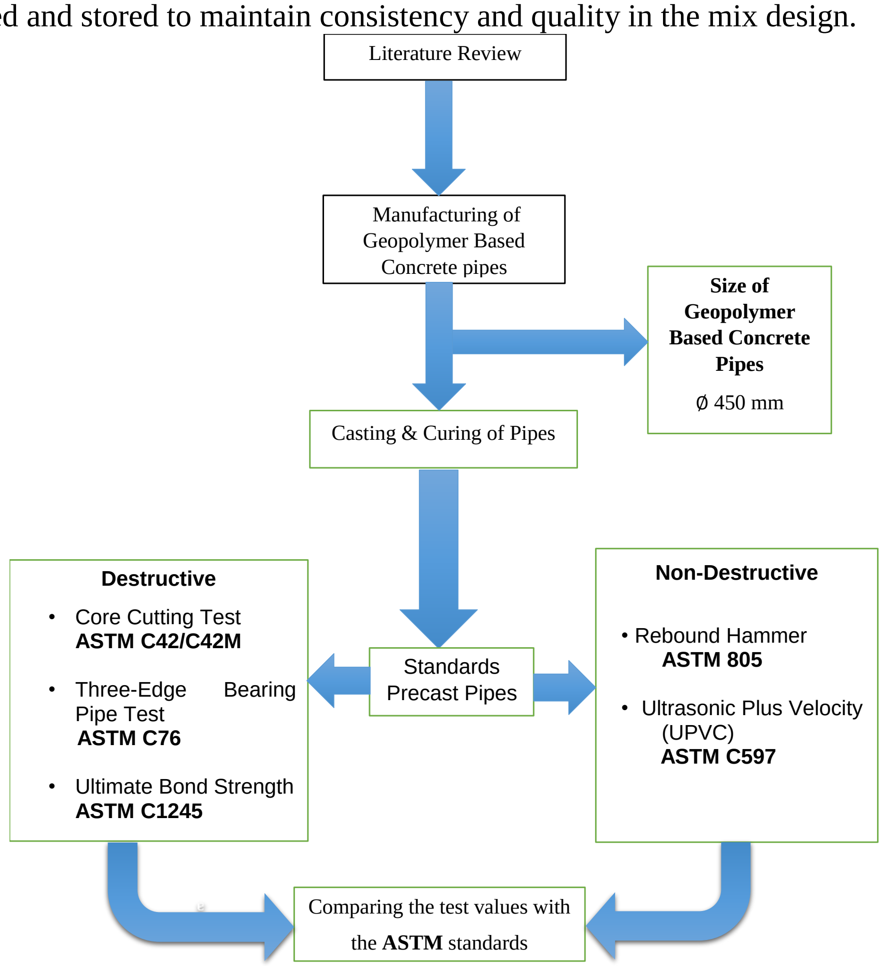

Figure 1: Methodology

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Figure 2: Fly ash for Pipe Manufacturing

V. PREPARATION OF PRECAST PIPES

The production of concrete pipes typically begins with assembling the reinforcement cage, if required. In a concrete pipe facility, the most frequently used equipment for constructing these cages includes cage machines, mandrels, and wire winding devices. Depending on the pipe's diameter, wall thickness, and the necessary structural integrity, a concrete pipe may incorporate up to three steel reinforcement cages. Worldwide, there are five main techniques employed in the manufacturing of concrete pipes. Four of these methods involve mechanical processes to insert and compact a low-moisture concrete blend into the mould. These include

Figure 3: Steel fibres used in GPC-SF30

centrifugal, dry cast with vibration, packer head, tamping, and wet casting techniques. The fifth approach—the wet cast method—utilizes a more traditional wet concrete mixture and pouring process. In the dry cast with vibration technique, the moulding system comprises an inner core and an outer shell.

VI. TESTING ON PRECAST PIPES

The testing of SFGPC (Steel Fiber-Reinforced Geopolymer Concrete) pipes is crucial to ensure their structural integrity, quality, and compliance with relevant standards. The testing process typically involves a combination of destructive and non-destructive methods. Here are some common tests conducted on GPC-SF30 pipes.

VII. RESULTS AND DISCUSSION

A. Workability Test

Slump test is a straightforward technique used to evaluate the flow ability and uniformity of freshly mixed concrete by measuring its height change after removal from a conical mold. It ensures the mix has the right fluidity for proper placement, compaction, and finishing without segregation or bleeding. The results help refine the mix design for better performance in construction projects. The slump test values are given in Table 1 and slump test graph are shown in the Figure 4 and Figure 5 respectively.

Table 4.1: Slump test value

Sr. No	**Slump Valve (mm) (OPC)**	**Slump Valve (mm) (GPC-SF30)**
1	33	35

B. Non-distructive Test

a) Rebound Hammer

The Rebound/Schmidt Hammer test is widely used non-destructive testing (NDT) technique to evaluate the compressive strength of concrete structures, including precast concrete pipes. During this test, a spring-driven hammer strikes the surface, and the rebound distance is measured. This rebound index correlates with the concrete's compressive strength. The test is performed at multiple points along the pipe’s surface to ensure a comprehensive strength evaluation. The Rebound Hammer test is quick, cost-effective, and provides immediate results, helping to evaluate the uniformity and quality of the concrete without causing damage. The compressive strength of precast concrete pipes, both GPC and OPC, presented in Figure 6 for the outer surface. Each value represents the average of 15 readings with a coefficient of variation of less than 3%.

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Figure 4: Slump test

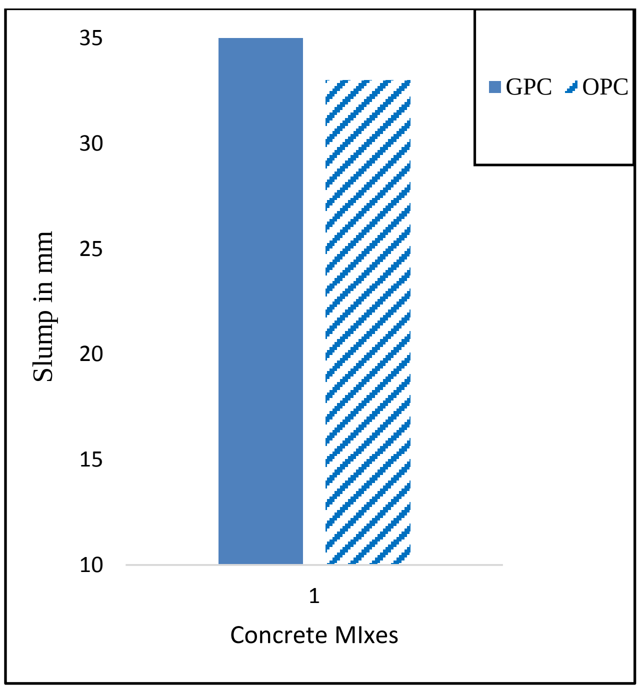

Figure 5 : Slump graph of GPC-SF30 and OPC

The pipe was divided into six longitudinal profiles, and compressive strength variations were observed along the circumference and length. The compressive strength of the GPC precast pipe ranged between 28 MPa and 32.5 MPa, while for OPC pipes, it varied between 26 MPa and 27 MPa. The pipe was divided into grids, with the Y-axis labeled numerically and the X-axis labeled alphabetically. Each grid contained 15 readings, and the average compressive strength was calculated, which is presented in the respective Table 2 for the outer surface.

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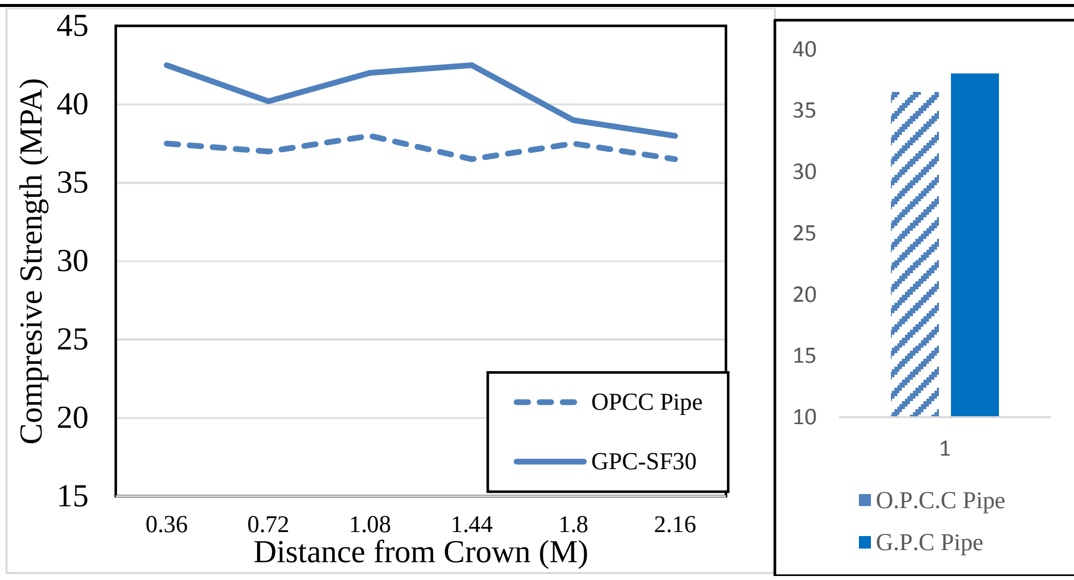


Figure 6: NDT graph of outer surface of GPC-SF30 and OPC pipe

Table 2 : Outer walls compressive strength

Outer Walls Compressive Strength (MPa)						
	AB	**BC**	**CD**	**DE**	**EF**	**FG**
0-1	38.0	39.0	42.0	42.0	40.2	42.5
1-2	41.0	40.2	42.0	39.0	42.0	42.5
2-3	41.0	40.2	42.5	41.5	41.5	41.0
3-4	42.0	39.0	42.5	40.2	42.0	43.0
4-5	42.0	43.0	42.0	41.5	42.0	42.0
5-0	43.0	40.2	42.0	41.0	43.0	43.0

Figure 7: Core samples for pulse velocity test

a) Ultrasonic Pulse Velocity Test

The Ultrasonic Pulse Velocity (UPV) test is a non-destructive technique used to assess concrete quality by detecting internal flaws, cracks, and segregation. Higher pulse velocities indicate better uniformity and strength. Results show that GPC-SF30 concrete has higher pulse velocity and compressive strength than OPC, confirming superior durability and structural integrity. For the conductance of Ultrasonic Pulse Velocity (UPV) test cores were extracted from pipes having diameter of 50mm and length of 75mm as shown in Figure 7. The pulse velocity range and compressive strength profile of OPC and GPC-SF30 are presented in the following Table 3 and Table 4. The ultrasonic pulse velocity and compressive strength of concrete samples are shown in the Figure 8, providing a comparison between OPC and GPC-SF30.The comparison of compressive strength and UPV between GPC-SF30 and OPC concrete is illustrated in the Figure 9, highlighting the variations in strength.

Table 3: Pulse velocity range

Pulse Velocity (km/sec)	**Concrete Quality**
> 5.5	Excellent
3.5 – 5.5	Good
3 - 3.5	Medium
< 3	Doubtful

Table 4: Ultrasonic pulse velocity and compressive strength of concrete samples

Concrete Type	Sr No	Time (µs)	length (m)	Velocity (m/sec)	Compressive Strength (MPa)	Quality
OPC	1	67	0.3	5074	29.32	Good

	2	68	0.3	5021	28.82	Good
	3	66.3	0.3	5047	29.07	Good
GPC-SF30	1	64	0.3	5289	31.37	Good
	2	63	0.3	5250	31.00	Good
	3	63,2	0.3	5263	31.12	Good

C. Destructive Test

a) Ultimate Bond Strength Test

The Ultimate Bond Strength Test measures how well concrete adheres to reinforcing steel bars by determining the force needed to break the bond. A stronger bond improves structural safety and durability. As shown in the Table 4.5, plain concrete has a bond stress of 1.5–2.5 MPa, geopolymer concrete (GPC) ranges from 2–3 MPa, and GPC with 30% steel fibers (GPC-SF30) achieves the highest bond stress of 3–4 MPa. This confirms that adding steel fibers enhances bond strength with reinforcing bars.

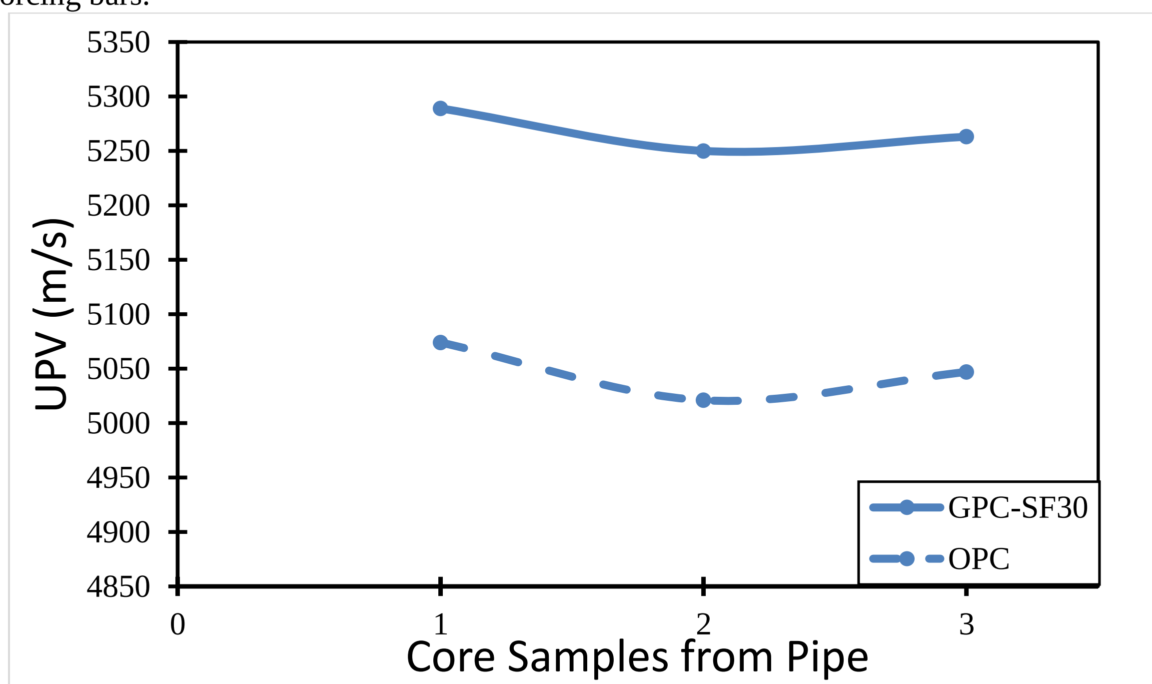
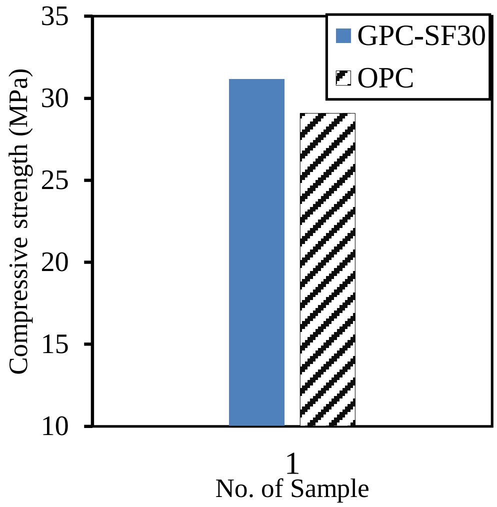


Figure 8: UPV compressive strength profile of OPC and GPC-SF30



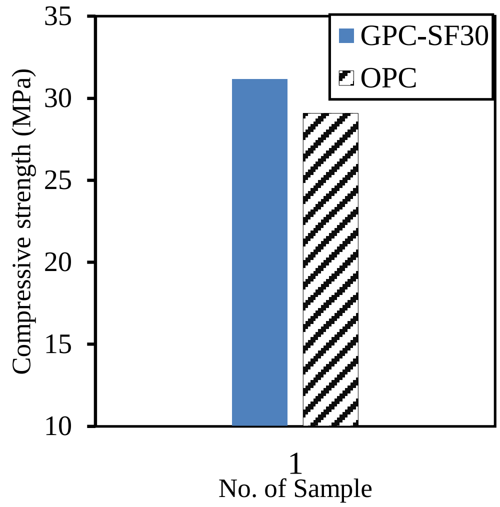


Figure 9: Comparison of compressive strength and UPV GPC-SF30 with OPC concrete.

The range of bond strength test results is illustrated in Figure 4.8 (a) presents the demolding process, ensuring uniform sample preparation before further testing. After demolding, the curing of cylindrical samples was carried out, as depicted in Figure 4.8 (b), the relationship between bond stress and slip of concrete samples is presented in Table 4.6, while Figure 4.9 compares the bond strength of GPC-SF30, GPC, and OPC.

b) Three Edge Bearing Test

The Three-Edge Bearing Test evaluates the structural integrity of precast concrete pipes by applying a load after 28 days of casting, following CSA A257 or ASTM C76 standards. Test results indicate that GPC-SF30 pipes have higher proof stress (813 lb/ft/ft) and ultimate stress (1441 lb/ft/ft) compared to OPC pipes (769 lb/ft/ft and 1334 lb/ft/ft, respectively). This demonstrates that GPC-SF30 offers superior load-bearing capacity and structural integrity. Additionally, the figure highlights crack patterns observed after testing.

c) Compressive Strength of Core

The core sample comparison shows that GPC-SF30 concrete pipes have 4.5% higher compressive strength than OPC pipes. In the compression test, specimens were loaded at a constant rate using a Universal Testing Machine to determine cracking and ultimate load capacity. Results indicate that GPC-SF30 achieved an average compressive strength of 27.12 MPa, compared to 26.66 MPa for OPC, confirming its superior load-bearing performance.

VIII. CONCLUSIONS

Geopolymer concrete (GPC) precast pipes offer several advantages over ordinary Portland cement (OPC) pipes, including reduced weight, improved mechanical performance with steel fiber reinforcement, and better bond strength. Various tests confirm their structural integrity, strength, and environmental benefits.

GPC pipes are 8–10% lighter than OPC pipes, making them easier to handle and transport. The use of steel fibers alone showed poor structural performance, but when combined with a conventional steel cage, it improved crack resistance and mechanical strength. Spun-cast fiber-reinforced concrete (SFRC) pipes met the strength requirements of ASTM C76 Class III.

The Rebound Hammer Test showed that GPC-SF30 pipes had higher external compressive strength than OPC pipes, with an average rebound number of 29 and minimal variation due to uniform concrete settling. The Ultrasonic Pulse Velocity (UPV) Test confirmed that the compressive strength of both GPC-SF30 and OPC pipes was within ASTM C597 limits. Bond tests further demonstrated that GPC-SF30 had a higher bond capacity, ensuring better reinforcement performance.
The Three-Edge Bearing Test conducted on 450 mm diameter pipes with 30 kg/m³ steel fiber classified GPC-SF30 as Class III, with values within the required range. Additionally, GPC pipes contribute to environmental sustainability by reducing water usage, accelerating strength gain, and lowering cement consumption.

REFERENCE

Albitar, M., Mohamed Ali, M. S., Visintin, P., & Drechsler, M. (2017). Durability evaluation of geopolymer and conventional concretes. Construction and Building Materials, 136, 374–385. https://doi.org/10.1016/J.CONBUILDMAT.2017.01.056

Faisal, A., Abbas, S., & Ahmed, A. (2023). Mechanical performance of spun-cast full-scale precast pipes incorporating hybrid conventional rebar cage and steel fibers. Structures, 52(April), 104–116. https://doi.org/10.1016/j.istruc.2023.03.176

Habert, G., D'Espinose De Lacaillerie, J. B., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: Reviewing current research trends. Journal of Cleaner Production, 19(11), 1229–1238. https://doi.org/10.1016/J.JCLEPRO.2011.03.012

Hassan, A., Arif, M., & Shariq, M. (2020). A review of properties and behaviour of reinforced geopolymer concrete structural elements- A clean technology option for sustainable development. Journal of Cleaner Production, 245. https://doi.org/10.1016/j.jclepro.2019.118762

Shayan, A., Xu, A., & Andrews-Phaedonos, F. (2014). Investigation of a geopolymer concrete used in retaining walls of a bridge. 36th International Conference on Cement Microscopy 2014, January 2014, 584–601.

Zheng, J., Qi, L., Zheng, Y., & Zheng, L. (2023). Mechanical properties and compressive constitutive model of steel fiber-reinforced geopolymer concrete. Journal of Building Engineering, 80, 108161. https://doi.org/10.1016/j.jobe.2023.108161

P. Rovnaník, "Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer," Constr. Build. Mater., vol. 24, no. 7, pp. 1176–1183, Jul. 2010, doi: 10.1016/J.CONBUILDMAT.2009.12.023.

A. Palomo, M. W. Grutzeck, and M. T. Blanco, "Alkali-activated fly ashes: A cement for the future," Cem. Concr. Res., vol. 29, no. 8, pp. 1323–1329, Aug. 1999, doi: 10.1016/S0008-8846(98)00243-9.

I. McKechnie, G. G. Singh, T. J. Braje, and B. Campbell, "Measuring Mytilus californianus: an Addendum to Campbell and Braje (2015) and Singh and McKechnie (2015) including commentary and an integration of data," J. Archaeol. Sci., vol. 58, pp. 184–186, Jun. 2015, doi: 10.1016/J.JAS.2015.03.011.

P. Rovnaník, "Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer," Constr. Build. Mater., vol. 24, no. 7, pp. 1176–1183, Jul. 2010, doi: 10.1016/J.CONBUILDMAT.2009.12.023.

P. D. Chimane, S. L. Hake, and M. N. Shirsath, “Investigation on Membrane Cured Geopolymer Concrete- Review,” vol. 5, no. 4, pp. 20–23, 2017.

“C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.” Accessed: Aug. 12, 2024. [Online]. Available: https://www.astm.org/c0618-15.html

H. Guo, N. T. Ingolia, J. S. Weissman, and D. P. Bartel, “Mammalian microRNAs predominantly act to decrease target mRNA levels,” Nat. 2010 4667308, vol. 466, no. 7308, pp. 835–840, Aug. 2010, doi: 10.1038/nature09267.

G. Habert, J. B. D’Espinose De Lacaillerie, and N. Roussel, “An environmental evaluation of geopolymer based concrete production: reviewing current research trends,” J. Clean. Prod., vol. 19, no. 11, pp. 1229–1238, Jul. 2011, doi: 10.1016/J.JCLEPRO.2011.03.012.

J. Davidovits, “Geopolymers - Inorganic polymeric new materials,” J. Therm. Anal., vol. 37, no. 8, pp. 1633–1656, Aug. 1991, doi: 10.1007/BF01912193.

Q.-J. Wen, H.-W. Jing, S. Sanda, and S.-S. Zhuang, “Experimental Investigation of Mechanical Properties of Centrifugal Concrete in Circular Pipes,” J. Mater. Civ. Eng., vol. 29, no. 4, 2017, doi: 10.1061/(asce)mt.1943-5533.0001771.

L. S. Wong and M. L. Nehdi, “Critical analysis of international precast concrete pipe standards,” Infrastructures, vol. 3, no. 3, pp. 1–25, 2018, doi: 10.3390/infrastructures3030018.

B. Rangan and D. Hardjito, “Studies on fly ash-based geopolymer concrete,” Proc. 4th World …, no. November, 2005, [Online].

P. Chindaprasirt, S. Homwuttiwong, and C. Jaturapitakkul, “Strength and water permeability of concrete containing palm oil fuel ash and rice husk-bark ash,” Constr. Build. Mater., vol. 21, no. 7, pp. 1492–1499, Jul. 2007, doi: 10.1016/J.CONBUILDMAT.2006.06.015.

C. Montes, R. Islam, J. Shi, K. Kupwade-Patil, and E. N. Allouche, “Towards a pre-cast geopolymer concrete pipe,” Pipelines 2013 Pipelines Trenchless Constr. Renewals - A Glob. Perspect. - Proc. Pipelines 2013 Conf., pp. 534–542, 2013, doi: 10.1061/9780784413012.049.