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Mechanical Behavior of Fiber-Reinforced Slag-Based Hybrid-Geopolymer Composite

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ABSTRACT: This project investigates steel fibre-reinforced slag-based geopolymer concrete as a sustainable alternative to conventional Ordinary Portland Cement (OPC) concrete to address high carbon emissions and inherent brittleness in construction materials. The study will develop a geopolymer binder using ground granulated blast furnace slag (GGBS) and fly ash activated by alkaline solutions (sodium hydroxide and sodium silicate), steel fibres at 0.5% and 1.0% volume fractions. Experimental work will involve designing M40 grade mixes, casting standard cube specimens, and evaluating compressive strength development at 7, 28, and 56 days. The research aims to quantify mechanical performance improvements from fibre reinforcement, assess workability and compaction effects at varying fibre contents, and conduct comparative analysis against OPC concrete. Through systematic testing and analysis, this project seeks to establish fibre-reinforced geopolymer concrete as a viable, high-performance material that enhances ductility via crack-bridging mechanisms while reducing environmental impact through industrial by-product utilization, thereby contributing to sustainable infrastructure solutions.

KEYWORDS: Geopolymer Concrete; GGBS; Fly Ash; Steel Fiber Reinforcement; Compressive Strength

I. INTRODUCTION

Concrete is the most widely used construction material in the world and plays a vital role in the development of modern infrastructure. Buildings, bridges, highways, dams, and industrial structures depend heavily on concrete because of its strength, durability, and ease of construction. Ordinary Portland Cement (OPC) is the primary binding material used in conventional concrete. However, the rapid growth of the construction industry has resulted in a significant increase in cement consumption, raising concerns about its environmental impact. The manufacturing of OPC requires large amounts of raw materials and energy, while also releasing substantial quantities of carbon dioxide (CO₂) into the atmosphere. It is estimated that the cement industry contributes nearly 8% of global CO₂ emissions, making it one of the major contributors to climate change and global warming. In recent years, researchers have focused on developing sustainable alternatives to conventional cement-based concrete. One of the most promising alternatives is Geopolymer Concrete (GPC). The concept of geopolymer was first introduced by Davidovits in 1978. Geopolymer concrete is produced using industrial by-products rich in silica and alumina instead of Portland cement. Common source materials include Fly Ash (FA) obtained from thermal power plants and Ground Granulated Blast Furnace Slag (GGBS) obtained from the iron and steel industry. These materials react with alkaline activator solutions such as sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) to form a strong binder through a process known as geopolymerization. The use of fly ash and GGBS in geopolymer concrete provides dual benefits. First, it reduces the disposal problems associated with industrial waste materials. Second, it significantly lowers the carbon footprint of concrete production by reducing or eliminating the need for OPC. Several studies have reported that geopolymer concrete can reduce greenhouse gas emissions by up to 80% compared to conventional concrete. In addition, geopolymer concrete exhibits excellent mechanical strength, low permeability, good resistance to chemical attack, and superior durability in aggressive environments. These characteristics make it a suitable material for sustainable construction and infrastructure development. Among the various geopolymer source materials, the combination of fly ash and GGBS has gained considerable attention. Fly ash contributes to long-term strength development and sustainability, while GGBS improves early-age strength and allows curing under normal ambient conditions. The presence of calcium in GGBS accelerates the geopolymerization process and enhances the formation of binding gels, resulting in improved mechanical performance. Therefore, a blended fly ash–GGBS geopolymer system offers a practical solution for producing high-strength concrete without requiring elevated-temperature curing. Despite these advantages, geopolymer concrete still exhibits a brittle

nature similar to conventional concrete. Although it can achieve high compressive strength, its tensile and flexural strengths are relatively low. Once cracks develop, they may propagate rapidly, leading to sudden failure. To overcome this limitation, fibers can be incorporated into the concrete matrix. Among the different types of fibers available, steel fibers are widely used because of their high strength, stiffness, and excellent crack-bridging ability. Steel fibers help control crack propagation, improve energy absorption capacity, and enhance post-cracking behavior. As a result, the toughness, ductility, impact resistance, and overall structural performance of geopolymer concrete can be significantly improved. The incorporation of steel fibers in geopolymer concrete combines the environmental advantages of GPC with the mechanical benefits of fiber reinforcement. Such a combination has the potential to produce a sustainable and high-performance construction material suitable for modern engineering applications. However, a detailed comparison between conventional OPC concrete and steel fiber-reinforced geopolymer concrete is necessary to evaluate their relative performance and practical applicability. Therefore, the present study aims to compare the properties of Ordinary Portland Cement concrete and Geopolymer Concrete prepared using fly ash, GGBS, alkaline activators, and steel fibers. The investigation focuses on evaluating key mechanical properties such as compressive strength, split tensile strength, and flexural strength. The study also examines the effectiveness of steel fibers in improving the performance of geopolymer concrete. The findings of this research are expected to contribute to the development of environmentally sustainable and structurally efficient concrete materials for future construction practices.

II. LITERATURE REVIEW

Several researchers have investigated the mechanical performance of fibre-reinforced geopolymer concrete using different fibres, binder systems, and reinforcement techniques. Previous studies have shown that fibres significantly improve tensile strength, flexural strength, toughness, and crack resistance, making geopolymer concrete a promising sustainable alternative to conventional OPC concrete.

Ahmed H. U. (2023)

Ahmed H. U. studied the effect of steel and polypropylene fibres on fly ash–slag based geopolymer concrete. The research evaluated workability, compressive strength, tensile strength, and flexural strength. The study found that steel fibres significantly improved strength, while polypropylene fibres effectively controlled shrinkage cracks. The hybrid fibre combination produced the best overall performance, highlighting the importance of fibre interaction and bond characteristics.

Adesina A. S. (2022)

Adesina reviewed the mechanical performance of fibre-reinforced geopolymer composites using metallic, synthetic, and natural fibres. The study emphasized that fibres improve toughness, fracture energy, and post-cracking behavior. The review concluded that the fibre–matrix bond is the most important factor affecting performance. Steel fibres showed the greatest improvement in flexural strength, while synthetic fibres enhanced energy absorption capacity.

Zhang P. and Wang K. (2021)

Zhang and Wang investigated slag-based geopolymer composites reinforced with carbon nanotubes and steel fibres. The study focused on microstructural development and mechanical properties. Results showed that carbon nanotubes improved matrix density and compressive strength, while steel fibres increased toughness and flexural strength. The research demonstrated that multi-scale reinforcement can effectively improve both strength and ductility in geopolymer composites.

Al-Mashhadani M. M. (2020)

Al-Mashhadani evaluated geopolymer composites reinforced with steel and polyvinyl alcohol fibres. The study analyzed compressive strength, flexural behavior, and fracture toughness. Results indicated that steel fibres provided greater strength enhancement, whereas PVA fibres improved ductility and crack control. The research concluded that proper fibre selection can significantly improve the mechanical performance of geopolymer concrete.

Noushini A. and Hastings (2019)

Noushini and Hastings investigated the flexural toughness and fracture properties of steel fibre-reinforced slag-based geopolymer concrete. The study revealed that steel fibres transformed the brittle geopolymer matrix into a more ductile material. Significant improvements in fracture energy, toughness, and residual strength were observed. The research confirmed that fibre pull-out mechanisms play a major role in increasing energy absorption capacity.

Behfarnia K. and Rostami M. (2018)

Behfarnia and Rostami examined the influence of steel fibres on geopolymer concrete performance. The study reported notable improvements in tensile and flexural strength due to crack-bridging action provided by steel fibres. The researchers concluded that steel fibres enhance ductility and delay crack propagation, resulting in improved structural performance and durability of geopolymer composites.

Al-Majidi M. H. and Cundy A. B. (2017)

Al-Majidi and co-researchers studied steel fibre reinforced geopolymer concrete with improved microstructure and fibre-matrix interaction. The findings showed that steel fibres enhanced tensile strength, toughness, and crack resistance. Improved bonding between fibres and the geopolymer matrix contributed to better stress transfer. The study concluded that steel fibres are highly effective in overcoming the brittle nature of geopolymer concrete.

Bernal S. A. and Provis J. L. (2015)

Bernal and Provis reviewed engineered cementitious composites based on geopolymer matrices. The study focused on achieving high ductility through fibre reinforcement. Results showed that properly designed geopolymer composites can develop multiple micro-cracks instead of sudden failure. The research concluded that geopolymer-based ECC materials offer excellent strain capacity and can serve as durable alternatives to conventional concrete systems.

Puertas F., Amat T. and Fernández-Jiménez (2014)

Puertas and co-authors investigated alkaline-activated slag mortars reinforced with polypropylene fibres. The study evaluated mechanical and durability performance. The results demonstrated improved crack control, flexural strength, and impact resistance. Although compressive strength gains were limited, the fibres effectively reduced shrinkage-related cracking. The study highlighted the importance of fibres in improving long-term durability.

N. Ganesan, P. V. Indira and A. Santhakumar (2013)

Ganesan and colleagues studied the engineering properties of steel fibre reinforced geopolymer concrete. The research focused on strength and structural performance. Experimental results showed improvements in compressive, tensile, and flexural strength with fibre addition. The study concluded that steel fibres significantly enhance toughness and ductility, making geopolymer concrete more suitable for structural applications requiring improved crack resistance.

III. MATERIALS AND TESTING

The performance of concrete is greatly influenced by the quality and characteristics of its constituent materials. Therefore, before the preparation of concrete mixes, all materials used in this study were subjected to standard laboratory tests to evaluate their physical properties and suitability for concrete production. The testing program included the assessment of cement, fine aggregate, coarse aggregate, fly ash, GGBS, and alkaline activators. The obtained properties were used for mix design calculations and to ensure consistency, reliability, and accuracy in the experimental investigation.

1. GGBS

Ground Granulated Blast Furnace Slag (GGBS) is a by-product obtained during the manufacture of iron in a blast furnace. It is rich in calcium, silica, and alumina, making it suitable for geopolymer concrete production. In this study, GGBS was used as a binder material to enhance strength and durability.

Table No. 1 Chemical properties

Chemical Compositon	% By Mass
CaO	45%
SiO ₂	38%
Al ₂ O ₃	16%
MgO	12%
Fe ₂ O ₃	1.5%
SO ₃	2.0%
Na ₂ Oeq	1.0%

Table No. 2 Physical properties

PROPERTIES	RESULTS
Specific gravity	3.09
Consistency	29%
Initial Setting Time	160 min
Final Setting Time	270 min
Fineness	96.8%

2. Fly Ash

Fly ash is a fine powder obtained as a by-product from coal-fired thermal power plants. It is rich in silica and alumina. In this study, Class F fly ash was used as a partial binder material along with GGBS to promote geopolymerization and improve the sustainability of concrete production. The material conforms to IS 3812 (Part 1): 2013.

Table No. 3 Properties of fly ash

PROPERTIES	RESULTS
Specific gravity	2.2
Consistency	28%
Initial Setting Time	285
Final Setting Time	350

3. Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used in the preparation of conventional concrete mixes. OPC 53 grade is widely used in structural construction due to its high early strength, good durability, and reliable performance.

Table No. 4 Properties of cement

PROPERTIES	RESULTS
Specific gravity	3.13
Consistency	29%
Initial Setting Time	160
Final Setting Time	270
Fineness	94.2%

4. Fine Aggregate

Fine aggregate is an essential constituent of concrete that fills the voids between coarse aggregate particles and improves the workability of the mix. In this study, natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate.

Table No. 5 Properties of fine aggregate

PROPERTIES	RESULTS
Particle size	4.75 mm
Silt content	1.67%
Specific gravity	2.71
Water absorption	3.14
Bulking of sand	4.19%
Bulk density	1793 kg/m ³
Fineness modulus	94.2%

5. Coarse Aggregate

Coarse aggregate forms the main structural framework of concrete and contributes significantly to its strength and durability. The angular shape and rough surface texture of the aggregates provide better interlocking and bonding with the concrete matrix. The coarse aggregate used conforms to IS 383:2016.

Table No. 6 Properties of coarse aggregate

PROPERTIES	RESULTS
Specific Gravity	2.90
Water Absorption	1.80 %
Flakiness Index	8.90 %
Elongation Index	10.85 %
Aggregate Impact Value	11.66 %
Specific Gravity	2.90
Water Absorption	1.80 %

6. Steel Fibre

Steel fibres are short, discrete reinforcing elements randomly distributed throughout the concrete matrix to improve its tensile strength, toughness, and crack resistance. In this study, steel factory crushed fibres were incorporated into geopolymer concrete to reduce brittleness and enhance post-cracking behavior.

Table No. 7 Properties of steel fibre

Properties	Results
Length	<10 mm
Width	0.45 mm

7. Water

Water is an essential ingredient in concrete production and is used for mixing and curing purposes. In this study, clean potable water free from harmful impurities was used for the preparation of both OPC and geopolymer concrete mixes. The water used conforms to the requirements of IS 456:2000.

8. Plasticizer

A plasticizer is a chemical admixture used to improve the workability and flowability of concrete without increasing the water content. In this study, a superplasticizer was added to achieve proper consistency and uniform mixing of the geopolymer concrete.

9. Sodium Hydroxide (NaOH)

Sodium hydroxide (NaOH), commonly known as caustic soda, is an alkaline activator used in geopolymer concrete. It helps dissolve silica and alumina present in fly ash and GGBS, initiating the geopolymerization process. In this study, sodium hydroxide solution was prepared at the required molarity and used as part of the alkaline activator system.

10. Sodium Silicate (Na₂SiO₃)

Sodium silicate (Na₂SiO₃), commonly known as water glass, is an alkaline solution used along with sodium hydroxide in geopolymer concrete. It provides additional silica, which enhances the geopolymerization reaction and improves the strength and durability of the concrete. In this study, sodium silicate solution was used as a component of the alkaline activator.

IV. MATERIALS AND METHODOLOGY

The present study was carried out to compare the compressive strength performance of Ordinary Portland Cement (OPC) concrete and Steel Fibre Reinforced Geopolymer Concrete (GPC). Initially, all constituent materials including OPC, fly ash, Ground Granulated Blast Furnace Slag (GGBS), fine aggregate, coarse aggregate, sodium hydroxide, sodium silicate, steel fibres, water, and superplasticizer were collected and tested for their physical properties in accordance with

relevant Indian Standards. The OPC concrete mix was designed as per IS 10262:2019, while the geopolymer concrete mix was prepared using fly ash and GGBS as binder materials activated by sodium hydroxide and sodium silicate solutions. Two geopolymer concrete mixes containing 0.5% and 1.0% steel fibres were developed for the investigation. The materials were weighed according to the designed mix proportions and thoroughly mixed to obtain a homogeneous concrete mixture. Standard cube specimens of size 150 mm × 150 mm × 150 mm were cast for each mix. After casting, the specimens were properly cured under laboratory conditions for predetermined curing periods of 7, 28, and 56 days.

The compressive strength test was conducted using a Compression Testing Machine (CTM) in accordance with IS 516:2018. The test results obtained for OPC concrete and geopolymer concrete mixes were analyzed and compared to evaluate the effect of steel fibres on the strength performance of geopolymer concrete.

Mix Design-

The Ordinary Portland Cement (OPC) concrete mix was designed for M40 grade concrete in accordance with IS 10262:2019 and IS 456:2000. Ordinary Portland Cement was used as the primary binder, while fine aggregate and coarse aggregate were used as filler materials. Water and superplasticizer were added to achieve the required workability and strength. The mix was prepared, cast into standard cube specimens, cured under normal conditions, and tested for compressive strength at different curing ages.

Mix Design Ordinary Portland Cement (OPC) Concrete

Ordinary Portland Cement (OPC) concrete is the most widely used construction material due to its good strength, durability, and ease of production. It is prepared by mixing cement, fine aggregate, coarse aggregate, and water in suitable proportions. In this study, M40 grade OPC concrete was used as the control mix for comparison with geopolymer concrete. The concrete mix was designed in accordance with IS 10262:2019 and IS 456:2000.

Table No. 8 Quantities for 9 cubes of OPC batch

MATERIAL	QUANTITY (KG)
Cement (OPC)	20.25
Fine Aggregate	34.36
Coarse Aggregate (10 mm)	18.26
Coarse Aggregate (20 mm)	34.11
Admixture	0.203

Mix Design of Geopolymer Concrete with 0.5% Steel Fibre

The geopolymer concrete mix containing 0.5% steel fibre was prepared using fly ash and GGBS as the binder materials. Sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solutions were used as alkaline activators to initiate the geopolymerization process. Fine aggregate, coarse aggregate, water, and superplasticizer were incorporated in the required proportions. Steel fibres were added at 0.5% by volume of concrete to improve crack resistance and ductility. The mix was cast into standard cube specimens and cured under ambient laboratory conditions before testing.

Table No. 9 Quantities of 9 cubes of GPC batch

Material	Quantity (kg)
Fly Ash	6.21
GGBS	28.98
OPC	6.21
Fine Aggregate	68.72
Coarse Aggregate (10 mm)	41.84
Coarse Aggregate (20 mm)	60.48
NaOH	2.12
Na ₂ SiO ₃	1.431
Steel Fibre	0.59 (0.5%)
Admixture	9.2

Mix Design of Geopolymer Concrete with 1.0% Steel Fibre

The geopolymer concrete mix containing 1.0% steel fibre was prepared using the same constituent materials and alkaline activator system as the 0.5% fibre mix. However, the steel fibre content was increased to 1.0% by volume of concrete to study its effect on compressive strength. The higher fibre dosage was intended to enhance crack-bridging action and improve post-cracking behavior. After thorough mixing, the concrete was cast into standard cube moulds, cured under laboratory conditions, and tested for compressive strength at specified curing periods.

Material	Quantity (kg)
Fly Ash	6.21
GGBS	28.98
OPC	6.21
Fine Aggregate	68.72
Coarse Aggregate (10 mm)	41.84
Coarse Aggregate (20 mm)	60.48
NaOH	2.12
Na ₂ SiO ₃	1.431
Steel Fibre	1.18(1.0%)
Admixture	9.2

V. RESULTS

Result of OPC- 9 cubes

Standard Portland cement baseline testing showing consistent strength development

	Weight [kg]	Strength [N/mm ²]	Avg strength [N/mm ²]
07 days	8.745	33.62	34.39
	8.859	33.44	
	9.087	36.11	
28 Days	8.889	39.89	39.89
	8.846	40.09	
	9.036	39.71	
56 Days	8.856	41.56	41.68
	8.697	40.85	
	9.125	42.65	

The OPC concrete exhibited the lowest compressive strength among all mixes at all curing ages. The average compressive strength obtained was 38.06 MPa at 7 days, 39.56 MPa at 28 days, and 41.68 MPa at 56 days. Although the strength increased with curing age, the rate of strength development was lower compared to geopolymer concrete mixes containing steel fibres. These results indicate the comparatively lower performance of conventional OPC concrete.

Result of GPC [for 0.5% steel fiber]- 9 cubes

Geopolymer concrete with 0.5% steel fiber reinforcement showing enhanced strength characteristics

	Weight [kg]	Strength [N/mm ²]	Avg strength [N/mm ²]
	8.947	33.11	
07 Days	8.889	34.27	33.13
	8.776	32.01	
	8.894	45.47	
28 Days	8.974	47.02	46.30
	9.024	46.40	
	8.362	52.65	
56 Days	8.957	51.26	51.63
	8.245	50.98	

The geopolymer concrete containing 0.5% steel fibre demonstrated the highest compressive strength among all the mixes. The average compressive strength recorded was 33.13 MPa at 7 days, 46.30 MPa at 28 days, and 51.63 MPa at 56 days. The addition of steel fibres enhanced crack resistance and improved the load-carrying capacity of the concrete. The results indicate that 0.5% steel fibre content provided the optimum balance between strength and workability.

Result of GPC [for 1% steel fiber]- 9 cubes

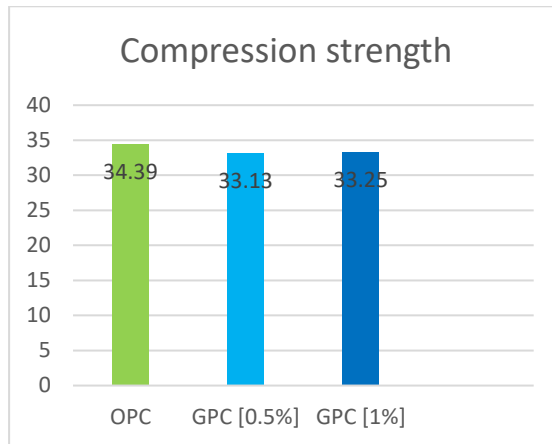
Geopolymer concrete with 1% steel fiber reinforcement demonstrating sustained strength growth

	Weight [kg]	Strength [N/mm ²]	Avg strength [N/mm ²]
	8.787	33.51	
07 Days	8.859	34.13	33.25
	9.023	32.13	
	8.541	42.47	
28 Days	8.002	44.80	43.68
	8.165	43.78	
	8.362	49.78	
56 Days	8.125	48.98	48.99
	8.542	48.21	

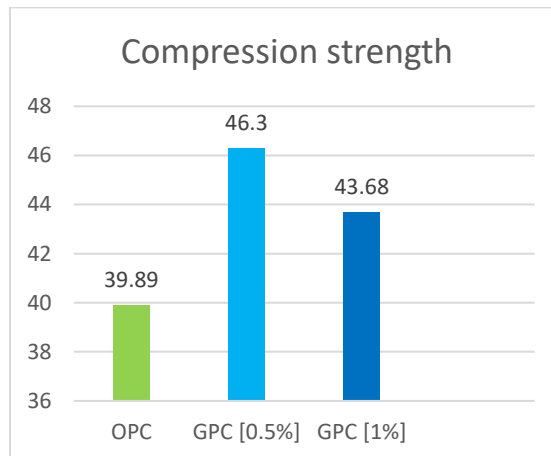
The geopolymer concrete containing 1.0% steel fibre also showed superior compressive strength compared to OPC concrete. The average compressive strength achieved was 33.44 MPa at 7 days, 43.68 MPa at 28 days, and 48.91 MPa at 56 days. Although the strength was higher than OPC concrete, it was slightly lower than the 0.5% fibre mix. This may be attributed to reduced workability and difficulties in compaction caused by the higher fibre content.

VI. GRAPH INTERPRETATION

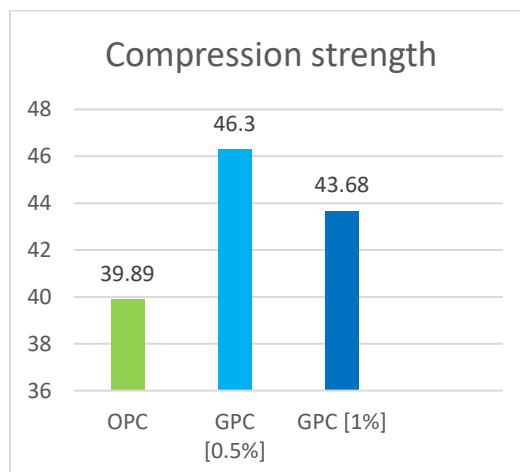
Comparison of 7 days result



Comparison of 28 days result



Comparison of 56 days result



VII. DISCUSSION

The compressive strength results indicate that all concrete mixes gained strength with an increase in curing age. The conventional OPC concrete achieved average compressive strengths of 38.06 MPa, 39.56 MPa, and 41.68 MPa at 7, 28, and 56 days, respectively. In comparison, the geopolymer concrete mixes containing steel fibres exhibited significantly higher strength at later ages. The geopolymer concrete with 0.5% steel fibre achieved compressive strengths of 33.13 MPa, 46.30 MPa, and 51.63 MPa at 7, 28, and 56 days, respectively, while the mix containing 1.0% steel fibre attained strengths of 33.44 MPa, 43.68 MPa, and 48.91 MPa.

The superior performance of geopolymer concrete can be attributed to the geopolymerization reaction between fly ash, GGBS, and alkaline activators, which produced a dense and strong binding matrix. The presence of GGBS contributed to rapid strength development under ambient curing conditions, resulting in higher long-term strength compared to OPC concrete. Additionally, the incorporation of steel fibres improved crack resistance and enhanced stress distribution within the concrete matrix.

Among the geopolymer mixes, the concrete containing 0.5% steel fibre exhibited the highest compressive strength. This indicates that 0.5% fibre content was the optimum dosage for the developed mix. Although the 1.0% steel fibre mix also showed higher strength than OPC concrete, its performance was slightly lower than that of the 0.5% fibre mix. This reduction may be due to decreased workability caused by the higher fibre content, leading to difficulties in compaction and the formation of internal voids within the concrete. Excess fibres can also result in fibre clustering, which adversely affects the uniformity and density of the matrix.

Overall, the results demonstrate that steel fibre reinforced geopolymer concrete is a promising sustainable alternative to conventional OPC concrete. The mix containing 0.5% steel fibre provided the best balance between workability and strength, achieving the highest compressive strength at all later curing ages while utilizing industrial by-products such as fly ash and GGBS.

VIII. CONCLUSION

The present study investigated the compressive strength performance of Ordinary Portland Cement (OPC) concrete and Steel Fibre Reinforced Geopolymer Concrete (GPC) containing 0.5% and 1.0% steel fibres. Based on the experimental results.

- Compressive strength increased with curing age for all concrete mixes, indicating continuous strength development over time.
- Geopolymer concrete exhibited superior long-term compressive strength compared to conventional OPC concrete, demonstrating the effectiveness of fly ash and GGBS as sustainable binder materials.
- The geopolymer concrete containing 0.5% steel fibre achieved the highest compressive strength of 51.63 MPa at 56 days, outperforming both OPC concrete and the 1.0% steel fibre mix.
- The incorporation of steel fibres improved the overall performance of geopolymer concrete by enhancing crack resistance and stress distribution within the concrete matrix.
- Increasing the steel fibre content from 0.5% to 1.0% did not result in additional strength improvement. The slight reduction in strength may be attributed to reduced workability, fibre clustering, and difficulties in compaction.
- The utilization of fly ash and GGBS in geopolymer concrete reduces dependence on Ordinary Portland Cement and promotes the beneficial use of industrial by-products.
- Based on the experimental investigation, geopolymer concrete containing 0.5% steel fibre was found to be the optimum mix, providing the best balance between strength and material performance.

Overall, steel fibre reinforced geopolymer concrete can be considered a sustainable and effective alternative to conventional OPC concrete for future construction applications due to its higher compressive strength and environmental benefits.

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