REVISTAMATÉRIA V.29 N.3
ISSN 1517-7076 articles e20240217, 2024

A comprehensive study on advanced strategies to improve the performance, durability, and flexible behavior of cementitious materials

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ABSTRACT

Because of its better strength-to-weight ratio, moldability, fracture resistance, and ability to employ local materials, ferrocement is becoming a more and more popular building material. An environmentally friendly substitute is provided by geopolymer technology, which uses alkali solutions to activate materials high in silica and alumina. This study focuses on geopolymer-based ferrocement slabs, exploring their flexural properties and substituting geopolymer mortar for cement to enhance performance. This study investigates the effects of varying percentages of fly ash (ranging from 0% to 20%), GGBS (ranging from 80% to 100%), and 2% of nano silica on the properties of ferrocement geopolymer concrete. Flexural behavior are tested using Carbon Fiber Reinforced Polymer (CFRP) wound wire mesh. Fly ash, a coal plant byproduct, is combined with GGBS to improve strength and setting. A 1:2 mortar ratio, containing sodium silicate, sodium hydroxide, GGBS and fly ash, is utilized. Optimal results are achieved with 80% GGBS addition, despite higher strength observed with 100% GGBS in fly ash. Nano silica further enhances performance, with a significant 240% strength increase observed with 1.5% nano silica and 80% GGBS. The study concludes by identifying superior combinations for practical application, considering specimen permeability, acid resistance, and heat resistance.

Keywords: Ferrocement; Geopolymer; GGBS; Flyash; Carbon Fiber Reinforced Polymer (CFRP).

1. INTRODUCTION

One important characteristic of geopolymer concrete that affects how it is used in building is workability. Setting and workability are two physical features of geopolymer materials that may be impacted by the inclusion of microfibers [1]. According to a research, polyester fibers produced the lowest flow and high-strength steel fibers the least change in workability, suggesting that fiber type has a big impact on how workable geopolymer mortars are [2].

The axial compression behavior of ferrocement geopolymer high-strength concrete (HSC) columns has been investigated, revealing that these columns can achieve greater ultimate failure loads compared to traditional reinforced concrete (RC) members. The use of various metallic and nonmetallic meshes in the columns has shown to significantly affect their performance under axial loading, with welded wire mesh providing a notable increase in ultimate failure load [3]. Ferro-geopolymer composites have also been studied for roofing applications, demonstrating that these materials can offer higher flexural strength and sustainability for infrastructure. The research has highlighted the importance of mesh type and span length on the flexural performance of prototype trapezoidal ferro-geopolymer roofing elements [4]. One important measure of the effectiveness of geopolymer concrete is its compressive strength. Studies have demonstrated that geopolymer concrete can outperform regular Portland cement (OPC) concrete in terms of durability, particularly under chemical solution

Corresponding Author: Meenakshi Sudarvizhi Seenipeyathevar Received on 03/05/2024 Accepted on 23/05/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0217

exposure. While OPC concrete was more vulnerable to sulfuric acid, geopolymer concrete made with class-F fly ash or a combination of fly ash and granulated lead smelter slag showed greater resilience to sodium sulfate attack [5].

The incorporation of ferrochrome slag as a partial replacement for coarse aggregate in geopolymer concrete has been shown to enhance the material's performance, with improvements observed in compressive, flexural, and split tensile strength [6]. Microstructural analyses have supported these findings, indicating that ferrochrome slag-based geopolymer concrete is a technically acceptable and environmentally compatible construction material [7]. Research on the flexural behavior of geopolymer ferrocement slabs has shed light on the consequences of changing the volume percent of reinforcement and the molarity of alkaline solutions. These parameters significantly influence the initial and ultimate crack loads, as well as the ultimate flexural strength of the slabs [8].

Durability is a crucial aspect of concrete performance, affecting the service life of structures. Geopolymer concrete has shown promising results in terms of durability. As compared to OPC concrete, geopolymer concrete was shown to have reduced water absorption and sorptivity, which is advantageous for preventing corrosion of embedded reinforcing steel and lowering the risk of concrete spalling under chemical assault [9]. Numerous studies have been conducted on the durability performance of geopolymer concrete, and the results show that it has strong resistance to acid attack and abrasion, low to medium chloride ion penetrability, and good compressive strength at increasing temperatures [10]. It has been proposed that adding fibers like polypropylene and micro-silica will increase the durability of geopolymer concrete [11]. Another important quality of construction materials is fire resistance. Ferro-geopolymer concrete has been discovered to have strong fire resistance because of the insulating qualities of the ferrocement mortar and the ceramic-like qualities of the geopolymer mortar [12].

The application of ferrocement composites for strengthening concrete columns has been reviewed, highlighting the material's potential for retrofitting and rehabilitation. Despite the lack of established codes for ferrocement jacketing, the uniform distribution of wire mesh reinforcement in ferrocement composites has been recognized for its crack-arresting capabilities [13]. Ambient cured geopolymer concrete products have been developed as an alternative to conventional cement-based products. These products, including beams and railway sleepers, have demonstrated superior performance when compared to their cement concrete counterparts [14]. Additionally, geopolymer mortar-built ferrocement roofing channels and domes have outperformed traditional ferrocement parts in terms of performance [15].

Research has been done on how ferrocement wrapping systems affect the flexural behavior and strength of geopolymer concrete beams. The results show that ferrocement can improve the behavior of both types of beams [16]. Understanding the serviceability of geopolymer concrete in structural applications requires an understanding of its flexural behavior. Research on the flexural strength and serviceability of geopolymer concrete beams reinforced with glass-fibre-reinforced polymer bars has shown that the flexural performance is typically underestimated by current prediction equations and that the reinforcement ratio improves serviceability performance [17]. Under axial compression, the behavior of concrete cylinders enclosed in a ferro-geopolymer jacket has been examined. The outcomes demonstrated increased axial stiffness and compressive load bearing capability, and a monolithic failure mechanism suggested a tight bond between the geopolymer jacket and the concrete core [18].

Geopolymer ferrocement concrete demonstrates considerable potential in terms of workability, strength, durability, and flexural behavior, positioning it as a compelling substitute for conventional concrete [19]. By integrating fibers and nano-materials into its composition, the inherent properties of geopolymer ferrocement concrete can be significantly augmented, thereby advancing the realm of sustainable construction materials [20]. This synergy not only fortifies its structural integrity but also fosters its longevity, reinforcing its status as a pragmatic solution for modern construction challenges [21]. Such innovations underscore a pivotal shift towards eco-conscious building practices, promising a future characterized by resilient and environmentally friendly infrastructure [22].

2. MATERIALS AND METHODS

2.1. Flyash

The specific gravity of sub-bituminous ash typically ranges around 1.9, whereas that of bituminous ash, particularly rich in iron, can escalate to approximately 2.95. Particle sizes vary between 10 to 100 microns, and the color spectrum spans from dark grey to black. These characteristics collectively define the physical properties of ash, influencing its behavior and potential applications in various industrial and environmental contexts.

The composition of Fly Ash Class F typically comprises various compounds in specified percentages. It predominantly consists of 56% SiO2 (Silicon Dioxide), 25% Al2O3 (Aluminum Oxide), and 9% CaO (Lime). Additionally, it contains 8% Fe2O3 (Iron Oxide), 1% MgO (Magnesium Oxide), and 1% SO3 (Sulfur Trioxide). These constituent elements play crucial roles in determining the chemical and physical properties of Fly Ash Class F, influencing its suitability for diverse industrial applications, including construction and environmental remediation.

2.2. GGBS

The specific gravity of the material is 2.89, indicating its density relative to water. With a bulk density of 1998 kg/m^3, the material possesses a considerable mass per unit volume. Its fineness, measured at 349 m^2/kg, denotes the surface area per unit mass, reflecting the particle size distribution and texture. These properties are pivotal in understanding the behavior and applications of the material, particularly in construction, where factors like density and fineness influence its performance and suitability for various uses. The chemical composition of Ground GGBS typically consists of various compounds, each contributing to its properties and behavior. In percentage composition, it comprises approximately 39% CaO (Calcium Oxide), 36% SiO2 (Silicon Dioxide), 13% Al2O3 (Aluminum Oxide), 9% MgO (Magnesium Oxide), and 1.8% Fe2O3 (Iron Oxide). These constituents determine GGBS's reactivity, strength development, and durability characteristics, making it a valuable supplementary cementitious material in concrete production, particularly for enhancing long-term performance and sustainability.

2.3. Sodium silicate

Sodium silicate, scientifically denoted as Na2O(SiO2), manifests as a transparent gel. Its composition usually comprises about 57% water (H2O), 30% silicon dioxide (SiO2), and 16% sodium oxide (Na2O). With a specific gravity of 1.39 at 20°C, it illustrates its density concerning water. These characteristics underscore sodium silicate's versatility, serving as a fundamental ingredient in diverse industrial applications, including adhesives, detergents, and cements, owing to its binding, sealing, and stabilizing properties.

2.4. Sodium hydroxide

Sodium hydroxide, recognized as caustic soda, appears as small white pellets. Its boiling point in a 40% aqueous solution registers at 102°C. The molecular weight of sodium hydroxide is 39.996 g/mol, indicating the mass of one mole of its molecules. At a specific gravity of 1.51, it demonstrates a density comparison with water. These attributes define sodium hydroxide's chemical behavior and industrial applications, including its role in manufacturing, chemical processing, and water treatment processes.

2.5. M-sand

The M-Sand utilized in the study originated from Coimbatore. It exhibits a specific gravity of 2.74, indicating its relative density compared to water. With a fineness modulus of 2.79, it characterizes the particle size distribution and texture of the sand. Additionally, the density of the M-Sand measures 1605 kg/m^3, denoting its mass per unit volume.

2.6. Nano silica

Nano silica exhibits distinctive properties that distinguish it as a versatile material in various applications. With a white color and an amorphous form, it boasts an apparent density of 0.3695 g/cm^3 and particle sizes ranging from 10 to 20 nm. Its silica content on a dry basis stands impressively at 99.75%, while its dispersity in CCl4 reaches 98.5%. Nano silica maintains a minimal free water content of less than or equal to 3%. In terms of physical composition, it possesses a density of 2.4 g/cm^3, a pH of 9.4, and a viscosity of less than 15 cps. Its molar mass is measured at 59.96 g/mol. Chemically, nano silica comprises 46.80% silicon and 53.30% oxygen, showcasing its composition's elemental balance. These properties collectively underscore nano silica's significance in various fields, including construction, electronics, and biomedical applications, owing to its unique physical and chemical characteristics.

2.7. Master glenium 51

Master Glenium 51, a notable concrete admixture, boasts a structure based on polycarboxylic ether. Its distinctive amber color sets it apart, making it easily identifiable. With a density ranging from 1.080 to 1.140 kg/liter, it exhibits a balanced weight relative to volume. Notably, its chlorine content remains minimal, typically measuring less than 0.1%, ensuring compatibility with various concrete compositions. Similarly, its alkaline content remains low, typically below 3%, contributing to its versatility in concrete formulations. These properties collectively position Master Glenium 51 as a reliable and effective admixture, enhancing concrete performance while maintaining structural integrity and durability.

2.8. Carbon fiber reinforced polymer (CFRP)

Carbon fiber laminate that has been pultruded and mixed with an epoxy resin matrix to give it a distinctive black color is what makes up Carbon Fiber Reinforced Polymer, or CFRP. It boasts a thickness of 1.2 mm, a width of 1000 mm, and a length of 150 m. With a fiber volume fraction (Vf) of 70%, it exhibits a high fiber content, ensuring superior mechanical properties. CFRP has a glass transition temperature (TGM) ranging from 100 to 125°C, making it suitable for various temperature conditions. In terms of mechanical properties, it demonstrates an impressive ultimate tensile strength of 1860 MPa, coupled with an ultimate elongation of 1.6% and an elastic modulus of 165 GPa. These properties collectively render CFRP as a lightweight, high-strength material ideal for applications requiring exceptional structural performance, such as aerospace, automotive, and construction industries.

2.9. Curing

In the curing process of ferrocement slabs, the cast specimens undergo a series of controlled environmental conditions to ensure optimal hydration and development of concrete properties. Initially, the slabs are subjected to a heating phase, typically reaching temperatures of approximately 60°C, followed by a cooling period before the curing process commences. The specimens are then subjected to two distinct curing environments for comparison: one under normal room temperature conditions, averaging around 27°C, and the other under a 24-hour hot air curing regime. Throughout the curing period, from the day of de-molding until the testing day, the specimens are carefully monitored to assess their strength, durability, and overall performance under each environmental condition. This meticulous approach allows for a comprehensive evaluation of the curing methods' efficacy and their impact on the final properties of the ferrocement slabs.

3. METHODOLOGY

The methodology involves the preparation and testing of different concrete mixtures (M1-M10) to evaluate the effects of various parameters on the properties of ferrocement slabs. Each mixture comprises different proportions of fly ash, GGBS, nano silica, sodium silicate, sodium hydroxide, M-sand, and the molarity of NaOH solution. Mixtures M1 to M5 are cured at room temperature, while mixtures M6 to M10 are cured at 60°C. The fly ash content ranges from 0% to 20%, while GGBS content ranges from 80% to 100%. Nano silica is kept constant at 2%, and the proportions of sodium silicate and sodium hydroxide relative to the cementitious material are maintained. M-sand constitutes 200% of the cementitious material. The slump percentage (SP) is kept constant at 0.38 for all mixtures. This systematic approach allows for the investigation of how variations in curing temperature and material composition impact the properties of ferrocement slabs. Table 1 shows the mix proposition used in this research.

Table 1: Shows the mix proposition.

MIX	CURING MODE	FLY ASH (%)	GGBS (%)	NANO SILICA (%)	SODIUM SILICATE % OF CEMENTITIOUS MATERIAL	SODIUM HYDROXIDE % OF CEMENTITIOUS MATERIAL	M-SAND % OF CEMENTITIOUS MATERIAL	MOLARITY OF NAOH SOLUTION	SP %
M1	Curing at Room Temperature	0	100	2	25	10	200	10	0.38
M2		5	95	2	25	10	200	10	0.38
M3		10	90	2	25	10	200	10	0.38
M4		15	85	2	25	10	200	10	0.38
M5		20	80	2	25	10	200	10	0.38
M6	Curing at 60°C Temperature	0	100	2	25	10	200	10	0.38
M7		5	95	2	25	10	200	10	0.38
M8		10	90	2	25	10	200	10	0.38
M9		15	85	2	25	10	200	10	0.38
M10		20	80	2	25	10	200	10	0.38

4. RESULTS AND DISCUSSION

4.1. Compressive strength test

The compressive strength of geopolymer concrete cured under different conditions was assessed at 7, 14, and 28 days. Mixtures M1 to M5, cured at room temperature, exhibited increasing compressive strength with curing duration. At 28 days, M1 recorded 36.23 N/mm^2, while M5 achieved 60.79 N/mm^2. Mixtures with higher proportions of fly ash and GGBS, such as M4 and M5, displayed superior strength. Conversely, mixtures cured at 60°C (M6 to M10) exhibited slightly lower compressive strengths compared to room temperature curing. For instance, M6 attained 31.14 N/mm^2 at 28 days, while M10 reached 59.03 N/mm^2. These findings suggest that while both curing methods contribute to strength development, compositions with higher fly ash and GGBS content generally yield stronger, emphasizing the importance of material selection and curing conditions in optimizing performance. Figure 1 shows the graphical representation of compressive strength test.

4.2. Flexural strength test

The flexural strength of geopolymer concrete was evaluated at 7, 14, and 28 days under varying curing conditions and material compositions. Beams cured at room temperature consistently displayed higher flexural strengths compared to those cured at 60°C. For instance, at 28 days, beams from M1 to M5, cured at room temperature, exhibited strengths ranging from 2.65 N/mm^2 to 3.43 N/mm^2, while those from M6 to M10, cured at 60°C, showed strengths ranging from 2.46 N/mm^2 to 3.38 N/mm^2. Moreover, mixtures with higher proportions of supplementary materials like fly ash and GGBS, such as M4 and M5, demonstrated superior flexural strengths across all curing durations. These results underscore the influence of curing temperature and material composition on the flexural properties of geopolymer concrete, highlighting the potential for optimizing structural performance through tailored material formulations and curing strategies. Figure 2 shows the graphical representation of flexural strength test.

4.3. Permeability test

The depth of penetration of geopolymer concrete was measured under different curing conditions. Cubes cured at room temperature (M1 to M5) exhibited penetration depths ranging from 0.225 mm to 0.234 mm. Conversely, cube cured at 60°C (M6 to M10) showed slightly reduced penetration depths, ranging from 0.227 mm to 0.231 mm. Overall, there was minimal variation in penetration depth between the two curing methods, with cubes from both groups demonstrating similar levels of penetration. These results suggest that curing temperature may have a limited effect on the penetration characteristics of geopolymer concrete, indicating the robustness of this material against changes in curing conditions. Figure 3 shows the graphical representation of permeability test.

4.4. Acid resistance test

The average percentage loss in weight from the hydrochloric acid resistance test was determined for geopolymer concrete cured under different conditions. Cubes cured at room temperature (M1 to M5) exhibited average

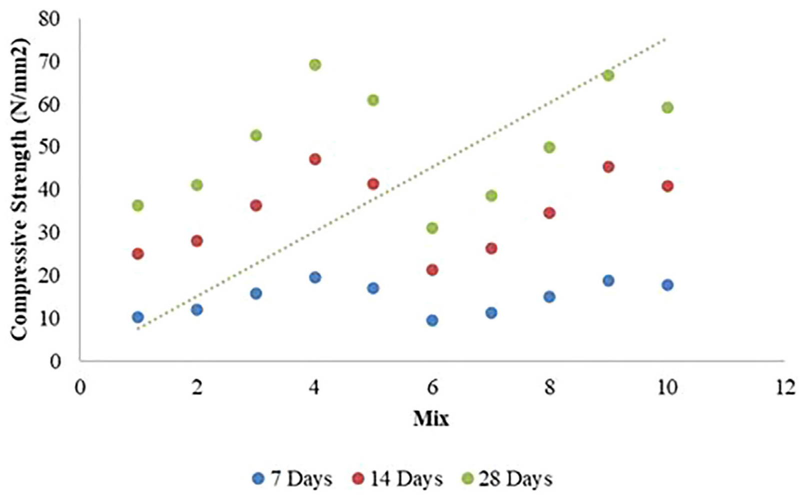

Figure 1: Shows the graphical representation of compressive strength test.

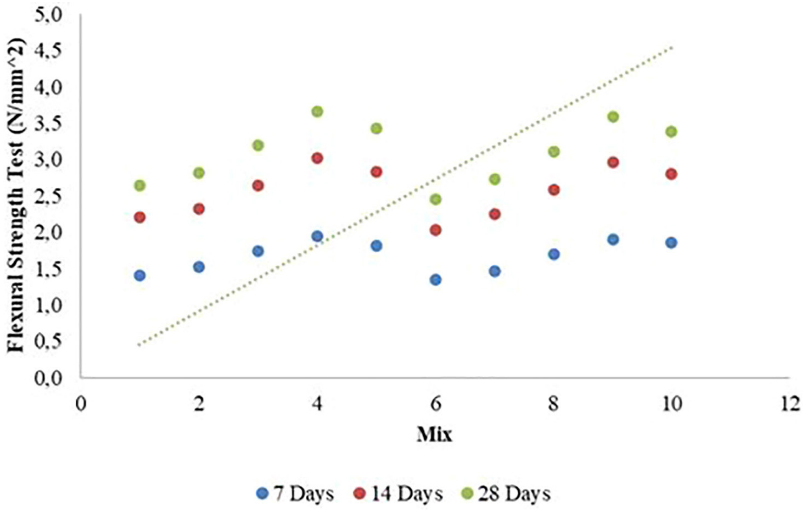

Figure 2: Shows the graphical representation of flexural strength test.

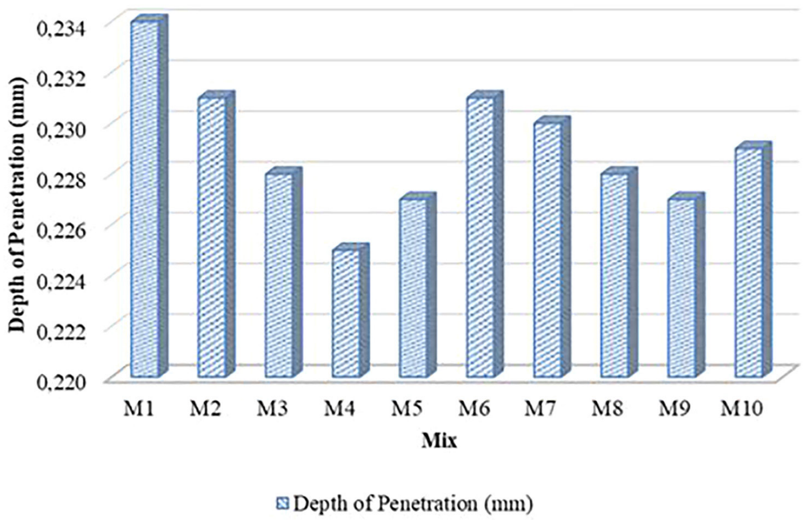

Figure 3: Shows the graphical representation of permeability test.

weight losses ranging from 4.48% to 4.62%. Similarly, cubes cured at 60°C (M6 to M10) showed average weight losses ranging from 4.61% to 4.74%. Overall, there was minimal variation in weight loss between the two curing methods, with both groups demonstrating similar levels of resistance to hydrochloric acid exposure. These results suggest that curing temperature may have limited influence on the acid resistance properties of geopolymer concrete, indicating the robustness of this material against corrosive environments.

The average percentage loss in strength from the hydrochloric acid resistance test was determined for geopolymer concrete cured under different conditions. Cubes cured at room temperature (M1 to M5) exhibited average strength losses ranging from 6.07% to 6.26%. Similarly, cubes cured at 60°C (M6 to M10) showed average strength losses ranging from 6.25% to 6.42%. Overall, there was minimal variation in strength loss between the two curing methods, with both groups demonstrating similar levels of resistance to hydrochloric acid exposure. These results suggest that curing temperature may have limited influence on the acid resistance properties of geopolymer concrete, indicating the robustness of this material against corrosive environments. Figures 4 and 5 shows the graphical representation of percentage of weight loss and strength loss in acid resistance test.

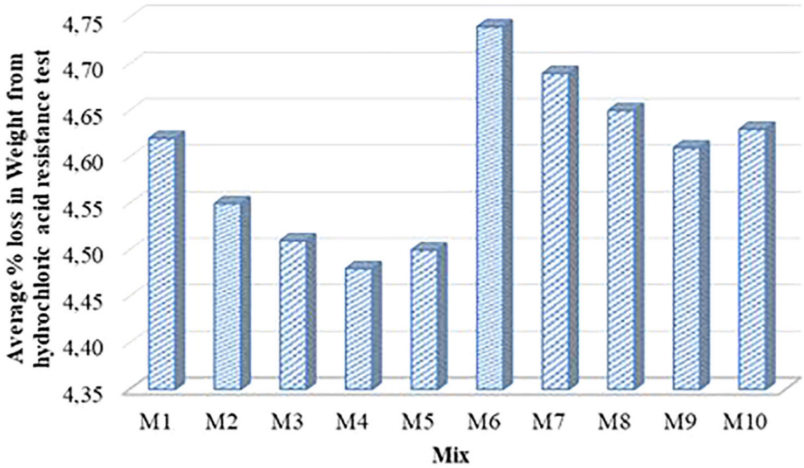

Figure 4: Shows the graphical representation of percentage of weight loss.

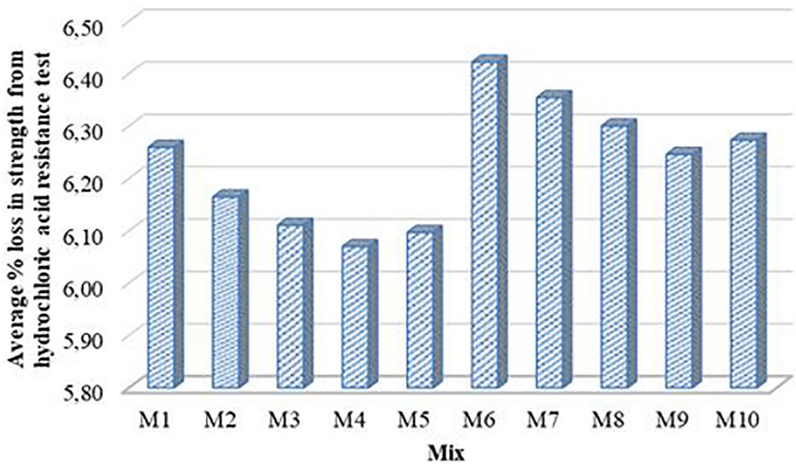

Figure 5: Shows the graphical representation of percentage of strength loss.

4.5. Thermal resistance test

The thermal resistance of geopolymer concrete was assessed under varying curing conditions. Cubes cured at room temperature (M1 to M5) exhibited thermal resistance values ranging from 0.131 to 0.138. Similarly, cubes cured at 60°C (M6 to M10) showed thermal resistance values ranging from 0.132 to 0.139. Overall, there was minimal variation in thermal resistance between the two curing methods, with both groups demonstrating similar levels of resistance to heat transfer. These results suggest that curing temperature may have limited influence on the thermal properties of geopolymer concrete, indicating the robustness of this material against changes in curing conditions. Figure 6 shows the graphical representation of thermal resistance test.

4.6. Ultrasonic pulse velocity test

The pulse velocity of geopolymer concrete was measured under different curing conditions. Cubes cured at room temperature (M1 to M5) exhibited pulse velocities ranging from 4.37 km/sec to 4.50 km/sec. Similarly, cubes cured at 60°C (M6 to M10) showed pulse velocities ranging from 4.41 km/sec to 4.48 km/sec. Overall, there was minimal variation in pulse velocity between the two curing methods, with both groups demonstrating similar levels of ultrasonic wave propagation through the material. These results suggest that curing temperature may have limited influence on the pulse velocity properties of geopolymer concrete, indicating the robustness of this material against changes in curing conditions. Figure 7 shows the graphical representation of ultrasonic pulse velocity test.

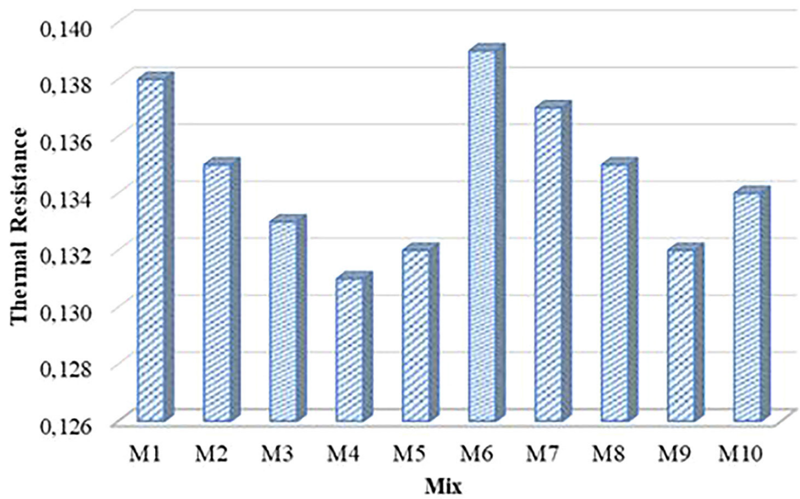

Figure 6: Shows the graphical representation of thermal resistance test.

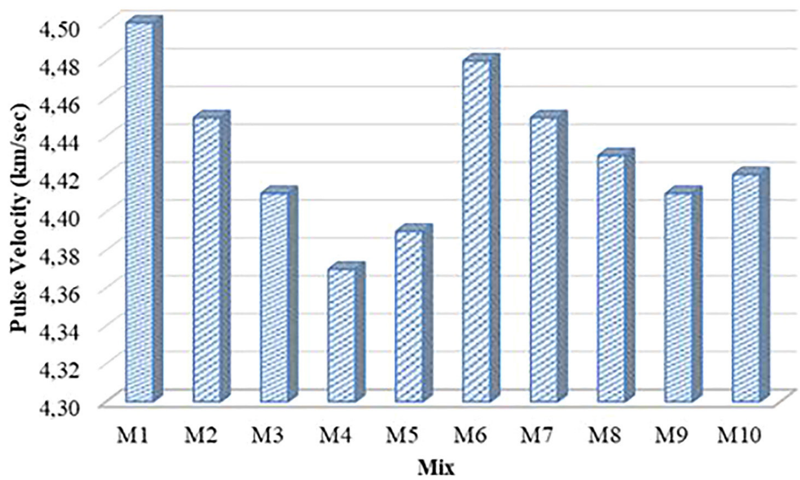

Figure 7: Shows the graphical representation of ultrasonic pulse velocity test.

4.7. Static load test

A hydraulic jack was used to provide stress up to 0.25 kN, and measurements were taken at the slab's midpoint as well as at loading locations to see strains and deflections. At each increase of 0.25 kN load, measurements were taken. The static load test was conducted to evaluate the performance of specimens M1 to M10 under normal curing conditions for M1 to M5, and elevated curing temperature at 60°C for M6 to M10. Load (kN) and corresponding deflection (mm) data were recorded and analyzed for each specimen. Under normal curing conditions, specimens M1 to M5 exhibited progressive load-deflection behavior. At the maximum applied load of 3 kN, M1 showed a deflection of 9.89 mm, while M5 exhibited a deflection of 2.22 mm. The load-deflection curves demonstrated typical elastic-plastic behavior, with increasing stiffness followed by plastic deformation upon reaching the yield point. In contrast, specimens subjected to elevated curing temperatures (M6 to M10) displayed enhanced load-bearing capacities and reduced deflections compared to their counterparts under normal curing. For instance, at a load of 3 kN, M6 showed a deflection of 5.27 mm, significantly lower than M1 under normal curing. This suggests that elevated curing temperatures contribute to diminish mechanical properties and structural integrity due to addition of GGBS and nano silica resulting in higher load-bearing capacities and reduced deflections. Table 2 shows the load deflection curve of various mixes.

Table 2: Shows the load deflection curve of various mixes.

SI. No.	Load (kN)	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
		Deflection (mm)									
1	0	0	0	0	0	0	0	0	0	0	0
2	0.25	0.09	0.09	0.08	0.05	0.05	0.10	0.10	0.08	0.05	0.05
3	0.5	0.15	0.13	0.12	0.1	0.09	0.16	0.14	0.13	0.11	0.10
4	0.75	0.28	0.25	0.23	0.18	0.12	0.30	0.26	0.24	0.19	0.13
5	1	0.55	0.43	0.35	0.27	0.21	0.58	0.46	0.37	0.29	0.22
6	1.25	0.91	0.75	0.63	0.43	0.4	0.96	0.79	0.67	0.46	0.42
7	1.5	1.65	1.3	1.1	0.78	0.7	1.75	1.38	1.16	0.83	0.74
8	1.75	3.25	2.3	1.65	1.28	1.1	3.44	2.44	1.75	1.36	1.16
9	2	8.89	3.68	2.5	1.9	1.56	9.41	3.90	2.65	2.01	1.65
10	2.25	–	6.9	4.2	2.65	2.34	–	7.31	4.45	2.81	2.48
11	2.5	–	9.84	6.8	3.5	3.21	–	10.42	7.20	3.71	3.40
12	2.75	–	–	9.92	5.2	4.98	–	–	10.50	5.51	5.27
13	3	–	–	–	9.94	10.45	–	–	–	10.53	11.07

5. CONCLUSION

Specimens containing 100% fly ash reached their ultimate setting time after 4 days. Addition of GGBS shortened the setting time, akin to cement mortar. An optimized mix of 80% GGBS and 20% fly ash demonstrated superior performance, achieving a 329% increase in strength compared to the control specimen under open air curing, and a 143% increase under hot curing conditions. However, 100% GGBS led to surface cracks on cube specimens, rendering it unsuitable for slabs. Incorporating Nano silica in the mix resulted in pore arrestation within mortar specimens, enhancing strength by 114% and 91% over the optimized mix with 1.5% Nano silica under open air and hot curing conditions, respectively. This indicates Nano silica's potential in improving material properties and durability. The combination of Nano silica and GGBS significantly reduced curing time, while maximizing strength and durability properties of ferrocement geopolymer cement. This obviates the need for hot curing, enhancing practicality and reducing energy consumption. Increasing the number of wire mesh layers improved the strength of ferrocement slabs. Employing three layers instead of a single layer resulted in approximately a 48% strength improvement, highlighting the importance of reinforcement in structural performance enhancement. Specimens cast with mix M4 and cured at room temperature exhibited reduced penetration depth and negligible penetration at normal temperature curing, indicating improved impermeability and potentially enhanced durability.

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