

Enhancement of Mechanical Properties of Geopolymer Ferrocement through Incorporation of a Novel Binder and through Optimization of Alkaline Activator Ratios

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KEYWORDS

Geopolymer ferrocement, binder composition, alkaline activator ratios, shear strength, flexural strength.

ABSTRACT

Geopolymer ferrocement is geopolymer mortar, reinforced with wire mesh. The ratios of binder composition and alkaline activator, with which the geopolymer has been prepared, have profound influence on the mechanical performance of geopolymer ferrocement. In this study the influence of a binder material Alccofine and variation in ratios of alkaline activators have been studied for their effect on mechanical properties of geopolymer ferrocement. Alccofine was replaced with varying proportions of Ground Granulated Blast-Furnace Slag (GGBS). The molarities of NaOH and NaOH/Na₂SiO₃ ratios were also varied to find their influence on strength and crack control of ferrocement, when combined with single, double, and triple-layers of ferro mesh configurations. Tests such as direct shear test, three-point bending, and four-point flexural tests were conducted to measure shear strength, flexural strength and to estimate region of pure bending. It was observed that the mix with 20% Alccofine and 80% GGBS, an A/B ratio of 0.5, and a NaOH/Na₂SiO₃ ratio of 1.5 yielded a compressive strength of 50 MPa at 90 days of geopolymer ferrocement. Also the triple-layer mesh configuration exhibited the best results, achieving 10 N/mm² in shear strength and 12 N/mm² in flexural strength, compared with other configurations. These findings indicate that by incorporation of Alccofine, optimizing binder composition, activator ratios and reinforcement, the strength parameters of geopolymer ferrocement can be significantly improved.

1. Introduction

Ferrocement is known for its adaptability and high performance in construction due to its remarkable tensile strength, toughness, and ability to resist cracking (Paul & Mathew, 2023). Traditional ferrocement structures, typically made with cement-based matrices, have proven their effectiveness in various applications. However, with the growing focus on sustainability, there is an increasing need to explore alternatives to ordinary Portland cement (OPC) that can reduce the carbon footprint associated with its production (Danish et al., 2022). One such alternative is the use of geopolymer binders, which are derived from industrial by-products such as Ground Granulated Blast-Furnace Slag (GGBS) and Alccofine. These materials offer not only environmental benefits but also mechanical advantages. Geopolymer binders, when activated by alkaline solutions, initiate a geopolymerization process, forming stable aluminosilicate networks that can improve the properties of traditional cementitious binders (Farooq et al., 2021). Despite these advancements, there remains limited knowledge on how geopolymers behave when combined with different mesh configurations in ferrocement structures, particularly under varying alkali activator compositions.

Considerable progress has been made in geopolymer research, especially concerning the optimization of binder compositions, alkali activator ratios, and curing processes to enhance compressive strength and durability. Studies by Mohana & Bharathi, (2024) and Paul & Mathew, (2023) have shown that GGBS-based geopolymers exhibit rapid early strength gains. The addition of supplementary materials like Alccofine has been found to further improve both early and long-term mechanical properties. Furthermore, research by Ghazy et al., (2022) suggests that higher molarities of NaOH and balanced NaOH/Na₂SiO₃ ratios can accelerate geopolymerization, leading to denser and more reactive matrices. While much is known about the benefits of these binder systems, there is a lack of detailed studies on how they perform in ferrocement sections under shear and flexural loads. Work is yet to be done on analysing its practical applications in crack control, flexural performance, and stiffness.

A key area that remains underexplored is the interaction between the reinforcement mesh layers (e.g., single, double, or triple) and the geopolymer matrix under mechanical loads. Traditional ferrocement relies on mesh reinforcement to provide tensile strength and crack control (Mohana & Bharathi, 2024a), but there is still

uncertainty about how different mesh configurations affect the mechanical properties of geopolymer ferrocement, especially in compound sections subjected to complex shear and flexural stresses. Additionally, the influence of various binder compositions, alkali activator ratios, and curing conditions on the shear behavior of these sections is not well understood. This gap is significant, considering the potential of geopolymer materials to serve as sustainable alternatives to traditional cement in ferrocement construction.

To bridge this gap, the present study investigates the shear behavior of geopolymer ferrocement in compound sections. This research examines the effects of varying binder compositions (GGBS and Alccofine), alkali activator ratios (NaOH molarity and NaOH/Na₂SiO₃ ratio), and mesh reinforcement configurations (single, double, and triple layers) on the mechanical performance of geopolymer ferrocement. The experimental approach includes direct shear tests, three-point bending tests, and four-point flexural tests to provide a comprehensive understanding of how different material combinations influence crack propagation, stiffness, and overall strength. The use of crack monitoring tools, such as digital imaging, will allow for a detailed analysis of crack control and ductility, both of which are crucial for evaluating the structural integrity of ferrocement.

The primary objectives of this study are: to evaluate the shear strength of geopolymer ferrocement in compound sections, to analyze the influence of binder composition, alkali activator ratios, and mesh reinforcement on shear performance, and to assess crack control, stiffness, and ductility under loading conditions. Thus, this work aims to improve the performance of geopolymer ferrocement.

2. Materials and methods:

The materials used in this study include Ground Granulated Blast-Furnace Slag (GGBS) with a fineness of $\geq 350 \text{ m}^2/\text{kg}$ and Alccofine 1203, a highly reactive material characterized by a specific surface area of $\geq 12000 \text{ cm}^2/\text{g}$. The fine aggregates used were natural sand, conforming to Zone II of IS 383:2016, and quarry dust, both of which passed through a 4.75 mm sieve to ensure consistency in particle size. The alkaline activators employed consisted of sodium hydroxide (NaOH) with a purity of $\geq 97\%$, prepared in molarity levels of 8M, 10M, and 12M, along with sodium silicate (Na₂SiO₃), featuring a silica modulus (SiO₂/Na₂O) of 2.5. For reinforcement, galvanized steel wire mesh was used in varying configurations, including single-layer, double-layer, and triple-layer setups, with wire diameters ranging from 0.5 mm to 1.0 mm and mesh sizes of 10 mm x 10 mm and 20 mm x 20 mm. The control mix followed a water-to-cement (w/c) ratio of 0.45, while the geopolymer mixes were designed with different binder compositions—ranging from 100% GGBS to 60% GGBS, with Alccofine content ranging from 0% to 40%. The alkali-to-binder (A/B) ratios varied from 0.4 to 0.6, impacting the reactivity and setting properties of the mixes.

For testing, the specimens were cast as I-sections, each with a height of 150 mm, a width of 100 mm, and a length of 500 mm. These were reinforced with the aforementioned mesh configurations. The experimental procedures included direct shear tests to measure shear strength, three-point bending tests to observe crack propagation and stiffness, and four-point flexural tests to evaluate load-deflection behavior. Additionally, crack monitoring was performed using digital imaging and crack gauges to assess crack width at different load levels. Specimens were subjected to two curing methods: ambient curing at room temperature ($27^\circ\text{C} \pm 2^\circ\text{C}$) for 7, 28, 56, and 90 days, and oven curing at 60°C for 24 hours, followed by storage at room temperature. Data analysis was performed to calculate shear strength, deflection, and crack width.

3. Results and Discussion:

Geopolymer mixes prepared using varying amounts of GGBS and Alccofine, different types of fine aggregates, and alkali activator ratios are as presented in Table 1. Molarity of NaOH and the NaOH/Na₂SiO₃ ratio are crucial in enhancing the dissolution of aluminosilicate materials, thereby improving the reactivity of the binder matrix and its subsequent strength development. Higher Alccofine content, in mixes 3 through 5 improved early reactivity and works synergistically with GGBS's latent hydraulic properties, as also noted by (Santhanam & Ramadoss, 2022). Additionally, the use of quarry dust in Mixes 3 and 4 alters workability and increases matrix density, which likely contributes to improved long-term durability and strength. Varying the NaOH molarity between 8M and 12M and the NaOH/Na₂SiO₃ ratio from 1.0 to 2.0 has been done. Higher molarity in Mix 3 speeds up the dissolution of silicate and alumina species, as mentioned by (Rohit et al., 2024). However, overly high molarity can reduce workability and cause early stiffening, limiting flowability. Previous research suggests that mixes with lower molarity as in Mix 1 and Mix 5 and good NaOH/Na₂SiO₃ ratios offer early and late strength respectively as also observed by Singh et al., (2024) .

Table 1 Materials Proportions for Control and Geopolymer Mixes

| Mix ID | GGBS (%) | Alccofine (%) | Fine Aggregate | NaOH Molarity | NaOH/Na ₂ SiO ₃ Ratio | A/B Ratio | w/b Ratio |
|--------|----------|---------------|----------------|---------------|---|-----------|-----------|
| Mix 1 | 100 | 0 | Sand | 8 | 1 | 0.4 | 0.4 |
| Mix 2 | 90 | 10 | Sand | 10 | 1.5 | 0.5 | 0.5 |
| Mix 3 | 80 | 20 | Quarry Dust | 12 | 2 | 0.6 | 0.6 |
| Mix 4 | 70 | 30 | Quarry Dust | 10 | 1.5 | 0.5 | 0.5 |
| Mix 5 | 60 | 40 | Sand | 8 | 1 | 0.4 | 0.4 |

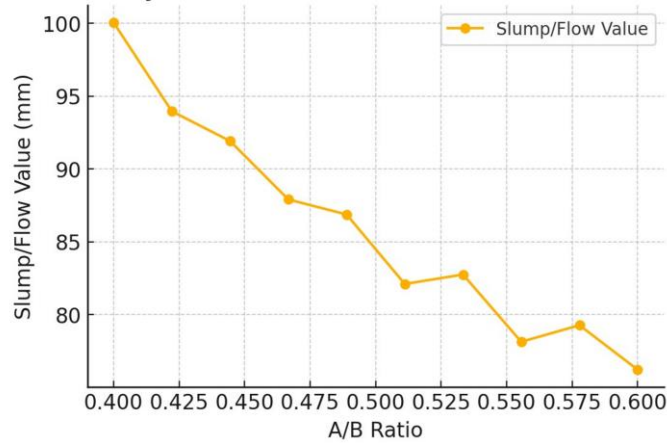


Figure 1 Influence of Alkali to Binder ratio on workability

Figure 1 provides a clear view of the relationship between workability, measured in terms of slump flow and the alkali-to-binder (A/B) ratio. As the figure shows, workability steadily declines as the A/B ratio increases. The slump/flow value decreases from 100 mm to around 80 mm as the A/B ratio rises from 0.4 to 0.6. This reduction in workability can be explained by the increased concentration of alkaline activators (NaOH and Na₂SiO₃), which raise the mix's viscosity and reduce the available free water. Nath and Sarker (2014) also observed this phenomenon, which results from the accelerated geopolymerization process. A higher alkali content promotes quicker stiffening of the paste, which, in turn, reduces the slump value. This behavior is supported by findings in other studies, where an increase in alkali content has been linked to a faster formation of aluminosilicate gels. These gels consume water and hinder the flow of the mix (Ghazy et al., 2022). Moreover, mixes with a higher A/B ratio tend to develop more cohesive matrices, further limiting ease of flow. Ryu et al. (Mohana & Bharathi, 2024a) noted similar findings. Overall, the trade-off between higher strength and reduced workability must be considered carefully to ensure the mix remains manageable during placement and curing.

Table 2 Alkaline Activator Ratios and Mix Properties

| Mix ID | NaOH Molarity | NaOH/Na ₂ SiO ₃ Ratio | A/B Ratio | Workability (Slump) | Setting Time (Initial) | Setting Time (Final) |
|--------|---------------|---|-----------|---------------------|------------------------|----------------------|
| Mix 1 | 8 | 1 | 0.4 | 100 | 45 | 120 |
| Mix 2 | 10 | 1.5 | 0.5 | 95 | 60 | 140 |
| Mix 3 | 12 | 2 | 0.6 | 90 | 70 | 150 |
| Mix 4 | 10 | 1.5 | 0.5 | 85 | 65 | 145 |
| Mix 5 | 8 | 1 | 0.4 | 100 | 50 | 125 |

As seen in Table 2, the relationship between NaOH molarity, NaOH/Na₂SiO₃ ratio, A/B ratio, and various mix properties, such as workability and setting times, is quite apparent. As the molarity of NaOH increases from 8M to 12M, and the NaOH/Na₂SiO₃ ratio rises from 1.0 to 2.0, workability decreases across the board (from 100 mm in Mix 1 and Mix 5 to 90 mm in Mix 3), which can be attributed to the higher concentration of alkaline activators. Higher alkali levels accelerate the geopolymerization process, consuming free water more quickly and stiffening the mix (Ghazy et al., 2022). Setting times also show an increase as molarity and A/B ratios rise, with initial setting times ranging from 45 minutes (Mix 1) to 70 minutes (Mix 3), and final setting times extending from 120 to 150 minutes. The more rapid dissolution of silicate and alumina species at higher molarities forms longer polymeric chains, which explains the longer setting times. These findings align with (Rekha et al., 2024), who found that higher concentrations of activators reduce workability initially but improve early and long-term strength gains. Selecting an appropriate NaOH molarity and NaOH/Na₂SiO₃ ratio is thus

essential to balancing strength, workability, and setting time in geopolymer mixes.

Figure 2 illustrates the compressive strength development for Mix 1 and Mix 2 over a curing period of 1 to 90 days. Both mixes show a sharp increase in strength up to 28 days, after which the strength gains become more gradual. Mix 2 consistently exhibits higher compressive strength than Mix 1, with Mix 2 reaching around 50 MPa by day 90, compared to Mix 1's 45 MPa. This difference is likely due to the higher NaOH molarity and NaOH/Na₂SiO₃ ratio in Mix 2, which increases the geopolymerization reaction rate, forming a denser microstructure. This aligns with findings from previous studies (Indriani et al., 2023; Leela Sai Rangarao et al., 2023). The early strength gain, particularly by day 7, highlights the role of GGBS in facilitating rapid strength development through the formation of calcium silicate hydrate (C-S-H), a process consistent with findings by (Divahar et al., 2023). The continued, albeit slower, strength development beyond 28 days can be attributed to the prolonged formation of geopolymeric gels, which further densifies the matrix. The better performance of Mix 2 underscores how optimizing alkali content can lead to more complete reactions between GGBS and Alccofine, thereby enhancing long-term strength.

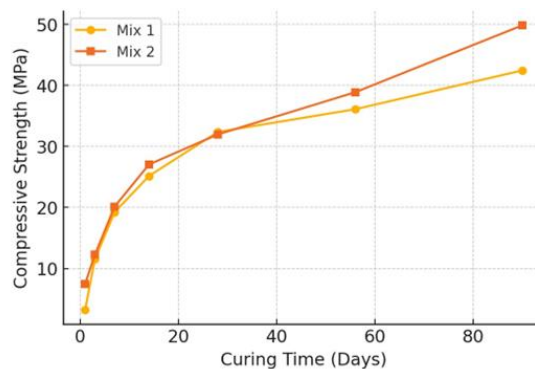


Figure 2 Influence of curing Time on Compressive strength

The compressive strength results for different geopolymer mixes, as outlined in Table 3, show clear trends in strength development over 7, 28, 56, and 90 days. Mix 2 achieves the highest compressive strength at 50 MPa by day 90, followed by Mix 3 (48 MPa) and Mix 4 (47 MPa). This higher performance can be attributed to the increased NaOH molarity and the optimal NaOH/Na₂SiO₃ ratio, which enhances the geopolymerization process. Faster dissolution of aluminosilicates allows for quicker gel formation, thus improving early strength development. This effect is particularly evident by day 7, where all mixes exhibit strengths between 20-25 MPa, with GGBS playing a key role in contributing to this early strength through rapid C-S-H formation, as also noted by (Divahar et al., 2023). The slow yet steady increase in strength from day 28 to 90 reflects the ongoing geopolymerization process, with the formation of a denser, three-dimensional aluminosilicate network that improves both strength and durability. Mix 1's slightly lower strength can be attributed to its lower NaOH molarity and the absence of Alccofine, which results in a less reactive and less dense matrix. These results mirror Ryu et al.'s (2013) findings, where higher alkali concentrations and supplementary cementitious materials like Alccofine were shown to enhance compressive strength.

Table 3 Compressive Strength Results for Geopolymer Mixes

| Mix ID | Day 7 (N/mm ²) | Day 28 (N/mm ²) | Day 56 (N/mm ²) | Day 90 (N/mm ²) |
|--------|----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Mix 1 | 20 | 30 | 38 | 45 |
| Mix 2 | 25 | 35 | 42 | 50 |
| Mix 3 | 23 | 33 | 40 | 48 |
| Mix 4 | 22 | 32 | 39 | 47 |
| Mix 5 | 21 | 31 | 38 | 46 |

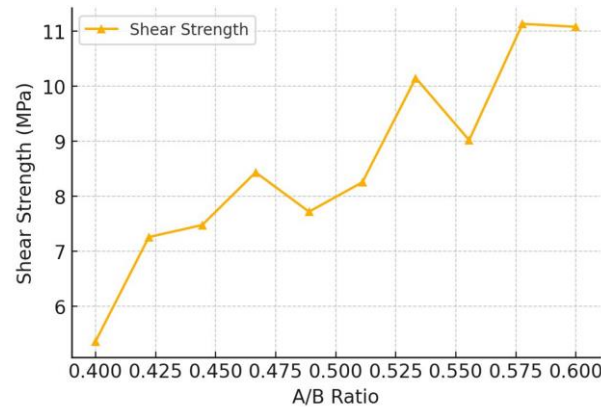


Figure 3 Influence of Alkali to Binder ratio on Shear strength

Figure 3 highlights the relationship between shear strength and the alkali-to-binder (A/B) ratio. Shear strength increases as the A/B ratio rises from 0.4 to 0.6, peaking at around 11 MPa at a ratio of 0.575. The steady increase in shear strength up to an A/B ratio of 0.525 suggests that higher alkali content facilitates a more complete geopolymerization process, creating a denser and more cohesive matrix that better resists shear forces. Beyond a ratio of 0.55, minor fluctuations in strength are observed, likely due to a reduction in workability or early stiffening of the mix, which affects stress distribution, as noted by (Liu et al., 2024). Higher alkali levels promote the dissolution of aluminosilicates, forming stronger aluminosilicate bonds and enhancing overall mechanical performance (Ettoumi et al., 2024). (Hossain et al., 2020) also observed that increasing alkali content, within an optimal range, results in improved shear performance, though excessive alkali content can cause brittleness and porosity, potentially explaining the fluctuations beyond an A/B ratio of 0.55. Optimizing the alkali-to-binder ratio is therefore critical in achieving a balance between strength and workability in geopolymer mixes.

Table 4 Shear Strength Test Results for Geopolymer Ferrocements

| Mix ID | Mesh Configuration | Shear Strength (N/mm ²) | Peak Load (kN) | Failure Mode |
|--------|--------------------|-------------------------------------|----------------|-------------------|
| Mix 1 | Single | 6 | 120 | Shear Cracking |
| Mix 2 | Double | 8 | 150 | Delamination |
| Mix 3 | Triple | 10 | 180 | Crack Propagation |
| Mix 4 | Double | 9 | 160 | Delamination |
| Mix 5 | Single | 7 | 130 | Shear Cracking |

Table 4 presents shear strength test results for geopolymer ferrocements, showing a clear correlation between mesh configuration and shear performance. Mixes with triple mesh layers, such as Mix 3, achieve the highest shear strength (10 N/mm²) and peak load (180 kN), indicating that additional reinforcement layers significantly improve the material's ability to resist shear forces. This improvement is due to the better distribution of stress across multiple reinforcement layers, which prevents localized cracking and allows the load to be carried more effectively (Sellier & Millard, 2019). Mixes with double mesh configurations, such as Mix 2 and Mix 4, also perform well, reaching shear strengths of 8-9 N/mm², though delamination was observed as the failure mode, suggesting that the interface between layers experiences high stress concentrations. Single mesh configurations (Mix 1 and Mix 5) show the lowest shear strengths (6-7 N/mm²), with shear cracking as the main failure mode, indicating that the reinforcement is less effective in distributing the load, leading to brittle failure.

Figure 4 demonstrates how increasing NaOH molarity impacts both the initial and final setting times of the mixes. As NaOH molarity rises from 8M to 12M, there's a noticeable lengthening of setting times. The initial setting time extends from about 45 hours at 8M to roughly 80 hours at 12M. Similarly, the final setting time moves from 120 hours up to around 155 hours. This extended setting time occurs because higher concentrations of alkali slow down the early stages of the geopolymerization process. Essentially, the initial formation of the geopolymeric network is delayed. Ettoumi et al., (2024) observed this behavior, explaining that higher dissolution rates of aluminosilicates at elevated molarities result in an increase in silicate species within the mix. The excess silicate then requires more time to undergo the polycondensation process and stabilize. This delay is consistent with what (Rekha et al., 2024) found regarding how NaOH concentration affects early reactions. Furthermore, studies like those by (Zhong et al., 2023) also point to a correlation between higher NaOH molarity and prolonged setting times due to the increased availability of reactive species. Interestingly, fluctuations in setting times after reaching 10M could be related to a complex interplay between the mix's reaction rate and its

rising viscosity. These findings emphasize that achieving the right balance of NaOH molarity is crucial in controlling both setting time and the eventual strength of geopolymer concrete.

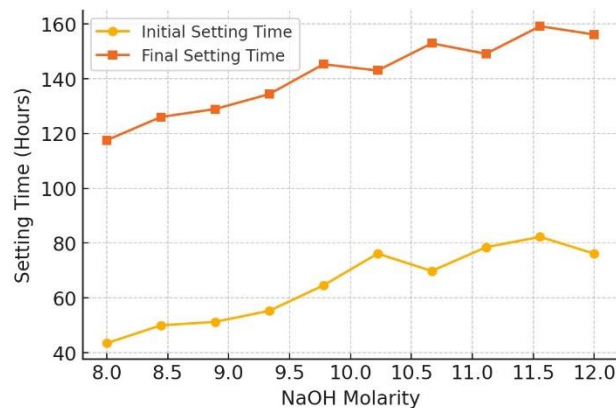


Figure 4 Setting time Vs Molarity of NaOH

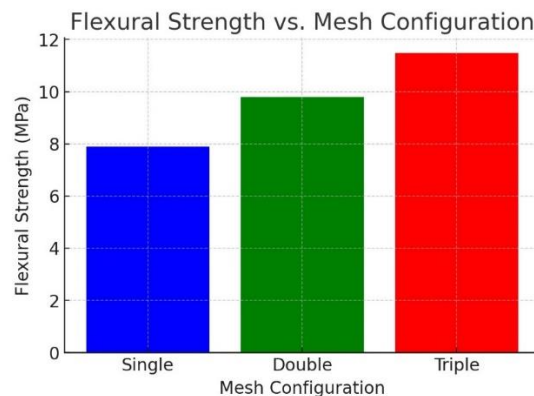


Figure 5 Flexural Strength Vs Mesh configuration

Figure 5 compares the flexural strength across different mesh configurations in geopolymer ferrocement. Flexural strength increases notably with the addition of more reinforcement layers, climbing from about 8 MPa for a single mesh layer to nearly 12 MPa for a triple layer. This upward trend underscores the importance of multiple mesh layers in distributing loads more evenly and improving the material's ductility and crack control. The added layers contribute significantly to crack bridging, which prevents crack propagation and allows the material to carry larger loads before failure. This observation is in line with Rangan's (2008) research, which highlighted how reinforcement layers enhance both ductility and the crack-arresting ability of geopolymer composites. (Mohana & Bharathi, 2024a) also discussed how increasing mesh layers improves the overall structural integrity of ferrocement. This is particularly evident in the triple-layer configuration, where cracks are less likely to propagate, thereby allowing the structure to withstand higher stress. Comparatively, single mesh configurations, with their limited capacity to arrest cracks, exhibit lower flexural strength, leading to earlier failure under flexural loads. Sellier & Millard, (2019) also concluded that double and triple-layered configurations provide superior resistance to both flexural and tensile stresses in geopolymer composites. These results highlight the critical role that proper mesh configuration plays in enhancing the overall performance of geopolymer ferrocements, particularly in applications requiring improved resistance to bending and cracking.

Table 5 Flexural Strength Results for Different Geopolymer Mixes

| Mix ID | Mesh Configuration | Flexural Strength (N/mm ²) | Crack Initiation Load (kN) | Crack Propagation Load (kN) |
|--------|--------------------|--|----------------------------|-----------------------------|
| Mix 1 | Single | 8 | 100 | 150 |
| Mix 2 | Double | 10 | 120 | 170 |
| Mix 3 | Triple | 12 | 140 | 190 |
| Mix 4 | Double | 11 | 130 | 180 |
| Mix 5 | Single | 9 | 110 | 160 |

The flexural strength results for different geopolymer mixes, summarized in Table 5, showcase how varying mesh configurations influence both flexural strength and crack behavior. Triple mesh configurations, such as in

Mix 3, show the highest flexural strength at 12 N/mm², with cracks initiating at 140 kN and propagating at 190 kN. This performance can be attributed to the effective distribution of tensile stresses across the three reinforcement layers. These layers help in delaying the formation and growth of cracks, allowing the material to resist higher loads for longer periods (Sellier & Millard, 2019). When compared to mixes with double mesh configurations, such as Mixes 2 and 4, which have slightly lower flexural strengths (10-11 N/mm²), it becomes clear that while double-layer reinforcement is beneficial, it doesn't offer the same level of crack control and load distribution as the triple mesh configuration. In contrast, single mesh configurations in Mixes 1 and 5 display the lowest flexural strengths (8-9 N/mm²), with crack initiation occurring much earlier at 100-110 kN. This highlights the reduced crack-arresting ability of single-layer reinforcement, which limits the material's capacity to resist bending stresses. (Mohana & Bharathi, 2024a) noted similar findings, stating that single layers of reinforcement are less effective in spreading out the load and are thus more prone to earlier failure. (Sinha & Talukdar, 2023) also emphasized the importance of increasing reinforcement layers to improve flexural performance in geopolymer composites, noting how these additional layers contribute significantly to crack control and delay the onset of structural failure. As such, optimizing mesh configurations is critical for achieving both higher flexural strength and improved structural durability in geopolymer ferrocement applications.

4. Conclusions:

The study shows that increasing the Alccofine content and optimizing the NaOH molarity and NaOH/Na₂SiO₃ ratio significantly increases the mechanical properties of geopolymer ferrocement. A mix containing 20% Alccofine and 80% GGBS, with an A/B ratio of 0.5 and a NaOH/Na₂SiO₃ ratio of 1.5, achieved the highest compressive strength of 50 MPa at 90 days. Similarly, using a triple-layer mesh configuration resulted in improved shear strength, reaching 10 N/mm², and flexural strength of 12 N/mm², as compared to 6-7 N/mm² in single-layer configurations. However, workability, as shown through slump tests, decreased from 100 mm to 80 mm when the A/B ratio was increased from 0.4 to 0.6, indicating a conflict between ease of handling and strength enhancement. These findings demonstrate that optimization of alkali activator ratios and the reinforcement layers can lead to significant improvements in the strength, crack resistance, and durability of geopolymer ferrocement.

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