

STRENGTH IN FUSION: ENHANCING CONCRETE PERFORMANCE WITH METAKAOLIN AND GLASS FIBERS

Madhava Krishna Reddy Gaddam^{1,3,*}, Gorle Papa Rao², and Boddepalli Krishna Rao¹

Received: July 11, 2024; Revised: November 01, 2024; Accepted: November 18, 2024

Abstract

This study investigates the use of metakaolin as a partial replacement for cement in concrete, ranging from 0% to 30% with an increment of 5% metakaolin a total of seven mixes is used in this study. In addition to its glass fibers are used to improve the properties of concrete from 0.5 to 2% with an increment of 0.5%. The primary objective is to evaluate the effects of metakaolin and glass fibers on the mechanical properties and durability of concrete. A comprehensive experimental program was conducted to measure various parameters, including compressive strength, tensile strength, and flexural strength. The experimental results were then compared using a numerical approach, specifically Analysis of Variance (ANOVA), to determine the statistical significance of the observed changes. Results indicate that 20% metakaolin replacement and 1.5% glass fiber content yielded the most favorable outcomes, significantly enhancing both compressive, tensile, and flexural strengths compared to other replacement levels. The ANOVA analysis confirms the statistical significance of these improvements, highlighting the optimal replacement percentage for maximizing concrete performance. The study concludes that metakaolin and glass fibers can serve as an effective supplementary cementitious material, offering improvements in concrete strength and durability while promoting sustainability.

Keywords: ANOVA; Glass fibres; Mechanical and durability properties; Metakaolin

¹ Department of Civil Engineering, University College of Engineering Kakinada (A) JNTU Kakinada, 533003, Andhra Pradesh, India. E-mail: civilmadhava@gmail.com*; krishnaraob102@gmail.com

² Department of Civil Engineering, Gayatri Vidya Parishad College of Engineering (A), Visakhapatnam, 530048, Andhra Pradesh, India. E-mail: gpao_74@gvpce.ac.in

³ Department of Civil Engineering, GMR Institute of Technology (A), Rajam, Andhra Pradesh, India.

* Corresponding author

DOI: <https://doi.org/10.55766/sujst-2024-06-e05763>

Suranaree J. Sci. Technol. 31(6):010339(1-11)

Introduction

The construction sector is actively pursuing sustainable solutions to enhance concrete performance and durability while minimizing environmental impact. Metakaolin, a pozzolanic material derived from kaolinite clay, has emerged as a promising supplementary cementitious material (SCM). This substance is renowned for its capacity to augment concrete properties, bolstering both strength and durability. By reacting with calcium hydroxide in cement, metakaolin forms additional cementitious compounds, thereby enhancing mechanical strengths such as compressive and tensile strength. (Ahmad *et al.*, 2022) Moreover, it fortifies concrete against chemical attacks and lowers permeability, thereby prolonging its service life. This review investigates the effects of substituting cement with metakaolin in concrete, with a focus on its influence on mechanical properties, durability, and environmental advantages. By incorporating metakaolin, the construction industry can achieve more sustainable and high-performance concrete structures, contributing to environmental conservation and resource efficiency. (Arasu *et al.*, 2023a)

The inclusion of metakaolin tends to reduce the workability of concrete mixes, as indicated by lower slump values and increased Veebee time. However, this reduction can be mitigated by optimizing the water-to-binder ratio and using superplasticizers. (Mansour *et al.*, 2023) These admixtures can enhance the flow properties of the concrete without compromising its strength. Additionally, combining metakaolin with other materials like pulverized fuel ash (PFA) can help improve workability while maintaining the benefits of metakaolin. The synergistic effect of metakaolin and PFA can result in a concrete mix that is easier to work with, offering better consistency and finishing properties. (Sivakumar *et al.*, 2017)

Several studies have demonstrated that metakaolin can significantly enhance the mechanical properties of concrete. For instance, the incorporation of metakaolin at varying percentages (10%, 15%, and 20%) has been shown to improve compressive strength, tensile strength, and flexural strength. The optimal replacement level often cited is around 15%, which balances strength improvements with workability. (Ganta *et al.*, 2020) High-performance concrete (HPC) with a 10% metakaolin replacement exhibited similar or improved mechanical properties compared to conventional HPC, particularly after 28 days of curing. The improvement observed in concrete properties with metakaolin is primarily due to its

pozzolanic reaction, which leads to the formation of an additional calcium silicate hydrate (C-S-H) gel. This process increases the density and strength of the concrete matrix (Zuaiter *et al.*, 2022). The metakaolin enhances concrete durability by decreasing permeability, thereby bolstering its resistance to sulfate attacks, alkali-silica reactions, and penetration by chloride ions. These benefits make metakaolin a valuable supplementary cementitious material for producing sustainable, high-performance concrete. (Ruben *et al.*, 2021)

Metakaolin's impact on the durability of concrete is another critical area of research. Studies have shown that metakaolin enhances the resistance of concrete to high temperatures, chloride ingress, and chemical attacks. Concrete incorporating 15% metakaolin replacement showed enhanced durability even under exposure to temperatures as high as 800°C. This improvement can be attributed to the formation of an additional calcium silicate hydrate (C-S-H) gel, which enhances the density and reduces the permeability of the concrete matrix. Additionally, metakaolin has been found to refine the pore structure of concrete, thereby reducing chloride penetration and increasing resistance to de-icing salts and chemical attacks. (Griffiths and Ball, 2000) This refinement leads to a more compact and durable concrete structure, less prone to cracking and deterioration. The combined use of metakaolin and other materials like glass powder further enhances these properties, as the synergistic effects of these materials contribute to an even more refined pore structure and greater chemical resistance. This combination extends the service life of concrete structures, making them more durable and sustainable in harsh environmental conditions. (Arasu *et al.*, 2023b)

The combined use of metakaolin with other supplementary materials like recycled coarse aggregates (RCA), glass powder, and crumb rubber. These combinations aim to advance both the mechanical and durability aspects of concrete while advocating for sustainability. For example, concrete mixes incorporating 100% Recycled Concrete Aggregates (RCA) and 15% metakaolin demonstrated performance comparable to traditional concrete. (George *et al.*, 2018) This approach highlights the feasibility of producing sustainable concrete with significant waste content, thereby promoting environmental stewardship. Similarly, the combination of metakaolin and glass powder improved the microstructural properties and increased the service life of concrete. This synergy enhances the concrete's density and reduces

porosity, resulting in better durability and longevity. (Bazli *et al.*, 2020)

The environmental advantages of using metakaolin as a partial replacement for cement are significant. The production of metakaolin generates lower CO₂ emissions compared to Portland cement, contributing to a reduction in the overall carbon footprint of concrete. This reduction is vital in addressing climate change and promoting sustainable construction practices. Additionally, the use of metakaolin can help in the sustainable management of industrial by-products, as it is derived from kaolinite clay, a readily available material. (Kumar *et al.*, 2024) This approach not only conserves resources but also minimizes waste. Moreover, incorporating metakaolin in concrete mixtures can decrease the demand for Portland cement, leading to further environmental benefits. The combined environmental and performance advantages make metakaolin an attractive option for creating more sustainable and eco-friendly concrete structures. (Parthasaarathi *et al.*, 2023)

Materials (SCMs) like silica fume and high-quality slag, the use of metakaolin is expected to grow. Future research should focus on cost-effective production methods for metakaolin and its long-term performance in various environmental conditions. (Banerjee *et al.*, 2023) Developing more efficient and scalable production techniques could make metakaolin more affordable and accessible. Additionally, research should investigate the durability and performance of metakaolin-enhanced concrete in different climates and exposure conditions to ensure its reliability and versatility. The development of standardized guidelines for the use of metakaolin in concrete mixes will facilitate its broader application. (Rajendhiran *et al.*, 2022)

Metakaolin is a highly effective supplementary cementitious material that enhances the mechanical properties, durability, and environmental sustainability of concrete. Optimal replacement levels of around 15% have been found to provide the best balance between performance and workability. (Ali *et al.*, 2020) The combined use of metakaolin with other materials like RCA, glass powder, and crumb rubber offers further improvements and promotes sustainable construction practices. As the construction industry continues to seek sustainable solutions, metakaolin is poised to play a significant role in the future of concrete technology. (Yurdakul *et al.*, 2015)

The integration of glass fibers into concrete has become a focal point in recent years due to its potential to bolster both the strength and durability of the material. This review aims to consolidate insights from various studies to provide a comprehensive overview of how glass fibers

influence concrete properties. Research indicates that glass fibers enhance several mechanical properties of concrete, including compressive, tensile, and flexural strength. For example, a study highlighted in the literature underscores that glass fibers notably elevate the tensile and flexural strength of concrete, although they may marginally decrease compressive strength. (More and Subramanian, 2022) Similarly, another study found that incorporating glass fibers into self-compacting concrete (SCC) enhances its splitting tensile and flexural strength, despite a slight reduction in workability. Moreover, the combination of glass fibers with other materials such as metakaolin and fly ash has been explored to further enhance mechanical properties. According to, the simultaneous incorporation of glass fibers and fly ash in recycled aggregate concrete (RAC) resulted in improved compressive and tensile strength. This synergistic effect is attributed to the improved bond between the glass fibers and the binder matrix facilitated by fly ash. (Jiang *et al.*, 2024)

The durability of concrete is a critical factor, especially in harsh environmental conditions. Glass fibers have been found to enhance various durability aspects of concrete. The glass fibers improve the resistance of concrete to transport properties and chemical attacks, thereby extending its lifespan. (Rezaei *et al.*, 2024) Additionally, demonstrates that hybrid steel/glass fiber-reinforced concrete exhibits superior durability performance, including resistance to acid attack and chloride ion penetration. However, the impact of glass fibers on durability is not universally positive notes that while glass fibers improve mechanical properties, they may marginally reduce resistance to chloride ion penetration and water absorption. This indicates a need for optimal fiber dosage and the potential use of supplementary materials to mitigate any adverse effects. (Hoy *et al.*, 2024)

The long-term durability of glass fiber-reinforced concrete under various environmental conditions has also been investigated, examining the effects of exposure to UV radiation, freeze/thaw cycles, and aggressive chemical environments (Kantatham *et al.*, 2024). Both studies found that while glass fibers significantly improve the initial strength and toughness of concrete, prolonged exposure to harsh conditions can lead to deterioration in mechanical properties. For instance, reductions in flexural, compressive, and tensile strength were reported after prolonged exposure to freeze/thaw cycles and seawater immersion (Samingthong *et al.*, 2023).

This study aims to determine the optimal combination of metakaolin and glass fibers for enhancing concrete properties, evaluate the effects

on mechanical and durability properties, and statistically analyze the significance of these effects using ANOVA.

Materials and Methods

Cement

The chemical composition of Grade OPC 53 cement reveals key components essential for its properties. It consists primarily of CaO (61.14%), SiO₂ (20.15%), and Al₂O₃ (4.55%), which are vital for the cement's hydration and strength development. Other elements include Fe₂O₃ (2.25%), MgO (1.08%), and a loss on ignition of 2.48%, contributing to its overall composition. These constituents interact during the cement hydration process, forming essential compounds like calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which enhance concrete's durability and strength. The physical properties of OPC 53 cement include a high surface area of 2258 cm²/gm, a relative density of 3.15, and a grey powder form with particle sizes less than 90 micrometers (< 90 µm). These attributes ensure its suitability for producing dense and robust concrete structures in various construction applications.

Fine Aggregate

River sand is characterized by its granular appearance, grey color, and specific physical properties essential for construction. It has a relative density of 2.63 and an apparent density of 15.6 gm/cc, indicating its compact nature and suitability for use in concrete and masonry. With a water absorption rate of 6.14% and dampness of 1.56%, river sand retains moisture efficiently, impacting its workability in mortar mixes. Classified as Zone II, it features a maximum grain size of 1.18 mm and a fineness modulus of 4.67, making it ideal for fine aggregate applications in concrete production.

Coarse Aggregate

Coarse aggregate, essential for concrete strength, exhibits specific physical properties vital for construction applications. It has a relative density of 2.75 and an apparent density of 2.5 g/cc, indicating its compact and solid structure. With a low water absorption rate of 1.3% and negligible surface moisture, it maintains stability and durability in concrete mixes. The aggregate impact value of 13.7% signifies its resistance to impact loads, ensuring structural integrity. Classified with a fineness modulus of 6, it features a size of 20mm and an angular shape, enhancing interlocking within concrete matrices for robust construction.

Metakaolin

Metakaolin, known for its beneficial properties in concrete, exhibits specific physical and chemical characteristics vital for construction applications. It appears as a white powder with a high purity level of 99.08%. With an extensive surface area of 11,100 m²/kg and a specific gravity of 2.52, it enhances the reactivity and binding capacity within concrete mixes. The chemical composition of metakaolin includes 55.5% SiO₂ and 44.1% Al₂O₃, essential for enhancing concrete strength and durability. It also contains minimal amounts of CaO (0.06%), SO₃ (0.09%), and Fe₂O₃ (0.18%), ensuring low alkali content and reducing the risk of efflorescence in concrete structures. These properties underscore metakaolin's role in improving the mechanical properties and long-term performance of concrete.

Glass Fibers

The glass fiber specified has a length of 12 mm, with a high aspect ratio of 857, indicating its slender and elongated form. It possesses a specific gravity of 2.68 g/cm³ and exhibits a modulus of elasticity of 72 GPa, providing excellent stiffness. The fiber's tensile strength is noted at 1700 MPa, showcasing its ability to withstand pulling forces. It boasts very high resistance to chemicals, is electrically non-conductive, and has a high softening point of 860°C. This alkali-resistant glass fiber is straight in shape, contributing to its suitability for reinforcing materials requiring durability and strength in harsh environmental conditions.

Glenium Stream 2

Glenium Stream 2, a vital additive in concrete, is characterized by its specific physical properties essential for enhancing concrete performance. It appears as a colorless liquid with a specific gravity of 1.01, making it easy to handle and mix into concrete batches. With a pH level greater than 6, it ensures compatibility with various concrete compositions without affecting their chemical balance. Glenium Stream 2 boasts a minimal chloride ion content of less than 0.18%, which helps prevent corrosion in reinforced concrete structures. These properties highlight its role in improving the workability, durability, and strength characteristics of concrete.

Methodology

This study examines the impact of metakaolin as a partial substitute for cement in concrete, ranging from 0% to 30% in increments of 5%. Seven distinct concrete mixtures were formulated to encompass this spectrum. The principal aim is to evaluate the

influence of varying metakaolin levels on both the mechanical properties and durability of concrete. Key components of the concrete mixes include Ordinary Portland Cement (OPC), metakaolin, fine aggregate (sand), coarse aggregate (gravel), and water. The study focuses on how these formulations affect vital aspects such as compressive strength, split tensile strength, flexural strength, as well as durability against factors like sulfate attacks and water absorption. The OPC conforms to Grade 53 specifications, ensuring consistency across all mixtures. Metakaolin, sourced from a reliable supplier, is added in varying proportions to replace cement content in the mixtures.

The concrete mixtures are prepared based on weight proportions to maintain consistency in water-cement ratio and aggregate grading. Mix designs are adjusted for each replacement level of metakaolin (0%, 5%, 10%, 15%, 20%, 25%, and 30%). Concrete specimens are fabricated in conventional molds for subsequent testing of compressive strength, tensile strength, and flexural strength. Strict adherence to ASTM standards governs the curing process to ensure consistent hydration and optimal development of concrete strength properties. Compression tests are conducted on cylindrical specimens measuring 150 mm in diameter and 300 mm in height at intervals of 7, 14, and 28 days using a compression testing apparatus. Direct tensile strength assessments are performed on cylindrical specimens of identical dimensions (150 mm diameter $\times$ 300 mm height) using a universal testing machine. This method enables precise determination of the concrete's ability to withstand direct tension under controlled conditions. Flexural strength evaluations are carried out on beam specimens measuring 100 mm $\times$ 100 mm $\times$ 500 mm at specified curing periods. These tests provide critical insights into the concrete's resistance to bending forces, vital for evaluating its suitability for structural applications. By adhering rigorously to these standardized procedures, the study ensures robust and comparable assessments of concrete performance across various mix compositions, including investigations into the influence of metakaolin as a partial substitute for cement. Test results are recorded for each concrete mixture and curing period, focusing on compressive, tensile, and flexural strengths. The tests include density measurements and water absorption tests to evaluate concrete durability. The 28 days concrete is fully immersed in water for 28 days and then tested for its compressive strength. The 28 days concrete is fully immersed in sulphate solution for 28 days and then tested for its compressive strength. The 28 days concrete is fully immersed in chloride solution for 28 days and then

tested for its compressive strength. Glenium Stream 2 boasts a minimal chloride ion content of less than 0.18%, which helps prevent corrosion in reinforced concrete structures.

Experimental results are statistically analyzed using Analysis of Variance (ANOVA) to determine the significance of differences among the concrete mixtures. ANOVA assesses the impact of metakaolin on strength properties and identifies the optimal replacement percentage for maximizing concrete performance. Findings are compared against control mixtures (0% metakaolin) to assess improvements in mechanical properties. Trends in strength development and durability enhancements are analyzed to validate the effectiveness of metakaolin as a supplementary cementitious material. Table 1 shows the mix description of various mixes.

Table 1. shows the mix description of various mix

Mix	Description
M1	Conventional Concrete
M2	5% Metakaolin + 95% OPC
M3	10% Metakaolin + 90% OPC
M4	15% Metakaolin + 85% OPC
M5	20% Metakaolin + 80% OPC
M6	25% Metakaolin + 75% OPC
M7	30% Metakaolin + 70% OPC
M8	20% Metakaolin + 80% OPC + 0.5% glass fibre
M9	20% Metakaolin + 80% OPC + 1.0 % glass fiber
M10	20% Metakaolin + 80% OPC + 1.5% glass fiber
M11	20% Metakaolin + 80% OPC + 2 % glass fiber
M12	20% Metakaolin + 80% OPC + 2.5% glass fiber

Results and Discussion

Compressive Strength Test

The compressive strength of various concrete mixes incorporating metakaolin and glass fibers was evaluated at 7, 14, and 28 days. The conventional concrete (M1) exhibited compressive strengths of 27.46 MPa, 34.33 MPa, and 39.16 MPa at the respective intervals. Introducing 5% to 30% metakaolin in mixes M2 to M7 generally enhanced the compressive strength, with the 20% metakaolin mix (M5) showing the highest improvement (44.03 MPa at 28 days). Beyond 20%, the compressive strength began to decline, indicating an optimal replacement level of around 20%. The addition of glass fibers to the 20% metakaolin mix further increased compressive strength. Mix M10, containing 1.5% glass fibers, achieved the highest 28-day compressive strength of 48.97 MPa,

demonstrating the synergistic effect of metakaolin and glass fibers in improving concrete performance. However, increasing the glass fiber content to 2% and 2.5% (M11 and M12) resulted in a slight reduction in compressive strength compared to M10, suggesting an optimal glass fiber content of around 1.5%. Overall, the results confirm that a combination of 20% metakaolin and 1.5% glass fibers significantly enhances the compressive strength of concrete, making it a viable approach for high-performance and durable concrete applications. Figure 1 shows the compressive strength test results.

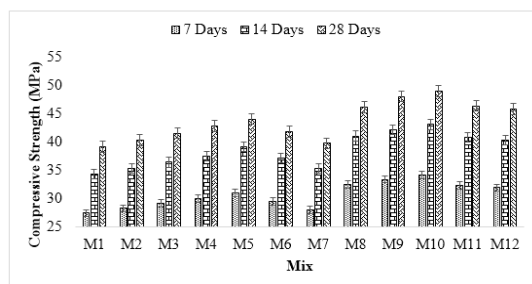


Figure 1. Shows the compressive strength test results

Split Tensile Strength

The split tensile strength of various concrete mixes incorporating metakaolin and glass fibers was evaluated at 7, 14, and 28 days. Conventional concrete (M1) exhibited split tensile strengths of 2.01 MPa, 2.23 MPa, and 2.39 MPa at the respective intervals. Introducing 5% to 30% metakaolin in mixes M2 to M7 generally enhanced the split tensile strength, with the 20% metakaolin mix (M5) showing the highest improvement (2.89 MPa at 28 days). Beyond 20%, the split tensile strength began to decline, indicating an optimal replacement level around 20%. The addition of glass fibers to the 20% metakaolin mix further increased split tensile strength. Mix M10, containing 1.5% glass fibers, achieved the highest 28-day split tensile strength of 3.24 MPa, demonstrating the synergistic effect of metakaolin and glass fibers in improving concrete performance. However, increasing the glass fiber content to 2% and 2.5% (M11 and M12) resulted in a slight reduction in split tensile strength compared to M10, suggesting an optimal glass fiber content around 1.5%. Overall, the results confirm that a combination of 20% metakaolin and 1.5% glass fibers significantly enhances the split tensile strength of concrete, making it a viable approach for high-performance and durable concrete applications. Figure 2 shows the split tensile strength test results.

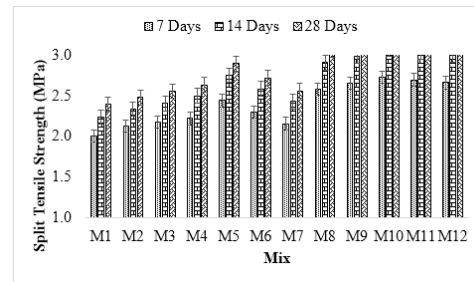


Figure 2. Shows the split tensile strength test results

Flexural Strength Test

The flexural strength of various concrete mixes incorporating metakaolin and glass fibers was evaluated at 7, 14, and 28 days. Conventional concrete (M1) exhibited flexural strengths of 2.48 MPa, 3.37 MPa, and 3.84 MPa at the respective intervals. Introducing 5% to 30% metakaolin in mixes M2 to M7 generally enhanced the flexural strength, with the 20% metakaolin mix (M5) showing the highest improvement (4.62 MPa at 28 days). Beyond 20%, the flexural strength began to decline, indicating an optimal replacement level around 20%. The addition of glass fibers to the 20% metakaolin mix further increased flexural strength. Mix M10, containing 1.5% glass fibers, achieved the highest 28-day flexural strength of 5.38 MPa, demonstrating the synergistic effect of metakaolin and glass fibers in improving concrete performance. However, increasing the glass fiber content to 2% and 2.5% (M11 and M12) resulted in a slight reduction in flexural strength compared to M10, suggesting an optimal glass fiber content around 1.5%. Overall, the results confirm that a combination of 20% metakaolin and 1.5% glass fibers significantly enhances the flexural strength of concrete, making it a viable approach for high-performance and durable concrete applications. This combination not only improves the mechanical properties but also contributes to the overall durability and resilience of concrete structures. Figure 3 shows the flexural strength test results.

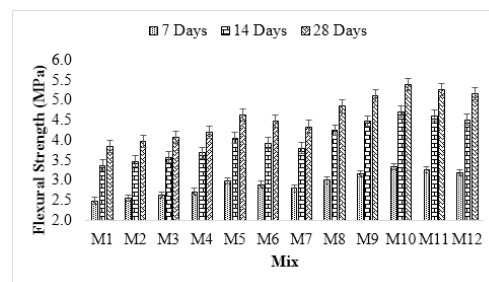


Figure 3. Graphical representation of flexural strength test results

Saturated Water Absorption

The percentage of saturated water absorption for various concrete mixes was evaluated at 28 days. Conventional concrete (M1) exhibited a saturated water absorption of 2.81%, serving as the control for comparison. Incorporating metakaolin in different proportions (M2 to M7) led to a gradual decrease in water absorption, with the 20% metakaolin and 80% OPC mix (M5) showing the lowest absorption at 2.68%. This indicates that metakaolin contributes to reducing the porosity of the concrete. Further improvements were observed with the addition of glass fibers to the metakaolin-OPC mix (M8 to M12). The inclusion of 0.5% glass fiber (M8) resulted in a water absorption of 2.65%, while increasing the glass fiber content to 1.0%, 1.5%, and 2.0% further reduced the absorption to 2.61%, 2.58%, and 2.60%, respectively. The mix with 1.5% glass fiber (M10) exhibited the lowest water absorption among all, at 2.58%. These findings suggest that both metakaolin and glass fibers effectively enhance the durability of concrete by reducing its water absorption capacity. The optimal combination was identified as 20% metakaolin with 1.5% glass fiber, which demonstrated the lowest water absorption, indicating improved resistance to moisture ingress and potential for greater durability in adverse environmental conditions. Figure 4 shows the saturated water absorption percentage.

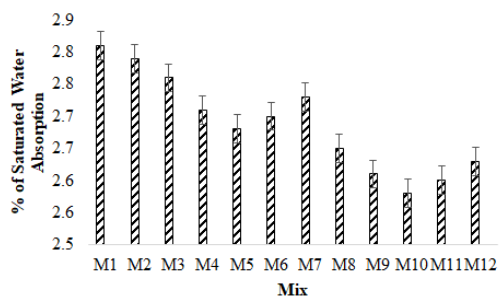


Figure 4. Shows the saturated water absorption percentage

Sulphate Attack Test

The percentage loss in compressive strength after sulfate attack for various concrete mixes was evaluated at 28 days. The conventional concrete mix (M1) exhibited a percentage loss of 5.08 MPa, serving as the baseline for comparison. Incorporating metakaolin in varying proportions (M2 to M7) showed a reduction in compressive strength loss, with the 20% metakaolin and 80% OPC mix (M5) achieving the lowest loss at 4.52 MPa. This indicates that metakaolin enhances sulfate resistance. Further enhancements were observed with the inclusion of glass fibers in the

metakaolin-OPC mix (M8 to M12). The addition of 0.5% glass fiber (M8) resulted in a compressive strength loss of 4.35 MPa, while increasing the glass fiber content to 1.0%, 1.5%, and 2.0% further reduced the loss to 4.21 MPa, 4.17 MPa, and 4.23 MPa, respectively. The mix with 1.5% glass fiber (M10) exhibited the best performance among all, with the lowest percentage loss in compressive strength at 4.17 MPa. These results suggest that incorporating metakaolin and glass fibers significantly improves the sulfate resistance of concrete. The optimal combination was found to be 20% metakaolin with 1.5% glass fiber, which achieved the minimum compressive strength loss, highlighting its potential for enhanced durability in sulfate-rich environments. Figure 5 shows the sulphate attack test results.

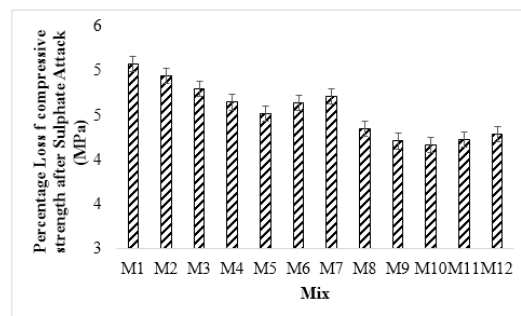


Figure 5. Shows the sulphate attack test results

Chloride Attack Test

The compressive strength after chloride attack testing for various concrete mixes reveals notable improvements with the incorporation of metakaolin and glass fibers. Conventional concrete (M1) has a compressive strength of 34.87 MPa. Adding metakaolin increases the strength, with the highest value at 39.18 MPa for the mix containing 20% metakaolin (M5). However, increasing the metakaolin content beyond this point results in a slight decrease in strength, as seen in M7, which contains 30% metakaolin and has a strength of 35.38 MPa. The inclusion of glass fibers in the 20% metakaolin mix further enhances the compressive strength. The highest value is observed in M10, which includes 1.5% glass fiber, achieving 43.61 MPa. This suggests that the optimal combination of metakaolin and glass fibers significantly enhances the concrete's resistance to chloride attack. Overall, the data indicate that a mix of 20% metakaolin with varying percentages of glass fibers provides superior compressive strength and durability compared to conventional concrete. Figure 6 shows the compressive strength of concrete after the chloride attack test results.

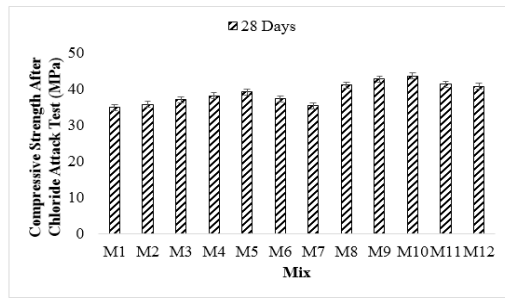


Figure 6. Shows the compressive strength of concrete after the chloride attack test

Numerical Approach

Compressive Strength Test

The analysis of variance (ANOVA) conducted for the compressive strength data reveals significant variations attributed to both the different concrete mixes (rows) and the factors influencing them (columns). The ANOVA results indicate a highly significant difference among the concrete mixes (rows), with an F-value of 76.20 and a remarkably low P-value of 6.84E-15, well below the standard significance level of 0.05. This suggests that the composition variations, including different percentages of metakaolin, OPC, and glass fibers, distinctly impact the compressive strength of the concrete mixes. Similarly, the factors represented by columns, which encompass the types and proportions of materials used, demonstrate an even more pronounced influence, as indicated by an F-value of 1662.00 and an exceedingly low P-value of 9.93E-25. This underscores the critical role of material selection and proportioning in determining concrete performance. The error term, reflecting variability within groups, was relatively small compared to the explained variances, further validating the robustness of the ANOVA results.

Overall, these findings highlight the importance of meticulous mix design and material selection in optimizing concrete properties such as compressive strength, vital for ensuring structural integrity and durability in construction applications. Table 2 shows the ANOVA Two-Factor without replication for the compressive strength test.

Split Tensile Strength Test

The ANOVA results for the split tensile strength test indicate significant variations attributable to both the different concrete mixes (rows) and the factors influencing them (columns). The analysis shows that the rows, representing various concrete mix compositions, exhibit a substantial difference in split tensile strength, with a calculated F-value of 292.5201 and an extremely low P-value of 3.42E-21, indicating strong statistical significance. This underscores the considerable impact of mix composition variations, including the incorporation of metakaolin, OPC, and glass fibers, on the tensile strength of the concrete. Similarly, the columns, which represent different factors such as material types and proportions, also demonstrate a significant influence on split tensile strength, with an F-value of 685.8833 and a very low P-value of 1.52E-20. This highlights the critical role of these factors in determining the tensile strength properties of the concrete mixes tested. The error term, reflecting variability within the groups, was minimal compared to the explained variances, further confirming the robustness of the ANOVA findings. These results underscore the importance of precise mix design and material selection in optimizing concrete performance, particularly in applications requiring high tensile strength for structural durability and resilience. Table 3 shows the ANOVA Two-Factor without replication for the split tensile strength test.

Table 2. shows the ANOVA Two-Factor without replication for the compressive strength test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	262.5086	11	23.86442	76.19655	6.84E-15	2.258518
Columns	1041.06	2	520.53	1661.997	9.93E-25	3.443357
Error	6.890301	22	0.313195			
Total	1310.459	35				

Table 3. shows the ANOVA Two-Factor without replication for split tensile strength test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	2.834452	11	0.257677	292.5201	3.42E-21	2.258518
Columns	1.208372	2	0.604186	685.8833	1.52E-20	3.443357
Error	0.01938	22	0.000881			
Total	4.062204	35				

Flexural Strength Test

The ANOVA results for the flexural strength test indicate significant variations attributed to both the different concrete mixes (rows) and the factors influencing them (columns). Analysis reveals that the rows, representing various concrete mix compositions, exhibit a notable difference in flexural strength, with an F-value of 31.56043 and a highly significant P-value of 6.5E-11, indicating strong statistical significance. This underscores the substantial impact of mix composition variations, including metakaolin, OPC, and glass fibers, on the flexural strength of the concrete. Similarly, the columns, which represent different factors such as material types and proportions, also demonstrate a significant influence on flexural strength, with an F-value of 504.0447 and an extremely low P-value of 4.22E-19. This highlights the critical role of these factors in determining the flexural strength properties of the concrete mixes tested. The error term, reflecting variability within the groups, was relatively small compared to the explained variances, further validating the robustness of the ANOVA findings. These results underscore the importance of precise mix design and material selection in optimizing concrete performance, particularly in applications requiring high flexural strength for structural integrity and resistance to bending stresses. Table 4 shows the ANOVA Two-Factor without replication for flexural strength test.

Saturated Water Absorption Test

The ANOVA results for the saturated water absorption test indicate variations attributed to both the different concrete mixes (rows) and the factors influencing them (columns). Analysis reveals that the rows, representing various concrete mix compositions, show no statistically significant difference in water absorption, with an F-value of 1 and a P-value of 0.5. This suggests that the composition variations, including metakaolin, OPC,

and glass fibers, do not significantly impact the water absorption properties of the concrete mixes tested. Similarly, the columns, which represent different factors such as material types, also demonstrate no significant influence on water absorption, with an F-value of 0.104536 and a P-value of 0.752516. This indicates that the factor tested in this study (likely a categorical variable such as the presence or absence of a specific additive) did not have a statistically significant effect on water absorption. The error term, reflecting variability within the groups, was relatively small compared to the explained variances, further confirming the consistency of the results. These findings suggest that for the saturated water absorption test conducted under these conditions, the factors examined do not contribute significantly to differences in water absorption among the concrete mixes. Table 5 shows the ANOVA Two-Factor without replication for the saturated water absorption test.

Sulphate Attack Test

The ANOVA results for the sulfate attack test indicate no statistically significant variations attributed to both the different concrete mixes (rows) and the factors influencing them (columns). Analysis reveals that the rows, representing various concrete mix compositions, show no significant difference in sulfate attack resistance, with an F-value of 1 and a P-value of 0.5. This suggests that the composition variations, including metakaolin, OPC, and glass fibers, do not significantly impact the sulfate attack resistance properties of the concrete mixes tested under these conditions. Similarly, the columns, which represent different factors such as material types, also demonstrate no significant influence on sulfate attack resistance, with an F-value of 0.117438 and a P-value of 0.738289. This indicates that the factor tested in this study (likely a categorical variable such as presence

Table 4. shows the ANOVA Two-Factor without replication for the flexural strength test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	6.096475	11	0.554225	31.56043	6.5E-11	2.258518
Columns	17.70281	2	8.851406	504.0447	4.22E-19	3.443357
Error	0.386337	22	0.017561			
Total	24.18562	35				

Table 5. shows the ANOVA Two-Factor without replication for saturated water absorption test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.502302	11	0.045664	1	0.5	2.81793
Columns	0.004774	1	0.004774	0.104536	0.752516	4.844336
Error	0.502302	11	0.045664			
Total	1.009378	23				

or absence of a specific additive) did not have a statistically significant effect on sulfate attack resistance. The error term, reflecting variability within the groups, was relatively small compared to the explained variances, further confirming the consistency of the results. These findings suggest that for the sulfate attack test conducted under these conditions, the factors examined do not contribute significantly to differences in sulfate attack resistance among the concrete mixes. Table 6 shows the ANNOVA Two-Factor without replication for the sulphate attack test.

Chloride Attack Test

The ANOVA table provided evaluates the statistical significance of the effects observed in the compressive strength data for different concrete mixes. The row representing different concrete mixes, the sum of squares (SS) is 216.1476 with 11 degrees of freedom (df). The mean square (MS) is 19.64978. The F-value is 286.5069, with a very small p-value (7.13E-12), indicating a significant difference between the different mixes. The F critical value is 2.81793, which is much lower than the calculated F-value, reinforcing the significance. Representing the two conditions (normal and after chloride attack), the sum of squares is 139.7055 with 1 degree of freedom. The mean square is 139.7055. The F-value is extremely high at 2036.999, with a p-value of 7.72E-14, again indicating a highly significant effect. The F critical value is 4.8443, much lower than the F-value. The error sum of squares is 0.75442 with 11 degrees of freedom, resulting in a mean square error of 0.06858. The total sum of squares is 356.6075 with 23 degrees of freedom. These results suggest that both the type of concrete mix and the condition (normal or after chloride attack) have a highly significant impact on the compressive strength. The extremely low p-values indicate that the observed differences are not due to random chance. Table 7 shows the

ANNOVA Two-Factor without replication for the chloride attack test.

Conclusion

The comprehensive evaluation of various concrete mixes incorporating metakaolin, OPC, and glass fibers reveals distinct trends in mechanical properties and durability. Across different testing durations (7 days, 14 days, and 28 days), compressive strength consistently improved with higher metakaolin content and the addition of glass fibers. At 28 days, mix M10, comprising 20% metakaolin, 80% OPC, and 1.5% glass fiber, demonstrated the highest compressive strength at 48.97 MPa, indicating optimal synergy in enhancing load-bearing capacity. Similarly, split tensile strength and flexural strength exhibited significant improvements with increased metakaolin and glass fiber proportions. Mix M10 showed the highest split tensile strength at 28 days (3.24 MPa) and flexural strength (5.38 MPa), highlighting enhanced resistance to tensile and bending stresses, vital for structural durability. Durability tests for sulfate attack, saturated water absorption, and chloride attack test, however, showed minimal variation across different mixes, indicating limited influence of additives on these properties under the tested conditions. The previous research also clearly indicated the use of metakaolin and fibers can be effectively used in concrete. The statistical analysis through ANOVA confirmed the significant effects of mix compositions on mechanical properties such as compressive strength, split tensile strength, and flexural strength. These findings underscore the importance of tailored mix designs in optimizing concrete performance for diverse structural applications. The study demonstrates the efficacy of incorporating metakaolin and glass fibers to enhance concrete strength and durability, vital for sustainable construction practices.

Table 6. shows the ANOVA Two-Factor without replication for the sulfate attack test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.031613	11	0.002874	1	0.5	2.81793
Columns	0.000337	1	0.000337	0.117438	0.738289	4.844336
Error	0.031613	11	0.002874			
Total	0.063562	23				

Table 7. shows the ANOVA Two-Factor without replication for the chloride attack test

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	216.1476	11	19.64978	286.5069	7.13E-12	2.81793
Columns	139.7055	1	139.7055	2036.999	7.72E-14	4.844336
Error	0.754424	11	0.068584			
Total	356.6075	23				

References

- Ahmad, J., González-Lezcano, R., Majdi, A., Kahla, N., Deifalla, A., and El-Shorbagy, M. (2022). Glass fibers reinforced concrete: Overview on mechanical, durability, and microstructure analysis. *Materials*, 15(15):5111. <https://doi.org/10.3390/ma15155111>
- Ali, B., Qureshi, L., Shah, S., Rehman, S., Hussain, I., and Iqbal, M. (2020). A step towards durable, ductile, and sustainable concrete: Simultaneous incorporation of recycled aggregates, glass fiber, and fly ash. *Construction and Building Materials*, 251:118980. <https://doi.org/10.1016/j.conbuildmat.2020.118980>
- Arasu, A.N., Muthusamy, N., Natarajan, B., and Parthasaarathi, R. (2023a). Optimization of high-performance concrete composites by using nanomaterials. *Research on Engineering Structures and Materials*, 1(2). <https://doi.org/10.17515/resm2022.602ma1213>
- Arasu, A.N., Muthusamy, N., Natarajan, B., and Parthasaarathi, R. (2023b). Utilizing recycled nanomaterials as a partial replacement for cement to create high-performance concrete. *Global NEST: The International Journal*, 25(6):89-92. <https://doi.org/10.30955/gnj.004780>
- Banerjee, P., Habib, M., Kuckian, S., Balushi, Y., and Hashami, S. (2023). Effects of glass fibre on the strength and properties of concrete. *E3S Web of Conferences*, 40:503003. <https://doi.org/10.1051/e3sconf/202340503003>
- Bazli, M., Zhao, X., Jafari, A., Ashrafi, H., Raman, R., Bai, Y., and Khezzadeh, H. (2020). Durability of glass-fibre-reinforced polymer composites under seawater and sea-sand concrete coupled with harsh outdoor environments. *Advances in Structural Engineering*, 24(6):1090-1109. <https://doi.org/10.1177/1369433220947897>
- Ganta, J., Rao, M., Mousavi, S., Reddy, V., and Bhojaraju, C. (2020). Hybrid steel/glass fiber-reinforced self-consolidating concrete considering packing factor: Mechanical and durability characteristics. *Structures*, 28:956-972. <https://doi.org/10.1016/j.istruc.2020.09.042>
- George, R.M., Das, B.B., and Goudar, S.K. (2019). Durability studies on glass fiber reinforced concrete. In B. Das & N. Neithalath (Eds.), *Sustainable construction and building materials* (pp. 781-790). Lecture Notes in Civil Engineering, vol. 25. Springer. https://doi.org/10.1007/978-981-13-3317-0_67
- Griffiths, R., and Ball, A. (2000). An assessment of the properties and degradation behaviour of glass-fibre-reinforced polyester polymer concrete. *Composites Science and Technology*, 60(14):2747-2753. [https://doi.org/10.1016/S0266-3538\(00\)00147-0](https://doi.org/10.1016/S0266-3538(00)00147-0)
- Hoy, M., Ro, B., Horpibulsuk, S., Suddeepong, A., Buritatum, A., Arulrajah, A., Yaowarat, T., and Horpibulsuk, J. (2024). Flexural fatigue performance of hemp fiber-reinforced concrete using recycled concrete aggregates as a sustainable rigid pavement. *Journal of Materials in Civil Engineering*, 36(11):04024378. <https://doi.org/10.1061/JMCEE7.MTENG-18367>
- Jiang, T., Liu, Z., Tian, X., Wu, J., and Wang, L. (2024). Review on the impact of metakaolin-based geopolymer's reaction chemistry, nanostructure, and factors on its properties. *Construction and Building Materials*, 412:134760. <https://doi.org/10.1016/j.conbuildmat.2023.134760>
- Kantatham, K., Hoy, M., Sansri, S., Horpibulsuk, S., Suddeepong, A., Buritatum, A., Yaowarat, T., Ro, B., and Phunpeng, V. (2024). Natural rubber latex-modified concrete with bottom ash for sustainable rigid pavements. *Civil Engineering Journal*, 10(8):2485-2501. <https://doi.org/10.28991/CEJ-2024-010-08-05>
- Kumar, S.N., Natarajan, M., and Arasu, A.N. (2024). A comprehensive microstructural analysis for enhancing concrete's longevity and environmental sustainability. *Journal of Environmental Nanotechnology*, 13(2):368-376. <https://doi.org/10.13074/jent.2024.06.242584>
- Mansour, M., Ismail, M., Latif, Q., Alshalif, A., Milad, A., and Bargi, W. (2023). A systematic review of the concrete durability incorporating recycled glass. *Sustainability*, 15(4):3568. <https://doi.org/10.3390/su15043568>
- More, F., and Subramanian, S. (2022). Impact of fibres on the mechanical and durable behaviour of fibre-reinforced concrete. *Buildings*, 12(9):1436. <https://doi.org/10.3390/buildings12091436>
- Parthasaarathi, R., Balasundaram, N., and Arasu, A. N. (2023, August). A stiffness analysis of treated and non-treated meshed coir layer fibre reinforced cement concrete. In AIP Conference Proceedings, 2861(1):0158672. AIP Publishing. <https://doi.org/10.1063/5.0158672>
- Rajendhiran, K., Gopinath, S., and Rajasekar, G. (2022). Experimental study on the strength of concrete using glass fiber. *Sustainable Materials and Smart Practices*, 23:290-296. <https://doi.org/10.21741/9781644901953-33>
- Rezaei Shahmirzadi, M., Gholampour, A., Hosseini, S.A., Ngo, T.D., and Nematzadeh, M. (2024). Wastepaper fiber-reinforced concrete containing metakaolin: Effect on fracture behavior. *Structural Concrete*, 25(4):2931-2946. <https://doi.org/10.1002/suco.202300849>
- Ruben, N., Venkatesh, C., Durga, C., and Chand, M. (2021). Comprehensive study on the performance of glass fibers-based concrete. *Innovative Infrastructure Solutions*, 6(2):1-11. <https://doi.org/10.1007/s41062-021-00490-4>
- Samingthong, W., Hoy, M., Ro, B., Horpibulsuk, S., Yosthasaen, T., Suddeepong, A., Buritatum, A., Yaowarat, T., and Arulrajah, A. (2023). Natural rubber latex-modified concrete with PET and crumb rubber aggregate replacements for sustainable rigid pavements. *Sustainability*, 15(19):14147. <https://doi.org/10.3390/su151914147>
- Sivakumar, V., Kavitha, O., Arulraj, G., and Srisanthi, V. (2017). An experimental study on combined effects of glass fiber and metakaolin on the rheological, mechanical, and durability properties of self-compacting concrete. *Applied Clay Science*, 147:123-127. <https://doi.org/10.1016/j.clay.2017.07.015>
- Yurdakul, A., Günkaya, G., Dölekçekiç, E., Kavas, T., and Karasu, B. (2015). Novel glass compositions for fiber drawing. *Ceramics International*, 41(10):13105-13114. <https://doi.org/10.1016/j.ceramint.2015.07.024>
- Zuaiter, M., El-Hassan, H., El-Maaddawy, T., and El-Ariss, B. (2022). Properties of slag-fly ash blended geopolymer concrete reinforced with hybrid glass fibers. *Buildings*, 12(8):1114. <https://doi.org/10.3390/buildings12081114>