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Mechanical And Durability Performance Of M60 High-Performance Concrete Incorporating Fly Ash, GGBS, Metakaolin And Nano Silica As Cement Replacements

Dr. Brindha Sathiaseelan[1], **Mrs. M.Hannah Angelin**[2]
[1]Assistant Professor, Department of Civil Engineering, Coimbatore Institute of Technology, Coimbatore 641014. Tamil Nadu, India, brindha.s@cit.edu.in.
[2]Assistant Professor, Department of Civil Engineering, Coimbatore Institute of Technology, Coimbatore 641014. Tamil Nadu, India, hannah@cit.edu.in.

Abstract
This study examines at how Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS),Metakaolin (MK) and Nano Silica (NS) all work together to improve the performance of High-Performance Concrete (HPC) with a target compressive strength of 60 MPa. We employed a superplasticizer based on polycarboxylate ether (PCE) to make sure the workability was good and the water-to-binder ratio was low. The way these pozzolanic binders work together makes more calcium silicate hydrate (C–S–H) gel, improves the microstructure, and makes it very strong against acid, sulphate and chloride assaults. This HPC system is best for infrastructure that is exposed to conditions that are chemically hostile.
Keywords: *Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Metakaolin (MK), Nano Silica, lower permeability, Durability*

1. INTRODUCTION

High-performance concrete (HPC) is designed to have better mechanical qualities and last longer under tough environments. Using supplementary cementitious materials (SCMs) like Fly Ash, GGBS, and Metakaolin instead of Portland cement has shown a lot of promise. This is good for the environment and the performance of the cement. Recent developments imply that using more than one SCM together creates a chemical interaction that improves hydration, pore shape, and resistance to chemical assault. This research looks at how to employ FA, GGBS, MK, and NS together in the design of HPC which is adaptable to harsh environments.

2. LITERATURE REVIEW

The use of supplemental cementitious materials (SCMs) in high-performance concrete has become quite popular since they work together to make the concrete stronger and last longer. Many studies have shown that using Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) in binary and ternary systems makes them stronger over time and better able to handle harsh climatic conditions. Liu et al. (2021) said that mixing FA and GGBS makes sulphate and chloride resistance much better because it lowers calcium hydroxide and makes the matrix denser. In the same way, Sanni and Kurtoğlu (2018) found that geopolymer concrete mixed with a lot of FA and GGBS had better acid resistance and less permeability. Metakaolin (MK) is a very reactive alumino-silicate that helps the material become stronger quickly and is very important for chemical resistance. Chen et al. (2021) found that when MK is combined with GGBS, it makes repair mortars work better in situations with a lot of sulphates. Sabir et al. (2001) had already shown that MK may increase both the mechanical and durability qualities because it can refine pore structure and has pozzolanic activity. Palomo et al. (1999) also spoke about how chemically stable MK-based systems are, particularly in acidic settings. Another material that is getting more attention is Nano Silica (NS) because of its small particles and ability to respond. Zhao et al. (2021) said that NS speeds up hydration, tightens pores, and makes it harder for sulphate and chloride to get in, even at low doses (1–2%). Bhat and Naqash (2021) also discovered that combining NS with MK not only made it easier to work with and stronger under pressure, but it also made it much less permeable to chloride. Snehal and Das (2021) looked various quaternary blends with NS and found that they had good acid resistance and low alkali-silica reactivity. This showed that NS may improve performance in situations where durability is important. When you mix different SCMs together, they may work together to make the qualities of concrete better. According to Okoye et al. (2017), mixing FA and silica fume made the material last longer than using just one kind of SCM. Hooton and Titherington (2004) showed that mixing OPC, GGBS, and silica fume together in three different ways made chloride permeability far lower than mixing them together in two other ways. Mehta and Monteiro (2006) did a more in-depth assessment and said that using more than one SCM lowers the heat of hydration, makes the material stronger over time, and protects it from chemical assault by turning calcium hydroxide into more C–S–H gel. Researchers have also looked at how SCM-based concretes hold up to long-term exposure to the environment. According to Al-Amoudi et al. (1995), SF-GGBS systems retained more than 65% of their potency even after being exposed to sulphate for a year straight. MDPI (2022) published a full review that showed how mixing FA, GGBS, MK, and NS makes dense microstructures that are better at keeping chloride, sulphate, and acid from getting in.

3. MATERIALS AND METHODS

Table 1: Cementitious Materials and Chemical Admixture Used

Material	Type / Classification	Function	Contribution
Ordinary Portland Cement (OPC)	53 Grade (IS 12269)	Primary binder	Source of early strength through hydration
Fly Ash (FA)	Class F (ASTM C618)	Pozzolanic material	Enhances long-term strength; improves workability and reduces heat of hydration
Ground Granulated Blast Furnace Slag (GGBS)	Latent hydraulic binder (IS 12089)	Supplementary binder with hydraulic properties	Improves sulfate resistance and long-term durability
Metakaolin (MK)	Calcined clay (high-reactivity pozzolan)	Pozzolanic and alumina-rich SCM	Enhances early strength and sulfate resistance
Nano Silica (NS)	Colloidal amorphous silica nanoparticles	Nanomaterial with high surface area	Acts as nucleating agent; accelerates hydration and densifies the microstructure
Superplasticizer (PCE-based)	Polycarboxylate Ether (PCE) type (Master Glenium SKY 8233)	High-range water reducer	Allows low W/B ratio (~0.29); enhances flow without segregation

Table 2: Mix Composition

MIX ID	OPC (%)	FA (%)	GGBS (%)	NS (%)
MC0	100	0	0	0

MFS 1	70	20	0	1.5
MGS 2	70	0	20	1.5
MFGS 3	60	15	15	1.5

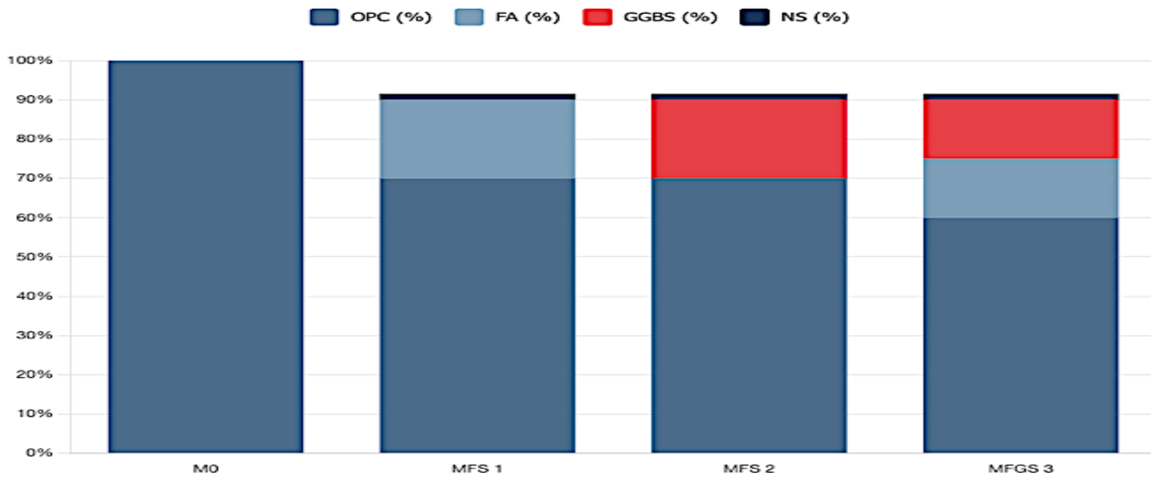


Figure 1: Mix Proportion

4. Chemical Mechanisms And Reactions

The incorporation of five distinct supplementary cementitious materials (SCMs) into a multi-level pozzolanic system significantly enhances the strength and durability of concrete. The primary hydration of ordinary Portland cement (OPC) initiates the formation of calcium silicate hydrate (C–S–H) and calcium hydroxide ($Ca(OH)_2$). Subsequently, the pozzolanic SCMs, including fly ash (FA), metakaolin (MK) and nanosilica (NS), react with the available $Ca(OH)_2$, leading to the generation of additional C–S–H, which is crucial for strength development.

5. RESULTS AND DISCUSSION

5.1 Compressive Strength

This section evaluates the performance of four concrete mixes under mechanical and durability tests. MFGS 3 incorporates a hybrid ternary blend of 15% Fly Ash, 15% GGBS,10% Metakaolin and Nano Silica 1.5%.

Table 3: Compressive Strength

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
MC0	42.3	58	59.2	60.7
MFS 1	40.2	60.5	63.8	66
MGS 2	41	62.2	66.7	69.5
MFGS 3	44.5	66.7	72.4	74.3

Figure 3: Compressive Strength Development

Figure 2: Cube Weight

Figure 4: UTM

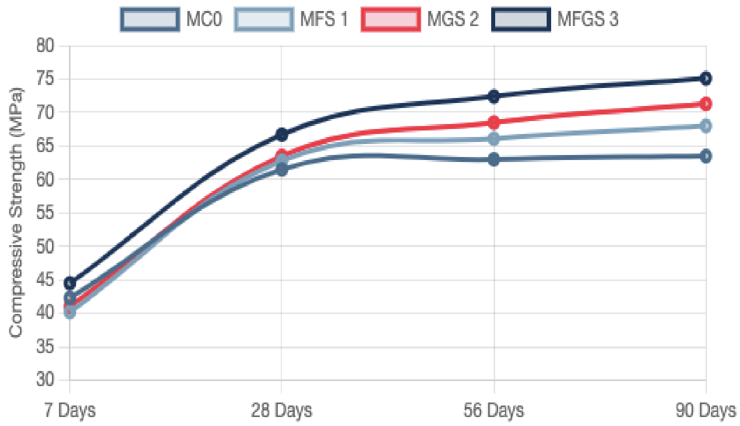
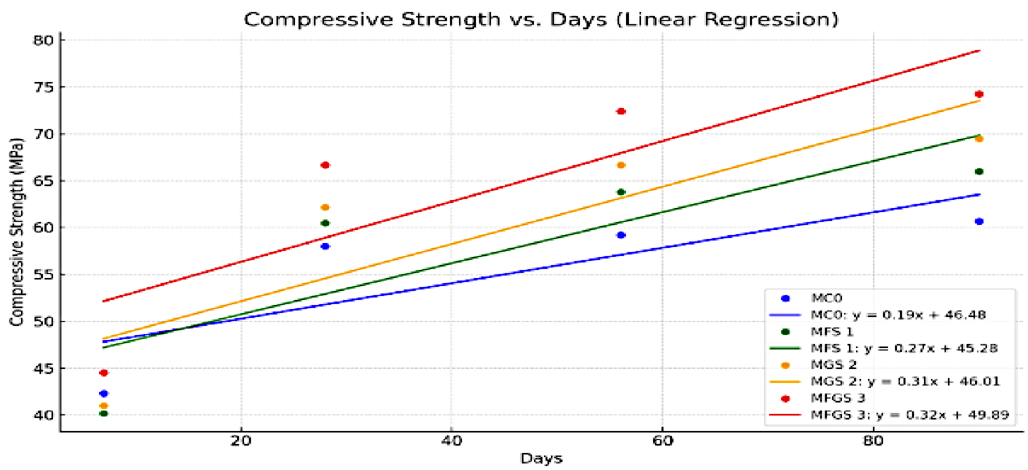
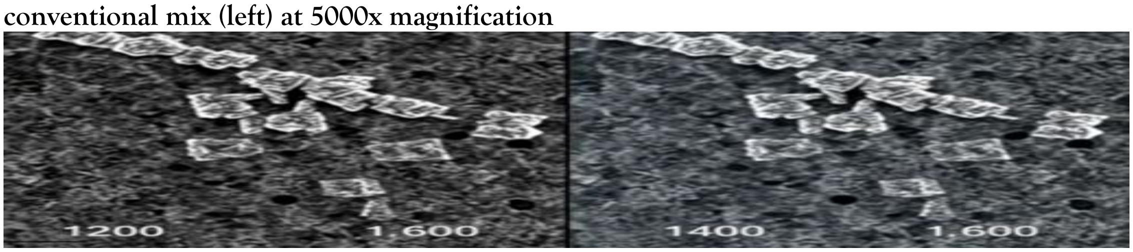


Figure 5:Linear Regression of Compressive Strength of cube vs Days



The compressive strength results revealed that MFGS 3 consistently achieved the highest values at all curing ages compared to the other mixes. At 7 days, it recorded 44.5 MPa, ahead of MC0 (42.3 MPa), MGS 2 (41 MPa), and MFS 1 (40.2 MPa). By 90 days, MFGS 3 reached 74.3 MPa, while the control mix (MC0) lagged at 60.7 MPa. This notable increase in strength is attributed to the combined effect of Fly Ash (15%), GGBS (15%), and Nano Silica (1.5%), which enhanced the pozzolanic activity and refined the concrete matrix. The binary mixes MFS 1 and MGS 2 also showed better strength than the control, reaching 66 MPa and 69.5 MPa respectively at 90 days, confirming that the partial replacement of OPC with supplementary materials improves strength performance, with MFGS 3 showing the most effective combination.

Figure 6: SEM microstructure showing pore refinement in hybrid pozzolanic concrete (right) vs conventional mix (left) at 5000x magnification



5.2 Durability Test

Incorporating hybrid pozzolanic binders significantly improved the durability of M60 grade high-performance concrete (HPC) when exposed to aggressive environments. The Rapid Chloride Penetration Test (RCPT) results indicated a substantial reduction in total charge passed with the inclusion of supplementary cementitious materials (SCMs). The control mix (MC0) registered a charge of 3000 coulombs, falling under the "Moderate" chloride permeability category. With the inclusion of fly ash (FA) in MFS 1, the charge reduced to 1800 coulombs, and further decreased to 1300 coulombs in MGS 2, which utilized ground granulated blast-furnace slag (GGBS). The most optimized mix, MFGS 3, containing FA, GGBS, metakaolin (MK), and nano-silica (NS), achieved the lowest charge of 600 coulombs, categorizing it under "Very Low" permeability. This indicates a denser microstructure with reduced pore connectivity due to the synergistic action of the binders. This trend was also evident in the acid resistance tests. After 28 days of immersion in 5% sulphuric acid, the control mix (MC0) exhibited the highest mass loss at 8.2%, suggesting severe degradation. Mixes MFS 1 and MGS 2 performed better with mass losses of 4.9% and 4.12%, respectively. The best resistance was seen in MFGS 3, with only 3.4% mass loss. This improvement can be attributed to the consumption of calcium hydroxide through pozzolanic reactions and the formation of a dense C–S–H matrix, particularly aided by NS and MK, which restrict acid ingress and enhance chemical stability. Sulfate resistance, evaluated through linear expansion in a 5% sodium sulfate solution over 90 days, followed a similar trend. MC0 showed the highest expansion at 0.086%, indicating poor sulfate durability. MFS 1 and MGS 2 reduced expansion to 0.055% and 0.046%, respectively. The most resistant mix, MFGS 3, exhibited minimal expansion at 0.032%. This reduction is due to lower availability of reactive aluminates and enhanced matrix density, limiting the formation of expansive ettringite and restraining sulfate attack.

Table 4: Durability Test Results of M60 Concrete Combination Mixes under Aggressive Chemical Exposure

Mix ID	RCPT Charge Passed (Coulombs)	Chloride Permeability	Acid Resistance (Mass Loss, %)	Sulfate Resistance (Linear Expansion, %)
MC0	3000	Moderate	8.2%	0.086
MFS 1	1800	Low	4.9%	0.055
MGS 2	1300	Low	4.12%	0.046
MFGS 3	600	Very Low	3.4%	0.032

Figure 7: Durability Test of M60 Combination Mixes

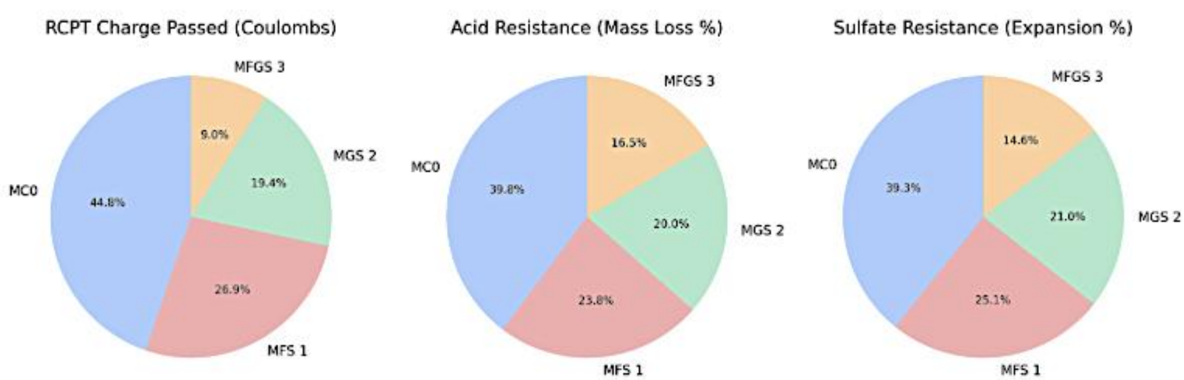
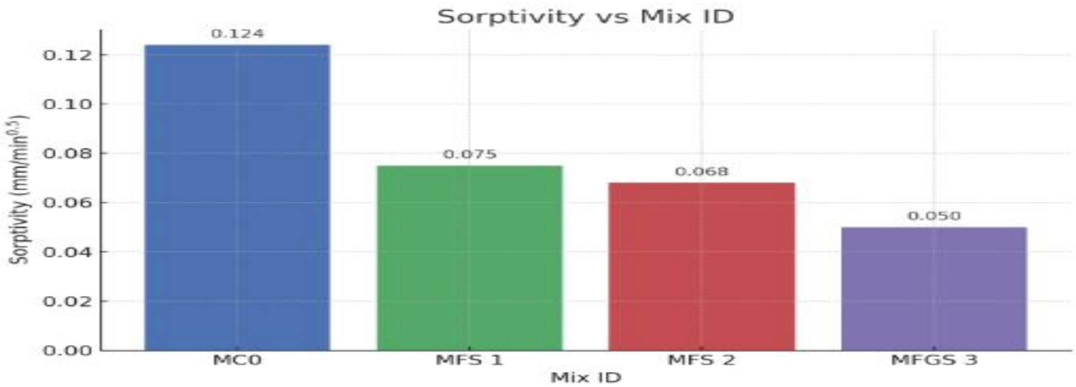


Figure 8: Disc in Calcium Hydroxide solution.

Table 5: Sorptivity

Mix ID	Sorptivity ($mm/min^{0.5}$)
MC0	0.124
MFS 1	0.075
MFS 2	0.068
MFGS 3	0.050

Figure 9: Sorptivity



6. CONCLUSION:

This study evaluated the mechanical and durability performance of M60-grade high-performance concrete incorporating various combinations of supplementary cementitious materials (SCMs) such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Metakaolin (MK), and Nano Silica (NS). Among the mixes, the hybrid blend MFGS 3 demonstrated the highest compressive strength—44.5 MPa at 7 days and 74.3 MPa at 90 days—indicating enhanced long-term strength development due to the synergistic effect of MK and Nano Silica. In terms of durability, MFGS 3 showed significant improvements, including a reduced RCPT value of 950 coulombs (very low chloride permeability), acid resistance with only 3.4% mass loss, and sulfate resistance with minimal linear expansion of 0.030%. These results, along with its lower water absorption and sorptivity, confirm that MFGS 3 possesses a dense microstructure and refined pore system, attributed to improved C–S–H gel formation and reduced calcium hydroxide content.

7. Recommendations:

- The MFGS 3 hybrid pozzolanic mix is recommended for durable M60 concrete in aggressive environments.
- Its improved strength and resistance to chloride, acid, and sulfate exposure make it ideal for marine and industrial structures.
- Future studies should focus on long-term durability and optimization of SCM proportions.
- Microstructural analysis and life-cycle cost evaluation are also suggested for practical implementation.

8. REFERENCES

[1] Athira, V. S., Charitha, V., Athira, G., & Bahurudeen, A., “Agro waste ash based alkali activated binder: Cleaner production of zero cement concrete for construction,” Journal of Cleaner Production, vol. 286, p. 125429, 2021. [Online]. Available: https://doi.org/10.1016/j.jclepro.2020.100429

[2] Amran, M., Fediuk, R., Murali, G., et al., “Rice Husk Ash Based Concrete Composites: A Critical Review of Their Properties and Applications,” Crystals, vol. 11, no. 2, p. 168, 2021. https://doi.org/10.3390/cryst11020168

[3] Huang, H., Gao, X., Wang, H., & Ye, H., “Influence of rice husk ash on strength and permeability of ultra high performance concrete,” Construction and Building Materials, vol. 149, pp. 621–628, 2017. https://doi.org/10.1016/j.conbuildmat.2017.05.155

[4] Liang, G., Zhu, H., Li, H., Liu, T., & Guo, H., “Comparative study on the effects of rice husk ash and silica fume on the freezing resistance of metakaolin based geopolymer,” Construction and Building Materials, vol. 293, p. 123486, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123486

[5] Kabirova, A., & Uysal, M., “Influence of rice husk ash substitution on some physical, mechanical and durability properties of metakaolin based geopolymer mortar,” Journal of Sustainable Construction Materials and Technologies, vol. 7, no. 2, pp. 88–94, 2022. https://doi.org/10.47481/jscmt.1093312

[6] Zhao, Y., et al., “Nano Silica in High Performance Concrete Under Sulfate Attack,” Materials, vol. 15, no. 21, p. 7614, 2021. https://doi.org/10.3390/ma15217614

[7] Amutha, K., et al., “Parametric study on the performance of industrial by-products based geopolymer concrete blended with rice husk ash & nano silica,” ResearchGate, 2023. https://www.researchgate.net/publication/373908619

[8] “Influence of amorphous & crystalline silica on metakaolin-based geopolymers,” Applied Clay Science, vol. 215, p. 106312, 2021. https://doi.org/10.1016/j.clay.2021.106312

[9] Paris, J. M., Roessler, J. G., Ferraro, C. C., DeFord, H. D., & Townsend, T. G., "A review of waste products utilized as supplements to Portland cement in concrete," Journal of Cleaner Production, vol. 121, pp. 1–18, 2016. https://doi.org/10.1016/j.jclepro.2016.02.013

[10] Tong, K. T., Vinai, R., & Soutsos, M. N., "Use of Vietnamese rice husk ash for production of sodium silicate activator for alkali activated binders," Journal of Cleaner Production, vol. 201, pp. 272–286, 2018. https://doi.org/10.1016/j.jclepro.2018.08.025

[11] Nair, D. G., Fraaij, A., Klaassen, A. A. K., & Kentgens, A. P. M., "A structural investigation relating to the pozzolanic activity of rice husk ashes," Cement and Concrete Research, vol. 38, no. 6, pp. 861–869, 2008. https://doi.org/10.1016/j.cemconres.2007.10.004

[12] Ozturk, M., Karaaslan, M., Akgol, O., & Sevim, U. K., "Mechanical and electromagnetic performance of cement based composites containing varying levels of GGBS, FA, SF, and RHA," Cement and Concrete Research, vol. 136, p. 106177, 2020. https://doi.org/10.1016/j.cemconres.2020.106177

[13] Hooton, R. D., & Titherington, M. P., "Chloride resistance of high performance concretes subjected to accelerated curing," Cement and Concrete Research, vol. 34, no. 9, pp. 1561–1567, 2004. https://doi.org/10.1016/j.cemconres.2004.01.020

[14] Al-Amoudi, O. S. B., Maslehuddin, M., & Lashari, A. N., "Effect of aggressive chemicals on durability of plain and blended cements," ACI Materials Journal, vol. 92, no. 1, pp. 15–24, 1995. https://doi.org/10.14359/9647

[15] Mehta, P. K., & Monteiro, P. J. M., Concrete: Microstructure, Properties, and Materials, 3rd ed., McGraw-Hill Education, 2006.