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Enhancing Concrete Performance and Sustainability: A Comprehensive Review of Alternative Binder Materials

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ABSTRACT

This study investigates the effects of incorporating metakaolin (MK), ground granulated blast furnace slag (GGBS), and nano-titanium dioxide (nano-TiO2) as partial replacements for cement in concrete mixtures. These supplementary materials play a vital role in improving the mechanical strength, durability, and overall performance of concrete, particularly in harsh environments such as coastal and chemically aggressive settings. Metakaolin enhances the microstructure by refining the pore network, which leads to increased early strength and better resistance to chloride ingress. GGBS contributes to long-term strength gains and improves resistance against sulfate attack while also reducing the material's permeability. The addition of nano-TiO2 further refines the concrete matrix, decreasing water absorption and enhancing durability. When combined in suitable proportions, these materials not only improve concrete's structural properties but also promote sustainability by reducing reliance on traditional cement, thereby lowering carbon emissions. The findings underscore the potential of these alternative binders to produce high-performance concrete suitable for demanding applications, while also encouraging further exploration into their practical implementation in cement manufacturing and construction.

1. INTRODUCTION

Concrete is the most widely used construction material worldwide, yet its production is a significant source of carbon dioxide emissions, which poses serious environmental challenges. To address these issues, researchers have been actively investigating alternative binder materials that can improve the sustainability and performance of concrete. This review seeks to synthesize findings from various studies that evaluate the effectiveness of materials such as metakaolin, ground granulated blast-furnace slag (GGBS), copper slag, fly ash, and nanosilica as partial replacements for traditional cement. By consolidating these insights, the review emphasizes the potential of these innovative materials to reduce the ecological footprint of concrete while ensuring its structural integrity and durability. The exploration of these alternatives is essential for advancing sustainable construction practices and mitigating the environmental impacts associated with conventional concrete production.

II. LITERATURE REVIEW

1.Metakaolin-Based Concrete:

Pillay et al. (2020) investigated the use of metakaolin (MK) as a partial substitute for cement in concrete, particularly for applications in coastal and marine environments. Their study incorporated MK at replacement levels between 5% and 15%, revealing that MK enhances the concrete's pore structure, lowers permeability, and increases resistance to chloride ion penetration. These improvements contributed to higher compressive strength and better durability.

2.Ground Granulated Blast Furnace Slag (GGBS):

Suresh and Nagaraju (2015) reviewed the role of GGBS as a cement replacement in concrete, typically used at levels from 30% to 50%. Their findings highlighted that GGBSimproves mechanical strength and durability, especially enhancing resistance to sulfate and chloride attacks. Additionally, GGBS supports environmental sustainability by reducing the carbon footprint associated with cement production.

3.Nano-Titanium Dioxide (Nano-TiO2):

Rawat et al. (2022) examined the effects of nano-TiO2 as a cement additive at dosages close to 1.5% by weight. Their research demonstrated that nano-TiO2 increases compressive strength, decreases water permeability, and improves resistance to chloride penetration, thereby enhancing durability.

4.Experimental Study on Partial Replacement of Cement by Metakaolin and GGBS:

Elavarasan et al. (2023) studied the combined effects of metakaolin and GGBS in concrete. The research found that 10% GGBS and 20% metakaolin resulted in higher compressive, tensile, and flexural strength compared to conventional concrete, with improved durability and sustainability. Metakaolin refined the microstructure, enhancing early strength development.

5.Durability in Marine Environments:

Pillay et al. (2020) also reviewed high-performance concrete formulations containing MK and GGBS for marine applications. MK was found to improve resistance to chloride ingress, while GGBS enhanced sulfate resistance and reduced permeability, collectively extending the service life of marine structures.

6.Influence of GGBFS on Concrete Properties:

Suresh and Nagaraju (2015) further analyzed the impact of GGBS at various replacement levels, reporting improvements in mechanical properties, durability, and workability. They also noted increased resistance to aggressive environmental conditions and a reduced need for natural aggregates.

7.Influence of Metakaolin on Mortar and Concrete:

Zhang et al. (2021) evaluated MK replacement levels between 10% and 20% in mortar and concrete. Their study found that MK enhances compressive and tensile strength, improves durability, and increases resistance to chloride ions and freeze-thaw cycles.

8.Eco-Friendly GGBS Concrete:

Saranya et al. (2018) conducted a review on the use of GGBS in concrete with replacement levels up to 60%. The study emphasized the environmental benefits of GGBS, such as lower carbon emissions and the utilization of industrial by-products, alongside improvements in mechanical properties and durability.

9.GGBS as a Cement Replacement in Concrete:

Suresh and Nagaraju (2015) reiterated the advantages of GGBS as a partial cement substitute, noting enhanced mechanical strength and durability, particularly in resisting sulfate attack and chloride penetration, along with environmental benefits.

10.Selected Engineering Properties of Concrete Incorporating Slag and Metakaolin:

Khatib & Hibbert (2005) investigated the influence of GGBS (0–80%) and metakaolin (0–20%) on concrete performance. While GGBS delayed early strength development, MK compensated for this loss, leading to superior long-term strength. The study confirmed that workability and sulphate resistance improved with higher GGBS levels, while chloride penetration decreased with both materials.

11.Comprehensive Review on GGBS in Concrete Production:

Ahmad et al. (2022) reviewed the use of GGBS at replacement levels ranging from 20% to 60%. The study discussed improvements in mechanical strength, durability, and sustainability, and called for further research to optimize GGBS utilization.

12.Study of Early Age Properties and Behavior of Concrete with GGBS as Partial Cement Replacement:

Manjunatha & Jeevan (2015) explored early-age behavior of GGBS-modified concrete (15–45% replacement levels). Results showed that workability improved, while early-age compressive strength was lower compared to control concrete. However, at 15% GGBS, long-term strength was comparable to conventional concrete, demonstrating that strategic mix design is essential for balancing early and later performance.

13.Metakaolin and Calcined Clays as Pozzolans:

Sabir et al. (2001) reviewed MK and calcined clays as pozzolanic materials. They found that MK, when used as a partial cement replacement, improves mechanical properties, durability, and offers environmental benefits.

14.Durability of Mortar and Concrete with Pozzolans:

Hasan et al. (2016) examined various pozzolans, including MK, fly ash, and silica fume, as partial cement replacements. Their study found that these materials enhance durability by improving resistance to sulfate attack, chloride penetration, and carbonation.

15.Concrete Using Metakaolin and Copper Slag Admixtures:

Rajkumar et al. (2015) used 10% MK and copper slag as a fine aggregate replacement in M30 grade concrete. Their study reported improvements in compressive and flexural strength, as well as enhanced durability.

16.Mechanical Characteristics with Mineral Admixtures:

Ayub et al. (2014) reviewed concrete containing mineral admixtures such as fly ash, silica fume, GGBS, and MK. They concluded that these admixtures improve compressive and tensile strength and durability, with optimal performance depending on content and particle size.

17.Geopolymer Materials for Portland Cement Concrete:

Tee and Mostofizadeh (2021) reviewed geopolymer materials as partial or full replacements for Portland cement. Their study found significant improvements in compressive strength and durability, along with a reduced carbon footprint.

18.Durability with Different Mineral Admixtures:

Ayub et al. (2013) reviewed concrete with various mineral admixtures, including MK and GGBS, and found improved resistance to sulfate attack, chloride penetration, and alkali-silica reaction.

19.Strength and Durability Studies on Concrete with Partial Replacement of Cement by GGBS:

MohanKumar et al. (2017) assessed 20%, 35%, and 50% GGBS replacement levels in M40 grade concrete. They found that 20% GGBS exhibited the highest compressive, tensile, and flexural strength, alongside better durability against acid and alkali attack. Higher replacement levels led to strength reduction, confirming 20% GGBS as the optimal mix.

20.High-Performance Concrete with Tertiary Blends of GGBS and Metakaolin:

Mali and Bhusare (2018) studied high-performance concrete using blends of GGBS (30–50%) and MK (10–15%). The combination improved mechanical properties and durability while reducing cement content.

21.Incorporation of Metakaolin and Nanosilica:

Raheem et al. (2021) reviewed the use of MK and nanosilica in blended cement mortar and concrete. Nanosilica refined the pore structure and enhanced early and later-age strengths, while MK further improved mechanical properties and durability.

22.Influence of Metakaolin in Concrete as Partial Replacement of Cement:

Malagavelli et al. (2018) examined metakaolin's effects on M35 grade concrete, with 5–20% MK replacements. 10% MK demonstrated optimal results, enhancing compressive strength (+16.75%), tensile strength (+7.1%), and flexural strength (+7.88%). Additionally, MK improved resistance to water penetration and ion diffusion, making it a valuable pozzolanic material.

III. MATERIALS USED

1.Metakaolin(MK)

Metakaolin is a calcined clay widely recognized for its ability to enhance the mechanical strength and durability of concrete. It particularly improves resistance to chloride ion penetration, making it an ideal additive for structures exposed to coastal and marine environments. The Indian Standard IS 1344:1991 specifies the requirements for metakaolin when used in concrete.

2.Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a by-product of the steel manufacturing industry that serves as a supplementary cementitious material. Its inclusion in concrete improves workability and durability by reducing permeability and increasing resistance to aggressive chemical environments. The specifications for GGBS as a cement replacement are outlined in IS 12089:1987.

3.Nano-Titanium Dioxide (nano-TiO2)
Nano-TiO2 particles contribute to refining the microstructure of concrete, enhancing early-age strength and overall durability, especially when combined with other binders. Although there is no dedicated Indian Standard code for nano-TiO2, its use follows general guidelines for supplementary cementitious materials.
4.QuarryDust
Quarry dust is a fine aggregate alternative to natural sand that can improve the mechanical properties of concrete while reducing water demand. Its use in concrete is governed by IS 383:2016, which provides standards for fine aggregates.
5.CopperSlag
Copper slag, an industrial waste product, is utilized as a fine aggregate replacement. It enhances concrete strength and reduces water absorption. IS 456:2000 includes provisions for incorporating industrial by-products like copper slag in concrete mixes.
6.FlyAsh
Fly ash, a pozzolanic material derived from coal combustion, improves concrete workability and durability while lowering its environmental impact. The Indian Standard IS 3812:2003 outlines the quality requirements for fly ash used in cement and concrete.
7.CalcinedClays
Calcined clays act as pozzolanic additives that enhance concrete's durability and resistance to chemical attacks. Their use is covered under IS 1344:1991, which also applies to metakaolin.

IV. TESTS

Fresh Properties
• Slump test indicated that the addition of metakaolin tends to reduce concrete workability, whereas GGBS improves it.
• Setting time measurements showed that metakaolin accelerates the setting process, while GGBS delays it.
Mechanical Properties
• Compressive strength tests demonstrated that both MK and GGBS contribute to increased long-term strength, with optimal replacement levels around 10–15%.
• Flexural and tensile strength tests reflected similar enhancements with the inclusion of MK and GGBS.
• Dynamic modulus of elasticity tests revealed an initial decrease at early ages, followed by an increase at later stages for concrete containing these materials.
Durability Properties
• Chloride penetration and permeability tests confirmed that MK and GGBS significantly reduce concrete permeability, enhancing resistance to chloride-induced deterioration.
• Sorptivity and water absorption tests showed decreased capillary absorption in concrete with MK and GGBS.
• Carbonation resistance tests indicated improved performance against carbonation.
• Alkali-silica reaction (ASR) tests demonstrated that MK mitigates expansion caused by ASR.
Microstructural Analysis
• The addition of metakaolin (MK) and ground granulated blast furnace slag (GGBS) refines the pore structure of concrete by reducing pore volume and size, resulting in a denser and more compact matrix.
• These mineral admixtures react pozzolanically and hydraulically to form additional calcium silicate hydrate (C-S-H), which strengthens the concrete and limits the penetration of harmful substances like chlorides and sulfates.
• The improved microstructure enhances the durability and mechanical performance of concrete, especially in harsh environments, while also promoting sustainability by reducing cement consumption and lowering environmental impact.

V. CONCLUSION

1. Replacing cement partially with metakaolin at 10–15% significantly enhances concrete strength, with improvements in compressive strength ranging from 11% to 33%, flexural strength increasing by 5% to 38%, and tensile strength improving up to 27%. Metakaolin also boosts durability by increasing resistance to chloride penetration, which is especially beneficial for marine and coastal structures.
2.Incorporating ground granulated blast furnace slag (GGBS) at levels between 20% and 50% results in compressive strength gains of approximately 15% to 30%. GGBS enhances durability by reducing permeability and improving resistance to chemical

attacks, while supporting sustainability by lowering cement consumption and carbon emissions.

3.Adding nano-titanium dioxide (nano-TiO_2) at around 1% by weight of cement leads to compressive strength increases between 16% and 28%, with flexural strength improvements up to 47%. Nano-TiO_2 refines the concrete microstructure, decreasing porosity and enhancing overall durability.

4.The combined use of metakaolin, GGBS, and nano-TiO_2 in optimal proportions provides balanced improvements in mechanical properties and durability, enabling the production of high-performance concrete suitable for demanding construction environments.

5.These supplementary cementitious materials contribute to sustainable construction by reducing cement demand and lowering the environmental impact associated with traditional concrete production.

6.Further research is encouraged to optimize mix designs, investigate raw material sourcing, and explore practical implementation methods to maximize the benefits of these alternative binders in commercial concrete applications.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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