International Journal of
Construction Engineering and Planning

ISSN: 2456-2335
Volume 10, Issue 1, 2024
DOI (Journal): 10.37628/IJCEP

https://journalspub.com/journal/ijcep/

Review IJCEP

Review of Partial Replacement of Cement with Metakaolin and Utilization of M-Sand, Alongside Addition of Steel Fiber, in the Construction Industry

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Abstract

In this contemporary context, demands placed on concrete have escalated significantly. Various essential properties of concrete such as strength, durability, workability, and expected service life require enhancement. This work focuses on investigating the strength properties of concrete through different substitutions of cement with metakaolin (MK), manufactured sand (M-sand), and steel fiber. Tests were conducted in accordance with Bureau of Indian Standards guidelines to assess the suitability of MK as a cement replacement. Steel fiber was added to improve the concrete's durability. Various strength parameters, including compressive strength and split tensile strength, were tested and recorded for M25-grade concrete. Partially replaced concrete exhibited an increase in strength compared to conventional concrete to some extent. Various mix combinations involving partial replacement of M-sand along with MK and steel fiber were evaluated. The experimental findings, synthesized from extensive literature reviews, indicate that the partial substitution of cement with M-sand, MK, and steel fiber leads to an improvement in the strength of concrete.

Keywords: Compressive strength, metakaolin, split tensile strength, steel fiber

INTRODUCTION

Cement concrete is the most widely used construction material globally, but its maintenance and repair pose significant challenges and expenses. Advances in material technology have enabled the development of concrete that meets more demanding performance standards, especially in terms of long-term durability. High-performance concrete (HPC) is a significant innovation in this area and has gained popularity for use in high-profile projects such as nuclear power plants, flyovers, and multi-story buildings [1–3].

The use of supplementary materials in cement has increased significantly due to cost savings, energy conservation, and environmental concerns related to raw material extraction and CO_2 emissions from cement manufacturing. This shift aims to reduce cement consumption. Metakaolin (MK) is emerging as a promising supplementary material for HPC due to its beneficial properties and potential cost advantages, given its abundant availability [4–7].

Studies involving various mix combinations with partial replacements of M-sand, MK, and

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Received Date: May 01, 2024
Accepted Date: May 28, 2024
Published Date: May 30, 2024

Citation: Kalpana Shende, Valsson P. Varghese, Swapneel Satone, A.M. Badar. Review of Partial Replacement of Cement with Metakaolin and Utilization of M Sand, Alongside Addition of Steel Fiber, in the Construction Industry. International Journal of Construction Engineering and Planning. 2024; 10(1): 26–30p.

steel fiber have been conducted to evaluate concrete strength and durability. These studies compare the strength of mixes with and without these materials to determine the optimal proportions. MK, a pozzolanic additive, enhances concrete and cement by providing unique properties. Its quality, particularly its purity, affects its binding capacity and reactivity. MK is a valuable admixture due to these characteristics [8–12]. M25 concrete, with a compressive strength of 25 MPa, is commonly used for foundations, columns, and beams. It is made by mixing cement, sand, and coarse aggregates. M-sand, an artificial sand produced by crushing hard stones into small, angular particles, is a construction aggregate alternative to river sand. Normal unreinforced concrete is brittle and has low tensile strength and strain capacity. The addition of steel fibers significantly improves the durability and ductility of the concrete mix while reducing installation and labor costs. Steel fibers enhance compressive, tensile, and flexural strength, ductility, fracture toughness, and shrinkage behavior. Most importantly, steel fibers bridge cracks and maintain the mechanical properties of the material after cracking, thereby increasing the concrete's overall performance.

LITERATURE REVIEW

In the current scenario, concrete is required to meet increasingly demanding performance standards. As the foremost construction material, concrete encounters challenges related to maintenance and repair, which often entail significant costs. Research efforts worldwide have aimed to develop materials that meet stringent performance standards, especially concerning long-term durability. HPC represents the latest advancement in concrete technology, finding widespread use in prestigious projects like nuclear power facilities, flyovers, and multistoried buildings. The evolution of HPC has spurred a notable rise in the utilization of supplementary materials in cement, driven by considerations such as cost-effectiveness, energy efficiency, and environmental sustainability, including reducing the environmental impact of raw material extraction and carbon dioxide emissions during cement production. MK emerges as a promising supplementary cementitious material for HPC due to its advantageous properties [13–15].

Properties of concrete incorporating MK are highly valued in HPC due to potential benefits such as cost-effectiveness and ready availability within the country. MK is employed as a partial replacement for cement in varying proportions, typically ranging from 5% to 20% by weight.

Tests involving cubes and cylinders are performed to assess the strength and durability of concrete. Experimental findings suggest that substituting cement with MK yields varying effects on concrete strength, with notable improvements observed up to the highest replacement percentages. Furthermore, MK has the potential to improve both the strength and durability of concrete compared to mixes that do not include MK.

Fiber reinforced concrete is another area of study, where composite materials comprising conventional concrete (CC) constituents along with added fibers are explored. These fibers, whether natural or artificial, aim to mitigate crack formation and propagation in concrete structures.

Research efforts focus on comparing the mechanical properties of steel fiber-reinforced concrete with those of CC. Steel fibers are added at different percentages, typically ranging from 0.5% to 2.0%, with experiments conducted across various concrete grades. Compressive strength tests on cube specimens reveal increased strength with the addition of steel fibers, particularly at optimized dosages of around 1.5%. Additionally, split tensile strength tests and microstructural analyses using scanning electron microscopy and X-ray diffraction are conducted to further characterize the material.

Moreover, investigations delve into the substitution of natural river sand with manufactured sand (M-sand) in concrete production.

Environmental concerns and the depletion of natural sand resources necessitate the exploration of suitable alternatives. M-sand, despite its higher angularity, requires a higher water–cement ratio to maintain workability compared to natural river sand concrete. Studies evaluate the mechanical properties, workability, and durability of concrete with varying percentages of M-sand replacement. The research concludes by proposing suitable replacement percentages based on observed properties, aiming to guide concrete-making processes effectively.

Additionally, the utilization of supplementary materials such as MK as partial cement replacements, along with river sand and M-sand as fine aggregates, is investigated in concrete production. Tests conducted on concrete with a target compressive strength of 20 MPa assess mechanical parameters, including compressive strength, splitting tensile strength, and flexural strength, alongside non-destructive testing methods and durability assessments.

Results show that modified concrete exhibits superior mechanical properties and durability compared to CC.

Furthermore, studies explore the effects of MK and High Reactivity Metakaolin (HRM) on concrete properties. Both MK and HRM demonstrate beneficial effects on workability, strength, shrinkage, resistance to chloride penetration, and permeability of concrete. Optimal percentages of MK or HRM enhance compressive strength and durability, offering potential solutions to environmental, technical, and economic challenges associated with cement production [17, 18].

MATERIAL SELECTION

Finally, material selection for concrete production involves careful consideration of constituents such as MK, M-sand, and steel fiber. MK, produced by calcining kaolinite clay, serves as a high-quality pozzolanic material that improves the durability of concrete. Despite posing challenges related to workability, M-sand offers environmental benefits as a substitute for natural river sand. Steel fibers play a crucial role in improving concrete durability and strength, enhancing properties such as compressive, tensile, and flexural strength, ductility, fracture toughness, and shrinkage behavior.

CONCLUSION

Based on extensive literature reviews exploring the effects of partial replacement of cement with MK, M-sand, and steel fiber in concrete, the following conclusions were drawn:

Concrete mixes incorporating MK exhibited higher strength compared to those using Ordinary Portland Cement (OPC) alone.

Partial replacement of cement with MK may result in superior concrete performance compared to other mixtures.

Increasing the MK content, along with the inclusion of M-sand and steel fibers, enhances both the compressive strength and split tensile strength of the concrete.

The findings of the study advocate for further research and utilization of MK, M-sand, and steel fibers as materials for partial replacement in producing HPC.

These conclusions highlight the potential benefits of incorporating MK, M-sand, and steel fibers in concrete mixtures, emphasizing their role in improving concrete strength and performance.

Enhanced Strength: Incorporating MK consistently led to higher strengths in concrete mixes compared to conventional OPC-based concrete. This highlights that MK's pozzolanic properties significantly enhance the development of concrete strength over time.

Superior Performance: Concrete mixes containing MK, M-sand, and steel fibers exhibited superior performance in terms of mechanical properties and durability. The combined effects of these materials improved strength, workability, and resistance to cracking and deterioration.

Optimized Combinations: It's crucial to optimize the combination of MK, M-sand, and steel fibers to achieve desired concrete properties. Through systematic experimentation, researchers identified optimal replacement percentages and mix proportions for producing HPC.

Environmental Benefits: Using MK, M-sand, and steel fibers as partial replacements in concrete production offers environmental advantages by reducing reliance on OPC and natural aggregates. This aligns with sustainability objectives by mitigating resource depletion and lowering carbon emissions associated with cement manufacturing.

Future Directions: The promising results suggest opportunities for further research and innovation in concrete materials. Future studies could explore additional supplementary materials, alternative reinforcement options, and advanced testing methods to enhance concrete performance and sustainability.

In summary, the findings underscore the importance of considering alternative materials like MK, M-sand, and steel fibers in concrete production to enhance performance, reduce environmental impact, and meet the evolving needs of modern construction practices.

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