A Comprehensive Review on Experimental Investigation of Metakaolin as a Partial Replacement of Cement for M25 Concrete

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Abstract

Concrete is extensively used in the construction industry because of its high strength, durability, versatility, and wide range of applications. However, the manufacturing of Ordinary Portland Cement (OPC) releases considerable amounts of carbon dioxide (CO_2), which has a major impact on environmental pollution and global warming. To reduce these environmental effects, researchers have explored the use of supplementary cementitious materials (SCMs) as partial substitutes for cement. Among various SCMs, **Metakaolin (MK)** has attracted significant interest because of its high pozzolanic activity and its potential to enhance the mechanical and durability characteristics of concrete.

This review paper examines experimental studies related to the utilization of Metakaolin as a partial replacement for cement in **M25 grade concrete**. The effects of Metakaolin on **workability, compressive strength, split tensile strength, flexural strength, water absorption, permeability, and durability** are reviewed. Based on the findings reported in previous studies, the replacement of approximately **10–15% of cement with Metakaolin** generally provides favorable results, particularly in terms of strength and durability improvement, reduced permeability, and lower cement consumption. Although the incorporation of Metakaolin may reduce the workability of fresh concrete due to its high fineness and water demand, this issue can be addressed by incorporating suitable superplasticizers.

The review indicates that **Metakaolin is a promising and environmentally sustainable supplementary cementitious material** for the development of high-performance concrete. Its use can help reduce cement consumption while enhancing the strength and durability of concrete. The review also highlights several areas for further investigation, particularly regarding the optimization of Metakaolin content and its long-term performance in different environmental conditions.

Keywords: Metakaolin, M25 Concrete, Cement Replacement, Supplementary Cementitious Material, Compressive Strength, Durability, Sustainable Concrete.

1. Introduction

Concrete is extensively used in the construction industry for structures such as buildings, bridges, highways, dams, tunnels, and various industrial facilities due to its desirable compressive strength, durability, versatility, and economical nature. The rapid growth of urbanization and infrastructure projects has resulted in a substantial increase in the consumption of concrete. Ordinary Portland Cement (OPC), which serves as the principal binder in conventional concrete, requires considerable energy during manufacturing and contributes nearly 7–8% of worldwide carbon dioxide (CO_2) emissions. Therefore, cement production is considered an important source of environmental pollution and greenhouse gas emissions.

In response to the environmental concerns associated with cement production, considerable research has been carried out on the incorporation of supplementary cementitious materials (SCMs) as partial substitutes for cement. Materials such as Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, Rice Husk Ash, and Metakaolin have been widely investigated for this purpose. Among these alternatives, Metakaolin has received significant attention because of its high content of reactive silica and alumina, very fine particle size, and strong pozzolanic activity.

Metakaolin is generally obtained through the controlled calcination of purified kaolin clay at temperatures between approximately 650°C and 850°C. When incorporated into cement-based materials, Metakaolin reacts with the calcium hydroxide generated during cement hydration and produces additional Calcium Silicate Hydrate (C–S–H) and other cementitious compounds. This pozzolanic reaction contributes to a denser and more compact concrete microstructure. Consequently, the use of Metakaolin can enhance compressive, tensile, and flexural strength while reducing permeability and water absorption. It can also improve the durability of concrete against aggressive environmental conditions, including sulphate and chloride exposure.

M25 grade concrete is commonly adopted in residential, commercial, and other general construction applications due to its satisfactory combination of strength, durability, and economic feasibility. Previous experimental studies have reported that partial replacement of cement with Metakaolin, particularly in the range of 10–15%, can improve several performance characteristics of M25 concrete. At the same time, such replacement reduces the quantity of OPC required, thereby contributing to the development of more sustainable and environmentally responsible concrete.

The present review paper focuses on the available experimental research concerning the partial replacement of cement with Metakaolin in M25 grade concrete. It critically examines the reported effects of Metakaolin on the mechanical and durability-related properties of concrete. In addition, the review identifies important research gaps and discusses potential areas for future investigation aimed at promoting sustainable

2. Literature Review

Many researchers have investigated the effect of Metakaolin on concrete properties.

Wild et al. (1996) reported that Metakaolin accelerates the pozzolanic reaction and improves compressive strength by producing additional C–S–H gel.

Sabir et al. (2001) concluded that Metakaolin enhances durability, reduces chloride penetration, and increases sulphate resistance due to its refined pore structure.

Poon et al. (2006) observed that concrete containing 10–15% Metakaolin exhibited lower water absorption, reduced permeability, and improved resistance to aggressive environments.

Khatib (2008) found that the optimum replacement level of Metakaolin is generally between 10% and 15%, beyond which strength gradually decreases because of the reduction in cement content.

According to **Siddique and Klaus (2009)**, although the workability of fresh concrete decreases with increasing Metakaolin content, the use of superplasticizers effectively compensates for this reduction. Their study also reported improvements in compressive, split tensile, and flexural strength.

Rashad (2013) reviewed several experimental studies and concluded that Metakaolin significantly improves the mechanical and durability properties of concrete. More recent studies have also shown that combining Metakaolin with Fly Ash, GGBS, Silica Fume, fibers, and recycled aggregates further enhances concrete performance and supports sustainable construction practices.

3. Effect of Metakaolin on the Properties of M25 Concrete

The performance of M25 concrete is greatly influenced by the percentage of Metakaolin used as a partial replacement for cement. Based on the findings of various experimental studies, Metakaolin improves both the fresh and hardened properties of concrete when used in an optimum quantity. The major effects are discussed below.

3.1 Effect on Workability

Workability is one of the most important properties of fresh concrete. The addition of Metakaolin generally decreases the workability because of its extremely fine particle size and high specific surface area, which increases the water demand of the concrete mix. As the percentage of Metakaolin increases, the slump value gradually decreases. However, this reduction in workability can be effectively compensated by using suitable superplasticizers without affecting the strength of concrete.

Several researchers have reported that concrete containing **10–15% Metakaolin** maintains satisfactory workability when chemical admixtures are incorporated in the mix design.

3.2 Effect on Compressive Strength

Compressive strength is a key parameter used to assess the performance and quality of concrete. When Metakaolin is added as a partial replacement for cement, its highly reactive silica and alumina participate in pozzolanic reactions with calcium hydroxide released during cement hydration. This reaction generates additional Calcium Silicate Hydrate (C–S–H) gel, which fills internal voids and produces a more compact and stronger cementitious matrix.

A number of experimental studies have reported that the replacement of cement with approximately **10–15% Metakaolin** can considerably improve the compressive strength of concrete compared with conventional mixtures. However, increasing the Metakaolin content beyond the optimum level may lead to a reduction in strength because of the lower availability of cementitious material and insufficient paste for effective hydration.

Major observations include:

- Enhancement in both **early-age and 28-day compressive strength**.
- Improved **bonding between cement paste and aggregate particles**.
- Reduction in **pore volume and pore size**, resulting in a denser concrete matrix.
- Improved resistance to **crack development and propagation**.
- Overall improvement in the **mechanical performance and durability** of concrete.

3.3 Effect on Split Tensile Strength

Concrete possesses relatively low tensile strength compared with its compressive strength. The addition of Metakaolin as a partial cement replacement can enhance the splitting tensile strength of concrete by improving the bond and strengthening the interfacial transition zone (ITZ) between the cement paste and aggregate particles.

Several experimental studies have reported an improvement of nearly **10–20% in split tensile strength** when Metakaolin is incorporated at an optimum replacement percentage. The enhanced tensile capacity contributes to better resistance against the development and propagation of microcracks, thereby improving the overall structural performance and durability of reinforced concrete elements.

3.4 Effect on Flexural Strength

Flexural strength is important for pavements, slabs, and beams. Metakaolin improves flexural strength by producing a denser cementitious matrix and reducing internal defects.

Experimental studies indicate that concrete containing **10–15% Metakaolin** exhibits higher flexural strength than conventional concrete. The improvement is mainly attributed to better particle packing and stronger bonding within the concrete matrix.

3.5 Effect on Durability

Durability determines the long-term performance of concrete under aggressive environmental conditions. One of the major advantages of Metakaolin is its ability to improve durability.

Researchers have reported that Metakaolin:

- Reduces water absorption.
- Lowers permeability.
- Minimizes chloride ion penetration.
- Improves sulphate resistance.
- Reduces alkali–silica reaction.
- Increases resistance against chemical attack.

The denser microstructure formed by additional C–S–H gel prevents harmful substances from entering the concrete, thereby increasing its service life.

3.6 Effect on Sustainability

The construction industry is continuously seeking environmentally friendly materials to reduce carbon emissions. Since Metakaolin replaces a portion of cement, its use reduces cement consumption and consequently lowers CO_2 emissions associated with cement production.

The use of Metakaolin also contributes to:

- Sustainable construction.
- Conservation of natural resources.
- Reduction in greenhouse gas emissions.
- Production of eco-friendly concrete.

Thus, Metakaolin supports the development of green and sustainable infrastructure.

4. Summary of Previous Studies

Author	**Metakaolin Replacement (%)**	**Major Findings**
Wild et al. (1996)	10	Improved compressive strength and reduced

Author	Metakaolin Replacement (%)	Major Findings
		permeability
Sabir et al. (2001)	10–15	Enhanced durability and sulphate resistance
Poon et al. (2006)	10–15	Reduced water absorption and chloride penetration
Khatib (2008)	10–15	Optimum replacement level for strength
Siddique & Klaus (2009)	10–15	Improved tensile and flexural strength
Rashad (2013)	Various	Better mechanical and durability properties
Kumar et al. (2018)	10	Maximum compressive strength in M25 concrete
Verma et al. (2023)	10–15	Improved strength under proper curing

5. Research Gap

Although numerous studies have investigated the use of Metakaolin in concrete, some important research gaps still exist. Limited research is available specifically on **M25 grade concrete** under different environmental conditions.

- Long-term field performance of Metakaolin concrete has not been extensively studied.
- More investigations are required on the combined use of Metakaolin with recycled aggregates, fibers, and nano-materials.
- Life-cycle assessment and economic analysis of Metakaolin concrete need further attention.
- Additional studies are required to optimize Metakaolin content for different exposure conditions and construction applications.

These research gaps provide opportunities for future investigations aimed at developing more durable and sustainable concrete

6. Conclusion

The findings of this review indicate that **Metakaolin (MK)** can be effectively used as a supplementary cementitious material to enhance the overall performance of M25 grade concrete. Based on the results reported in previous experimental investigations, replacing approximately **10–15% of Ordinary Portland Cement (OPC) with Metakaolin** generally provides a suitable combination of mechanical strength, durability, and environmental benefits. The high pozzolanic reactivity of MK leads to the formation of additional Calcium Silicate Hydrate (C–S–H) gel, which improves the compactness of the cement matrix, strengthens the paste–aggregate interface, and reduces internal porosity.

The incorporation of Metakaolin may result in a reduction in the workability of fresh concrete because of its fine particle size and high surface area. However, this issue can be addressed through the appropriate use of chemical admixtures such as superplasticizers. The addition of MK has been reported to improve **compressive strength, split tensile strength, and flexural strength**, while also reducing water absorption and increasing resistance against chloride penetration and sulphate-related deterioration. Furthermore, partial cement replacement with Metakaolin decreases the requirement for OPC and can consequently contribute to lower CO_2 emissions.

Overall, Metakaolin represents a **promising and sustainable material** for the production of durable and high-performance M25 concrete. Further research is required to evaluate its long-term performance under actual field conditions, assess its cost-effectiveness, and investigate its combined application with other supplementary cementitious materials. Such studies can help optimize MK-based concrete for wider and more sustainable construction applications.

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