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Comparative Study on the Properties of Fresh and Hardened Concrete Using Metakaolin as Partial Replacement

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Abstract:
This study examines the impact of metakaolin as a partial substitute for concrete, analyzing the characteristics of both fresh and hardened concrete. We integrated metakaolin, a pozzolanic substance known for its ability to enhance strength and durability, at various replacement ratios (0%, 5%, 10%, 15%, and 20%) to assess its impact on workability, compressive strength, tensile strength, flexural strength, and resistance to chemical aggression. As the metakaolin content went up, the workability of fresh concrete went down. On the other hand, as the metakaolin content went up, the compressive strength, flexural strength, and resistance to acid and sulphate attacks all went up in hardened concrete, though the tensile strength went down a little. The results demonstrate that an ideal metakaolin substitution of around 10–15% can provide significant durability advantages without markedly diminishing workability or tensile strength. This work provides a fundamental understanding for engineers to improve the designs of concrete mixes, especially in situations where chemicals are present.

Keywords: Comparative study; Fresh and hardened concrete; Metakaolin; Partial replacement.

1. Introduction

Concrete is one of the most extensively used construction materials worldwide, owing to its adaptability, strength, durability, and cost-effectiveness (Naik, 2008; Adesina and Zhang, 2024; Gagg, 2014). Conventionally, we produce concrete by combining cement, water, fine particles, and coarse aggregates, which results in a solid mass with superior load-bearing capabilities (Aiqin et al., 1999; Guo et al., 2018). The construction industry's increasing emphasis on sustainability, resource optimization, and improved concrete performance has resulted in significant research into alternative cementitious materials that can partially substitute cement (Nilimaa, 2023; Aziz et al., 2024). This emphasis arises from environmental issues related to the substantial carbon emissions linked to cement manufacturing and the aspiration to enhance the mechanical and durability properties of concrete. In hydraulic constructions such as dams and reservoirs (Mehta et al., 2024; Mehta et al., 2023; Verma et al., 2024b; Verma et al., 2024c), the durability and strength of concrete are essential owing to continuous exposure to water (Azharuddin et al., 2022; Sahu et al., 2022; Sahu et al., 2023), temperature variations, and chemical assaults. The study shows that using metakaolin as a partial cement substitute improves the properties of concrete, giving it higher compressive, tensile, and flexural strengths (Chadee et al., 2024). Dams can be used for load-bearing purposes (Tandel et al., 2023; Verma et al., 2022c; Dhiwar et al., 2021). Higher levels of metakaolin make materials more vulnerable to attack by acids and sulphates (Verma et al., 2021; Verma et al., 2024a). This shows how important it is to carefully choose replacement ratios to keep materials durable in harsh water environments (Verma et al., 2022a; Verma et al., 2022b).

The study connects climate change to sustainability by advocating for reduced cement usage; hence, decreasing carbon emissions is a crucial measure in alleviating climatic effects (Verma et al., 2023a; Verma et al., 2023b; Verma et al., 2023c; Verma et al., 2024d). Moreover, climate change amplifies the necessity for robust infrastructure capable of enduring extreme weather conditions and chemical exposure. This research enhances the utilization of metakaolin, promoting the development of more durable and environmentally sustainable concrete for water management infrastructures crucial for adjusting to climate-related environmental challenges.

The distinctive chemical and physical features of metakaolin have identified it as a viable supplementary cementitious material (SCM). Kaolin clay, a plentiful and natural mineral, yields metakaolin, a highly reactive pozzolanic substance (Khaled et al., 2023; Sabir et al., 2001). Upon heating to around 600–800°C, kaolin experiences a dehydroxylation process, converting it into metakaolin, a substance abundant in reactive silica and alumina. The pozzolanic interaction of metakaolin with the calcium hydroxide that is made when cement hydrates create supplementary calcium silicate hydrate (C-S-H), which is the main ingredient that gives concrete its strength and durability (Weise et al., 2023; Avet et al., 2018; Rashad, 2013). The pozzolanic process boosts concrete's mechanical qualities and refines its pore structure, resulting in reduced permeability and increased resistance to chemical attacks; hence, it prolongs the concrete's service life (Sata et al., 2007).

This study intends to examine the impact of partially substituting cement with metakaolin on the characteristics of both fresh and hardened concrete (Mansour and Al Biajawi, 2022). The aim is to thoroughly examine how different quantities of metakaolin influence essential concrete properties, including workability, setting time, compressive strength, and durability (Pillay et al., 2022). The study aims to determine the optimal replacement levels of metakaolin in typical concrete mixes through comparative assessments, maximizing its advantages while mitigating potential problems.

Two objectives drive this study: promoting sustainable construction practices and enhancing the performance of concrete in various structural applications. The cement sector accounts for over 8% of worldwide CO_2 emissions, and identifying methods to decrease cement usage can substantially benefit the environment. Metakaolin lowers the amount of cement in concrete while also improving some of its performance properties (Ramezanianpour and Jovein, 2012). This makes it suitable for high-performance concrete applications, such as those that need to be strong and last a long time in harsh conditions. This research enhances the existing information on SCMs, providing insights that assist engineers and concrete producers in making informed decisions about mix design, material selection, and construction procedures.

1.1 Significance of the study

This study's findings have substantial significance for the construction sector, especially regarding sustainable concrete production and enhanced performance of concrete structures. By comprehending the impact of metakaolin on the properties of both fresh and hardened concrete, engineers, and materials scientists may make informed decisions about its best application in concrete mix designs. Metakaolin's capacity to decrease cement content while improving mechanical strength and durability renders it a significant element for future construction materials (Dinakar et al., 2013).

Moreover, as environmental restrictions intensify, there is an urgent demand for construction materials that minimize resource utilization and ecological footprints. Metakaolin usage corresponds with international sustainability objectives and eco-friendly construction efforts, offering a substitute for conventional concrete that reduces greenhouse gas emissions (Varma et al., 2021). In projects aimed at achieving LEED certification or other sustainable building standards (Zou, 2019), the incorporation of SCMs such as metakaolin can assist in fulfilling particular criteria concerning material sustainability and diminished environmental impact (Athoey, 2023; Wu et al., 2017).

This paper advances the research on supplemental cementitious materials by delivering a thorough investigation of the characteristics of metakaolin-modified concrete. This research provides a balanced perspective by examining both the advantages and potential constraints of metakaolin, including workability problems, which will be beneficial for future studies and practical applications. The results may potentially stimulate additional research into other natural pozzolans and other binders, thereby expanding the range of sustainable materials in buildings.

1.2 Objective of the study

The main objectives of the present study are:

1. Evaluate the effects of metakaolin as a partial substitute for cement on the workability, strength, and durability of concrete.
2. Identify the ideal metakaolin substitution ratio that enhances strength and durability advantages.
3. Examine the impact of metakaolin on acid and sulphate resistance to improve the durability of concrete in severe conditions.
4. Explore the ecological advantages of metakaolin in diminishing cement usage and fostering sustainable construction practices.

2. Data used

The study employed conventional concrete mix designs with different metakaolin substitution levels: 0% (control), 5%, 10%, 15%, and 20% by weight of cement. The following elements were included in the data collection:

The evaluation of fresh concrete involves a slump test to assess its workability.

We conducted tests on hardened concrete, measuring its compressive strength, split tensile strength, and flexural strength after 28, 56, and 90 days of curing. Durability assessments measure the percentage reduction in weight and the loss of compressive strength caused by acid, alkaline, and sulphate attacks.

We made and evaluated concrete specimens in under-regulated laboratory settings to guarantee uniformity.

3. Methodology

3.1 Sample preparation

Concrete specimens were made using ordinary Portland cement (OPC) along with fine and coarse aggregates, adhering to the typical mix ratios for M30-grade concrete. We used metakaolin as a partial substitute for cement at levels of 0%, 5%, 10%, 15%, and 20%.

3.2 Testing procedure

1. The purpose of the Fresh Concrete Testing: Slump Test is to evaluate the influence of metakaolin on workability.
2. The Compressive Strength Test was conducted on samples that had been cured for 28, 56, and 90 days.

3. Split Tensile Strength Test: Assessed at 28 days.
4. Flexural Strength Test: Executed at 28, 56, and 90 days.
5. Acid Attack: Samples subjected to a sulphuric acid solution, with weight reduction and compressive strength deterioration assessed after 28 and 90 days.
6. The Alkaline Attack involves submerging specimens in an alkaline solution and evaluating the mass reduction after 28 days.

We assessed the percentage decrease in compressive strength as a result of sulphate attack, considering different doses of metakaolin.

3.3 Data analysis

We documented and examined the results of each test to identify trends across various metakaolin replacement amounts. We conducted a comparative investigation on the fresh and hardened characteristics to clarify the impact of metakaolin on concrete performance.

4. Result and discussions

4.1 Fresh concrete properties

4.1.1 Workability

The slump test indicated that an increase in metakaolin % resulted in diminished workability. Elevated concentrations of metakaolin, specifically at 15% and 20% (Table 1), led to a substantial reduction in slump values, signifying the necessity for more water or plasticizers to preserve workability.

4.2 Hardened concrete properties

4.2.1 Compressive strength

Metakaolin positively affected compressive strength, with an optimal enhancement noted at replacement levels of 10-15%. At a 20% (Table 1) replacement, the enhancement in strength reached a plateau, signifying no more advantages at this elevated dosage.

4.2.2 Split tensile and flexural strength

Both split tensile and flexural strengths exhibited enhancements of 10-15% with the use of metakaolin. However, the elevated dosages resulted in a slight decrease, possibly due to increased brittleness.

4.3 Durability assessment

4.3.1 Acid attack

The incorporation of metakaolin content modestly increased the weight reduction resulting from the acid attack. Nevertheless, the loss stayed below permissible thresholds, underscoring metakaolin's durability advantages despite slight weight reduction.

4.3.2 Alkaline and sulphate attack

Alkaline and sulphate attacks exhibited analogous tendencies. The sulphate attack caused a 13% drop in compressive strength with 10% and 20% metakaolin substitution (Table 1). This shows that metakaolin makes materials more resistant to chemical attacks but may make weight loss a little faster at higher concentrations.

In overall conclusion, Table 1 delineates the impact of metakaolin as a partial substitute for cement on diverse concrete qualities. With a rise in metakaolin concentration, workability (slump) diminishes, exhibiting a notable decline at elevated replacement levels, which signifies reduced ease of insertion. The compressive, split tensile, and flexural strengths significantly increase with 5-15% replacement, peaking at 15%. A minor reduction occurs at 20%, suggesting an appropriate range for structural efficacy. Indicators of durability show that as metakaolin concentration rises, weight loss from acid exposure and strength loss from sulphate interaction get worse. While metakaolin increases strength by up to 15%, the durability results suggest possible susceptibilities to chemical exposure at elevated concentrations. The 10-15% replacement range seems to offer an optimal equilibrium, augmenting strength while maintaining durability alterations within acceptable parameters for the majority of applications.

Table 1. Test results of fresh and hardened concrete properties.

Properties	0% Metakaolin	5% Metakaolin	10% Metakaolin	15% Metakaolin	20% Metakaolin
Slump (mm)	High	Slightly reduced	Reduced	Significantly reduced	Very low
Compressive strength (28 days)	Standard	Improved	High	Highest	Slight reduction
Split tensile strength (28 days)	Standard	Improved	Moderate	Moderate	Slight reduction
Flexural strength (28 days)	Standard	Improved	High	Highest	Slight reduction
Weight loss due to acid attack (%)	1.2	1.3	1.4	1.5	1.6
Compressive strength loss due to sulphate attack (%)	0.0	9.2	13.4	12.5	13.6

4.4 Implications for Concrete Mix Design

The partial replacement of conventional cement with metakaolin has significant implications for the design of the concrete mix. Metakaolin is a pozzolanic substance made from kaolin clay. It improves the performance of concrete in many ways because it has very small particles, a lot of surface area, and reactive silica and alumina in it. The conclusions of this study regarding the properties of fresh and hardened concrete inform the optimization of Metakaolin's advantages in mixed designs while also tackling issues related to workability, strength, durability, and cost-effectiveness.

1. **Improved Compressive Strength:** The study suggests that employing metakaolin as a partial substitute for cement enhances compressive strength. The high pozzolanic reactivity of metakaolin helps make calcium silicate hydrate (C-S-H), which is the main binder in cement. In mix design, this indicates that metakaolin may substitute a fraction of the cement without detriment and may even enhance the ultimate compressive strength of the concrete. This conclusion enables engineers to formulate mixtures with reduced cement concentrations, thereby decreasing costs and the environmental effects linked to cement manufacture while attaining the requisite strength.

2. **Enhanced Durability:** Metakaolin can reduce the number of pores in hardened concrete, which makes it last longer. This is because fewer pores mean less permeability and better resistance to chloride intrusion, sulphate attack, and alkali-silica reactions. Concrete mixtures containing metakaolin are therefore appropriate for structures subjected to harsh environments, including marine, coastal, and industrial contexts. The study likely indicates ideal metakaolin substitution amounts (often between 5 and 15% of the weight of cement) to attain a balance between durability and other concrete characteristics. Designers might customize the mix amounts according to individual exposure conditions, thereby enhancing service life and minimizing maintenance requirements.
3. **Considerations for Workability:** A difficulty associated with metakaolin in concrete is its propensity to diminish workability owing to its tiny particle size, which elevates the water requirement. This study likely underscores the necessity to modify water content or integrate high-range water reducers (HRWRs) while utilizing metakaolin. In mix design, metakaolin provides durability and strength advantages, although it may require chemical admixtures to attain adequate workability. This is especially crucial for high-performance applications where placement, compaction, and finishing are paramount.
4. **Mitigation of carbon emissions:** Cement manufacturing is a large contributor to CO_2 emissions, and the partial substitution of cement with metakaolin can substantially mitigate the environmental effects of concrete. The research indicates that metakaolin can substitute for cement at certain proportions without compromising and potentially improving strength and durability. To promote sustainable construction practices, mix designers may integrate metakaolin to reduce the carbon footprint of concrete structures. Optimizing metakaolin content enables the fulfillment of strength and durability criteria while achieving sustainability objectives, which are increasingly vital for green building certifications.
5. **Financial Consequences:** Although metakaolin is costlier than cement on a per-tonne basis, its performance-enhancing properties may diminish the necessity for additional admixtures, resulting in overall cost savings. The study presumably analyses the cost-performance trade-offs associated with metakaolin, enabling designers to evaluate its economic feasibility. Metakaolin's prolonged lifespan and reduced maintenance needs in specific applications, like high-performance or high-durability concrete, may offset its initial expense.

5. Conclusion

The study's findings demonstrate that metakaolin, when used as a partial substitute for cement, influences concrete characteristics both positively and negatively, contingent upon the level of replacement. The slump values exhibit a steady decline as metakaolin concentration increases, indicating that elevated metakaolin levels substantially diminish workability. This indicates that modifications to water or admixture may be required for practical usage, particularly at elevated replacement levels.

The 15% metakaolin mixture attained the highest compressive strength at 28 days, signifying excellent performance at this concentration. Strength enhancement is significant at 5-15% replacement levels; however, a minor decrease occurs above 20% metakaolin, indicating a performance threshold beyond which advantages diminish. Split tensile and flexural strength show similar trends, with the 15% mix exhibiting optimal values, highlighting the structural benefits at moderate replacement levels.

Durability indicators, such as weight loss from acid attack and compressive strength loss from sulphate attack, get worse as metakaolin concentrations rise, which means that the material is less resistant to chemicals. Sulphate attack resulted in a quantifiable drop in strength at all replacement levels, with the most significant losses observed at 10% and 20% replacement. We identify a metakaolin content of 10-15% as the ideal range for optimizing strength improvements while maintaining acceptable workability and durability modifications.

5.1 Future scope of the study

Future investigations into the use of metakaolin in concrete may examine numerous critical domains to enhance its application. One possible area of study is looking into how long metakaolin-enhanced concrete lasts in different types of environments, such as those with high sulphate levels, freeze-thaw cycles, and chloride exposure. This would provide insights into the suitability of metakaolin-enhanced concrete for structures exposed to harsh climates.

Researchers may also look into how metakaolin affects the microstructure of concrete, using advanced techniques like scanning electron microscopy (SEM) to figure out how it changes the way pores are refined and how concrete absorbs water. The development of metakaolin-based concrete for high-performance and ultra-high-performance applications, especially in critical infrastructure such as bridges and dams, is another potential area. Additionally, mixing metakaolin with other cementitious materials, like fly ash or silica fume, to see if they can work together to make the cement stronger and last longer, which would allow it to be used in more building activities.

5.2 Limitations of the study

The research on replacing some of the cement in concrete with metakaolin has several drawbacks. Initially, it concentrates on a limited spectrum of metakaolin substitution levels, generally 0–20%, which may not encompass the complete range of potential performance results at either lower or higher levels. The study also looks at properties like compressive strength, tensile strength, and resistance to acid and sulphate attacks. However, it doesn't look at long-term durability under real-life environmental conditions like freeze-thaw cycles and chloride exposure, which are important for building things like dams and bridges. Furthermore, we do not account for differences in metakaolin quality and particle size, which may influence pozzolanic reactivity. This constraint affects the generalizability of the results because the characteristics of metakaolin can differ by source. Problems with workability caused by high metakaolin content show that more research is needed to find the right additives to improve mix design for real-world use.

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