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Use of Metakaoline in Concrete

[*1]Kunal Satish Jadhav, [2]Shyam Satish Jadhav, [3]Siddesh Popat Belkar, [4]Omkar Gurunath Desale and [5]Dr. Dipali Prakash Patole

[*1, 2, 3, 4]UG Scholar, Department of Civil Engineering, Samarth Polytechnic Belhe, Pune, Maharashtra, India.

[5]Professor, Samarth Polytechnic Belhe, Pune, Maharashtra, India.

Abstract

This study investigates metakaolin's potential as a sustainable and environmentally friendly ingredient for ultra-high performance concrete (UHPC). The study aims to fill existing knowledge gaps by examining the physical and chemical characteristics of metakaolin and how it affects UHPC's mechanical qualities, such as compressive and flexural strength. Furthermore, the durability of UHPC with metakaolin is evaluated, with special focus on its ability to withstand prolonged stress and its resistance to environmental impacts. This review seeks to further understanding of metakaolin's role in UHPC and suggests areas for further study in order to optimize its use in sustainable construction. The manufacture of UHPC has a wellknown negative environmental impact, which emphasizes the need for more affordable and environmentally friendly alternatives. Metakaolin, which is rich in SiO2 and Al2O3, is produced when kaolin is calcined, and it enhances the properties of concrete. Microstructure studies indicate that thick calcium silicate hydrate (C-S-H) is produced by mixes with smaller particle sizes and lower water-to-binder ratios (0.16-0.24), and ettringite and alkali-silica reactions are less common. The ideal metakaolin level for boosting compressive strength is between 5% and 15% of the cementitious materials, whereas flexural strength typically improves between 5% and 10%. Proper curing is essential for UHPC containing metakaolin to reach its maximum efficacy. This study supports the usage of metakaolin as a green addition to improve the durability of UHPC and promote more ecologically friendly building practices.

Keywords: Natural denitrification, IEMB-Ion trade layer bioreactor, MBR-Membrane bioreactor, ED-Electro dialysis.

1. Introduction

Metakaolin, a highly reactive pozzolanic material, has gained significant attention in the field of concrete technology due to its potential to improve the performance and sustainability of concrete. Derived from the calcination of kaolinite clay at specific temperatures, metakaolin is known for its fine particle size and its ability to react with lime (calcium hydroxide) in the presence of water, forming additional cementitious compounds. When incorporated into concrete mixtures, metakaolin enhances various properties, such as workability, strength, durability, and resistance to chemical attacks, making it a valuable additive for producing high-performance and eco-friendly concrete.

By partially replacing Portland cement, metakaolin not only lowers carbon emissions but also increases the long-term durability of concrete structures by reducing problems like permeability, shrinkage and cracking. Metakaolin is a useful way to create more ecologically friendly concrete while preserving the material's intended mechanical and functional qualities as the building sector continues to move toward sustainable practices. The advantages, uses, and difficulties of metakaolin in concrete are examined in this introduction, along with its increasing significance in the creation of high-quality, long-lasting, and environmentally friendly concrete.

2. Literature Review

Sabir. B.B *et al* (2001) carried out a study on the utilization of Metakaolin as pozzolanic material for mortar and concrete and mentioned about the wide range application of Metakaolin in construction industry. They reported that the usage of Metakaolin as a pozzolana will help in the development of early strength and some improvement in long term strength. They mentioned that Metakaolin alters the pore structure in cement paste mortar and concrete and greatly improves its resistance to transportation of water and diffusion of harmful ions which lead to the degradation of the matrix.

Tong Ding *et al* (2002) experimentally found out the effects of Metakaolin and Silica Fume on the properties of Concrete. Experimental investigation with seven concrete mixtures of 0, 5, 10, and 15% by mass replacement of cement with high-reactivity Metakaolin or Silica fume, at a water cement ratio of 0.35 and a sand-to-aggregate ratio of 40% was carried out. The effect of Metakaolin or Silica fume on the workability, strength, shrinkage, and resistance to chloride penetration of concrete was investigated. The incorporation of both Metakaolin and Silica fume in concrete was found to reduce the free drying shrinkage and restrained shrinkage cracking width. It is also reported that the incorporation of Metakaolin

***Corresponding Author:** Kunal Satish Jadhav

or Silica fume in concrete can reduce the chloride diffusion rate significantly. The performance of Silica fume was found to be better than Metakaolin.

Bado Giannis E *et al* (2004) evaluated the effect of Metakaolin on concrete. Eight mix proportions were used to produce high-performance concrete, where Metakaolin replaced either cement or sand of 10% or 20% by weight of the control cement content. The strength development of Metakaolin concrete was evaluated using the efficiency factor (k value). With regard to strength development the poor Greek Metakaolin and commercially obtained Metakaolin yielded the same results. The replacement with cement gave better results than that of sand. When Metakaolin replaced cement, its positive effect on concrete strength generally started after 2 days where as in case of sand it started only after 90 days. Both Metakaolin exhibited very high k-values (close to 3.0 at 28 days) and are characterized as highly reactive pozzolanic materials that can lead to concrete production with excellent performance.

3. Properties of Metakaoline

Metakaolin is a finely ground, highly reactive material characterized by its ability to react with calcium hydroxide (CH) to form additional cementitious compounds. These reactions enhance the properties of concrete, especially its strength and durability. Some of the key properties of metakaolin include**:**

- **i). High Reactivity:** The calcination process transforms kaolinite into metakaolin, increasing its pozzolanic reactivity. When added to concrete, metakaolin reacts with CH, leading to the formation of calcium silicate hydrate (C-S-H), which contributes to the strength and durability of the material (Ramezanianpour & Malhotra, 2010).
- **ii). Particle Size and Surface Area:** Metakaolin is characterized by its fine particle size and large surface area, which enhances its ability to fill voids in the concrete matrix, improving the material's density and reducing porosity (Wang & Scrivener, 2007).
- **iii). Mineral Composition:** Metakaolin is primarily composed of alumina (Al_2O_3) and silica (SiO_2), which are crucial for its pozzolanic reaction. Its mineralogical properties can vary depending on the source clay, but generally, metakaolin contains over 90% amorphous silica and alumina, both of which are reactive in the presence of water and lime (Akçaöz & Kızılkan, 2022).

4. Effects of Metakaolin on Concrete Performance

i). Mechanical Properties

Metakaolin's incorporation into concrete has been found to improve its mechanical properties, such as compressive strength, flexural strength, and tensile strength. Several studies have shown that metakaolin enhances the early and long-term strength of concrete when used as a partial replacement for cement (Bhanja & Sengupta, 2005). The improved strength is attributed to the pozzolanic reaction, which consumes calcium hydroxide and generates additional C-S-H gel, increasing the overall binding properties of the concrete matrix.

However, the effect of metakaolin on strength can be influenced by the replacement level. Typically, replacement levels of 5-15% cement by weight lead to significant improvements, while higher levels may result in a slight reduction in strength due to the increased water demand of the mix (Bhanja & Sengupta, 2005).

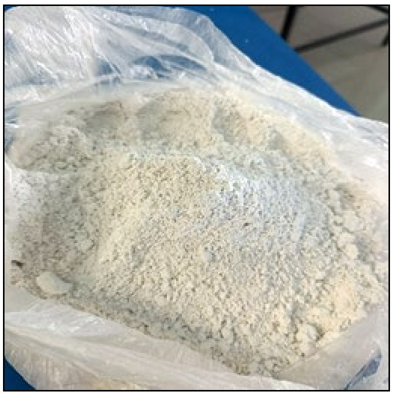

Fig 1: Metakaolin

ii). Durability

Metakaolin has been shown to significantly increase concrete's durability. Metakaolin enhanced concrete is more resistant to water penetration, sulfate assault, chloride intrusion, and alkali-aggregate reactions because of its thick microstructure and decreased porosity (Mehta & Monteiro, 2006). For structures subjected to harsh climatic conditions, as those found in maritime regions or places with a high sulfate content, this makes it the perfect material. Furthermore, metakaolin concrete has demonstrated exceptional resistance to shrinkage and cracking, which qualifies it for uses where long-term stability is essential.

iii). Workability

Concrete's workability may be impacted by the use of metakaolin. Metakaolin's high surface area and tiny particle size can make fresh concrete less workable since it takes more water to reach the right consistency. Superplasticizers, on the other hand, can lessen this problem and preserve workability without sacrificing metakaolin's advantages (Gómez-Soberón, 2002).

iv). Heat of Hydration

Metakaolin has a lower heat of hydration compared to Portland cement, which is beneficial in mass concrete applications where excessive heat generation can lead to cracking. The slower rate of hydration also means that concrete containing metakaolin can achieve strength more gradually, reducing the risk of thermal cracking in large-scale pours (Ramezanianpour & Malhotra, 2010).

5. Environmental Benefits of Metakaolin in Concrete

- **i). Reduction in Carbon Emissions:** One of the primary drivers for incorporating metakaolin into concrete is its potential to reduce the environmental impact of cement production. By substituting a portion of cement with metakaolin, the overall CO_2 emissions from concrete production can be significantly reduced. Studies suggest that replacing 10-20% of cement with metakaolin can reduce carbon emissions by 10-15%, making it a key material in the drive towards more sustainable construction practices (Mollah & Siddique, 2015).
- **ii). Resource Efficiency:** Metakaolin is derived from abundant kaolinite clay, which is widely available and does not require extensive energy-intensive processes for extraction. The calcination process for producing metakaolin consumes less energy than traditional cement production, further enhancing the material's sustainability profile (Khan *et al*., 2013).

iii). Waste Minimization: The use of metakaolin also promotes the recycling of industrial waste. For example, fly ash and slag are commonly used as supplementary cementitious materials, and metakaolin can be produced from waste kaolinite clay, reducing the need for landfilling and promoting the circular economy in the construction sector.

6. Challenges and Limitations

While the benefits of metakaolin in concrete are clear, its widespread adoption faces several challenges**:**

i). Cost: Metakaolin can be more expensive than traditional Portland cement, which may limit its use in cost-sensitive projects. However, as production techniques improve and demand increases, it is expected that the cost of metakaolin will decrease over time.

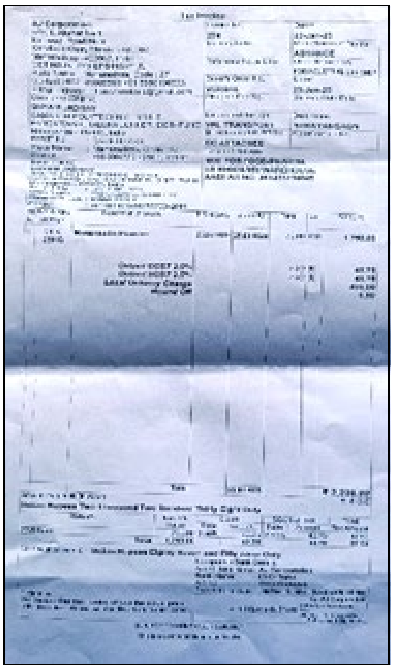

Fig 2: Bill

ii). Mix Design Complexity: Achieving optimal performance with metakaolin requires careful consideration of mix design, particularly in terms of water demand and curing conditions. Inadequate mix design can negate the positive effects of metakaolin on concrete strength and durability.

iii). Availability: While kaolinite clay is abundant, the availability of high-quality kaolinite for metakaolin production may vary by region, which could limit the widespread use of metakaolin in certain areas.

7. Methodology for Using Metakaolin in Concrete

The methodology for incorporating metakaolin into concrete involves several key steps, including material selection, mix design, preparation, and testing. This section outlines the general approach used in experimental studies that evaluate the effects of metakaolin on concrete properties. The methodology typically involves systematic experimentation to determine the optimal dosage of metakaolin, assess its impact on various concrete properties, and compare the performance of metakaolin-enhanced concrete with conventional concrete.

i). Material Selection

i). Cement: Ordinary Portland Cement (OPC) is commonly used as the primary binder in concrete. For the purposes of this methodology, OPC is typically selected based on the grade and standard of concrete being produced (53 MPa strength class).

ii). Metakaolin: Metakaolin is sourced from kaolinite clay, which is calcined at temperatures between 600°C and 800°C to form the active pozzolanic material. The metakaolin used in the experiments is characterized by its fine particle size and high amorphous silica content. It is important to ensure that the metakaolin is free of impurities that may negatively affect the performance of the concrete.

iii). Aggregates: The aggregates used include natural fine aggregates (sand) and coarse aggregates (gravel or crushed stone). The aggregates are typically selected to meet the grading requirements according to relevant standards (e.g., IS 383 in India or ASTM C33 in the United States).

iv). Water: Water used for mixing concrete is generally clean, potable water with low chemical content to avoid adverse reactions with the cement or metakaolin.

ii). Mix Design

Proportions of Materials

The mix design for concrete containing metakaolin is based on the required strength and performance specifications. The following steps are typically involved in the mix design process**:**

i). Control Mix (without metakaolin): A control concrete mix is first prepared using only cement, aggregates, and water. The mix proportions are determined based on the desired workability and strength of the concrete.

ii). Metakaolin Replacement Levels: Metakaolin is incorporated into the concrete mix by replacing a portion of the Portland cement. The replacement levels typically range from 5% to 20% by weight of cement, with common levels being 10% and 15%. The effect of different replacement levels on the concrete's performance is studied.

iii). Adjustments for Workability: Given the fine particle size and high surface area of metakaolin, additional water may be required to maintain the desired workability of the fresh concrete. The use of superplasticizers can help reduce the water demand without compromising workability.

iv). Water-Cement Ratio: The water-to-cement (w/c) ratio is carefully controlled to ensure proper hydration of the cement and pozzolanic reaction of metakaolin. The w/c ratio is typically kept in the range of 0.35 to 0.50, depending on the desired concrete strength and durability.

iii). Casting of Concrete Specimens

i). Mold Preparation: Concrete specimens are cast in standard molds according to the specifications of relevant standards (such as IS 516 in India or ASTM C192 in the United States). Commonly used molds include cubes, cylinders, and beams, which are prepared for testing compressive strength, tensile strength, and flexural strength.

ii). Mixing and Pouring: After thorough mixing, the concrete is poured into the molds, ensuring that the mixture is evenly distributed. The molds are vibrated using a mechanical vibrator to remove any air pockets and ensure the concrete is compacted properly.

iii). Curing: Once the specimens are cast, they are covered with a damp cloth or plastic sheet to prevent premature drying. The specimens are cured under controlled conditions (either in a water tank or moist curing chamber) for a specified period, typically 7, 14, and 28 days, to allow for proper hydration and pozzolanic reactions.

Fig 3: Material mixing and Curring Tank

iv). Testing and Analysis

The concrete specimens are tested at various curing ages to evaluate the effects of metakaolin on its properties. Common tests include**:**

Compressive Strength: Compressive strength tests are conducted using a universal testing machine (UTM) according to relevant standards (e.g., ASTM C39 or IS 516). Concrete cubes or cylinders are loaded until failure to determine the maximum compressive strength, which is one of the most critical parameters for assessing concrete quality.

Fig 4: Compressive strength Test

Conclusion

Conclusions on the ideal dosage of metakaolin for enhancing the qualities of concrete are made using the testing and analytical data. Practical uses are suggested, including the possible use of metakaolin in long-lasting infrastructure, sustainable building, and high-performance concrete. The investigation of different mix designs or the impacts of metakaolin in conjunction with other supplemental cementitious materials could be future research avenues.

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