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Article

Enhancing the Compressive Strength of Concrete using Metakaolin as a Partial Replacement for Cement

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Abstract: This experimental study examines the crucial role of the pozzolanic reaction of High-Reactivity Metakaolin (HRM) when used as a highly active partial replacement to enhance the mechanical and structural properties of conventional concrete. The experimental program was established by designing a control mix with a cement content of 400 kg/m^3 and a constant water-to-cement (w/c) ratio of 0.5 to ensure optimal workability. The research methodology adopted a weight-based cement replacement strategy, incorporating 15% metakaolin to evaluate its efficiency in micro-void filling and stimulating secondary reactions. Laboratory results following a 28-day water curing cycle revealed a qualitative leap in structural performance: compressive strength increased substantially from an average of 33.4 MPa for the control specimens to 38.2 MPa for the metakaolin-modified specimens, with peak values reaching 39.57 MPa. This mechanical strength enhancement, approximately 14.3%, is attributed to the synergistic "filler effect" and the vigorous chemical reaction between the silica in metakaolin and the free calcium hydroxide Ca(OH)_2 liberated during cement hydration. This reaction facilitates the transformation of weak hydration products into dense Calcium Silicate Hydrate (C-S-H) gel, thereby refining capillary porosity and strengthening the Interfacial Transition Zone (ITZ) between the aggregate and the cement paste. Beyond mechanical improvements, the study highlights the environmental and economic dimensions of this approach. Reducing cement content directly lowers the carbon footprint of its production, positioning metakaolin as a strategic choice for producing sustainable High-Performance Concrete (HPC) with superior durability and exceptional resistance to external stresses.

Keywords: compressive strength test, High-Reactivity Metakaolin, High-performance, cement Replacement

1. Introduction

A recent study compared concrete slabs with and without high-reactivity metakaolin, a high-performance mineral admixture that produces results similar to those of silica fume. It was found that high-reactivity metakaolin enhances concrete properties while maintaining good workability and finishing qualities. According to the concrete supplier and contractor involved in the experiment, both non-pozzolanic concrete and metakaolin-modified concrete display similar properties.

However, the concrete containing metakaolin exhibited a creamier consistency, set somewhat faster, and produced less bleeding water. High-reactivity metakaolin is a pozzolanic material that can be used to produce highly durable concrete composites.

Metakaolin, relatively new to the concrete industry, is effective in increasing compressive strength, reducing sulfate attack, and improving the air-void system.

Metakaolin differs from more commonly used mineral admixtures, such as fly ash and silica fume, in that it is not a by-product.

It is manufactured under controlled conditions through the thermal activation of purified kaolin clay within a specific temperature range (650–800°C). The resulting anhydrous aluminosilicate ($Al_2Si_2O_7$) is largely amorphous in nature and behaves as a highly reactive artificial pozzolan.

Concrete mixtures made with high-reactivity metakaolin need less high-range water reducer than silica fume mixtures to achieve similar workability at the same water-to-cementitious materials ratio. The reactivity of metakaolin depends on its chemical composition and reactive surface area. High-reactivity metakaolin has become available as a highly reactive pozzolanic material in concrete. This type of material differs from other admixtures, like fly ash, blast-furnace slag, and silica fume, in how it is produced: it is made from high-purity kaolin clay by calcination at 700-800°C.

The average particle size of high-reactivity metakaolin, which is smaller than cement particles, ranges from 1 to 2 micrometers, and it is white, affecting the color of the final product. The specific gravity of high-reactivity metakaolin is 2.5. This article will explain the properties of high-reactivity metakaolin, its effects on the properties of fresh and hardened concrete, durability, and the applications of concrete containing high-reactivity metakaolin.

Durability of Hardened High-Reactivity Metakaolin Concrete:

Air-entrained concrete containing about 10% high-reactivity metakaolin in significant amounts shows strong resistance to chloride ion penetration and demonstrates excellent durability under repeated freeze–thaw cycles. Metakaolin in concrete tends to reduce pore size, which increases strength, density, and resistance to acidic environments. Additionally, metakaolin enhances the concrete's resistance to alkali–silica reactions and sulfate attack.

Literature Review

The increasing consumption of concrete in the world, environmental issues and the need for optimal utilization of materials, and the positive effects of using supplementary cementitious materials (SCMs) on the properties of concrete have led to the widespread use of these materials in the concrete industry. Metakaolin is a relatively new SCM obtained by heating pure kaolin at a temperature ranging between 500 °C and 800 °C. This SCM is used to make high-performance concrete and also improve the mechanical properties, along with the durability of conventional concrete [1]. Compressive strength can be deemed as the most important mechanical property of concrete, and this parameter is generally used to estimate some other concrete properties; on the other hand, the design of concrete structures is mostly based on concrete's compressive strength. The effect of using metakaolin on the compressive strength of concrete has been studied by several researchers. In the studies by Zhang and Malhotra [2], Wild et al. [3], Brooks and Johari [4], Ding and Li [5], Khatib and Hibbert [6], Poon et al. [7], Kim et al. [8], Khatib [9], Güneyisi et al. [10], Muthupriya et al. [11], Ramezanianpour and Jovein [12], Dubey et al. [13], an increase in the compressive strength of concrete has been observed with the use of MK, whereas in the study of Vejmelková et al. [14] and Salimi et al. [15] adding MK reduced the compressive strength of concrete. These discrepancies are mainly because the compressive strength of concrete containing MK depends on several factors, including the water-to-cementitious materials ratio of concrete, the specific surface area of MK, its pozzolanic activity, the replacement level of metakaolin, and the mixing composition [15]. Among these parameters, the pozzolanic activity of MK, which is related to its physical and chemical characteristics, has received insufficient attention.

In general, knowing the impact of each of these parameters on the compressive strength of concrete containing metakaolin can be extremely useful. Assessment of the compressive strength dependency on each factor requires the use of complex numerical calculations, which has been resolved thanks to computers. One of the computational methods for determining the general relationship between abundant and complex information is the artificial neural network (ANN). An ANN can model almost any complex relationship between the inputs and outputs. One of the most important types of neural networks in engineering applications is the multi-layer perceptron (MLP) network [16], [17]. Inputs given from the outside to the neural network are applied to a group of neurons arranged in one or two layers. These inputs are aggregated with specific weights and are fed to each neuron function, which involves processing the weighted sum of inputs applied to the neuron and sending the output of the neuron to the output layer [18]. Using the error-back propagation algorithm, the accuracy of responses can be further enhanced. The neural network uses the results of previous experiments to estimate the effective parameters on compressive strength. By doing this, the neural network can be trained with an ample amount of experimental results. In this way, the network is able to predict the expected output with some error if its input parameters are available [19]. Developing accurate and reliable models to predict the compressive strength of concrete can be time-saving and cost-effective by providing designers and structural engineers with vital data. Thus, accurate and early-stage prediction of concrete strength is a critical issue in concrete construction [20].

Metakaolin recently has been introduced as a highly active and effective pozzolan for the partial replacement of cement in concrete. It is an ultrafine material produced by the dihydroxylation of a kaolin precursor upon heating in the temperature range of 700–800 °C [21] . Metakaolin is a silica-based product that, on reaction with Ca (OH)2, produces CSH gel at ambient temperature. Metakaolin also contains alumina that reacts with CH to produce additional alumina-containing phases, including C4AH13, C2ASH8, and C3AH6 [22] [23] Research results have shown that the incorporation of metakaolin in concrete significantly enhances early strength [24]. Metakaolin increases resistance of concrete to alkali–silica reaction [25], and its effect on sulfate resistance increases systematically with increasing replacement of cement by metakaolin [26]. Energy absorption or toughness of high-performance steel-fiber-reinforced concrete increases with the introduction of high-reactivity metakaolin into the mix. Therefore, for applications where both enhanced durability and high toughness are required, the use of high-reactivity metakaolin concrete may be advantageous [27]. However, other research has also shown that increasing replacement levels of metakaolin produce increasing water demand, although this can be adjusted by adding a water reducer or blending the metakaolin with PFA to maintain the workability or flow properties [28].

Concrete production has a significant environmental impact due to high CO_2 emissions from Portland cement. To promote sustainability, research focuses on partially replacing cement with waste materials like fly ash, GGBS, and Metakaolin. Metakaolin, when used at 5–30% replacement levels, enhances concrete's cementitious properties. Compressive strength tests at 3, 7, and 28 days show that Metakaolin is effective as a partial cement substitute, supporting eco-friendly concrete production and sustainable construction practices [29].

Aim of Work

The objective is to study how the partial replacement of cement with metakaolin leads to an increase in the compressive and tensile strength of concrete. Furthermore, it aims to enhance durability by developing high-performance concrete (HPC) mixtures capable of withstanding harsh conditions and reducing crack formation.

Experimental Work

In this study, several concrete specimens (cubes) were prepared by replacing part of the cement with metakaolin at different percentages. These specimens were cast, cured, and tested to examine how metakaolin as a partial cement substitute affects the compressive strength, tensile strength, and durability of the concrete. The experimental program aims to optimize the mix design to produce high-performance concrete (HPC) that can withstand harsh environmental conditions and minimize crack formation.

2. Materials and Methods

A- Cement: ordinary Portland cement (type karasta) used in this study as shown in fig (1)

Fig (1)

B- Fine aggregate: local fine aggregate from Karbala' region in Iraq is used throughout the experimental work in this study, as shown in fig 2)

Fig (2)

C-Coarse aggregate: natural crushed aggregate from Nibaa'i region in Iraq is used throughout the experimental work in this study, as shown in fig (3)

Fig (3)

D- metakaolin was incorporated as a 15% partial replacement of the total cement weight within the concrete mixture. in fig (4)

Fig (4)

Specimen preparation

Specimen Preparation In this study, several concrete cubes with dimensions of (150 × 150 × 150) mm were prepared using a concrete mix design with a cement content of 400 kg/m³ and a water-to-cement (w/c) ratio of 0.5. The specimens were divided into two main groups based on the percentage of Metakaolin (MK) added as a partial replacement for cement. The total volume of the mix was calculated as 0.027 m³ for the production of 8 standard cubes. The groups can be described as follows:

a. Group S (Control Mix): This group represents the reference concrete mix made with 0% Metakaolin (100% Ordinary Portland Cement). It serves as the baseline for comparing the mechanical properties. As shown in the data, the compressive strength for this group at 28 days ranged between (30.66 - 36.07) MPa.
b. Group SM (Modified Mix): This group consists of concrete specimens where the cement was partially replaced by Metakaolin at a replacement percentage of 15% (by weight of cement). For this mix, 60 kg/m³ of Metakaolin was utilized. The results indicated a significant performance improvement, with compressive strength reaching values up to 39.57 MPa after 28 days of water curing.

Tests of Concrete Specimens

At 28 days of age, all concrete cube specimens underwent compressive strength testing to assess the effect of Metakaolin (MK) on the mix's mechanical performance. Each specimen's ultimate load-bearing capacity was tested using a hydraulic compression machine that had been calibrated. In order to ensure that the load was delivered axially and steadily until failure occurred, the testing technique adhered to defined criteria. The formula was used to determine the compressive strength.

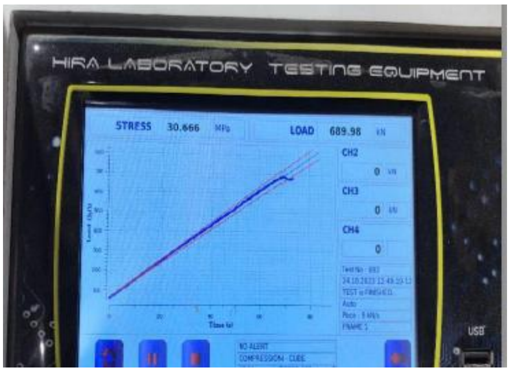
$$\sigma = \frac{P}{A}$$

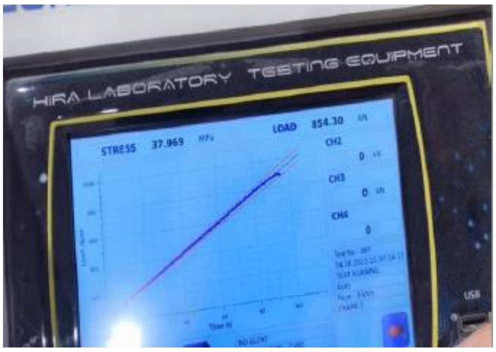
Where:
σ: Compressive strength (MPa).
P: Maximum load at failure (N).
A: Cross-sectional area of the specimen
(150 x 150 = 22,500 mm2).

The experimental results for both the control group (S) and the metakaolin-modified group (SM) are summarized in Table (1) below:

Table 1. Compressive Strength Results at 28 Days

Group	**Specimen No.**	**Casting Date**	**Testing Date**	**Compressive Strength (MPa)**	**Average Strength (MPA)**
S (0% MK)	**1**	20/02/2026	19/03/2026	33.64	33.46
S (0% MK)	**2**	20/02/2026	19/03/2026	36.08	
S (0% MK)	**3**	20/02/2026	19/03/2026	30.67	
SM (15% MK)	**1**	20/02/2026	19/03/2026	37.01	38.29
SM (15% MK)	**2**	20/02/2026	19/03/2026	39.56	
SM (15% MK)	**3**	20/02/2026	19/03/2026	38.31	





As illustrated in the results, the incorporation of 15% Metakaolin led to a noticeable increase in strength, with the maximum recorded value reaching 39.57 MPa. This enhancement confirms the high pozzolanic activity of the added Metakaolin and its efficiency in densifying the concrete.

3. Results and Discussion

The experimental findings demonstrate that the partial replacement of cement with 15% High-Reactivity Metakaolin (HRM) led to a significant leap in the structural performance of the concrete. This improvement can be analyzed through the following scientific perspectives: Efficiency of Pozzolanic Reaction: The notable increase in compressive strength—from an average of 33.46 MPa for the control mix to 38.29 MPa for the modified mix—is primarily attributed to the active chemical reaction between the amorphous silica in metakaolin and the calcium hydroxide Ca(OH)_2 produced during cement hydration. This reaction generates additional Calcium Silicate Hydrate (C-S-H) gel, which is the fundamental component responsible for the strength and cohesion of the concrete matrix. Micro-filler Effect: Due to the ultra-fine particle size of metakaolin (typically 1–2 \mu m), which is significantly smaller than cement particles, it acted as an efficient filler for the microscopic voids within the cement paste. This physical filling reduced capillary porosity and densified the Interfacial Transition Zone (ITZ) between the aggregate and the paste, resulting in a more compact and less permeable concrete structure. Strength Development at 28 Days: Some modified specimens (SM) achieved peak strength values reaching 39.57 MPa. This confirms that a 15% replacement level is highly effective in transforming conventional concrete into High-Performance Concrete (HPC), characterized by exceptional resistance to external mechanical stresses. Sustainability and Environmental Impact: Beyond mechanical enhancement, reducing the cement content by 60 kg/m³ directly contributes to lowering the carbon footprint associated with cement production. This positions the use of metakaolin as a strategic choice for sustainable, eco-friendly construction practices.

4. Conclusion

Based on the experimental results and the analysis of the concrete specimens modified with High-Reactivity Metakaolin (HRM), the following conclusions can be drawn: Strength Enhancement: The partial replacement of cement with 15% Metakaolin led to a significant improvement in compressive strength. The average strength increased from 33.46 MPa (Control Mix) to 38.29 MPa (HRM Mix), representing a growth rate of approximately 14.3%. Synergistic Effect: The enhancement in mechanical properties is a dual result of the Pozzolanic Reaction, which produces additional C-S-H gel, and the Micro-filler Effect, where fine metakaolin particles fill the microscopic voids, creating a denser and more homogeneous matrix. Optimal Efficiency: A 15% replacement ratio proved to be highly effective for achieving High-Performance Concrete (HPC) characteristics, as some specimens reached peak values of 39.57 MPa, confirming the high reactivity of the HRM used. Environmental and Economic Impact: Utilizing Metakaolin as a cement substitute (60 kg/m³) not only enhances structural performance but also promotes sustainability by reducing the carbon footprint of concrete production and potentially lowering long-term maintenance costs due to improved durability.

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