ISSN 2286-4822
www.euacademic.org

EUROPEAN ACADEMIC RESEARCH
Vol. XII, Issue 12/ March 2025

Impact Factor: 3.4546 (UIF)
DRJI Value: 5.9 (B+)

Efficacy Factor of Metakaolin as a Partial Cement Replacement and Predictive Model for Compressive Strength of High-Strength Concrete

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Abstract

This study examines the efficacy of metakaolin as a partial substitute for cement in high-strength concrete. The cementitious efficacy of metakaolin was evaluated at different water/binder ratios of 0.2, 0.25, 0.3, and 0.35. The chosen mix design uses the absolute volume method, a standard technique endorsed by the American Concrete Institute (ACI) for concrete mixture proportioning. A nonlinear regression model was created through the logarithmic transformation of a linear regression model. The results indicated that a water/binder ratio of 0.30 and a metakaolin addition of 7.5% yielded a maximum compressive strength increase of 25.08%. The investigation found that a 10% partial cement substitute with metakaolin, at a water-to-binder ratio of 0.20, resulted in a compressive strength of 95.33 MPa after 28 days of water curing. Consequently, a 10% substitution is advisable for realistic implementations. The nonlinear regression model forecasted the compressive strength of concrete with enhanced accuracy, as evidenced by elevated R^2 values and other statistical tests that remain within an acceptable range.

Keywords: Nonlinear, regression, concrete, metakaolin, compressive

1.0 INTRODUCTION

The building sector is endeavouring to transition from traditional concrete technologies to green concrete by minimizing cement usage and, hence, decreasing cement production.

Around 12 billion tonnes of concrete are manufactured globally every year, consisting of about 1.6 billion tonnes of Portland cement (Malhotra, 2005). Cement manufacturing accounts for around 5 to 8% of worldwide CO_2 emissions (Scrivener & Kirkpatrick, 2007). Alongside CO_2, gasses such as SO_3 and nitrogen oxides are emitted during cement production, exacerbating environmental issues such as acid rain and the greenhouse effect (Rasheed & Zeedan, 2011). The environmental impact of cement production can be alleviated by utilising various supplementary cementitious materials (SCMs) such as silica fume, rice husk ash, fly ash, and ground granulated blast furnace slag (GGBS), which can partially substitute cement in concrete mixtures. Metakaolin is regarded as one of the most efficacious supplementary cementitious ingredients, substantially enhancing the strength and durability of concrete.

Metakaolin is produced when kaolin is subjected to temperatures over 600 ℃.

A multitude of experimental and analytical investigations have been conducted to examine the role of metakaolin and various supplemental cementitious ingredients in diverse concrete formulations.

Peiliang et al. (2017) examined the influence of Metakaolin (MK) on the hydration, microstructure, and volumetric stability of steam-cured high-strength concrete (HSC) with a low water-to-binder ratio (w/b) of 0.25 at 80 °C. The findings indicated that the mechanical properties of high-strength concrete containing metakaolin surpass those of the reference sample. A recommended optimal content of 10% Metakaolin was established. The total porosity diminished from 14.4% to 11.3% with the incorporation of Metakaolin. Compared to the HSC control specimen, the expansion resulting from heat treatment is diminished by the incorporation of MK.

Kasini et al. (2012) examined the impact of Metakaolin (MK) and Calcined Kaolins (CKs) on the compressive strength of concrete. The research employed Metakaolin obtained from four distinct regions in the Czech Republic. Portland cement was substituted with Metakaolin in varied proportions of 5%, 10%, 15%, and 20% to evaluate its effect on concrete strength. A control mix devoid of any extra materials was generated for comparative analysis. The compressive strength of the concrete was assessed at curing intervals of 3, 7, 28, and 90 days. The results demonstrated that the inclusion of 15% Calcined Kaolin yielded the maximum compressive strength at both 28 and 90 days of curing.

Jun et al. (2016) investigated the characteristics of High-Porosity Cement Foams (HPCF) created from ternary mixtures of Portland cement, Metakaolin, and Silica fume. Their research concentrated on elucidating the impact of these combinations on the early-age air-void structure and the mechanical properties of hardened cement foams. The HPCF mixes were formulated with Ordinary Portland Cement, Supplementary Cementitious Materials (SCMs), chemical accelerators, superplasticizers, foaming agents, and water. The study concluded that Metakaolin and Silica fume substantially enhanced the stabilization of the air-void structure owing to their elevated pozzolanic activity.

Chithra et al. (2016) conducted a multiple regression analysis (MRA) and an Artificial Neural Network (ANN) to forecast the compressive strength of high-performance concrete incorporating nano-silica and copper slag as partial replacements for cement and fine aggregate, respectively. The results indicated that MRA met statistical tests, including the Durbin-Watson test, due to multicollinearity, and exhibited a very low coefficient of determination. They determined that MRA is not statistically sufficient for forecasting concrete strength.

Haque and Rasel-Ul-Alam (2016) utilized non-linear models to forecast designated design strengths of concrete. The trivial nonlinear model resulted in inadequate predictions of compressive strength.

Jin et al. (2018) indicated that linear regression is inadequate for predicting concrete strength. Consequently, non-linear and mixed regression models were employed to predict the compressive strength of Recycled Aggregate Concrete (RAC). The results indicated that both non-linear and mixed regression models predicted the strengths of RAC with greater accuracy. Nevertheless, these models are confined to RAC. The analysis was inadequate for predicting the strengths of concrete.

Rathan et al. (2013) introduced a comprehensive mix design methodology for high-strength concrete, integrating principles from the Bureau of Indian Standards (BIS) and American Concrete Institute (ACI) codes, with a target compressive strength of 60 MPa. To assess compressive strength, three concrete cubes were tested for each mix variation at curing durations of 1, 7, 14, 28, and 56 days. Their findings indicated that augmenting the proportion of metakaolin in the concrete mixture resulted in improved compressive strength at all curing ages.

Abdul and Wong (2002) formulated a mathematical model to forecast the compressive strength of high-strength concrete containing pozzolanic materials. A control mix was created utilizing conventional Portland cement devoid of pozzolans to provide a baseline, hence assuring uniform combination characteristics and curing conditions. The study utilized metakaolin and silica fume to substitute cement at 5%, 10%, and 15% by mass, determining the best replacement level to be 15%. Ping et al. (2013) examined the influence of slag, silica fume, and metakaolin on the pore architectures, Interfacial Transition Zone (ITZ), and compressive strength of concrete at 28 and 180 days, as well as the thermodynamic stability of hydrate phase characteristics.

The results indicated that the incorporation of mineral admixtures leads to a denser interfacial transition zone, an optimized pore structure, and a suitable pore size distribution. The mineral admixture was found to enhance the microstructure, with effects ranked in descending order as follows: metakaolin, silica fume, and slag. Their research has shown that metakaolin substantially affects the microstructure of concrete. The boost in compressive strength is chiefly associated with decreases in overall porosity and improvements in the microhardness of the interfacial transition zone (ITZ).

Mohamed and Khaled (2015) examined the impact of substituting Portland cement with nano-silica on several mechanical parameters of concrete, such as compressive strength, split tensile strength, flexural strength, and modulus of elasticity. Nano-silica was included at five distinct weight percentages of 1%, 2%, 3%, 4%, and 5% in relation to the total cementitious materials (cement and silica fume). The research employed two varieties of coarse aggregates: dolomite and granite. The results demonstrated that nano-silica enhances the compressive strength of concrete. Mohammed et al. (2018) investigated the advantages of employing two prominent ultrafine pozzolans: metakaolin (MK) and silica fume (SF). The research indicated that silica fume necessitated a greater quantity of superplasticiser than metakaolin. Egwuonwu et al. (2019) investigated the impact of partially substituting cement with metakaolin on the compressive strength of high-strength concrete across different water-to-binder ratios. The findings indicated that a 10% incorporation of metakaolin had a peak compressive strength of 95.33 MPa.

Obunwo et al. (2018) examined the effect of metakaolin on the fresh characteristics and compressive strength of high-strength self-compacting concrete through the particle packing model. The peak compressive strength was recorded with a 10% substitution of metakaolin.

Mohamed, A.M. & Tayeh, B.A. A rigorous assessment conducted in 2024 on the utilization of ultra-high-performance concrete revealed a substantial enhancement in mechanical performance with a 10% substitution of metakaolin. Santos et al. (2024) investigated the formulation of a geopolymer utilizing metakaolin (MK) and incorporating mining waste from a decommissioned iron mine, primarily composed of hematite (Hem). The results indicated that geopolymers composed of 100% metakaolin and 90% metakaolin with 10% hematite demonstrated the highest compressive strengths of 41 MPa and 40 MPa, respectively, after 90 days of curing.

De La Rosa et al. (2024) investigated the influence of cellulose nanofibers on the rheological and mechanical characteristics of Portland cement pastes including pozzolanic additives, with a focus on compressive ductility.

Table 2.1: Chemical Composition of Metakaolin

Chemical composition	Silica (SiO_2)	Aluminum (Al_2O_3)	Ferric Oxide (Fe_2O_3)	Calcium oxide (CaO)	Magnesium (MgO)	Titanium Oxide (TO_2)	Loss on Ignition
% by weight	53.26	43.93	0.3	0.36	0.49	1.25	0.18

Source: Egwuonwu et al. (2019).

2.4 Mix Design

The absolute volume mix design approach was used to developed the mix proportion. **The mix proportion used was obtained from Egwuonwu et al. (2019) as depicted in table 2.2.**

Table 2.2: Mix Design Proportion

Mix	Percentage replacement (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Course aggregate (kg/m^3)	Metakaolin (kg/m^3)	Water (kg/m^3)	Superplasticizer (% of Cement)
0.2	0	620	645.98	984.47	0	124	1.2
	2.5	604.5	645.98	984.47	15.5	120.9	1.2
	5	589	645.98	984.47	31.0	117.8	1.2
	7.5	573.5	645.98	984.47	46.50	114.7	1.2
	10	558	645.98	984.47	62.0	111.6	1.2
0.25	0	496	687.07	1047.06	0	160124	1.2
	2.5	483.60	687.05	1047.06	12.40	120.9	1.2
	5	471.20	687.05	1047.06	24.80	117.8	1.2
	7.5	458.8	687.05	1047.06	37.20	114.7	1.2
	10	446.4	687.05	1047.06	49.60	111.6	1.2
0.3	0	413.33	715.32	1090.15	0	123.999	1.2
	2.5	403	715.32	1090.15	10.33	120.9	1.2
	5	392.67	715.32	1090.15	20.66	117.8	1.2
	7.5	382.33	715.32	1090.15	30.99	114.7	1.2
	10	372	715	1090.15	41.33	111.6	1.2
0.35	0	354.29	734.46	1119.32	0	124	1.2
	2.5	345.45	734.46	1119.32	8.86	120.9	1.2
	5	336.58	734.46	1119.32	17.71	117.8	1.2
	7.5	327.72	734.46	1119.32	26.57	114.7	1.2
	10	318.86	734.46	1119.32	35.43	1119.32	1.2

2.3 Basis of Nonlinear Regression Analysis

Nonlinear regression analysis was used to examine the functional relationship between the response and input variables.

The logarithmic transformation of a linear regression model yields dependable non-linear models. Therefore, this study employed the logarithmic transformation of the multiple linear regression model for data analysis.

The linear regression model to be modified is represented by equation 2.1.

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n \qquad 2.1$$

We employ a logarithmic adjustment on the aforementioned equation to derive the non-linear model. Applying the natural logarithm to equation (2.1) produces the following equation;

$$\ln Y = \ln\alpha_0 + \alpha_1 * \ln X_1 + \alpha_2 * \ln X_2 + \cdots + \alpha_n * \ln X_n \qquad 2.2$$

By using the principles of logarithms and finding the antilogarithm of equation (2.7), it transforms into

$$Y = \alpha_0 * X_1^{\alpha_1} * X_2^{\alpha_2} * \ldots * X_n^{\alpha_n} \qquad 2.3$$

Where
Y = Dependent variable
X_i = Independent variables (where i = 1, 2, n)
α_0= constant term (exponential of any constant given by the regression result)
α_i = Coefficients of independent variables of regression.

3.0 RESULTS

3.1 Compressive Strength obtained from experiments

Table 3.1 shows the compressive strength test results of the cubes for all mixtures at 7, 14, and 28 days. The variation in compressive strength for specimens with Metakaolin (MK) and differing amounts of Metakaolin incorporation is illustrated at various curing ages. The data reveals that the concrete sample exhibiting a water-cement ratio of 0.20 and a 10% cement substitution with Metakaolin achieves the highest compressive strength of 95.33 MPa.

Table 3.1: Compressive Strength Result for Concrete Mixtures under Different Curing Ages.

Water-cement ratio	**% Replacement of cement with Metakaolin (%)**	**Compressive Strengths (MPa)**		
		7 days	**14 days**	**28 days**
0.2	0.0	64.67	71.00	82.07
	2.5	79	81.67	89
	5.0	80	83.33	91
	7.5	81.5	84.67	92.67
	10	83.33	88.67	95.33
0.25	0.0	58.67	67.50	73.44
	2.5	66	69.67	79
	5.0	70	72.67	78
	7.5	72.67	78	82.67
	10	75.33	77.33	85.33
0.30	0.0	40.43	49.07	61.56
	2.5	43.33	54.67	54.66
	5.0	44.67	57.83	73.33
	7.5	46	54.73	77
	10	48.33	55.33	70.67
0.35	0.0	37.82	47.51	58.67
	2.5	39.33	51.33	65
	5.0	44.67	52.33	68
	7.5	46	54.33	70
	10	47.33	55.23	73

Table 3.2: increase in strength due to metakaolin

W/C ratios	Metakaolin content	Percentage increase in strength
0.2	2.5	16.17
0.25	5.0	16.19
0.30	7.5	25.08
0.35	10	24.42

Based on these results, it can be concluded that Metakaolin content exhibited the most significant effect at water-cement ratio (w/c) of 0.30.

3.2 Efficiency Factor

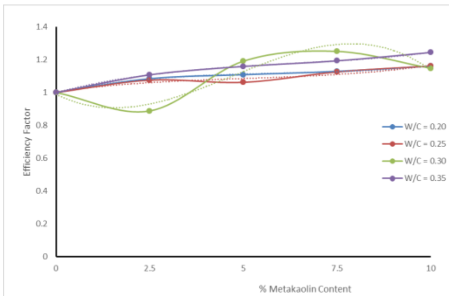

Fig 1: Efficiency Factor Plot for 28 Days Strengths.

Table 3.2: Efficiency Factor Equations for 28 Days Strengths.

Water-cement ratio	Equation	R-Square Value
0.2	$K = 0.002M^3 – 0.0373M^2 + 0.2251M + 1.0047$	0.99
0.25	$K = 0.0016M^3 – 0.0284M^2 + 0.1694M + 1.0078$	0.9595
0.30	$K = 0.0008M^3 – 0.0155M^2 + 0.1069M + 1.0011$	0.9986
0.35	$K = -0.0029M^3 + 0.0385M^2 - 0.3288M + 0.9897$	0.9425

Recently, the cementitious efficacy of metakaolin has been utilized to attain designated strength ratings. The efficiency factor (k-value) is defined as the fraction of pozzolanic material deemed equivalent to Portland cement (Papadakis and Tsimas, 2002). A value of k = 1 signifies that the pozzolanic material employed is comparable to cement regarding compressive strength performance. A number below 1 signifies that the efficacy of the pozzolanic material is subpar compared to cement. The quantity of pozzolanic material is multiplied by the k value to estimate the equivalent cement content, which is then added to the Portland cement content to determine the resulting water to effective cementitious materials ratio. Prior studies indicated that metakaolin demonstrates values exceeding 1 at multiple replacement levels. The findings from various studies highlight the crucial significance of metakaolin in augmenting concrete strength, establishing it as an essential element in the formulation of high-strength concrete. The research conducted by Dinakar and Manu (2014) corroborates this, demonstrating the effective use of metakaolin in the formulation of high-strength self-compacting concrete with compressive strengths beyond 100 MPa.

3.3 Regression Analysis Result

Compressive Strength Regression

Table 3.3: Coefficients for Compressive Strength Regression.

Model	Unstandardized coefficients	Standardized Coefficients	T	Sig.
Costant	-28.472		-1.480	0.147
Cement content	0.534	0.470	0.285	0.777
Fine aggregate content	1.061	0.215	0.455	0.652
Coarse aggregate	2.963	0.695	4.758	0.000
Metakaolin content	0.107	0.250	0.999	0.324
Water-cement ratio	-1.251	-1.093	-0.599	0.553
Curing age	0.201	0.475	10.234	0.000

Therefore, the predicted compressive strength from equation (3.3) is given by

$$Y = e^{-28.472} \times X_1^{0.534} \times X_2^{1.061.} \times X_3^{2.963} \times X_4^{0.107} \times X_5^{-1.251} \times X_6^{0.201} \qquad 3.1$$

The above equation can be re-written as

$$Y = e^{-28.472} \times \frac{X_1^{0.534} \times X_2^{1.061.} \times X_3^{2.963} \times X_4^{0.107} \times X_6^{0.201}}{X_5^{1.251}} \qquad 3.2$$

From the above, Y = compressive strength, X_1 = cement content, X_2 = fine aggregate (sand) content, X_3 = coarse aggregate content, X_4 = Metakaolin content, X_5 = water-cement ratio and X_6 = Curing age.

From Table 3.3, it is also seen that the water-cement ratio has the highest absolute value of 1.093 for standardized coefficient, indicating that the water-cement has the highest influence on the regression model obtained.

Table 3.4: Model Summary of Compressive Strength Regression Analysis

R	R-square	Adjusted R-squared	Standard error of estimate	Durbin-Watson
0.955	0.912	0.899	0.076892244548	0.581

Table 3.5: ANOVA for Compressive Strength Regression

Model	Sum of squares	Degree of freedom	Mean square	F	Sig
Regression	2.500	6	0.417	70.478	0.000
Residual	0.242	41	0.006		
Total	2.743	47			

Table 3.6: Coefficient for Regression of Predicted and Experimental Compressive Strength under 28 Days Curing

Model	Unstandardized coefficient	Standardized coefficient	t	Sig
Constant	5.713		0.857	0.406
Experimental compressive strength	0.924	0.946	10.886	0.000

The linear relationship is given by equation 3.3

$$Y = 5.713 + 0.924X \qquad 3.3$$

Let Y represent the predicted compressive strength and X denote the experimental compressive strength.

The correlation coefficient between anticipated and experimental compressive strength is 0.946, suggesting that the predicted values closely align with the experimental measurements.

Table 3.7: Model Summary for Regression of Predicted and Experimental Compressive Strength under 28 Days Curing

R	R-square	Adjusted R-square	Standard error of estimate	Sig	Durbin-Watson
0.946	0.894	0.887	3.663262305131	0.000	2.061

Table 3.7 presents the R-squared value and the standard error of the estimate. The elevated standard error contributes to the low R-squared values in the estimate, yet the significance of the estimate remains valid. The statistical outcome of the regression can be illustrated visually using a scatter plot comparing projected compressive strength with experimental compressive strength, as depicted below.

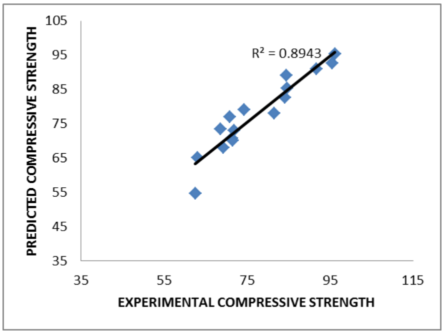

Figure 2: Scatter plot of Predicted and Experimental Compressive Strength under 28 Days Curing

4.0 CONCLUSION

This study examines the cementitious effectiveness of metakaolin in producing high strength concrete, confirming its role as a sustainable construction material. A maximum compressive strength of 95.33 MPa was recorded with a 10% cement replacement at a water-cement ratio of 0.2 after 28 days of curing. With similar replacement level they was a 28.85% increase in strength at 7 days compared to the control mix, this shows the advantageous impact of metakaolin on strength at early age. The increase in strength is as a result of reduced voids, leading to enhanced hydration and microstructural properties. Throughout the substitution, metakaolin consistently improved concrete strength range from 2.5% to 10%, which affirms that it is viable in mix design. The efficiency factor (K) exceeded 1 in most cases, by reaching a maximum of 1.28 at 7 days, indicating accelerated hydration.

Nonlinear regression models were developed to predict compressive strength, excluding superplasticizer content due to multicollinearity. The cure length was identified as a crucial factor influencing strength development. The statistical analysis confirmed the models' reliability, demonstrated by high regression coefficients and minimal standard errors. The models demonstrated strong predictive accuracy with significance values less than 0.05. These data validate the effectiveness of metakaolin in enhancing concrete performance and optimizing high-strength concrete design.

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