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Evaluating the Performance of Metakaolin as a Sustainable Cement Replacement in Conventional Concrete Mixes

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Abstract

Supplementary Cementitious Materials like Metakaolin are widely used all over the world by incorporating concrete mix due to their economic, environmental, and structural benefits. In this study, partial replacement of cement with Metakaolin up to 20% at an increment of 4% was carried out to evaluate the resulting strength activity index of Metakaolin obtained by calcination of Kaolinite clay achieving 98.34% strength activity index by 20% Metakaolin replacement using mortar test. Concrete mix design was carried out for C25 grade normal concrete with varying cement and Metakaolin amount and constant water binder ratio, aggregate and water concrete ingredients, and the laboratory tests such as the chemical composition of Metakaolin, cement, and Metakaolin paste properties, concrete workability, and compressive strength were performed. The Metakaolin properties were found within the acceptable limits as per code standards and previous studies. Test results reveal a 12% optimum replacement of cement by Metakaolin using weight batching. As a result, Metakaolin was found to be an effective pozzolanic material for partially replacing cement in concrete production. Its use offers a promising way to produce more economical and environmentally sustainable concrete by reducing cement consumption

Keywords: *Concrete, Kaolinite Clay, Metakaolin, Compressive Strength*

1. Introduction

Supplementary Cementitious Materials (SCM) are widely used all over the world by incorporating concrete mix due to their economic, environmental, and structural benefits. In addition, the utilization of these materials as a partial replacement of cement in concrete may improve the properties of fresh concrete and hardened concrete (Sathiparan et al., 2024, Machado et al., 2024, Yao et al., 2024). Apart from the industrial wastes some of the most popular Supplementary Cementitious Materials that are mostly incorporated in the concrete mix are fly ash, silica fume, ground granulated blast furnace slag and Metakaolin (MK). According to various research reports, Metakaolin is a thermally activated Alumino-Silicate material obtained by calcining raw kaolinite clay within the temperature range of 600 °C and 800 °C. After activation, it has been reported that the replacement of cement by Metakaolin (MK) significantly increases compressive strength and improves durability properties, including the resistance to chloride penetration, freezing and thawing like other pozzolanic materials (Marsh et al., 2023, Sake et al., 2024, Yang et al., 2023b, N, 2023, Yang et al., 2023a).

Kaolinite is a naturally available material as kaolin clay deposit. Kaolinite clays are widely available in earth's crust as diatomaceous earth mineral, but require heat treatment which leads to dihydroxylation of clay oxides and dis-structure of the crystalline structure to give fine-grained pozzolanic material Metakaolin (Chen et al., 2024, Luo et al., 2024, Ferreira et al., 2024, Sun et al., 2024). In addition, naturally available clays are highly heterogeneous in composition and almost have different chemical properties from region to region while they are forming due to the chemical weathering of rocks after a century. Besides chemical composition of kaolin clay varies from place to place (A.J.S.L and N.S.B.M, 2024, Guzmán et al., 2024, Jiang et al., 2024, Peng et al., 2024).

2. MATERIALS AND METHODS

Mainly the materials and methods followed were fieldwork and experimental works for primary data collection. The material kaolinite clay was extracted from Kebelle Simret, Adwa woreda, Tigray, Ethiopia. The kaolinite clay was estimated at 3-4hetars following previous studies by Tigray Mines and Energy Agency. The experimental work includes the Selection of Calcination Temperature, specific gravity and fineness test results of metakaolin, OPC with MK paste and mortar property test results, chemical composition of metakaolin, and concrete mix design and trial mixes.

2.1 Selection of Calcination Temperature

Metakaolin can be obtained by the calcination of kaolin clay at a controlled temperature ranging between 600 °C to 800 °C for one and a half hours. However, the effective critical temperature is determined by mortar test since the formation of clay crystalline is changed from place to place. Therefore the kaolin clay was burnt in a controlled temperature furnace at various calcination temperatures (600, 650, 700, 750, and 800ºC) for one and a half hours. After firing each sample by the mentioned temperature, the mortar test was made for each calcined kaolinite clay to determine the calcination temperature of kaolin, which can exhibit active pozzolanic calcined clay

named Metakaolin as shown in Table 1. The specific gravity and fineness test results of metakaolin, OPC with MK paste and mortar property test results, and test results for the chemical composition of metakaolin as shown in

Table **2**,

Table **3**, and

Table **4**.

.**Table 1: Calcination temperature selection**

Two Days strength (MPa) (1:3 mortar)	Cement with 20 % MK replacement Calcined for 1½hr.					
	Control	600 ^{0}C	650 ^{0}C	700 ^{0}C	750 ^{0}C	800 ^{0}C
Flexural (average of 3 prism molds)	4.72	3.10	3.34	3.53	4.10	3.43
Compressive (average of 6 cubes)	22.11	15.42	15.80	16.00	16.61	15.83

Table 2: Specific gravity and fineness test results of metakaolin

Sample no.	Weight (g)	Specific gravity	% retained in Wet sieving using a 45 µm sieve	Blaine fineness (cm^2/gm) using Air permeability
1	100	2.62	16%	5860
2	100	2.57	18.5%	6300
3	100	2.58	15.65%	6100
Mean	100	2.59	16.72%	6086.67

Table 3: OPC with MK paste and mortar property test results

Cement and Metakaolin paste property		Test designation	Method	Control (0% - MK)	Test result (20% - MK)
Water requirement/demand		ASTM C618 class N	workability	132ml	145 ml
Soundness		ASTM C618 class N	Le Chatllier's	0.03%	0.03%
Setting time	Initial	ES 1176-3:2005	Vicat Apparatus	135 min	160 min
	Final			320 min	385 min
Cement and Metakaolin mortar property					
Flexural strength	2 Day	ES 1176-1:2005	Flexural (Prismatic test)	4.8	4.14
	7 Day	ASTM C618 class N and ES 1176-1:2005		6.57	5.49
	28 Day			7.51	6.91
Comp. strength)	2 Day	ES 1176-1:2005	Cube test	21.89	16.69
	7 Day	ASTM C618 class N and ES 1176-1:2005		37.85	31.48
	28 Day			48.08	47.28

Table 4: Test results for the chemical composition of metakaolin

Common name	Oxides chemical formula	Results (%chemical analysis)	ASTM C618 chemical requirement

Silica	SiO_2	67.03	
Alumina	Al_2O_3	18.26	>70%
Ferric oxide	Fe_2O_3	2.32	
Loss on ignition,	LOI	0.88	Max. 10%
Sulfur trioxide	SO_3	0.076	Max. 4%
Moisture content	H_2O	0.15	Max. 3%
Lime	CaO	0.5	-
Magnesia	MgO	0.11	-
Alkali content (Potash, Titania, Soda)	K_2O, TiO_2, Na_2O	0.62	Max. 1.5%

2.2 Concrete Mix Design and Trial Mixes

The reference mix design has been prepared first to have a benchmark without the replacement of metakaolin. Secondly, different mix proportions have been developed by varying 4% replacement of metakaolin incrementally up to 20% to find out the optimum replacement and evaluate its replacement effect comparatively with the reference mix and varying replacement as shown in Table 5.

Table 5: Mass proportion of concrete ingredients per mix batch

Mix Code	Cement (Kg)	Metakaolin (Kg)	Water/binder Ratio	Sand (kg)	Aggregate (Kg)
0% - MK	12.4	0	0.58	34.9	43.6
4% - MK	11.904	0.496	0.58	34.9	43.6
8% - MK	11.408	0.992	0.58	34.9	43.6
12% - MK	10.912	1.488	0.58	34.9	43.6
16% - MK	10.416	1.984	0.58	34.9	43.6
20% - MK	9.920	2.480	0.58	34.9	43.6

3. RESULTS AND DISCUSSIONS

3.1 Kaolinite Composition

Kaolinite clay primarily consists of oxides like silica, alumina, and iron as major chemical oxides and calcium. Magnesium, potassium, sodium, and sulfur were also present to lesser degrees as miner elements [38, 39]. In the present study, the total chemical composition of kaolinite clay oxides (SiO_2 + Al_2O_3+ Fe2O3) was found 86.69%. This result meets the minimum percentage value of 70% specified by ASTM C 618 standard for natural pozzolana (Class N). So from this test result, the major chemical composition of kaolinite clay conformed to the specified requirement standard of ASTM C 618.

3.2 Concrete Property

In the present study, the workability test for fresh concrete and hardened concrete compressive strength has been tested at 3, 7, and 28 days after the concrete has been cured on normal portable water as per the ages for the test provided. Then the test was carried out using a compressive strength-testing machine. The recorded slump test and compressive strength test results for each sample are discussed in Table 3.1 and 3.2 respectively with varying percentages of replacement of cement with metakaolin. Each replacement was compared with the reference mix of 0% replacement concrete cubes at each age of curing.

3.2.1 Workability

Concrete workability was measured by using a slump test and the results have been found as follows in Table 6.

Table 6: Percentage replacement and slump test results

% replacement of Cement	Slump Result (mm)
0	41
4	40
8	40
12	38.5
16	38
20	37

The slump test, which is conducted to determine the concrete workability, implies that the workability of concrete with partial replacement of Metakaolin was decreased as the percentage replacement of Metakaolin was increased. It demands more water to lubricate the cementitious materials as per the result indicated in the previous

Table **3** for water requirement OPC and MK paste. Similarly, in prior studies Jagtapet. al., (2017) identified that as the incorporation of Metakaolin in concrete increases workability decreases. Since there is an increase of fineness, the pozzolanic reaction between metakaolin and calcium hydroxide are potential reason for cementitious material, the quantity of cement paste available for providing lubricating effect is less per unit surface area of aggregate as shown in Figure 1. Replacing cement with Metakaolin affects concrete workability negatively as evidenced by decreasing slump values with increasing percentages of replacement. While low levels (up to about 8%) have minimal impact on workability, higher levels significantly reduce it, which should be considered when designing concrete mixes for specific applications.

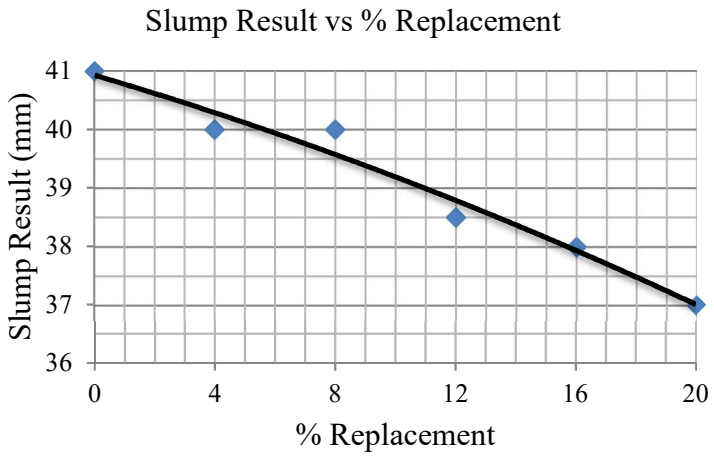


Figure 1: Slump reduction vs. % replacement

3.2.2 Compressive Strength

A concrete compressive strength test of a cube specimen was carried out to determine the concrete strength property in different percentage replacement levels of Metakaolin. The result of each percentage replacement has been compared with the reference control mix, which is zero percent Metakaolin replacement to determine the effect of Metakaolin on the concrete compressive strength resistance and to find the optimum replacement percentage, which gives maximum strength in the present study. Accordingly, the resulting compressive strength for each percentage replacement at 3, 7, and 28 days of curing are shown in

Table 7.

Table 7: Concrete cube compressive strength results

% Cement Replacement by Metakaolin	Cube Strength (MPa)		
	3 Days	7 Days	28 Days
0	12.39	17.69	27.26
4	12.15	17.71	27.59
8	11.95	17.90	28.14
12	11.83	17.96	28.89
16	10.57	17.74	27.64
20	9.38	16.69	27.04

The compressive strength is calculated by taking an average of three cubes for each 0%, 4%, 8%, 12%, 16%, and 20% percentage replacement. As shown in Figure 2 the replacement confirms up to 16% without frailer in compressive strength compared to 0% replacement. In addition, the optimum replacement about the maximum strength effect has been found at a percentage replacement of 12% by weight of cement since the recorded compressive strength is 28.89MPa as shown in

Table 7 at 28 days, which is exceeded by 1.63MPa from the control (0%) mix. Therefore, the use of Metakaolin proves to

be very useful to modify the properties of concrete compressive strength as shown in Table 8 and Figure 3.

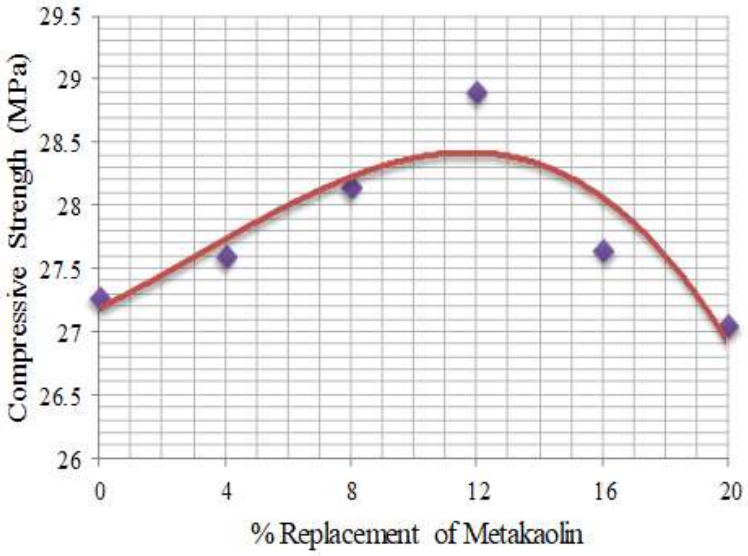


Figure 2: Compressive Strength at 28 days vs. % replacements of metakaolin

Table 8: Effect of metakaolin on concrete compressive strength

% Replacement	Compressive Strength at 28 Days	Strength Effect (%)
0	27.26	0
4	27.59	1.21
8	28.14	3.23
12	28.89	5.98
16	27.64	1.40
20	27.04	-0.80

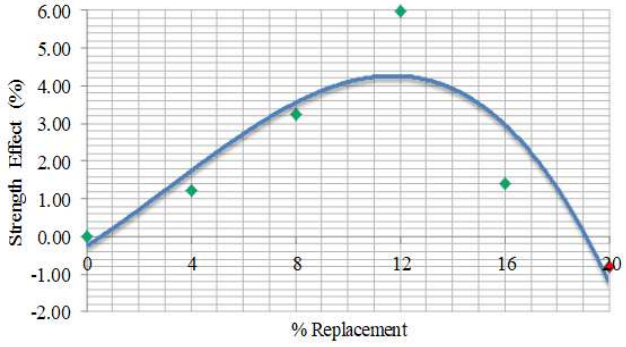


Figure 3: Effect of Percentage Variation in Compressive Strength

The change in compressive strength may result due to the pozzolanic reaction of the replacement SCM material. As Malagavelli (2018) investigates, the main reason for improving the strength of concrete with metakaolin is, that to silica present in metakaolin reacts with the Calcium Hydroxide [Ca $(OH)_2$] by-product of the hydration process of cement and it helps to

produce additional C-S-H gel which is main gel for the development of strength.

4. CONCLUSIONS

The study was carried out to evaluate the partial replacement of cement by metakaolin, which is specifically located in Kebele Simret, Adwa City, and Tigray region in Ethiopia for normal concrete. Accordingly, it has been tested through 0% up to 20% level of replacement by 4% difference interval. As a result, the following conclusions are forwarded.

1. The property of fresh concrete under partial replacement of metakaolin shows a minor slump decrease and thus minor reduction of concrete workability as the percentage replacement increases. The compressive strength of concrete under partial replacement of cement by metakaolin decreases in the early age Perera, A. J. S. L., & Mendis, A. N. S. B. M. (2024). Ammonia capturing capacity of biochar and kaolinite. *Proceedings of International Forestry and Environment Symposium, 27*, 45-50. (Note: Page range is assumed; replace with actual data if available.)

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but increases as the concrete age increases.

2. The optimum replacement of cement by metakaolin, which is extracted from Simret Kaolinite clay, is 12%. Simret metakaolin replacement is suitable for producing relatively economical and environmentally friendly concrete by substituting cement using metakaolin compared to conventional concrete.

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