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The Effect of Elevated Temperature on Compressive Strength of Waste Glass Powder and Metakaolin Concrete

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ABSTRACT: *This paper presents the results of the investigation into the effect of Elevated Temperature of 200 ^{0} C, 400 ^{0} C, 600 ^{0} C, 800 ^{0} C and 1000 ^{0} C on the compressive strength of Waste Glass Powder (WGP) and Metakaolin (MK) concrete. Plain, binary (containing 10% WGP only) and ternary concretes (containing 10% WGP with 5, 10, 15 and 20% MK) were produced and cured for 90days. The results showed that generally strengths decrease with increase in temperature and MK content up to 200 ^{0} C. Concrete cubes made with (5-15) % MK achieved the 28days target strength of 25N/mm^2 even at 600 ^{0} C. The optimum replacement level observed was M10%W10% at 400 ^{0} C with compressive strength increase of 18.3% compared to the control samples at the same temperature. The data obtained were subjected to regression analysis and Analysis of Variance (ANOVA) in the MINITAB 16 statistical software. The model developed to predict compressive strength with MK and Temperature as predictors was highly significant at 5% level. The coefficients of determination, R^2 of 95.8% for the model is reasonably high, indicating a good correlation between the response and the predictor variables.*

Keywords: *Compressive strength, Elevated temperature, Metakaolin, Regression and Waste glass powder.*

I. INTRODUCTION

The risk of fire outbreak increases with modernization, and this is because modern surroundings are full with objects made from highly flammable materials, which are potential ignition sources. All over the world, concrete structures are exposed to high risk of fire and hazards daily, resulting in human and materials losses [1]. High temperature have negative effects on concrete because it causes the decomposition of hardened cement paste and aggregate, it decreases the stiffness of concrete and increases irrecoverable deformation [1]. Reference [2] reported that the fire resistance of concrete can be improved by partial replacement of cement with pozzolanic materials such as (Rice Husk Ash, Fly Ash, and Saw dust ash, Metakaolin (MK), Waste Glass Powder (WGP)) just to mention a few.

Glass is a unique inert material that has similar oxide composition to that of Portland cement and could be recycled many times without changing its chemical properties [2]. Waste glass is readily available in most part of the world. There is no clear information about the total amount (quantity) of waste glass generated in the whole world, due to poor documentation in the Middle East and African countries including Nigeria [2]. However, according to the United Nation, the estimation of solid waste in 2004 is about 200 million tones, out of which seven (7%) is waste from glass which is equivalent to about 14 million tones [2]. The non-biodegradable nature of waste glass makes its disposal to landfills a problem, while cement and concrete industries can provide an environmentally friendly means of disposing it. Use of WGP in concrete not only helps in reducing the cost of cement in concrete production, but also has numerous other benefits such as reduction in landfill cost, saving in energy, and protecting the environment form possible pollution effects. Incorporation of WGP in concrete brings additional advantage such as increased workability, reduced drying shrinkage and increased resistance to chloride ion penetration [3]. However, the major disadvantage of WGP in concrete is the reduction in strength due to weak bonding between the smooth glass particles and the cement especially at temperatures of 300^0 C and above [3]. Hence, there is a need to incorporate additional pozzolanic material such as metakaolin to modify the properties of WGP concrete at elevated temperature.

Metakaolin (MK) is a resultant product of calcined kaolin at 600-900^0 C. It improves strength and concrete durability through the acceleration of Ordinary Portland Cement (OPC) hydration and the pozzolanic reaction with calcium hydroxide ($Ca(OH)_2$) and had proven to have good fire resistance when blended with cement in concrete up to 400^0 C [4, 5]. Human safety in the case of fire is one of the major considerations in cooperated in the design of buildings. It's therefore, extremely necessary to have a complete knowledge about the behavior of all construction materials at elevated temperature before using them as structural element. Therefore, this study is geared towards assessing the effect of elevated temperature on the strength of concrete containing waste glass powder and metakaolin.

II. MATERIALS AND METHODS

Materials: The waste glass or discarded glass bottles were collected from coca-cola depot in Bauchi state Northeast Nigeria. It was sorted out, washed and sun dried before crushing it by a mechanical crusher to smallest possible size, and then sieved using 75µm British Standard sieve size. The kaolin was obtained from Alkaleri Local Government Area of Bauchi State Northeast Nigeria. After air drying, it was calcined at 700^0 C to produce metakaolin (MK). After cooling the resultant MK was grinded using pestle and mortar and then sieved using 75µm British Standard sieve size. Ashaka brand of Ordinary Portland Cement (OPC) was used for this study, and the properties of the cement conform to BS EN 197 (1992)-part 1 specification. The coarse aggregates used for the study was normal weight dry aggregates from an igneous rock source with a maximum size of 20mm, the coarse aggregates was procured from Triacta quarry site in Bauchi state Northeast Nigeria. The dry fine aggregates used for the study was obtained from a stream at Bayara town along Bauchi-Dass road, Northeast Nigeria. The aggregates were tested in accordance with BS 882: (1983) specification. The water used for the study was from tap source which is free from impurities and almost fit for drinking.

2.1 Characterisation of waste glass powder (WGP) and metakaolin (MK)

Chemical analysis of the representative samples of waste glass powder and metakaolin were carried out using XRF spectrometer to ascertain the oxide constituents. The test was conducted at the quality control laboratory of Ashaka Cement Factory Gombe, North Eastern Nigeria. The result of the oxide composition of WGP, MK and Ashaka cement is presented in table 2.

2.2 Slump Test

Slump test of the freshly prepared concrete was carried out to determine the effect of WGP/MK cement replacement on the workability of concrete. The test was conducted in accordance with BS EN 12350: Part 2 (1999) specifications.

2.3 Production of concrete using constituent materials

Concrete cubes of size 100mm x 100mm x 100mm were produced using the six (6) mix proportion as presented in table 1, and cured for 90days to determine the compressive strength of the concrete before and after heating. The water-cement used was 0.48 by weight of cement. The cured concrete cubes were heated at 200^o C, 400^o C, 600^o C, 800^o C and 1000^o C, the temperature was maintain for a period of one hour to achieve the thermal steady state, the heating was conducted in accordance with BS 8110 Part 1: (1997) specification. The study focused on concrete strength of grade $25N/mm^2$. MK and WGP were used as cement replacement in concrete production. The levels of replacement for cement with MK were at 0, 5, 10, 15 and 20 percent while the WGP was kept constant at 10% cement replacement in line with [6-9] recommendations. A total of one hundred and eight (108) samples of concrete cubes were cast, cured, heated and tested. For each temperature, three (3) cubes were produced and the average of the three results was recorded and used.

2.4 Compressive strength test

The compressive strength test was carried out on the hardened concrete before and after heating the samples. The samples were tested using the ELE motorized compression machine. The test was conducted in accordance with BS EN 12390, Part 4 (2000) specifications. The compressive strength of the concrete cubes was determined using equation (1).

$$compressive\ strength = \frac{Failure\ Load\ (KN)}{Area\ of\ Specimen\ (mm^2)} \quad \ldots (1)$$

Table 1: Mix proportions of constituent materials used for MK/WGP concrete production

MIX ID	Constituents Materials (Kg/m^3)					
	Binders			Aggregates		
	WGP (Kg/m^3)	MK (Kg/m^3)	Cement (Kg/m^3)	Coarse (Kg/m^3)	Fine (Kg/m^3)	Water (Kg/m^3)
M0W0	0	0	385	1170	663	185
M0W10	32	0	346	1170	663	185
M5W10	32	14	329	1170	663	185
M10W10	32	27	311	1170	663	185
M15W10	32	41	294	1170	663	185
M20W10	32	55	277	1170	663	185

III. RESULTS AND DISCUSSIONS

3.1 Oxide Composition and Physical Properties of Waste Glass Powder (WGP)

The result of chemical analysis conducted on WGP reveals the presence of similar oxides to those of cement as shown in table 2, which implies that it can be used as cement replacement materials. The sum of oxides of Silicon, Iron and Aluminium is 75.43% exceeds the 70% minimum specified by ASTM C618 (2012) for raw or calcined pozzolana (class N). The combined alkalis ($N_2O + K_2O$) percentage of 13.41% is high and thus increases the possibility of the destructive aggregate alkali reaction which causes disintegration of concrete [7]. Another interesting oxide present is sulphur trioxide (SO_3) which is 0.1% and is below the maximum of 4% specified by ASTM C618 (2012) which shows the tendency for improved durability and prevent unsoundness of the paste [8]. The result of some physical properties of WGP is presented in table 3. The loss on ignition (LOI) which is a measure of organic and carbonate content and sediment in WGP is 3.53% which is below the maximum of 10% specified by ASTM C618 (2012). The low LOI of WGP indicates its high reactivity when blended in concrete [9]. The specific gravity of WGP is 2.61, while that of Ashaka cement is 3.15. This indicates that WGP is lighter than cement and more volume of WGP will be required to replace equal weight of cement in concrete. The pH of WGP is 7.8, this value shows that WGP is neither acidic (pH<7.0) nor alkaline (pH>11.0) but neutral (pH between7-11). This implies that WGP can be used in concrete without much concern for durability related problem [9].

3.2 Oxide Composition and Physical Properties of Metakaolin(MK)

The result of chemical analysis conducted on MK reveals the presence of similar oxides to those of cement as shown in table 2, which implies that it can be used as cement replacement materials. The sum of oxides of Silicon, Iron and Aluminium is 95.99% exceeds the 70% minimum specified by ASTM C618 (2012) for raw or calcined pozzolana (class N). The combined alkalis ($N_2O + K_2O$) percentage of 1.43% is low and thus reduces the possibility of the destructive aggregate alkali reaction which causes disintegration of concrete [10]. Another interesting oxide present is sulphur trioxide (SO_3) which is 0.02% and is below 4% maximum specified by ASTM C618 (2012) which shows the tendency for improved durability and prevent unsoundness of the paste [10]. The result of some physical properties of MK is presented in table 3. The loss on ignition (LOI) which is a measure of organic and carbonate content and sediment in MK is 1.76% which is below 10%, the maximum specified by ASTM C618 (2012). The low LOI of MK indicates its high reactivity when blended in concrete [11]. The specific gravity of MK is 2.50, while that of Ashaka cement is 3.15. This indicates that MK is lighter than cement and more volume of MK will be required to replace equal weight of cement in concrete. The pH of MK is 9.5, this value shows that MK is neither acidic (pH<7.0) nor alkaline (pH>11.0) but neutral (pH between7-11). This implies that MK can also be used in concrete without much concern for durability related problem [11].

Table 2: Chemical Composition of Waste Glass Powder (WGP) and Metakaolin (MK)

Oxide	Waste Glass Powder (%)	Metakaolin (%)	Ashaka Cement (%)
S_iO_2	69.40	52.67	19.68
Al_2O_3	3.81	41.96	6.44
Fe_2O_3	2.58	1.37	3.32
CaO	11.54	1.23	60.92
MgO	0.67	0.26	0.97
SO_3	0.10	0.02	2.28
K_2O	0.43	1.34	0.85
Na_2O	12.98	0.09	0.12

Table 3: Some Physical Properties of Cement, WGP, MK, Fine Aggregate and Coarse Aggregate

Property	Cement	WGP	MK	Fine Aggregate	Coarse Aggregate
Specific Gravity	3.15	2.61	2.50	2.62	2.66
Bulk Density (Kg/m^3)	-	-	-	1530	1415
pH	-	7.8	9.5	-	-
Loss on Ignition	1.0	3.53	1.76	-	-
Blaines Fineness (m^2/Kg)	370	305	367	-	-
Aggregate Crushing value (%)	-	-	-	-	22.33

3.3 Workability of WGP/MK-OPC Blended Concrete

The results of the slump test carried out on the concrete with varying percentage of metakaolin (MK) as cement replacement are presented in table 4 while figure 1 shows the plot of slump versus MK in percentage. All the slumps values obtained were the true type of slump which is suitable for most concrete works. The results also shows that the slump decreases with increase in the amount of MK, which indicates that more water is required to maintain the same consistency as the MK content increases. For instance, 5%, 10%, 15% and 20% MK content decrease slump by 19.05%, 33.33%, 42.86% and 52.38% respectively. This implies that MK absorbs more water than Portland cement in concrete. All the values of slump obtained falls within the limit for class S1 (10mm-40mm) specified by BS-EN 206-part 1: (2000).

Table 4: Slump test result of OPC-MK/WGP blended concrete

Mix-ID	Slump(mm)
M0W0	26
M0W10	21
M5W10	17
M10W10	14
M15W10	12
M20W10	10

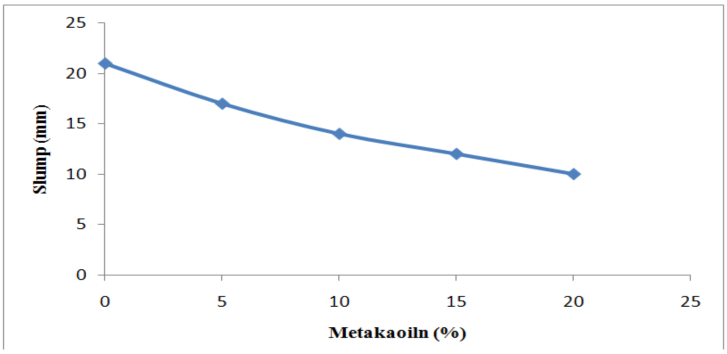

Figure 1: plot of slump versus metakaolin (MK) content in concrete

3.4 Compressive strength test result

The result of compressive strength test on OPC-MK/WGP concrete is presented in table 5 and shown in figure 2. The result reveals that the compressive strength decreases as the MK content increases from the ambient temperature (25^0 C) up to 200^0 C. At temperatures of 400^0 C and above, the compressive strength of M0%W10%, M5%W10% and M10%W10% increased with increase in temperature. For instance, at (M0%W10%) replacement, there was a strength decrease of 1.69%, 1.10% with an increase of 14.53%, 20.20%, 45.56% and 12.73% when compared to the strength of control specimen at temperatures of 25^0 C, 200^0 C, 400^0 C, 600^0 C, 800^0 C and 1000^0 C respectively. Similarly, (M5%W10%) exhibited strength decrease of 3.28%, 2.52% with an increase of 15.96%, 67.14%, 134.57% and 29.10% at temperatures of 25^0 C, 200^0 C, 400^0 C, 600^0 C, 800^0 C and 1000^0 C respectively, when compared to the strength of control specimen. Concrete containing (M10%W10%) exhibited strength decrease of 4.21%, 3.28% with an increase of 18.30%, 75.81%, 218.26% and 148.73% at temperatures of 25^0 C, 200^0 C, 400^0 C, 600^0 C, 800^0 C and 1000^0 C respectively, when compared to the strength of control specimen. In a similar manner, concrete containing (M15%W10%) exhibited strength decrease of 6.27%, 6.00% with an increase of 15.28%, 73.69%, 182.56% and 125.09% at temperatures of 25^0 C, 200^0 C, 400^0 C, 600^0 C, 800^0 C and 1000^0 C respectively, also when compared to the strength of control specimen. Concrete containing (M20%W10%) exhibited strength decrease of 9.80%, 11.63% with an increase of 7.70%, 54.24%, 125.36% and 95.27% at temperatures of 25^0 C, 200^0 C, 400^0 C, 600^0 C, 800^0 C and 1000^0 C respectively, when compared to the strength of control specimen. From all the results presented, it can be observed that higher MK content results in greater reduction of Compressive strength. This behavior may be attributed to the replacement of cement with MK in concrete, results in the reduction of tri-calcium silicates (C_3S) which is a main strength contributing compound, hence the reduction in the compressive strength of the concrete [12]. At temperatures of 400^0 C and above the increase in compressive strength recorded may be attributed to dense concrete formed as a result of hydrothermal interaction between the cement particles and MK/WGP incoporated due to the rise in temperature with the liberated free lime during hydration reaction [12]. These are all strong indication of the ability of pozzolanic material to improve strength of concrete with increase in temperature [13].

Table 5: Compressive strength test results for OPC-MK/WGP blended concrete

	Compressive Strength(N/mm^2)					
Mix ID	25^0 C	200^0 C	400^0 C	600^0 C	800^0 C	1000^0 C
M0W0	32.05	31.73	25.19	16.04	6.19	2.75
M0W10	31.50	31.38	28.85	19.28	9.01	3.10
M5W10	31.00	30.93	29.21	26.81	14.52	3.55
M10W10	30.70	30.69	29.80	28.20	19.70	6.84

M15W10	30.04	29.83	29.04	27.86	17.49	6.19
M20W10	28.91	28.04	27.13	24.74	13.95	5.37

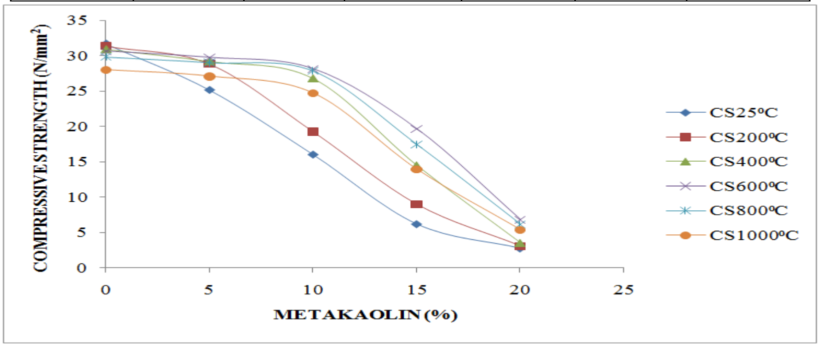

Figure 2: Plot of compressive strength versus Metakaolin

3.2 Residual compressive strength

The percentage residual compressive strength of concrete is expressed as percentage in their respective 28days compressive strength of control specimen. The residual compressive strength is presented in table 6. It shows the variation of compressive strength gain and loss with increase in temperature for all the replacement level. Figure 3 shows the residual compressive strength of each specimen at different elevated temperature. The result shows a relative decrease in the compressive strength of each specimen thermally treated as compared to its original compressive strength before heating. From the figure, it can be seen that the heating conditions were divided in to three regions, these are: 25-200^{o} C, 200-600^{o} C and 600-1000^{o} C. Distinct pattern of strength loss were observed in these regions constant compressive strength was first observed, followed by slow and steady strength loss was observed in the second region and finally a sharp strength loss in the third region. The constant nature of strength observed between 25-200^{o} C may be attributed to low thermal conductivity and very high specific heat capacity of concrete [13]. The gradual reduction in strength observed between 200-600^{o} C may be attributed to the driving out of free water and the pozzolanic reaction of MK/WGP blended concrete [13]. The observed sharp decrease in strength between 600-1000^{o} C may be due to internal thermal stress generated which led to surfacing of micro cracks on the sample and eventual collapse of the concrete [14]. The decrease in compressive strength was seen to be much at 800^{o} C and 1000^{o} C temperature. This behavior may be attributed to the decomposition of calcium silicate Hydrate (C-S-H) gel or interfacial transitional zone between the aggregates and the cementitious paste in the concrete mix [14]. Dehydration of (C-S-H) gel and its low additional (C-A-H) gel formation from the secondary pozzolanic reaction may be responsible for the much decrease in compressive strength observed in the plain concrete as compared to the blended concrete from 200^{0} C to 1000^{0} C [14].

Table 6: Residual compressive strength test results for OPC-MK/WGP blended concrete

Temp. (^{o} C)	Replacement Level (%)											
	M0W0		M0W10		M5W10		M10W10		M15W10		M20W10	
	Comp. Streng. (Mpa)	Res. C.S. (%)	Comp. Streng. (Mpa)	Res. C.S (%)	Comp. Streng. (Mpa)	Res. C.S (%)	Comp. Streng. (Mpa)	Res. C.S (%)	Comp. Streng. (Mpa)	Res. C.S (%)	Comp. Streng. (Mpa)	Res. C.S (%)
25	32.05	100	31.50	100	31.00	100	30.70	100	30.04	100	28.91	100
200	31.73	99.00	31.38	99.62	30.93	99.77	30.69	99.97	29.83	99.30	28.04	96.99
400	25.19	78.60	28.85	91.59	29.21	94.23	29.80	97.06	29.04	96.67	27.13	93.84
600	16.04	50.05	19.28	61.21	26.81	86.48	28.20	91.86	27.86	92.74	24.74	85.58
800	6.19	19.31	9.01	28.60	14.52	46.84	19.70	64.17	17.49	58.22	13.95	28.21
1000	2.74	8.55	3.10	9.84	3.55	11.45	6.84	22.28	6.19	20.61	5.37	18.57

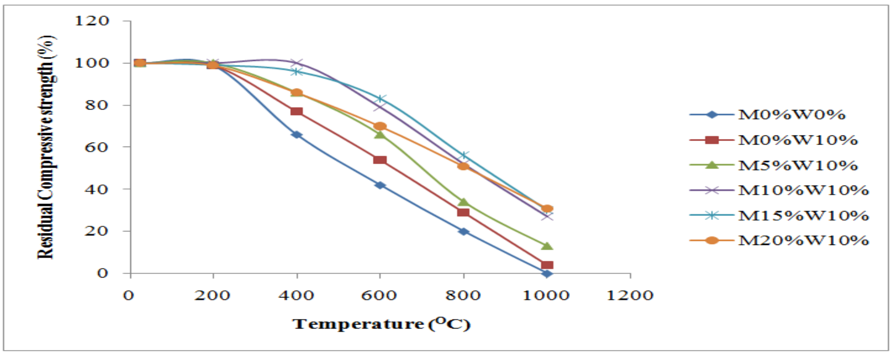

Figure 3: Residual Compressive Strength versus Temperature

3.3 Statistical analysis of the compressive strength results

Statistical analysis of the data presented in table 5 resulted in table 7, which shows the result of regression analysis on compressive strength results. The regression equation is given by equation (2):

$$c_s = 31.2 + 0.513a - 0.000031b^2 - 0.0456a^2 - 0.000550ab \quad \text{. . . (2)}$$

Where a and b (predictor variables) are Metakaolin content and Temperature respectively, while C_s is the compressive strength (Response variable) which is the response in the model equation. The P-values is a measure of the likelihood that the true coefficient is zero. From the p-values of the terms in the model, it can be seen that the constant, a, b, a^2 and a*b (interaction between Metakaolin and Temperature) are highly significant at (P< 0.05) and thus are useful predictors in the regression model developed. Therefore, it can be concluded that all predictor variables significantly influence the response (Compressive strength in this case).The coefficient of variation of the selected model obtained was 95.8 %(R^2=95.8%). This implies that 95.8% of variation in the compressive strength is explained by the regression model with MK content and Temperature as predictor variables. The standard deviation of the model equation, S = 2.2244. The smaller the S value, the better the model equation, which shows a perfect correlation between predictors and the response, implying that the generated model is highly significant [15].

The compressive strength results were further subjected to a one way analysis of variance (ANOVA).The computation is presented Table 8. Although, the concrete cubes containing MK/WGP have lower compressive strength compared to the control samples, there was no statistically significant difference between the compressive strength of control samples and those of concrete containing MK/WGP (ρ > 0.05) at 5% level of significance.

Table 7: Regression analysis of compressive strength

Predictor	Coeff	SE Coeff	T	P	Remarks
Constant	31.2031	0.8304	37.58	0.000	Significant
A	0.5135	0.1890	2.72	0.011	Significant
b^2	-0.00003125	0.00000150	-20.85	0.000	Significant
a^2	-0.035624	0.009843	-3.98	0.000	Significant
a*b	-0.0005500	0.0001421	3.87	0.001	Significant
Basic ANOVA					
Source	DF	SS	MS	F	P
Regression	4	3523.85	880.96	178.04	0.000
Error	31	153.39	4.95		
Total	35	3677.24			

Table 8: Analysis of one way ANOVA for the compressive strength results at a significance level of 5%

Mix ID	Mean Comp. Strength	Variance	N	F	P	Remarks
M0W0	18.99167	161.51826	6	-	-	-
M0W10	20.52	149.0726	6	0.04512	0.83605	Significant*
M5W10	22.67	125.90492	6	0.28244	0.60671	Significant
M10W10	24.32167	90.65218	6	0.67595	0.43015	Significant
M15W10	23.40833	93.6495	6	0.45869	0.5136	Significant
M20W10	21.35667	91.38607	6	0.1327	0.72324	Significant

*the means are significant at the 0.05 level.

IV. CONCLUSIONS

Based on the results obtained, the following conclusions were drawn

i. Compressive strength generally decreases with increase in temperature and decrease in metakaolin (MK) content up to 200^0 C. However, at temperatures of 400^0 C and above, the compressive strength of

M0%W10%, M5%W10% and M10%W10% increased with increase in temperature over the control samples.

ii. The optimum replacement level of the blended concrete was obtained at M10% W10%. The optimum at 400^0 C, recorded highest strength increase of 18.3% for compressive strength over the control sample.

iii. The workability was reduced by incorporating MK in concrete, hence more water is required to maintain uniform slump.

iv. The regression model for compressive strength is given by: $c_s = 31.2 + 0.513a - 0.000031\,b^2 - 0.0456\,a^2 - 0.000550ab$, R^2=95.8% where a and b are metakaolin content and temperature respectively.

v. The statistical model developed provides good prediction for the compressive strength and there is no statistical significant difference between the experimental and predicted strength values at 5% level of significance.

vi. Metakaolin and temperature are useful predictors of the regression model for compressive strength.

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