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Effect of Metakaolin on the Strength Properties of Sisal Fibre Reinforced Concrete

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This paper presents the results of the investigation into the effect of metakaolin on the strength properties of sisal fibre reinforced concrete. Plain control concrete and binary concrete mixes (containing 5, 10, 15, 20, 25 and 30% metakaolin by weight of cement) were produced and cured for 7, 14, 28, 60 and 90 days respectively. A total of one hundred and five (105) cubes and beams were cast and tested for compressive strength, flexural strength as well as the density. The results showed that generally strengths decrease with increase in metakaolin content and increase with prolong curing period. The results also showed that, the density of the concrete decreases with increase in metakaolin content. Concrete cubes made with (5-10)% metakaolin and cured for beyond 28 days, achieved the 28 days target strength of 20 N/mm^2. The optimum replacement level was observed at MK-10% cured for beyond 28 days. The data obtained were subjected to regression analysis and analysis of variance (ANOVA) in the MINITAB 16 statistical software. Models were developed to predict compressive strength, flexural strength and concrete density with curing period and metakaolin content as predictors at 5% level of significance, the result showed that, there is no significant difference between the predicted and the experimental values. The result of the regression analysis for compressive strength, flexural strength and density test indicated metakaolin and curing age are good predictors in the models developed.

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Keywords: Compressive strength; density; flexural strength metakaolin and regression.

1. INTRODUCTION

Concrete is a building material produced from the mixture of sand, gravel, cement and water. The growing depletion of natural resources and increase in human population globally are partly responsible for the release of about 30% of carbon (IV) oxide (CO_2) per anum [1]. The amounts of CO_2 released to the atmosphere constitute a serious challenge [1]. For better construction industry, European Union Countries (EU) maintained that construction raw material consumption rate must be reduced by 20% [2]. Steel reinforced concrete is required to form building materials that caters for both compressive and tensile strengths [3]. However, steel bars are permeable to water and other active element causing corrosion when blended with cement in concrete [4]. The negative consequences of ever increasing demand of steel reinforcement for concrete production include environmental degradation and ecological imbalance resulting from the emission of CO_2 during steel production [5]. Reference [6] reported that, an average of 200 kg steel bar is used for each cubic meter of concrete structure produced. In view of this, it is clear that the replacement of reinforced steel bar by vegetable fibres is a major step to achieve sustainable construction with little or no maintenance. On the other hand, reinforced steel is a highly expensive material and has high energy consumption during its production as such the use of an alternative or substitute will be a welcome development.

Vegetable fibres are natural composites with a cellular structure. The use of vegetable fibres to reinforce concrete offers many advantages, some of which are: improve flexibility, ductility and crack resistance [6]. In addition to that, its low cost, availability, lightness and strength providea potential option for construction for still replacement in concrete.

Despite all the aforementioned advantages, the production of concrete reinforced with vegetable fibre is currently limited by the inadequate durability of these materials [7]. Researchers have been making effort worldwide to utilize natural waste or bye-product to improve durability properties of the fibre reinforced concrete. This had been achieved through the use of waste such as fly ash, rice husk ash, saw dust ash and glass to mention just a few [7-9]. Apart from the above mention waste materials, there exist little or no studies on sisal fibres and metakaolin as cement replacement in concrete [9].

Research carried out by [10] evaluated the effect of carbonation on the durability of cementatious composites reinforced with sisal fibre. They reported that, there is an improved mechanical strength, decrease in calcium hydroxide and a denser concrete. Studies by [10] also indicated some of the advantages of using metakaolin as cement replacement in fibre reinforced concrete include high strength, reduction of dead load, modulus properties and improved durability. More so, research by [11] reported that the metakaolin absorbs less moisture due to its low cellulose content; other reasons are superior mechanical properties, reduction of shrinkage in concrete, reduction in permeability of concrete, increase resistance against chemical effect which results in the formation of denser concrete. This study is therefore, aimed at assessing the effect of metakaolin on the strength properties of sisal fibre reinforced concrete.

2. MATERIALS AND METHODS

Materials: The sisal fibres were obtained from agaves plants through retting by scrubbing in Toro town of Bauchi State, Nigeria. The fiber were pieces to about 70 mm length approximately. Metakaolin was obtained from the kaolin calcined at 800ºC which was procured from Alkaleri town of Bauchi State, Nigeria. After cooling the raw metakaolin 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 obtained from an igneous rock source with a maximum size of 20 mm. The fine aggregates used for the study was obtained from a stream at Bayara town along Bauchi-Dass road, Nigeria. The coarse and fine aggregates were tested in accordance with BS 882: (1983) specification. Clean water was used for the study from tap source which is almost free from impurities.

2.1 Mix Proportion

A grade 20 concrete was design using a mix proportion of 1:2:4 by weight of ordinary Portland cement, metakaolin, sisal fibre, river sand and coarse aggregate were obtained and used to cast the concrete. The comprehensive mix proportion of the constituent materials is presented in Table 1.

2.2 Characterisation of the Constituent Materials

The physical properties of ashaka cement, metakaolin, coarse aggregate and fine aggregate were carried out at the structures laboratory of Department of Civil Engineering, Abubakar Tafawa Balewa University (ATBU), Bauchi. The test result of the physical properties is presented in Table 2. The oxide composition test of metakaolin was carried out using XRF spectrometer to determine the constituents oxide. The tests were conducted at the quality control laboratory of Ashaka Cement Factory Gombe state, Nigeria. The result of the oxide composition of MK and Ashaka cement is presented in Tables 1 and 2

2.3 Preparation of Sample Using Constituent Materials

The constituent materials were measured using beam balance. Water used was measured by volume. Hand mixing was adopted in accordance with BS EN 12390 (2000), Part 2: specification. The concrete were cured by complete water immersion for 7, 14, 28, 60 and 90days. The levels of replacements for cement with metakaolin were at 0, 5, 10, 15, 20, 25 and 30 percent and 3% constant volume of sisal fibre was used as an additive. Average of three concrete samples were produced, cured and tested for compressive and flexural strength tests as shown in Plates 1 and 2 respectively.

Plate 1. Concrete cubes

Plate 2. Concrete beams

Table 1. Quantities of materials used for the production of metakaolin and sisal fibre reinforced concrete

MIX ID	Cement (kg/m^3)	Constituents materials (kg/m^3)				
		Metakaolin (kg/m^3)	Sisal fibre (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
MK-00	345	00	3	185	623	1170
MK-05	340	05	3	185	623	1170
MK-10	335	10	3	185	623	1170
MK-15	330	15	3	185	623	1170
MK-20	325	20	3	185	623	1170
MK-25	320	25	3	185	623	1170
MK-30	315	30	3	185	623	1170

Table 2. Some physical properties of cement, metakaolin, fine aggregate and coarse aggregate

Property	Cement	MK	Fine aggregate	Coarse aggregate
Specific Gravity	3.15	2.49	2.63	2.68
Loss on Ignition	1.0	1.76	-	-
Blaines Fineness (m^2/Kg)	370	367	-	-

2.4 Slump Test

Slump test was carried out to determine its workability of the sisal fibre and metakaolin concrete. The test was conducted at the structures laboratory of Department of Civil Engineering, ATBU, Bauchi. The test was performed as specified by BS EN 12350: Part 2 (1999).

2.5 Compressive Strength Test

Concrete cubes of size 100 mm x 100 mm x 100 mm were produced for determination of compressive strength. The samples were tested for compression. The test was conducted at the structures laboratory of Department of Civil Engineering, ATBU, Bauchi. 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).

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

2.6 Flexural Strength Test

Flexural strength test was performed on hardened concrete beams of 100 mm x 100 mm x 500 mm. The flexural strength of the concrete beam was determined for each curing period. This test was conducted at the structures laboratory of the Department of Civil Engineering, ATBU Bauchi. The test was conducted in accordance with BS EN 12390 Part 5: (2000) specification. The flexural strength is expressed as a modulus of rupture (MOR) in (N/mm^2), and it was determined using the equation (2).

$$\text{Modulus of rupture } (MOR) = \frac{PL}{bd^2} \quad (2)$$

Where:

P = Maximum load (kN)
L = Span of the beam (i.e. 500 mm)
d = Depth of the beam (i.e. 100 mm)
b = Breadth of the beam (i.e. 100 mm)

2.7 Density Test

The density of the hardened concrete samples was determined in accordance with BS EN 12390 Part 7: (2000). The densities were calculated using equation (3).

$$Density, \rho = \frac{Mass, m\ (kg)}{Volume, v\ (mm^3)} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 Physical Properties and Oxide Composition of Metakaolin (MK)

Physical properties of metakaolin are shown in Table 2. The specific gravity of metakaolin determined was 2.49, and that of Ashaka cement is 3.15. This shows that cement is heavier than metakaolin as such more weight of metakaolin will be needed to substitute equal weight of cement in the production of the blended concrete. The loss on ignition (LOI) is a measure of organic, carbonate and sediment content is 1.76% which is far below 10%, the maximum specified by ASTM C618 (2012). The low LOI shows that it is highly reactive when blended in concrete [12]. The result of chemical composition test carried out on metakaolin indicates the existence of main oxides present in cement as shown in Table 3, which indicate metakaolin is a pozzolana that can be used to replace cement [13]. The sum of oxides of Silicon, Iron and Aluminium is 95.99% which is far more than the 70% minimum according to ASTM C618 (2012) specification for raw or calcined pozzolana (class N). The sum of alkalis oxide of sodium and potassium (N_2O + K_2O) is 1.43% which shows there is no or litle possibility of the alkali aggregate reaction which causes segregation of concrete [14]. Sulphur trioxide (SO_3) was also present in metakaolin which is 0.02% and is far below 4% maximum according to ASTM C618 (2012) specification which implies there is possibility of improved durability [15].

Table 3. Oxide composition of metakaolin (MK) and ashaka cement

Oxide	Metakaolin (%)	Ashaka cement (%)
SiO_2	52.67	19.68
$Al2O_3$	41.96	6.44
$Fe2O_3$	1.37	3.32
CaO	1.23	60.92
MgO	0.26	0.97
SO_3	0.02	2.28
K_2O	1.34	0.85
Na_2O	0.09	0.12

3.2 Workability of Sisal Fibre Reinforced Concrete

The results of the slump test performed on the fresh concrete containing metakaolin as cement replacement are presented in Table 4 and the plot of slump versus metakaolin content is shown in Fig. 1. The result indicated a decrease in slump with increase in metakaolin which simply means additional water is need to maintained uniform consistency as metakaolin increases from five percent (5%) to thirty percent (30%) at interval of five (5). For example at 5%, 10%, 15%, 20%, 25% and 30% metakaolin content, the slump decreases by 19.05%, 33.33%, 42.86%, 52.38% and 76.92% respectively. This implies that metakaolin absorbs more water in concrete than ordinary cement. The results slump values determined are within the rage for class S1 (10 -40 mm) according to BS-EN 206-part 1: (2000) specification for true slump type for construction purposes, with the exception of 30% metakaolin content.

Table 4. Slump test result of sisal fibre reinforced concrete with metakaolin

Mix-ID	Slump (mm)
MK-00	26
MK-05	21
MK-10	17
MK-15	14
MK-20	12
MK-25	10
MK-30	6

3.3 Compressive Strength Test Result

The compressive strength test result is presented in Table 5, while Fig. 2 presents the plot of compressive strength of concrete versus metakaolin content. It can be observed from the plot that, the compressive strength decreases with increase in metakaolin. For instance at MK-10 cement replacement level, there was a strength decreases of 7.41%, 8.41%, 8.41%,, 6.65% and 5.34% when compared to the compressive strength of control specimen(MK-00) at 7, 14, 28, 60 and 90 days of curing periods respectively. Similarly, MK-10 exhibited strength decrease of 11.67%, 14.79%, 15.11%, 10.15% and 7.52% at 7, 14, 28, 60 and 90 days of curing periods respectively. All the remaining cement replacement levels, exhibited similar pattern of strength loss in comparison to the strength of the plain concrete sample. Considering the result presented above it can be concluded that the higher percentage of metakaolin in concrete the more reduction in compressive strength. This may have connection to two main reasons. First reason the fineness of cement is greater than that of metakaolin hence metakaolin cannot react rapidly with water as cement to attained the target strength compared to plain concrete [16]. Second reason addition of metakaolin causes decrease in the amount of main strength contributing compound (tri-calcium silicates (C_3S)) present in concrete therefore, the overall strength of the blended concrete was decreased [17]. However, compressive strength above the design mix of 20 N/mm^2 where obtained at MK-05 and MK-10 when cured beyond 28 days respectively.

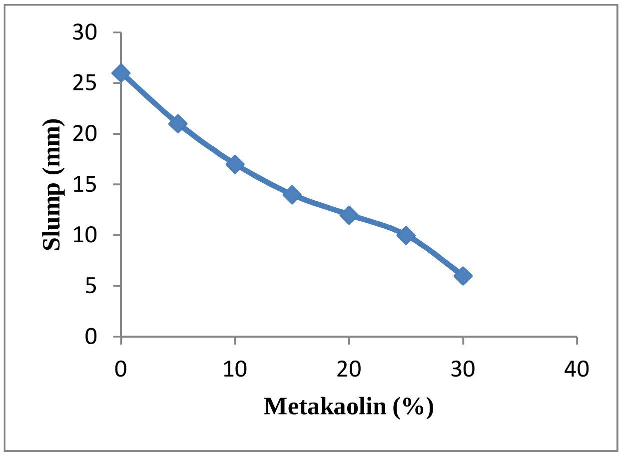

Fig. 1. Plot of slump versus metakaolin content

Table 5. Compressive strength test result for metakaolin and sisal fibre reinforced concrete

Mix ID	Compressive strength (N/mm^2)				
	7 days	**14 days**	**28 days**	**60 days**	**90 days**
MK-00	15.24	18.32	21.05	22.85	23.95
MK-05	14.11	16.78	19.28	21.33	22.67
MK-10	13.46	15.61	17.87	20.53	22.15
MK-15	11.83	14.49	15.66	17.06	19.35
MK-20	10.18	12.73	14.74	16.28	18.42
MK-25	8.09	10.24	12.59	14.27	16.53
MK-30	5.81	6.63	8.12	9.42	10.75

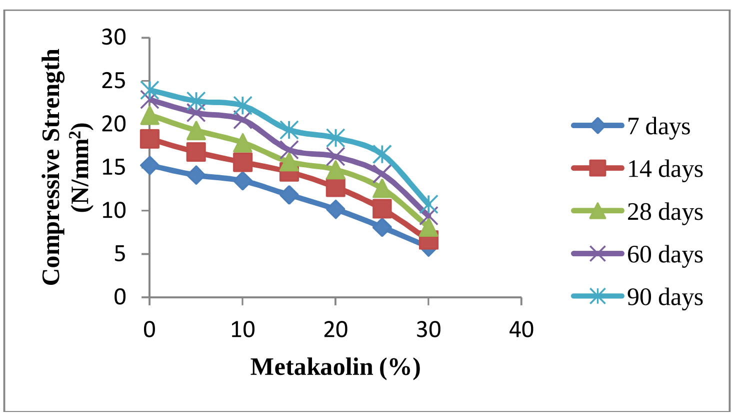

Fig. 2. Plot of compressive strength versus metakaolin content

Fig. 3 shows the plot of compressive strength of concrete versus curing periods. It can be observed that the compressive strength of metakaolin concrete increases as the curing age is extended beyond 28 days irrespective of the replacement levels. From the results obtained, MK-05 at 7 days curing period, exhibited 20.21%, 38.12%,49.93% and 57.15% increase in strength as compared to the control concrete at the age of 14, 28, 60 and 90 days curing ages respectively.

In a similar manner, MK-10 exhibited 18.92%, 36.64%, 50.46% and 60.67% increase in strength when compared with the corresponding strength of the control concrete at the age of 7, 14, 28, 60 and 90 days of curing. Considering the nature of the remaining results, it can be observed that compressive strength increases with increase in curing period. It can be observed from the result presented above, that the percentage increase in strength for all metakaolin concrete increases slowly up to 28 days curing age. However, the percentage increase in compressive strength increases significantly at the age of 60 and 90 days of curing. This indicates that there is a significant strength gain with extended curing. The possible explanation to this behavior is that at early ages (28days and below), the metakaolin act as a filler in the concrete with no significant contribution to strength, but at latter ages(beyond 28 days) metakaolin react with Calcium Hydroxide released during hydration to produce the strength forming calcium silicate hydrates(C-S-H) [18]. The optimum replacement level was observed at MK-10 because it gives better strength increase than the other replacement levels.

3.4 Flexural Strength Test Result

Table 6 shows the result of the flexural strength of concrete while the variation of flexural strength with percentage replacement of cement with metakaolin is presented in Fig. 4. And the variation of flexural strength versus curing period is presented in Fig. 5. It can be seen from the figure that, the flexural strength decreases with increase in metakaolin content. For instance at MK-05 cement replacement level, there was a flexural strength decreases of 2.13%, 3.24%, 8.62%, 9.04% and 1.81% when compared to the flexural strength of control specimen(MK-00) at 7, 14, 28, 60 and 90 days of curing periods respectively. Similarly, MK-10 exhibited flexural strength decrease of 14.59%, 9.03%, 14.31%, 15.70% and 6.92% at 7, 14, 28, 60 and 90 days of curing periods respectively. All the remaining cement replacement levels, exhibited similar pattern of flexural strength loss when compared to the strength of the control sample. The decrease in flexural strength may be attributed to the water absorption ofmetakaolin. It absorbs most of the water in the mix, resulting in poor hydration hence, greater strength reduction [19].

3.5 Density Test

Table 7 shows the result of the density of concrete while the variation of density with percentage replacement of cement with metakaolin is presented in Fig. 6. And the variation of density versus curing period is presented in Fig. 7. The density test result is expected in view of the fact that the specific gravity of metakaolin (2.51) as against (3.15) for cement. It can be seen that the maximum density of 2,380 kg/m^3 was obtained at 0% cement replacement level, this value falls within the range of 2,000 – 2,600 kg/m^3 specified by BS EN 206 part 1 (2000) for normal weight concrete while the minimum density of 1,246 kg/m^3 was obtained at 30% cement replacement level, this value is within the range of 800 – 2,000 kg/m^3 specified by BS EN 206 part 1 (2000) for normal lightweight concrete. This implies that concrete made with metakaolin as cement replacement can comfortably be used as lightweight concrete material, when cement is replaced below 30% with metakaolin.

Table 6. Flexural strength test result for metakaolin and sisal fibre reinforced concrete

Mix ID	Flexural strength (N/mm^2)				
	7 days	**14 days**	**28 days**	**60 days**	**90 days**
MK-00	3.29	4.32	5.45	5.86	6.07
MK-05	3.22	4.18	4.98	5.33	5.96
MK-10	2.81	3.93	4.67	4.94	5.65
MK-15	2.43	3.46	4.26	4.55	5.35
MK-20	2.03	2.83	3.58	3.88	4.82
MK-25	1.65	2.28	3.04	3.37	4.13
MK-30	0.91	1.54	2.43	2.69	3.14

Table 7. Density test result for metakaolin and sisal fibre reinforced concrete

Mix ID	Density (kg/m^3)				
	7 days	**14 days**	**28 days**	**60 days**	**90 days**
MK-00	2043	2197	2328	2359	2480
MK-05	1842	1954	2065	2176	2288
MK-10	1691	1826	1953	2077	2199
MK-15	1597	1712	1836	1948	2059
MK-20	1489	1601	1709	1815	1924
MK-25	1360	1473	1588	1691	1795
MK-30	1346	1398	1407	1510	1621

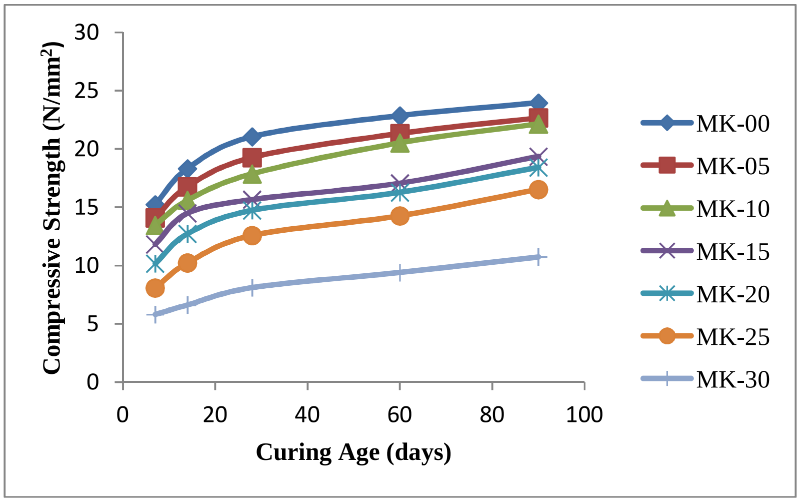

Fig. 3. Plot of compressive strength versus age of curing

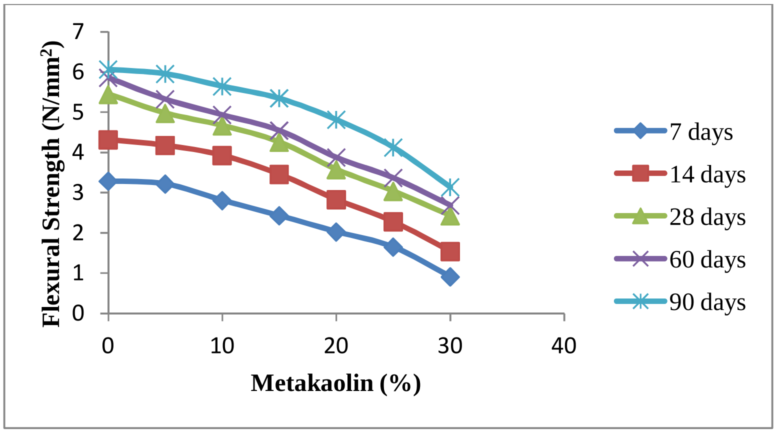

Fig. 4. Plot of flexural strength versus metakaolin content

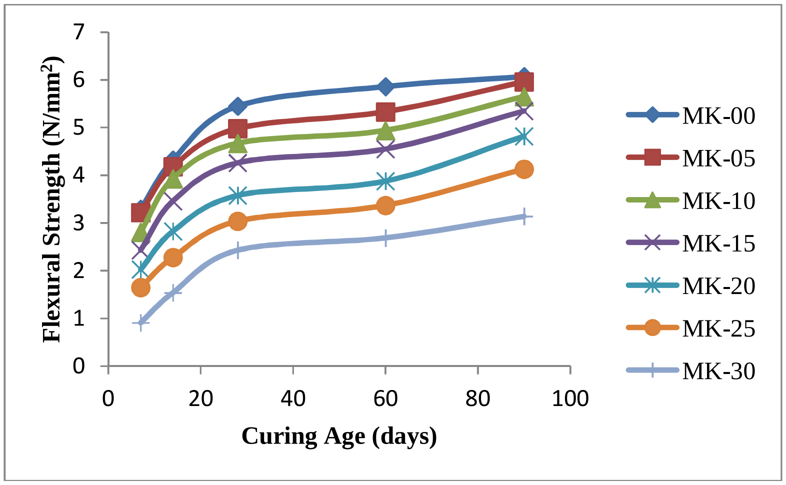

Fig. 5. Plot of flexural strength versus curing age

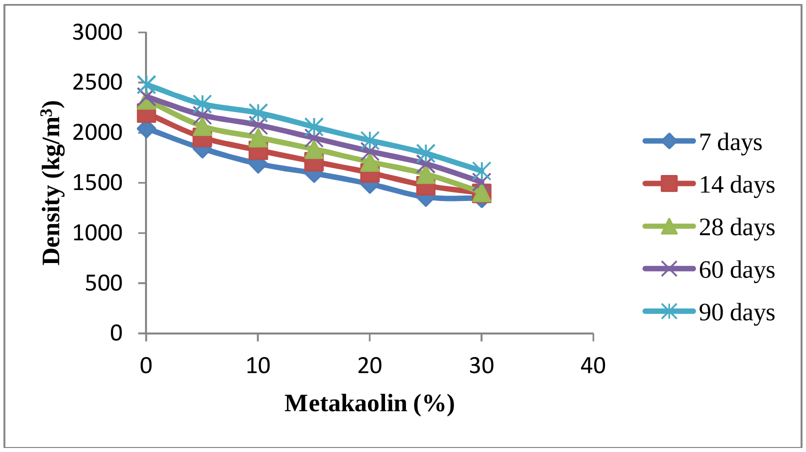

Fig. 6. Plot of density versus metakaolin content

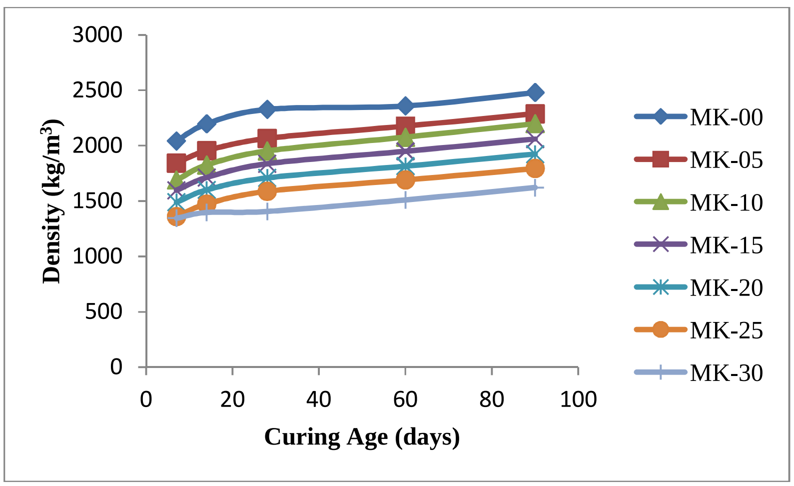

Fig. 7. Plot of density versus curing age

3.6 Regression Models for Concrete Containing Coconut Shell as Coarse Aggregate

The regression models generated for predicting compressive strength, flexural strength and density for metakaolin and sisal fibre reinforced concrete are given by equations (4-6) respectively.

$$c_s = 17.6636 + 0.0849395x_1 - 0.377443x_2 \quad (4)$$

$$f_s = 4.12 + 0.0276x_1 - 0.0944x_2 \quad (5)$$

$$d_s = 2048 + 4.66x_1 - 26.3x_2 \quad (6)$$

Where:

c_s is the concrete compressive strength, f_s is the concrete flexural strength, d_s is concrete density, is the curing age of concrete and is the percentage of metakaolin used to replace cement in concrete respectively.

The likelihood of the true coefficient of P-values is zero, indicate that the particular predictor is significant in the proposed model at a specified significant level. From the p-values of the proposed models in this research work, it can be seen that at ($P < 0.05$) level of significance, p-value = 0.000 for both curing age and percentage metakaolin in the concrete and thus are predictors in the equations developed, signifying that the variation in the concrete compressive strength, flexural strength and the density is caused by curing age and metakaolin content [20]. The coefficient of determination (R^2) of the selected models obtained were 92.23%, 90.0% and 96.7% respectively and it indicate that the variation in concrete compressive strength, flexural strength and density is significantly

Table 8. Regression analysis of compressive strength

Predictor	Coeff	SE Coeff	T	P	Remarks
Constant	17.6636	0.522746	33.7900	0.000	Significant
x1	0.0849	0.007617	11.1511	0.000	Significant
x2	-0.3774	0.023622	-15.9781	0.000	Significant
Basic ANOVA					
Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	2	741.480	370.740	189.824	0.000000
x1	1	242.859	242.859	124.347	0.000000
x2	1	498.621	498.621	255.301	0.000000
Error	32	62.498	1.953	-	-
Total	34	803.978	-	-	-

Table 9. Regression analysis of flexural strength

Predictor	Coeff	SE Coeff	T	P	Remarks
Constant	4.1191	0.1662	24.79	0.000	Significant
x1	0.027593	0.002421	11.40	0.000	Significant
x2	-0.094429	0.007508	-12.58	0.000	Significant
Basic ANOVA					
Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	2	56.838	28.419	144.03	0.000000
Error	32	6.314	0.197	-	-
Total	34	63.152	-	-	-

Table 10. Regression analysis of density

Predictor	Coeff	SE Coeff	T	P	Remarks
Constant	2048.15	21.62	94.72	0.000	Significant
x1	4.6560	0.3151	14.78	0.000	Significant
x2	-26.3129	0.9771	-26.93	0.000	Significant
Basic ANOVA					
Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	2	3153019	1576510	471.75	0.000000
Error	32	106939	3342	-	-
Total	34	3259958	-	-	-

dependent on the percentage of metakaolin and curing age [21]. The standard deviations of the model equations (S) of 1.39752, 0.444202 and 7.8087 respectively are reasonably small. The lesser value of S, the better the selected regression equation fits the data, which indicates a positive correlation between predictors and the response variables in the model [21]. Tables 8, 9 and 10 shows the regression analysis for the compressive strength, flexural strength and density of concrete respectively to further examine how well the models fit the data used [22].

4. CONCLUSIONS

Based on the results obtained, the following conclusions were drawn:

i. The slump values reduces by the addition of more metakaolin in concrete, hence more water is required to obtained workable concrete.
ii. The compressive strength, flexural strength and the density generally decreases with increase in metakaolin content and increase with increase in curing period. However, metakaolin and sisal fibre reinforced concrete satisfied requirement of ASTM C 330 (2004) for lightweight concrete considering compressive strength, flexural strength and density of the blended concrete produced.
iii. The optimum replacement level of the blended concrete was obtained at MK-10% and should be cured beyond 28 days. The

concrete performed relatively better at the optimum replacement level when compared to the control sample, than other cement replacement levels.

iv. The statistical models developed provide better estimate for compressive strength, flexural strength and density, indicating there is no much statistical significant difference between the experimental and predicted values at 5% level of significance.

v. Metakaolin could be used to improve the strength of sisal fibre reinforced concrete.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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