Effects of Concrete Grades on Strength Characteristics of Metakaolin Modified Recycled Aggregate Concrete

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ABSTRACT: In this study, locally produced Metakaolin (MK) was used as an admixture in recycled aggregate concrete of grades M 25 and M 30. The content of MK varied from 0-15% at 5% intervals. The physical and mechanical properties (bulk density, specific gravity, water absorption, aggregate crushing value and aggregate impact value) of aggregates were determined, the chemical composition as well as reactivity of MK was evaluated using X-Ray Fluorescence (XRF) technique and modified Chappelle test. The workability (slump) and strength (compressive and split tensile) properties of fresh and hardened RAC were examined relative to that of conventional concrete. The results of the experiments revealed that the specific gravity (SG), water absorption and aggregate impact value of recycled aggregates (RA) were 2.23, 5.35% and 32%, respectively. The MK used had an optimum reactivity of 2060.8 mg of $Ca(OH)_2$ fixed at a temperature of 660 °C. The slump values for M 25 and M 30 control specimens were 72 mm and 65 mm, respectively while the slump values of MK modified RAC decreased from 67-45 mm for M 25 and 55-35 mm for M 30 as MK increased from 0-15%. The 56th-day compressive strength of the control samples was 21.73 N/mm^2 for M 25 and 26.8 N/mm^2 for M 30, respectively, while RAC samples ranged from 14.96 - 17.04 N/mm^2 for M 25 and 20.55 - 22.67 N/mm^2 for M 30 whereas the split tensile strength for the control samples was 2.71 N/mm^2 and 3.06 N/mm^2 for the two grades in that sequence, while those of RAC ranged from 2.26-2.49 N/mm^2 for M 25 and 2.62 – 2.84 N/mm^2 for M 30. Despite the fact that metakaolin modified RAC had lower strength properties than conventional concrete, the use of 10% metakaolin as a RA modifier in concrete production will provide a sustainable alternative to conventional aggregates in concrete mix design.

KEYWORDS: Conventional concrete, Compressive strength, Metakaolin, Recycled concrete, Split tensile strength

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I. INTRODUCTION

Concrete is one of the world's most frequently utilized building material, significantly more than any other material in the construction industry (Dhanada et al., 2018; Gagan and Summit, 2015). The demand for concrete in infrastructural development almost doubled that of steel and wood combined between 1990 and 2010 (Monterio et al., 2017). As a result of this increase in the demand for concrete, the built environment is currently dealing with two main concerns. The first is the corresponding growth in demand for the various components of the concrete mix, and the second is the vast number of wastes generated by the demolition of concrete structures (Akthar and Samarh, 2018). In a study by Polata et al. (2017), it was reported that wastes emanating from construction sites around the world climaxed at about 10-30% of the total wastes deposited in landfills and that these wastes consist of harmful matters unlike those obtained from household wastes.

The major concern for environmentalist and other resource professionals is that the continuous disposal of these wastes has significant adverse effects on the planet, some of which comes with ruthless environmental hazards such as the pollution of marine life, loss of habitat, sedimentation, noise pollution, erosion and changes to the visual scene (Martín-Morales et al., 2011).

This trend if not harnessed positively will leave the world with huge amounts of potentially recyclable aggregates from Construction and Demolition (C & D) wastes. For instance, the construction industries within the EU alone generated well over 450 million tonnes of C & D wastes per year (Bravo et al., 2015; Deloitte, 2014; Li et al., 2013; Rodríguez et al., 2015). With these figures in mind, there is room for the utilization of these readily available resources as a close substitute for natural aggregates in construction works. However, there seems to be a downside to the use of these materials in place of conventional aggregates.

Previous studies have shown that when recycled aggregates (RA) are used in the production of concrete, the presence of RA will deteriorate the workability and other engineering properties that are of interest; this is due to several factors such as; the mode of processing, age of the concrete at recycling and quantity of adhered mortar and other properties of the parent material (Xiao, 2012; Zega and Di Maio, 2011). Shi et al. (2015) disclosed that the reason for this behaviour is

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primarily due to the presence of adhered mortar in RA and the interfacial transition zone (ITZ) that exists between the natural aggregates and the cement mortar.

Despite the defects associated with the use of RA as a potential replacement for conventional aggregates, the quantity of usable RA generated from construction works is still very much on the increase globally, thus, there is a need to seek ways by which the properties of RA can be improved. The modification of RA properties via various treatment techniques is fast becoming a more recent developing interest amongst researchers. Several techniques have been deployed to achieving this goal and quite a number of researchers have reported that the properties of RA and the concrete produced improved reasonably when any or a combination of the following methods were used; mechanical abrasion, thermal treatment, coating of RA with slurry, ultrasonic cleansing, polymer impregnation, bio deposition treatment, chemical immersion, carbonation and pozzolanic coating (Al-Bayati et al., 2016; Grabiec et al., 2012; Ismail and Ramli, 2013; Spaeth and Tegguer, 2013; Shi et al., 2015; Juan and Guetterez, 2019; Kim et al., 2016; Kukadia et al., 2017; Zhang et al., 2015a)

Metakaolin (MK) also known as De-Hyrdoxylated Kaolin (DHK) is a pozzolanic material obtained from the calcination of kaolin at temperatures within the range of 600 - 800 ^{o}C (Shafiq et al., 2015). During the process of de-hydroxylation (i.e. removal of H_2O molecules) amorphous alumina-silicate which is reactive in concrete is produced. When in concrete MK reacts with calcium hydroxide ($Ca(OH)_2$) liberated during the hydration process of cement present in concrete to produce additional calcium silicate hydrate (C-S-H) which subsequently fill the pores in concrete and increase the concrete strength thereby aiding the bonding of the concrete matrix (Mermerdaş *et al.,* 2012). Therefore, the presence of a lesser amount of $Ca(OH)_2$ and more cementing compounds of C-S-H gives rise to a much stronger concrete. Akthar and Samarh, (2018) reported that the de-hydroxylation of kaolin in an isothermal furnace begins at temperatures above 400 ^{o}C and the quality of MK in terms of reactivity increases as the temperature rises to about 800 ^{o}C. In another study, Shafiq et al. (2015) discovered that when metakaolin was calcinated at a temperature of 800 ^{o}C for 3 hours the reactivity of the MK obtained was better than those calcinated at other temperatures.

The pozzolanic reactivity of MK can either be ascertained directly by determining the amount of $Ca(OH)_2$ consumed using established analytical methods or indirectly by measuring the physicochemical properties of the material (Donatello et al., 2010). One major shortfall of the latter is that it only provides a qualitative approach to determining the reactivity of the pozzolanic material which may not be sufficient to describe the reactions taking place in the concrete hence the modified Chappelle test which is an improvement to the Fratini developed by Largent in 1978 provides a more quantitative result of the amount of $Ca(OH)_2$ used up by the pozzolan (Eduardo et al.,1978)

Previous research into the effects of MK on the mechanical properties of concrete made with natural aggregates has revealed that the presence of MK had a significant impact on the properties of the resulting concrete. Narmatha and Felixkala (2016) reported that when MK was added to conventional concrete at varying percentages of 0-20 % at an increment of 5%, the 7- day compressive strength ranged between 45-55 MPa and the 28-day strength for all samples tested falls between a lower limit of 61 MPa and an upper limit of 73 MPa. It was then concluded that the optimum dosage of MK was 15% and that the 20% addition was lower than all other percentages. In all circumstances, none of the samples with MK was lower than the control. In a similar study, but with a fixed water-binder ratio of 0.4 and various dosages of super-plasticizer, Jagtap et al. (2017) discovered that 15% of metakaolin in concrete demonstrated the highest 28-day compressive strength. However, when the water content was further reduced to 0.3. Dinakar et al., (2013) observed that the samples of concrete with 10% of MK had a 5.2% increase in compressive strength after 90 days of curing.

In all of these, the aggregates used were conventional and there are few pieces of literature on the behaviour of MK modified recycled concrete (Hassan et al. 2015; Kapoor et al. 2016; Shen et al. 2012). In instances where it was used, there were no explanation as to how the variation of grades of concrete affected the strength properties of the resulting concrete.

This research assessed the effects of concrete grades on strength characteristics of metakaolin modified recycled aggregate concrete. To fill this gap, the study evaluated the physical, mechanical and chemical properties of aggregates and metakaolin, respectively. In addition to this, two different grades of concrete were designed in accordance with Building Research Establishment (BRE) mix design manual and used in the preparation of concrete samples. Findings from the experiment were then compared vis a vis results obtained for conventional concrete of the same grades, and it was observed that the increase in cement content may not necessarily be beneficial to the concrete at certain percentages of the addition of metakaolin.

II. MATERIALS AND METHODS

A. Materials

Portland limestone cement of grade 32.5 N (CEMII) was used as the binder for the concrete mixture. The fine aggregates used in this research was obtained from Abayomi river located around Old-Ife road, Ibadan, Oyo State (7.3923 ^{o}N, 3.9355 ^{o}E). After collection, the fine aggregates were sieved to a uniform size using a 4.75 mm BS sieve. For the coarse aggregates, recycled aggregates obtained from construction and demolition waste of concrete origin were obtained from a quarry site in Ibadan, Oyo State, Nigeria (7.4904 ^{o}N, 3.9172 ^{o}E). The concrete waste was then reduced into smaller sizes as shown in Figure 1. Thereafter, the coarse aggregates were sieved, saturated in water and allowed to dry attaining the saturated surface dry (SSD) condition before mixing. Only aggregates retained on sieves of sizes 9.5-25 mm were used as coarse aggregates in the production of concrete with RCA. Raw kaolin samples were collected from a Kaolin mining site in Ijero, Ekiti State, Nigeria (7.8113 ^{o}N, 5.0677 ^{o}E). A picture of the site is presented in Figure 2. The large kaolin sample was milled into powdery form and allowed to pass through sieve No 200 (75μm). Thereafter it was calcined between 600-700 °C to obtain MK as shown in Figure 3.

Figure 1: Crushed concrete reduced into coarse aggregate sizes.

Figure 2: Kaolin mining site in Ijero, Ekiti State.

Figure 3: Calcination of Kaolin.

B. *Experimental Methods*

The physical properties of the aggregates such as bulk density, specific gravity, water absorption, particle size distribution (PSD), aggregate crushing value (ACV) and aggregate impact value (AIV) were obtained according to BS EN 1097-2:2020. The reactivity of the metakaolin used was ascertained using the modified Chappelle test in accordance with NF P18-513 2012 Standard (Annex A). This test permits the quantification of $Ca(OH)_2$ fixed by 1 g of metakaolin when mixed with 2 g of CaO and 250 ml of distilled CO_2 free water. The suspension was boiled at 85± 5 ºC for 16 hours with continuous stirring in a 500ml conical flask. At the end of the 16 hours, the conical flask and its content were cooled to room temperature by immersing in water. The portlandite content that was not consumed (free in solution) was determined by sucrose extraction and acid titration. Figure 4 shows the configuration of the locally fabricated apparatus to carry out the test.

Two grades of concrete were designed using BRE Mix Design Manual for a targeted 28-day concrete strength of 25 N/mm^2 and 30 N/mm^2, respectively. The mix ratios obtained from the design were (1: 2.42: 2.73) for C25 and (1: 1.7: 2.30) for C30 at water-cement ratios of 0.45 and 0.55. In all, a total of 150 cubes of size (150 mm × 150 mm × 150 mm) and 80 cylinders of size (150 mm ×300 mm) were produced with various percentages of the addition of MK ranging from 0-15% by weight of cement at 5% intervals. The concrete samples were cured in water for 7, 14, 21, 28 and 56 days before subjecting to mechanical tests. The rheology (slump) and technical properties (compressive and split tensile strengths) of the concrete were conducted in line with the provisions of BS 1881-124:2015+A1:2021.

Figure 4: Arrangement of apparatus for the Modified Chappelle test.

III. RESULTS AND DISCUSSION

A. *Physical Properties of Kaolin and Metakaolin*

Table 1 shows a summary of the physical properties of materials used in this study; the specific gravity of kaolin used in this study ranged between 2.16 - 2.45. These values are less than the range of 2.58 - 2.68 specified by Gushit *et al.* (2010) and Talabi *et al.* (2012) where it was reported that the predominant clay mineral in samples with an average SG of 2.61 is predominantly kaolinite. Ismail *et al.* (2014) reported that hydrothermally formed kaolin showed higher specific gravities (> 2.0) when compared to kaolin samples formed by chemical weathering (< 2.0). Thus, this suggests that the kaolin used in this study could have been formed hydrothermally. However, the specific gravity of metakaolin falls within the range of 2.13 - 2.21. These results agree with the findings of Yilmaz (2011) where it was reported that kaolinite did not indicate an appreciable change in specific gravity when exposed to a temperature within the range of 400-600 ºC.

B. Physical Properties of Aggregates

Bulk density and specific gravity values obtained for the fine aggregates were within the permissible limits as specified by ASTM C29/C29M-09. The value of the bulk density was 1424 kg/m^3 while that of the specific gravity was 2.63 as shown in Table 1. For the Recycled Concrete Aggregate (RCA) used, the result of the SG of the RCA shows that the specific gravity of the samples randomly picked were less than that of conventional coarse aggregates which are usually within the range of 2.6 - 2.9 (Kim and Lee, 2011; Saravanakumar *et al.,* 2016). Saravanakumar and Dhinakaran (2012) explained that some of the reasons why the SG of RA is lesser than that of NA are the origin of the parent concrete, the mix proportion and the age of the concrete before recycling. However, the values of the water absorption test obtained were considerably higher when compared with normal aggregates, this finding agrees with the works of Al-Bayati *et al.* (2016), Kim *et al.* (2016), Qiu *et al.* (2014) and Zhang *et al.* (2015b) where it was reported that the presence of adhered mortar on RAC made it absorb more water but can be improved by subjecting the aggregates to acidic surface treatment (Ismail and Ramli, 2013; Katkhuda and Shatarat, 2017; Kazmi *et al.*, 2019)

Table 1: Physical properties of materials used.

	Kaolin	MK	Fine aggregates	RCA
Bulk Density (kg/m^3)	983-1094	938-985	1421.6-1426.3	1328.2-1379.3
Specific Gravity	2.16 - 2.45	2.13 - 2.21	2.63	2.18 - 2.23
Water absorption (%)	-	-	0.68 – 1.15	5.31 – 5.42
Fineness (m)	<75	< 75	2.87	7.8
ACV (%)	-	-	-	18
AIV (%)	-	-	-	32
PSD (%)			Uniformly graded	Uniformly graded

The bulk density of RCA falls within the range as specified by ASTM C29/C29M-09: 2009 for coarse aggregates (1200- 1750 kg/m^3). A study of these results suggests that RCA will require much water to saturate its particles when used in concrete production owing to its high absorption rate which is typical of aggregates with a large number of pores in its matrix, hence it could affect the workability and strength of the concrete produced if not given due consideration before mixing.

C. Mechanical Properties of Coarse Aggregates

The ACV of recycled aggregates used was obtained as 18% which is less than the value of 30% as prescribed by BS EN 12620:2002+A1:2008. The limiting Aggregate Impact Values (AIV) for aggregates used in heavy-duty concrete floor finishes and pavement wearing surfaces are 25% and 30%, respectively, according to BS EN 12620:2002+A1:2008. Conversely, an AIV of 32% was obtained for RCA in this study, implying that RCA may not be appropriate for either of the two previously indicated applications. However, it can be used in other situations where the expected impact from external loads is much less as the value obtained is still within the limit of 45% as provided by BS EN 12620:2002+A1:2008. Results of the sieve analysis for both coarse and fine aggregates shows that they were both uniformly graded as shown in Figure 5.

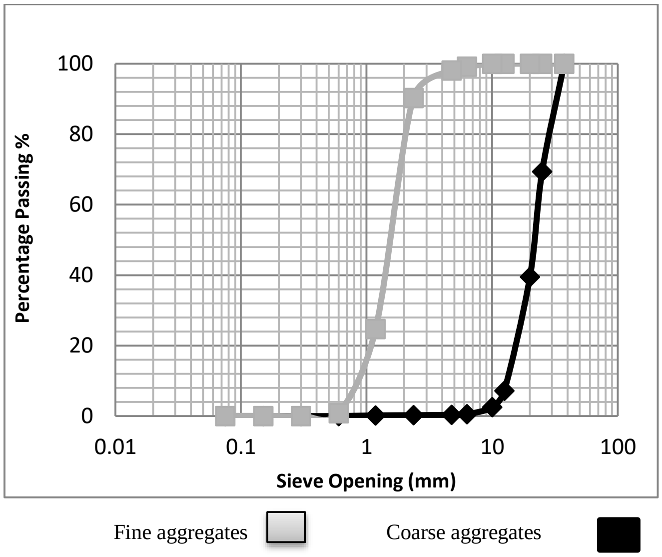

Figure 5: Sieve analysis of fine and coarse aggregates content.

D. Pozzolanic Reactivity of Metakaolin

The pozzolanic reactivity of the MK samples calcined at temperatures of 600 ºC, 650 ºC and 700 ºC were found to be 1172.5, 2009.1 and 1718.0, respectively. These values are expressed in terms of the mg of $Ca(OH)_2$ consumed by the pozzolan. The temperature of optimum calcination was then obtained by way of differentiating the equation of the second-degree polynomial generated for the temperature and an optimum temperature of 660 ºC was obtained as shown in Figure 6. From the results of XRF analysis, the sum of the chemical concentrations of SiO_2, Al_2O_3, and Fe_2O_3 as shown in Table 2. was 93.47 which exceeds the minimum of 85

Table 2: Composition of chemical constituents in kaolin calcined at optimum temperature.

Chemical Constituents	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	P_2O_5	K_2O	MnO	MgO	Na_2O	LOI
% Composition	59.90	32.29	1.28	0.36	0.04	0.06	2.79	0.01	0.17	0.24	2.80

specified by ASTM C618-12:2012 for Class F pozzolans. Nevertheless, when compared with the findings of Patil *et al.* (2015), the concentration of SiO_2 gotten is higher than the maximum permissible of 55% while the 32% Al_2O_3 content falls below the minimum (42%) required which suggests that the silica content of the MK used is much higher than the aluminate.

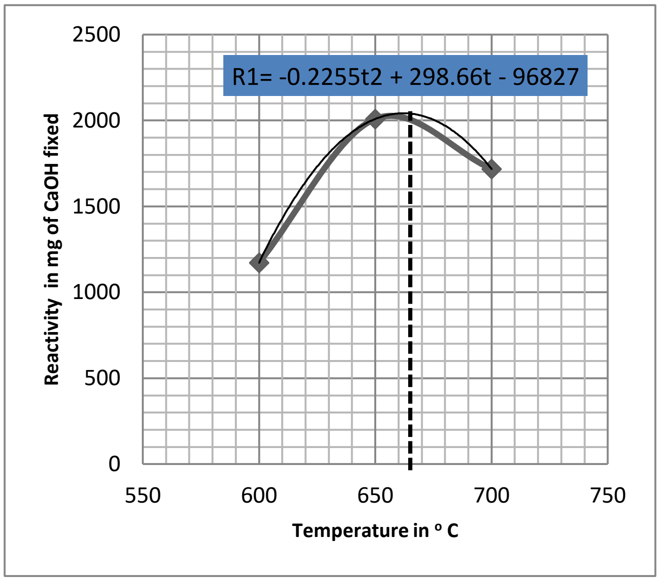

Figure 6: Reactivity of MK against temperature.

A. Rheological Properties of Concrete with RCA

For a constant water-cement ratio, the slump values for both grades (M 25 and M 30) of concrete examined decreased as the content of metakaolin increased. It was also observed that the values of the slump obtained for the control samples with conventional aggregate were much higher when compared with that of the concrete with recycled aggregates. This could have occurred as a result of the lower water absorption rate exhibited by conventional aggregates as reported by Oladejo (2017). The trend herein observed and presented as Table 3.0 agrees with the findings of Siddique and Kaur (2011) and Ramezanianpour and Bahrami (2012).

B. Effect of Concrete Grades on the Compressive Strength of Concrete with RCA Across the Ages of Curing

The results of the compressive strength across the various ages of curing herein presented as Figures 7-8 revealed that on the 7th day none of the samples attained the minimum expected compressive strength (i.e. 65-70% of 28th-day strength). The average compressive strength of the M 25 concrete was 14.74 N/mm^2, while those of concretes with 0-15% of metakaolin modified RCA were within the range of 9.33-9.41 N/mm^2, respectively.

Table 3: Behaviour of concrete in slump test.

Samples	**Slump (mm)**				
	0% of MK	**5% of MK**	**10 % of MK**	**15 % of MK**	**Water Content**
GRADE 25 Control	72	-	-	-	0.55
GRADE 30 Control	65	-	-	-	0.45
GRADE 25 RAC	67	59	41	45	0.55
GRADE 30 RAC	55	47	43	35	0.45

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For M 30 concrete, the average compressive strength obtained from the control sample was 19.04 N/mm^2, while the values for various percentages of modification ranged between 13.33-14.43 N/mm^2. After 14 days, the control sample for M 25 metakaolin modified RAC had increased to 13.26 N/mm^2, 13.59 N/mm^2, 14.00 N/mm^2, and 14.79 N/mm^2, for 0%, 5%, 10% and 15% respectively. When compared to samples without metakaolin, RAC with 15% metakaolin inclusion exhibited the maximum compressive strength and differed by 3.51 N/mm^2 from the control. For grade 30, the average compressive strength observed at 14 days for concrete with normal aggregate was 24 N/mm^2, while concrete samples with recycled aggregates and metakaolin of 0%, 5%, 10% and 15% gave compressive strengths of 17.93 N/mm^2, 18.22 N/mm^2, 19.14N/mm^2 and 18.37N/mm^2, respectively.

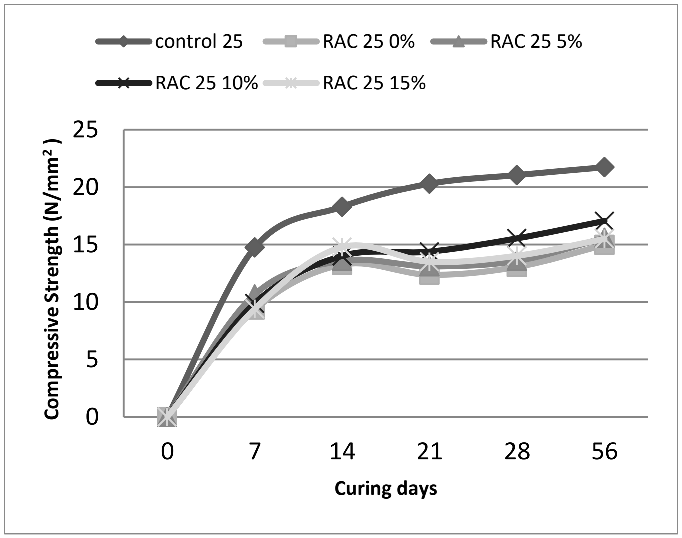

Figure 7: Compressive strengths of grade 25 concrete at different ages of testing.

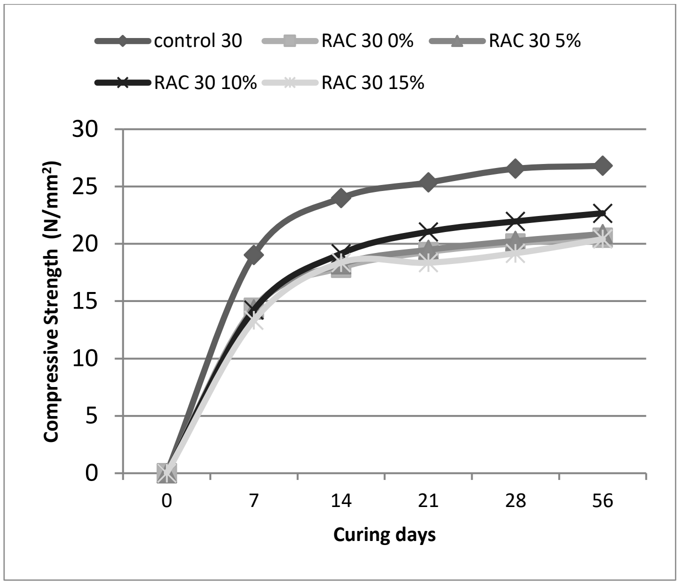

Figure 8: Compressive strengths of grade 30 concrete at different ages of testing.

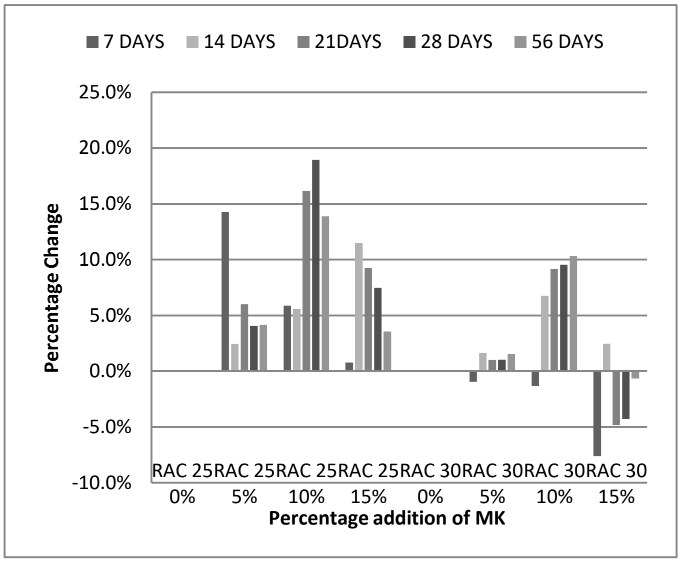

Figure 9: Percentage change in compressive strength experienced at different ages of testing due to the presence of MK.

The average compressive strength obtained for the control sample after 21 days of curing was 20.30 N/mm^2 for grade 25 while the average compressive strengths for samples with 0-15% of metakaolin were within the range of 12.37-14.37 N/mm^2. At this age, the percentage change in strength for grade 25 concrete observed in comparison with the samples without metakaolin are 6%, 16%, 9% for 5, 10 and 15% inclusion of metakaolin, respectively. A similar trend was observed for the grade 30 samples with a percentage change in strength of 1%, 9.1%, -4.82% for 5,10 and 15% inclusion of metakaolin. The 28 days compressive strength shows that the strength of the grade 25 concrete with normal aggregate was 21.05 N/mm^2 while that of metakaolin modified RAC was between 13.05-14.03 N/mm^2. The percentage change in strength as a result of metakaolin was 4.1%, 19.0% and 7.5% for 5%, 10% and 15 % of metakaolin, respectively.

Although, none of the samples met the targeted design strength, samples of modified RAC showed a better compressive strength when compared with unmodified RAC samples and 10% of metakaolin modified RAC had the highest percentage change in strength. The most likely cause for the reduction in strength of RAC is the presence of loose mortars on the surface of RA. These loose mortars are considerably porous and affect the bonding between the cement pastes and aggregates (Muduli and Mukharjee, 2019). For grade 30 concrete at this age, the average compressive strength of the control was 26.56 N/mm^2 while the values obtained for RAC with metakaolin ranged between 19.19-21.96 N/mm^2. The percentage change in strength, when compared with RAC without metakaolin, are 1.0%, 9.5% and -4.3% for 5%, 10% and 15 % of metakaolin, respectively as shown in Figure 9. The 56 days compressive strength reveals that the overall percentage change in strength due to the addition of MK for grade 25 concrete are 4.2%, 13.9% and 3.6% for 5 %, 10% and 15 % addition, respectively while that of the RCA grade 30 concrete is 1.5%, 10.3% and -0.6%, as shown in Figure 9, the negative values obtained suggests that there was a reduction in strength. By this result, the 10% inclusion of metakaolin was most beneficial for both grades of concrete.

From the results enumerated above, it was observed that none of the samples with RCA exceeded the control samples for both grades considered. However, there was a significant improvement in the compressive strength of recycled concretes with metakaolin and the 10% inclusion had the most consistent effect across all the ages of curing averaging at 12.10% for grade 25 and 6.9% for grade 30. One would have expected that higher cement content will amount to a corresponding increase in strength, but this is not the case in this research suggesting that too high a cement content may not necessarily be beneficial to concrete at certain percentages of the addition of metakaolin. These results agree with Ghorpade and Sudarsana (2011) and Dinakar *et al.* (2013) which reported that 10% inclusion of metakaolin enhanced the compressive strength of plain concrete.

C. *Effect of Concrete Grades on the Tensile Strength of Concrete with RCA Across the Ages of Curing*

For the tensile behaviour of the concrete the values ranged between 1.73 - 2.52 N/mm^2 at 7 days, 2.16 - 2.90 N/mm^2 at 14 days, 2.14- 3.05 N/mm^2 at 28 days and 2.26 – 3.06 N/mm^2 for 56 days as depicted in Figures 10-11. For grade 25 samples the tensile strength of the control at 7 days was 2.27 N/mm^2 while the tensile strength obtained for 0-15% inclusion of metakaolin was between 1.73-1.94 N/mm^2. The values obtained for grade 30 concrete were slightly higher than those of M 25 concrete, the control sample was 2.52 N/mm^2 while for the various percentages of inclusion of MK from 0-15%, the values were 2.25 N/mm^2, 2.24 N/mm^2, 2.23 N/mm^2 and 2.16 N/mm^2. Furthermore, the 14-day tensile strength results show a general increase in the tensile strength of all samples tested. The average tensile strengths of the control samples were 2.52 N/mm^2 and 2.90 N/mm^2 for grades 25 and 30 respectively while the tensile strengths of grade 25 RCA concrete dosed with metakaolin are 2.16 N/mm^2, 2.19 N/mm^2, 2.23 N/mm^2 and 2.29 N/mm^2. For grade 30 RCA concrete dosed with metakaolin, the values are 2.50 N/mm^2, 2.54 N/mm^2, 2.60 N/mm^2 and 2.64 N/mm^2. The 28 day splitting strength for both controls are 2.72 N/mm^2 and 3.05 N/mm^2, while values for RAC are 2.14 N/mm^2, 2.18 N/mm^2, 2.34 N/mm^2, 2.21 N/mm^2, for grade 25 and 2.64 N/mm^2, 2.65 N/mm^2, 2.78 N/mm^2, 2.60 N/mm^2, for grade 30. Although none of the samples examined performed better than the control, the integration of MK as a modifier in RAC showed a significant enhancement in the split tensile strength as the percentage of addition increased to 10%. Lotfy and Al-Fayez (2015) observed a similar trend and explained that the most probable explanation for this occurrence is the fact that the split tensile strength of concrete is primarily affected by ITZ, the strength of the paste and bonding between the paste and aggregates, it was further explained that since MK possessed pozzolanic and filler properties this would aid the bonding between pastes and aggregates (Kou *et al.*, 2011).

The 56th-day results revealed that there was no substantial increase in tensile strength when compared with samples tested on the 28th day, this can be seen at a glance in Figure 12. For the grade 25 concrete the average splitting tensile strength obtained are 2.71 N/mm^2 , 2.26 N/mm^2, 2.33 N/mm^2, 2.49 N/mm^2 and 2.29 N/mm^2 while the values gotten for the grade 30 concrete are 3.06 N/mm^2, 2.62 N/mm^2, 2.74 N/mm^2, 2.84 N/mm^2 and 2.65 N/mm^2 for the control, 0%, 5%, 10% and 15%, respectively.

D. *Relationship between compressive and tensile strength at latter days of curing*

Four mathematical models were developed to ascertain the relationship between the compressive strength and tensile strength of the concrete at 28 and 56 days of curing for the different cement contents evaluated. The R^2 values of the concrete with lower cement content for the two ages of curing were 0.9955 and 0.9407 respectively, whereas the R^2 values for the concrete with higher cement content was 0.9965 and 0.9422 respectively as shown in Figure 13. These values suggest that there is a strong relationship between the behaviour of the concrete in compression and tension, even when all the samples with construction and demolition aggregates were lower than the control samples. However, the 28-day strengths showed better consistency in the values obtained and became less significant as the age of curing increased. Generally, samples of RAC with 10 % metakaolin exhibited the highest improvement in strength averaging at 5.99% for grade 25 and 4.08% for grade 30 across all ages. Dinakar *et al.* (2013) and Radonjanin *et al.* (2013) also have the same view as regards the results of the tensile test of concrete with 10% of metakaolin.

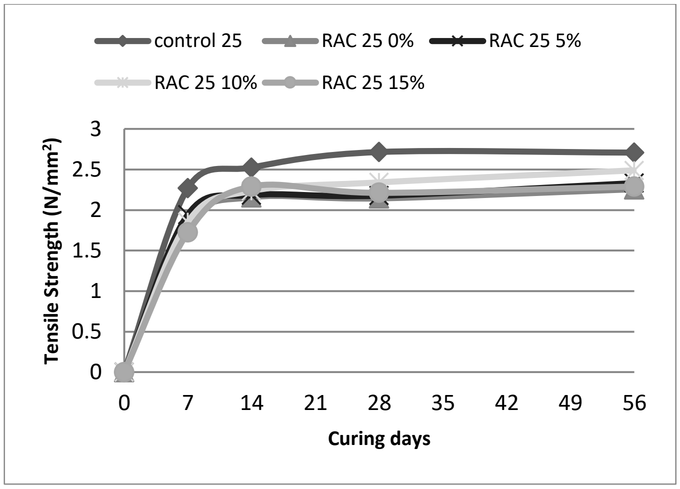

Figure 10: Split tensile strength for grade 25 concrete.

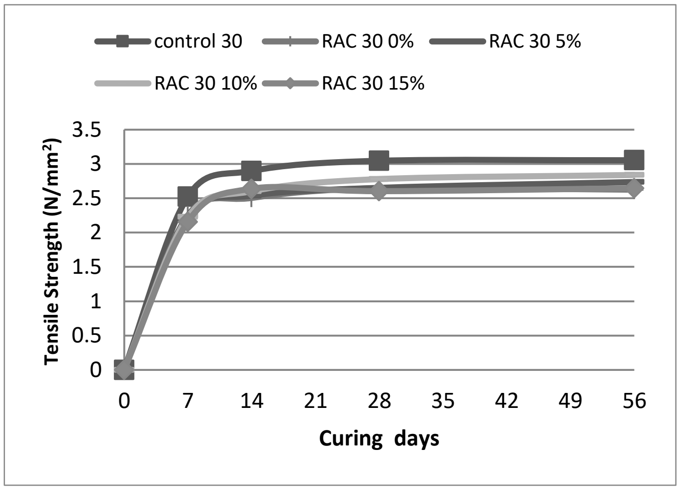

Figure 11: Split tensile strength for grade 30 concrete.

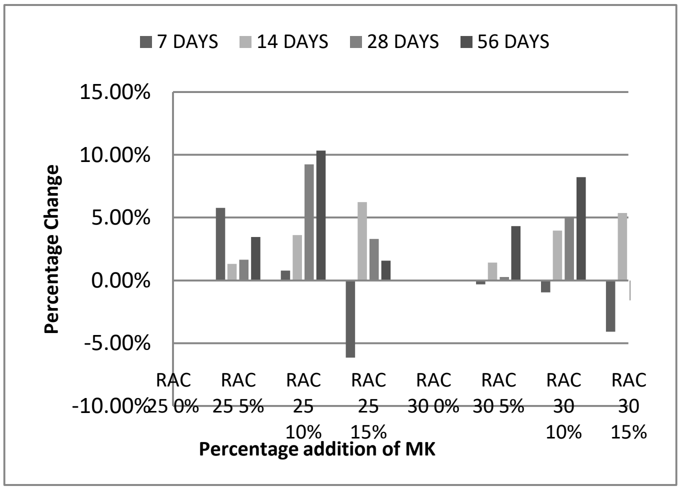

Figure 12: Percentage change in tensile strength experienced at different ages of testing due to the presence of MK.

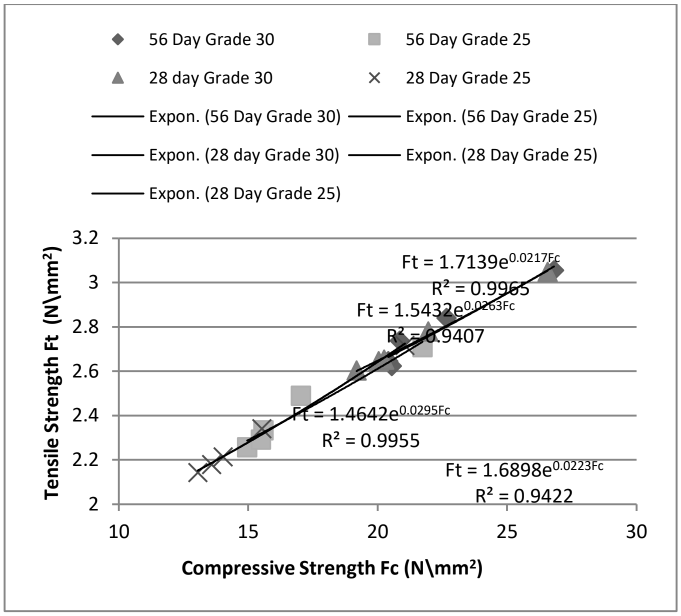

Figure 13: Relationship between compressive and tensile strength at later days of curing.

IV. CONCLUSION

Based on the tests conducted, the following conclusions can be made on the effect of concrete grades on strength characteristics of metakaolin modified recycled aggregate concrete:

i. The physical properties of RCA are comparable to those of conventional aggregates and, the water absorption of RCA was higher than that of natural aggregates.

ii. The specific gravity of RCA was less than that of conventional aggregates and, the resistance of RCA to fragmentation under the action of sudden impact, falls short of what is obtainable with normal aggregates.

iii. The optimum temperature of calcination for kaolin samples obtained from Ekiti State, Nigeria is 660 °C.

iv. The addition of metakaolin as an admixture in concrete produced from RCA reduced the workability of the concrete as the percentage addition of MK increases. Although none of the concrete produced from RCA exceeded the control sample, it can be rightly concluded that the use of MK as an admixture in concrete produced from RCA aggregates enhanced both the compressive and tensile strength of concrete.

v. In general, a 10 % addition of metakaolin as an admixture in concrete with RCA had 12% and 10% increase in mechanical properties for grades 25 and 30, respectively. Also, an increase in cement content improved the mechanical properties of RCA concrete appreciably.

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