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STATISTICAL ANALYSIS OF STRENGTH PROPERTIES OF REACTIVE POWDER CONCRETE PRODUCED FROM UNREFINED METEKAOLIN AND GEAR INNER WIRE

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Abstract
Reactive Powder Concrete (RPC) is one of the latest developments in the field of concrete technology and contains about 20% to 25% silica fume and fibre which are not readily available in Nigeria. The research aims at evaluating the effect of incorporating unrefined metakaolin (MK) as substitute of silica fume and gear inner wire (GIW) as fibre on the properties of the RPC using Analysis of Variance (ANOVA). The quantity of the GIW was fixed at 0.25% (by weight of concrete) while that of MK was 10%, 20% and 30% of the cementitious materials. The study considered GIW and MK as factors while compressive, tensile and flexural strengths as responses. The ANOVA of test results depicted that the two factors (unrefined MK & GIW) have significant effect on compressive strength, tensile strength and flexural strengths of the RPC. Moreover, there are substantial influences of interaction of two factors on the selected properties of the RPC. Therefore, unrefined MK and GIW are suitable in the production of RPC.

Keywords: Reactive powder concrete (RPC), Unrefined Metakaolin (MK), Gear inner wire (GIW), Analysis of variance (ANOVA).

1.0 INTRODUCTION

The desire to have high performance concrete has been on trend globally due to the fact that the coarse aggregates in conventional concrete is its source of weakness [1]. In order to achieve homogeneity and enhance the concrete microstructure, the coarse aggregate is excluded in the production of new generation of concrete known as Reactive Powder Concrete (RPC).

RPC is associated with ultra-high compressive strength and excellent flexural behaviour, addressing the strength and durability performance deficiencies associated with Normal Strength Concrete (NSC) and High Strength Concrete (HSC). RPC is made up of cement, silica fume, fine sand, quartz sand, fibre and high dosage of super plasticizer. However, the silica fume and steel fibre in RPC are not readily available in developing countries like Nigeria and where they are available are accompanied with high cost [2]. Moreover, the silica fume content in RPC is high (about 20 to 25%) and it causes drying shrinkage when used in conventional concrete [3].

Recently, the use of other pozzolanic materials in RPC has become essential in order to improve its inherent characteristics as well as reduce the cost of the concrete associated with silica fume. The most common type of pozzolanic materials used are fly ash, rice husk ash and metakaolin. Addition of these alternative materials to silica fume has the potential to reduce the overall cost of producing RPC as evident in some few researches.

Yazici et al. [4] replaced 60% Portland cement with ground granulated blast furnace slag 45 (GGBFS) and achieved a compressive strength of over 250 N/mm^2 with autoclaving and 400 N/mm^2 with external pressure application during setting and hardening stage. Reduction of cement led to reduction in heat of hydration. RPC without quartz powder was produced by replacing up to 15% of cement with fly ash and GGBFS [3]. The results indicated improvement in compressive strength and modulus of elasticity. Kushartomo et al. [5] used glass powder of up to 30% of cement by weight to replace quartz in the production of RPC. With 20%, a compressive strength of up to 136 N/mm^2, average split tensile strength of 17.8 N/mm^2 and flexural strength of 23.2 N/mm^2 were achieved.

Reduction of cement content using fly ash was also investigated by [4], [6] which shows improvement in the properties of the RPC. Moreover, [7] studied a number of RPC mixtures with varying steel fibres lengths (8 mm, 12 mm and 16 mm) and dosages (1%, 3% and 6%) by volume. Results show an increase in mechanical properties (up to 173 N/mm^2 of strength) as the fibre dosage increase. RPC mixtures incorporating short steel fibres exhibited enhanced flexural properties compared to that of mixtures with similar volume of longer steel fibre.

Rice Husk Ash (RHA) has been used as a partial substitute for SF [2], [8], [9] and its effect on the mechanical and durability properties of RPC was determined. Test results from the findings of [2] showed that RPC containing RHA has satisfactory mechanical and durability performance under both normal and steam curing condition. Hence RHA can be used as an alternative material for silica fume to produce RPC without compromising the required qualities. Recently, research was conducted by [10] with aim of producing environmentally friendly RPC where 50% of the cement in RPC was replaced with combination of metakaolin and fly ash. Finding indicated that the combination of MK and FA improved the fresh properties of RPC while the hardening properties were decreased. Therefore, this research evaluated the effect of unrefined MK and Gear inner wire (GIW) on the properties of RPC using ANOVA.

Metakaolin is obtained by heating kaolinitic clay at a temperature between 650°C to 750°C for about 1 to 2 hours. This is to transform the material from crystalline to amorphous form which makes it reactive. There is an estimated reserve of about three billion metric tons of kaolin deposit scattered in different parts of Nigeria [11]. Some percentage (15%) of the SF has been partially replaced with commercial MK in the production of RPC, which indicates savings [3]. In normal concrete, unrefined metakaolin has been shown to improve the strength and durability properties of concrete similar to the refined one [12]. Therefore, further savings could be realized if the refined metakaolin is replaced with the unrefined one in the production of RPC. Nigeria's large deposits of kaolinitic clay may be used to produce the unrefined metakaolin.

2.0 MATERIALS AND METHODS

The materials and their properties as well as methods used in this experiment are described in Subsections 2.1 to 2.4.

2.1 MATERIALS

The materials used for this research are cement; unrefined metakaolin (MK) and densified silica fume (SF) and gear inner wire. The cement is Dangote brand of Portland Limestone. MK was produced by heating unrefined kaolin at 750°C for 2 hrs in an electric furnace which satisfied the ASTM C-618 requirements. The kaolin was sourced from a kaolinitic clay deposit situated in Getso; Kano State-Nigeria as shown in Figure 1 while Table 1 depicted the coordinates of the kaolin site. The chemical composition and physical properties of the cementitious materials are presented in Table 2. Gear Inner Wires (GIW) are galvanized cables which are readily available in the markets and are used for bicycles' brakes. The GIW with an aspect ratio of 43 was cut into pieces and used as fibre. Polycarboxylate ether based super plasticizer (Conplast SP 430) conforming to ASTM C-494 was used to achieve the required consistency of the mixes. Naturally occurring river sand with particle sizes of 600µm - 150µm and absorption of 4% was used as fine aggregate.

Table 1: Coordinate of laolin sites

S/No.	Coordinate	Latitude	Longitude
1.	GT1	11.870878°	7.968568°
2.	GT2	11.871047°	7.968699°
3.	GT3	11.871184°	7.968491°
4.	GT4	11.870879°	7.968246°
5.	GT5	11.871053°	7.968180°

Table 2: Oxide compositions and physical properties of RPC constituents

Oxide (%)	Sand	Cement	Silica fume	Metakaolin
SiO_2	86.53	17.519	92.00	65.05
Fe_2O_3	2.94	2.768	0.50	2.59
Al_2O_3	1.64	4.74	0.70	20.65
CaO	0.40	71.297	0.50	0.82
CuO	0.00	0	0	0.02
NiO	0.00	0	0.015	0.03
MnO	0.01	0.072	0.128	0.08
Cr_2O_3	0.00	0	0.006	0.03
TiO_2	0.00	0.105	0.071	0.00

MgO	0.60	0	0.50	1.66
SO_3	0.10	0.00	0.00	0.18
ZnO	0.00	0.007	0.006	0.01
$SiO_2 + Al_2O_3 + Fe_2O_3$				88.29
LOI	0.84	3.492	3.00	1.80
Physical properties				
Surface area (m^2/kg)		561.9	2 0, 000	509.0
Strength activity index (%)			-	87
Specific gravity			2.21	2.53

Figure 1: Coordinates of Kaolin site in Getso town

2.2 MIX PROPORTIONING

Mix design of the RPC evolved from several trials due to the absence of an established design method. However, the mix proportions used by [13] was adopted as basis for the trial and error. The ingredients used in this study for the control mix of RPC include cement, silica fume, fine sand, GIW as fibre, superplasticizer, and water. The specimens were then produced by totally replacing the SF content with MK. The unrefined MK was used in different percentages (10%, 20% and 30%) of the weight of cement. Quartz powder was not used in the RPC because it is only used for heat-treated RPC [13]. The mix proportions of the RPC specimens are presented in Table 3 where 20SF means, the specimen was produced with 20% silica fume (SF) while 10MK is that specimen produced with 10% metakaolin (MK).

2.3 SPECIMENS' PREPARATION

The specimens were prepared by dry mixing the cementitious materials in a mortar mixer for about one minute at low speed of 10 rpm. The mixing water (about 80% of the total) and super-plasticizer were added into the mixer and mixing continued for three minutes at medium speed (140 ± 5 rpm). Fine sand and GIW were then added into the mixer and mixing continued for another four minutes. The remaining mixing water (about 20%) was then added to the mixer and mixed at high speed (285 ± 10 rpm) for additional four minutes. At the end, the mixer was then returned to the medium speed (140 ± 5 rpm) and mixed for three minutes. This method was adopted from [14].

All the fresh mixes had consistency of 270±5 mm which were cast and kept in moulds for 24 hours in the laboratory condition (27 ± 2^{o}C). Cube moulds of 50x50 x50 mm, cylindrical moulds of 50mmx100mm and prismatic moulds of 40x40x160mm were cast for compressive strength, split-tensile strength and flexural strength tests (with each having 24 number of specimens), respectively. Specimens were then taken out from the moulds and cured in water until the testing age of 28 days.

Table 3: Mix proportion of RPC specimens

Specimen ID	20SF	10MK	20MK	30MK	20SF	10MK	20MK	30MK
	Non fibred				Fibred			
Cement	1	1	1	1	1	1	1	1
Silica fume	0.20	0	0	0	0.20	0	0	0
Metakaolin	0	0.10	0.20	0.30	0	0.10	0.20	0.30
Sand (150-600 μm)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Crushed quartz	-	-	-	-	-	-	-	-
Superplasticizer	3.5	2.8	3.8	4.5	3.6	3.2	3.9	5.0
(GIW) L=12mm	-	-	-	-	0.02	0.02	0.02	0.02
Water	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Comp. press	-	-	-	-	-	-	-	-
Heat treatment temp. (^{o}C)	27	27	27	27	27	27	27	27

Note: Cement Content = 900Kg/m^3, Fibre Content = % of weight of concrete, SP content = % of binder

2.4 TESTING METHODS

2.4.1 Flowability

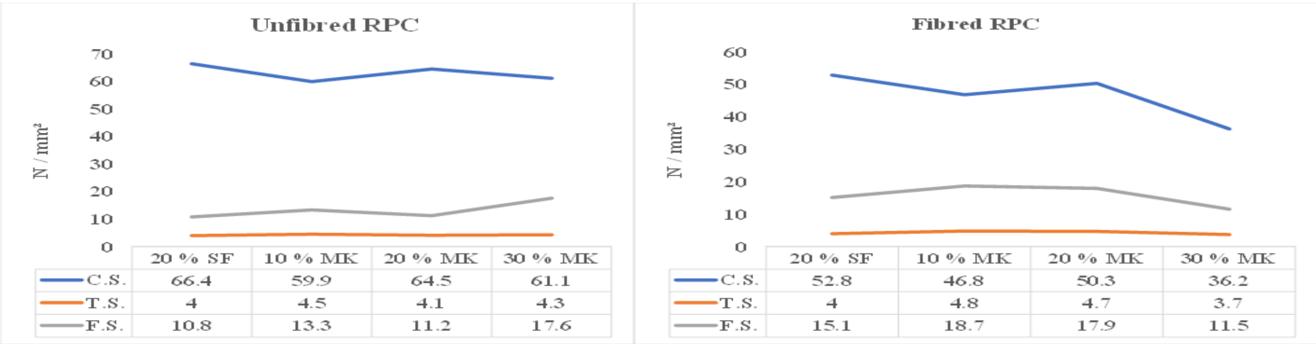
The Flow of the different mixes was tested using a flow table in accordance with ASTM C143. This was done by filling a mini-slump cone. The cone was then carefully removed to allow the mix to flow under the influence of gravity. The flow of the mix was obtained by measuring the spread using a measuring tape. Average of four measurements of the spread was reported for each mix.

2.4.2 Strength Properties

Compressive strength, split-tensile strength and flexural strength tests on the specimens were carried out according to BS EN 12390-3:2002, ASTM C-496, ASTM C-78 respectively. The average of five measurements was reported for each test.

3.0 RESULTS AND DISCUSSIONS

For analysis of experimental results, procedures of general factorial design with two factors have been followed. Two-way ANOVA was used for the analysis of the results. In this study, the levels of factor unrefined MK (%) have been kept at three levels (10%, 20% and 30%) and the level of other factor GIW (%) was kept at two (0% and 0.25%). The 28 days compressive, tensile and flexural strengths of fibred and unfibred RPC were determined as shown in Figure 2. The number of replicates for each observation was three. The ANOVA tables and interpretation of all responses have been analyzed and discussed in subsequent sections.



(a) (b)

Figure 2: Hardened properties of RPC

Figure 2 shows the hardened properties of the unfibre (a) and fibred (b) RPC. These properties are compressive strength (C.S.), tensile strength (T.S.) and flexural strength (F.S.), the statistical analysis of which are as follows;

3.1 COMPRESSIVE STRENGTH

Table 4 gives the descriptive and inferential statistics of Compressive Strength of Unfibred RPC. At level of significance, 0.05, a repeated measure ANOVA was conducted and the result indicated that there was no significant difference between compressive strengths of the unfibred samples with $F(3, 12)=1.329$, $P > 0.05$. This means, the compressive strength mean values of all samples are similar.

Table 5 shows comparison between the control (I) and the other three unfibred samples (J). The mean differences along with their corresponding *P-values* were given. At *0.05* level of significance, there was no significance difference between the control (I), that is, 20%SF and the other three (10%, 20% & 30%) unfibred samples (J) with $P>0.05$. Statistically, the result showed that the difference between the control and the other three unfibred samples was very small in terms of compressive strength.

Table 6 displays the descriptive and inferential statistics of Compressive Strength of Fibred RPC. At *0.05* level of significance, a repeated measure ANOVA was conducted and the result implied that there was significant difference between compressive strength of the fibred RPC with $F(3, 12)=63.650$, $P < 0.05$ and the extent of the difference was 0.941 (94.1%). The results indicate that 20%MK has similar compressive strength with 20%SF (control) while 30% MK recorded the least.

Table 7 is for comparison between the control (I) and the other three (10%, 20% & 30%MK) fibred samples (J). The mean differences with their corresponding *P-values* were shown. At *0.05* level of significance, there was significance difference between the control (I), that is, 20%SF and 30%MK with $P<0.05$ while the other two fibred samples (J) with $P>0.05$ indicated no significant difference. Reliably, the result showed that the difference between 20%SF and 30%MK was reasonable.

Table 4: Compressive strength of unfibred RPC

Unfibred Sample	Mean	Std. Deviation	N	df1	df2	F-cal	P-value	Remarks
20%SF	62.0200	12.01112	5					
10%MK	57.8800	11.72783	5	3	12	1.329	0.311	NS
20%MK	60.4600	11.64530	5					

30%MK	59.6200	5.46004	5

α=level of significance (0.05)

Table 5: Comparison between the Control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	4.14	0.80	0.390
	20%MK	1.56	0.25	0.210
	30%MK	2.40	3.01	1.000

α=level of significance (0.05)

Table 6: Compressive strength of Fibred RPC

Fibred Sample	Mean	Std. Deviation	N	dfl	df2	F-cal	P-value	Eta-Square	Remarks
20%SF	51.9800	9.10643	5	3	12	63.650	0.001	0.941	Sig.
10%MK	46.6800	6.54576	5						
20%MK	49.6000	7.19618	5						
30%MK	36.5800	4.73783	5						

α=level of significance (0.05)

Table 7: Comparison between Control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	5.300	1.165	0.063
	20%MK	2.380	1.007	0.464
	30%MK	15.400*	1.976	0.009

α=level of significance (0.05)

3.2 TENSILE STRENGTH

Table 8 depicts the descriptive and inferential statistics of Tensile Strength of unfibred RPC specimens. At *0.05* level of significance, a repeated measure ANOVA was conducted and the result suggested that there was significant difference between the tensile strength of the unfibred specimens with $F(3, 12)=12.252, P < 0.05$ and the extent of the difference was 0.754 (75.4%).

Table 9 shows comparison between the tensile strength of the control (I) and the other three unfibred samples (J). The mean differences along with their corresponding *P-values* were given. At *0.05* level of significance, there was significance difference between the control (I), that is, 20%SF and 10%MK with $P<0.05$ while the other two unfibred samples (J) with $P>0.05$ showed no significant difference. Statistically, the result showed that the difference between 20%SF and 10%MK was reasonable.

Table 10 represents the descriptive and inferential statistics of Tensile Strength Fibred RPC. At *0.05* level of significance, a repeated measure ANOVA, was conducted and the result indicated 183 that there was significant difference between the tensile strength of the fibred samples with $F(3, 12)=11.963, P < 0.05$ and the extent of the difference was 0.749 (74.9%).

Table 11 shows the comparison between the tensile strength of the control (I) and the other three fibred samples (J). The mean differences along with their corresponding *P-values* were shown. At *0.05* level of significance, there was significance difference between the control (I), that is, 20%SF and 20%MK with $P<0.05$ while the other two unfibred samples (J) with $P>0.05$ implied no significant difference. Statistically, the result suggested that the difference between 20%SF and 20%MK was realistic.

Table 8: Tensile strength of unfibred RPC

Unfibred Sample	Mean	Std. Deviation	N	df1	df2	F-cal	P-value	Eta-square	Remarks
20%SF	3.9800	.83487	5	3	12	12.252	0.001	0.754	Sig.
10%MK	4.7000	.77136	5						
20%MK	4.2020	.97930	5						
30%MK	4.2600	.68775	5						

α=level of significance (0.05)

Table 9: Comparison between Control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	0.720	0.120	0.023

	20%MK	0.222	0.132	1.000
	30%MK	0.280	0.066	0.081

α=level of significance (0.05)

Table 10: Tensile strength of fibred RPC specimens

Fibred Sample	Mean	Std. Deviation	N	df1	df2	F-cal	P-value	Eta-square	Remarks
20%SF	4.0400	0.79246	5	3	12	11.963	0.001	0.749	Sig.
10%MK	5.1400	1.14149	5						
20%MK	4.7200	0.97570	5						
30%MK	4.1800	1.07331	5						

α=level of significance (0.05)

Table 11: Comparison between Control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	1.100	0.268	0.089
	20%MK	0.680	0.116	0.025
	30%MK	0.140	0.248	1.000

α=level of significance (0.05)

3.3 FLEXURAL STRENGTH

Table 12 depicts the descriptive and inferential statistics of Flexural Strength Unfibred RPC made with unrefined MK. At *0.05* level of significance, a repeated measure ANOVA was conducted and the result indicated that there was significant difference between the flexural strength of the unfibred samples with $F(3, 12)=4.567$, $P < 0.05$ and the extent of the difference was 0.533 (53.3%).

Table 13 shows comparison between the flexural strength of the control (I) and the other three fibred samples (J). The mean differences along with their corresponding *P-values* were given. At *0.05* level of significance, there was significance difference between the control (I), that is, 20%SF and 10%MK with $P<0.05$ while the other two unfibred samples (J) with $P>0.05$ suggested no significant difference. Statistically, the result showed that the difference between 20%SF and 10%MK was reliable.

Table 14 displays the descriptive and inferential statistics of Flexural Strength Fibred RPC. At *0.05* level of significance, a repeated measure ANOVA, was conducted and the result suggested that there was no significant difference between the flexural strength of the fibred samples with $F(3, 12)=3.511$, $P \geq 0.05$.

Table 15 depicts the comparison between the flexural strength of the control (I) and the other three fibred samples (J). The mean differences along with their corresponding *P-values* were shown. At *0.05* level of significance, there was no significance difference between the flexural strength of the control (I), that is, 20%SF and the other three fibred samples (J) with $P>0.05$. Statistically, the result showed that the difference between the control and the other three fibred samples was very minimal.

Table 12: Flexural strength of the unfibred RPC specimens

Unfibred Sample	Mean	Std. Deviation	N	df1	df2	F-cal	P-value	Eta-square	Remarks
20%SF	11.7800	2.51833	5	3	12	4.567	0.024	0.533	Sig.
10%MK	14.9800	3.27063	5						
20%MK	12.6200	4.19786	5						
30%MK	15.7400	1.84472	5						

α=level of significance (0.05)

Table 13: Comparison between the Control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	3.200	0.524	0.022
	20%MK	0.840	0.859	1.000
	30%MK	3.960	1.260	0.209

α=level of significance (0.05)

Table 14: Flexural strength of fibred RPC

Fibred Sample	Mean	Std. Deviation	N	df1	df2	F-cal	P-value	Remarks
20%SF	15.9800	1.53199	5	3	12	3.511	0.050	NS
10%MK	16.6600	4.71731	5					
20%MK	17.0780	3.94923	5					

30%MK	13.1400	4.67632	5

α=level of significance (0.05)

Table 15: Comparison between the control and specimens with unrefined MK

(I) Control	(J) Specimens	Mean Difference (I-J)	Std. Error	Sig.
20%SF	10%MK	0.680	1.582	1.000
	20%MK	1.098	1.371	1.000
	30%MK	2.840	1.448	0.728

α=level of significance (0.05)

3.4 CORRELATION/RELATIONSHIP OF THE STRENGTH PROPERTIES

Table 16 depicts the descriptive and correlation statistics of compressive strength versus tensile strength of unfibred RPC. At *0.05* level of significance, a Pearson's Product Moment Correlation Coefficient (PPMCC), was conducted and the result showed that there was significant relationship between compressive and tensile strengths of the unfibred RPC with *R(18)=0.817*, $P < 0.05$ and the extent of the relationship was R^2= 0.667 (66.7%) which was a strong positive relationship [15].

Table 17 gives the descriptive and correlation statistics of compressive strength versus tensile strength of fibred RPC. At *0.05* level of significance, a Pearson's Product Moment Correlation Coefficient (PPMCC), was conducted and the result indicated that there was significant relationship between compressive and tensile strengths of fibred RPC with *R(18)=0.620*, $P < 0.05$ and the extent of the relationship was R^2= 0.384 (38.4%) which was a moderate positive relationship[15], [16].

Table 18 shows the descriptive and correlation statistics of compressive versus flexural strengths of unfibred RPC. At *0.05* level of significance, a Pearson's Product Moment Correlation Coefficient (PPMCC), was conducted and the result suggested that there was significant relationship between compressive and flexural strengths of unfibred RPC with *R(18)=0.634*, *P* 247 < *0.05* and the extent of the relationship was R^2= 0.402 (40.2%) which was a moderate positive relationship.

Table 19 depicts the relationship between compressive and flexural strengths of fibred RPC having $r = 0.766$ and $r^2 = 0.587$ (58.7%) with $p < 0.05$. The r – value is correlation coefficient that gives the measure of direction of positive relationship between the two variables of compressive and flexural strengths, that is, changes in compressive strength met with similar changes in flexural strength. At 0.05 level of significance, a Pearson's Product Moment Correlation Coefficient (PPMCC), was conducted and the result implied that there was significant relationship between compressive and flexural strengths of fibred RPC with *R(18)=0.766*, *P* < 255 *0.05* and the extent of the relationship was R^2= 0.587 (58.7%) which was a strong positive relationship in accordance with [15]–[18].

Table 16: Correlation/Relationship between Compressive and Tensile strengths of unfibred RPC

Variable	N	Mean	Std Dev	Df	Correlation/Relationship (R)	R^2	P-value	Remarks
Compressive	20	60.00	9.824	18	0.817	0.667 (66.7%)	0.001	Sig.
Tensile	20	4.29	0.803					

α=level of significance (0.05)

Table 17: Correlation/Relationship between Compressive and Tensile strengths of fibred RPC

Variable	N	Mean	Std Dev	Df	Correlation/Relationship (R)	R^2	P-value	Remarks
Compressive	20	46.21	8.852	18	0.620	0.384 (38.4%)	0.004	Sig.
Tensile	20	4.52	1.026					

α=level of significance (0.05)

Table 18: Correlation/Relationship between compressive and flexural strengths of unfibred RPC

Variable	N	Mean	Std Dev	df	Correlation/Relationship (R)	R^2	P-value	Remarks
Compressive	20	60.00	9.824	18	0.634	0.402 (40.2%)	0.003	Sig.
Flexural	20	13.78	3.288					

α=level of significance (0.05)

Table 19: Correlation/Relationship between compressive and flexural strengths of fibred RPC

Variable	N	Mean	Std Dev	Df	Correlation/Relationship (R)	R^2	P-value	Remarks
Compressive	20	46.21	8.852	18	0.766		0.001	Sig.

SFlexural	20	15.71	3.944	0.587 (58.7%)

α=level of significance (0.05)

4.0 CONCLUSION

Based on the outcomes of the study, the following conclusions can be made:

The statistical analysis of the experimental data using ANOVA indicated that while percentage of Unrefined MK affected compressive strength, tensile strength and Flexural strength of RPC most significantly, the 0.25% of GIW had major effect on the tensile and flexural strength of RPC. It is observed from the results that 20% unrefined MK has the most significant effects on the properties of the RPC and comparable to that of 20% silica fume. Therefore, 20% unrefined MK and GIW can be used in making RPC in Nigeria.

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