Mechanical Performance of Palm Oil Fuel Ash Blended Concrete for Sustainable Construction

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Abstract
The increasing cost of cement and CO_2 gas emissions associated with its usage and production has led to the search for an alternative binder for sustainable environment. This research examines the mechanical performance of palm oil fuel ash (POFA) as binder in concrete for sustainable construction. Ninety (90Nos) cubes (150mm), Ninety (90Nos) cylinders (300mmlong × 150mmdia) and Seventy-two (72Nos) beams (750mm × 150mm × 150mm) specimens were produced at varying POFA percentage replacement of 0 -50% at 10% interval with a water to cement ratio of 0.55 and a mix ratio of 1:1.5:3. Physical properties, chemical compositions and mechanical properties were investigated at the fresh and hardened stages. Coefficient Equations Approach method was used for predicting the mechanical performance of POFA blended concrete. The results showed that palm oil fuel ash exhibited some pozzolanic properties and can be classified as class N pozzolan. The degree of workability increases gradually as the POFA increased from 0 to 50% replacement level. High strength was recorded at 10% replacement in all mechanical tests carried out. At 10% replacement of POFA, compressive strength value of 30.2N/mm^2 was recorded which was higher than the control specimen having 24.2N/mm^2. At 28-day, the tensile strength of the concrete at 10% was 2.88N/mm^2 and 2.2N/mm^2 for control *and for flexural strengths 10% replacement with POFA gave a strength of 4.85N/mm*^{2} compared to 3.9 *N/mm*^{2} of control specimens. Further increase in POFA replacement *resulted in declined strengths. The developed models were in good agreement with the experimental data. This research work has led to the creation of POFA blended concrete which can be used in Civil Engineering construction works*

Keywords: Mechanical Performance, Palm oil fuel ash (POFA), Workability, Density, Structural Strengths.

1.0 INTRODUCTION

Today, rapid growth of towns and cities in Nigeria caused by population growth, industrialization and the drift from the rural areas has created a demand for building material which traditional producers are unable to meet, not only in terms of quantity and quality and also on year basis (Michael *et al.*, 2014). The increasingly high cost of these materials particularly when local production is non-existent, or has to be supplemented by imports is forcing the building industry to look at ways of producing building materials using locally abundant raw materials (Ikponmwosa *et al.*, 2014).

For concrete production, the reduction of cement content in concrete can be achieved by utilization of supplementary cementitious materials such as fly ash, blast-furnace slag, natural pozzolans, and biomass ash (Sata *et al*., 2007; Donatello *et al.*, 2010; Raheem *et al.*, 2012; Gnanavel and Murthi, 2015). Also, the generation of large quantities of industrial by-products every year by chemical and agricultural process industries has created environmental pollution as well as increasing the expenditure of the industry for disposing this waste. As a result, solid waste management has become one of the major environmental concerns in the world. With the increasing awareness about the environment, scarcity of land-fill space and due to its ever-increasing cost, waste materials and by-products utilization has become an attractive alternative to disposal (Adesogan, 2014; Oj *et al.*, 2015; Manjunath, 2016; Resch *et al.*, 2016). Use of these materials not only helps in getting them utilized in cement, concrete, and other construction materials, it helps in reducing the cost of cement and concrete manufacturing, but also has numerous indirect benefits such as reduction in land-fill cost, saving in energy, and protecting the environment from possible pollution effects (Mclellan *et al.*, 2011; Ukpong, 2012; Islam *et al.,* 2017).

Oil palm is a tall-stemmed tree in the palm family, cultivated as a source of oil. The oil palm is grown extensively in the native west and central Africa, as well as Malaysia and Indonesia of which Malaysia is the largest producer of palm oil and palm oil products (Joshua and Ogunde, 2015). Over half of the world's total palm oil is produced from the oil palm industry in Malaysia; the country is set to grow further with the global increase in vegetable oil demand. However, the nation's pollution problem is also increased for this sector- which includes the annual production of 2.6 million tons of solid waste in the form of oil palm shells (Rezaul *et al.*, 2011). POFA is an agro-waste ash from which palm oil residue, such as palm fibre and shell, are burnt at temperature of about 750°C to produce steam for electricity generation in biomass thermal plant (Deepak, 2014). The result is palm oil fuel ash (POFA), which is about 5%, by weight, of solid waste product (Oyejobi *et al*., 2015). The silica oxide content in POFA could react with calcium hydroxide $Ca(OH)_2$ from the hydration process and the pozzolanic reactions produce more calcium silicate hydrate (C-S-H), which is a gel compound as well as reducing the amount of calcium hydroxide (Munir *et al.*, 2015). Thus, this contributes to the strength of the concrete as well as enhanced the durability of the concrete (Sooraj, 2013).

Subramani and Anbuchezian (2017) investigated on the experimental study of palm oil fuel ash as cement replacement of concrete. They reported that the compressive strength increases up to 12.5 percentage replacement level and further increase in palm oil fuel ash led to a decline in strength. Also, the values recorded that the final observed replacement level was still higher than the control value which reveals the strength benefit of POFA. Karim *et al.* (2011) reviewed the strength of concrete as influenced by the use of POFA as partial replacement of cement in concrete. The authors concluded that the palm oil fuel ash (POFA) reveal an excellent pozzolanic property having no significant strength reduction up to 30% replacement level when used in concrete production.

This paper investigated the use of palm oil fuel ash as a partial replacement for Portland cement in production of concrete. The objectives in achieving this aim are to determine the chemical composition of palm oil fuel ash (POFA) as potential replacement for cement in concrete production and to determine the mechanical properties of POFA- Concrete.

2.0 MATERIALS AND METHOD

2.1 Materials

The Palm oil wastes were collected for the production of concrete specimens using palm oil fuel ash (POFA) has partial replacement for cement. The Palm oil wastes were sourced from two different places; Bariga and Oyingbo markets in Lagos, Nigeria. The palm oil waste was then taken to the laboratory at the Civil and Environmental Engineering department to be oven dried at 110°C before taken to the Federal Institute of Industrial Research Oshodi (FIIRO), where it was burnt to ash at a temperature of 750°C for 6 hours and allowed to cool for 24 hours in the furnace. The temperature and duration of burning were in accordance with what was reported by Awal and Hussin (1997). The dried ashes were sieved through a 75 mm sieve in order to remove bigger size of ash particles and impurities.

The Fine aggregate which passed through I.S sieve No. 480 (4.75mm) and sourced from natural riverbed was used. The coarse aggregate was air dried to obtain saturated surface dry condition to ensure that water cement ratio was not affected. In this study granite with the nominal size 20 mm were used.

2.2 Method

2.2.1 Mix Proportioning of Concrete

In this study, control mix A was designed to achieve a compressive strength of 25N/mm^2. Palm oil fuel ash was used to replace ordinary Portland cement at various levels of 0%, 10%, 20%, 30%, 40% and 50% by mass of binder content. The mix proportions of different mixes are shown in Table 1. Six (6) mixes were done for proper investigation of the partial replacement of cement using palm oil fuel ash. For each mix, nine (9) cubes were moulded; three (3) each to test for the compressive strength at 3, 7, 14, 21 and 28 days. Three (3) cylinders and three (3) beams each were also cast for each mix. The size of each cube was (150 mm x 150 mm x 150 mm) for compressive strength test, cylinder (150 mm x 300 mm Dia.) for tensile strength test and beam (150 mm x 150 mm x 750 mm) for flexural strength test.

Table 1. Concrete Design for all Mixes

MIX No.	MIX ID	WATER (Kg)	CEMENT (kg)	POFA (Kg)	COARSE AGGREGATE (kg)	FINE AGGREGATE (kg)	W/C
1	A	16.8	31.7	-	125.8	46.6	0.53
2	B	16.8	28.53	3.17	125.8	46.6	0.53
3	C	16.8	25.36	6.34	125.8	46.6	0.53
4	D	16.8	22.19	9.51	125.8	46.6	0.53
5	E	16.8	19.02	12.68	125.8	46.6	0.53
6	F	16.8	15.85	15.85	125.8	46.6	0.53

2.2.2 Sample Preparation

A total of 90 cubes for compressive strength, 90 cylinders for split tensile strength and 72 beams for flexural strength of concrete specimens were produced. Mechanical method of mixing was employed using a concrete mixer. The fine aggregates were first poured into the concrete mixer with the coarse aggregates and were mixed properly. The cement and palm oil fuel ash were added and mixed thoroughly in the dry state until homogeneity was achieved and water added. After about five minutes of thorough mixing, the freshly mixed concrete was filled into moulds for the cube, cylinder and beam specimens. The moulds were coated with diesel oil prior to filling for ease removal of the specimens. Placement of the concrete into the moulds was carried out in three layers and tamping rod was used to ensure adequate compaction of the concrete after each layer was placed. A steel hand trowel was used to finish the top surface after tamping. The specimens were demoulded from the moulds after 24hrs and were kept in curing tanks at 32±2℃ until testing at age of 3, 7, 14, 21 and 28 days for both compressive and split tensile strength tests and 7, 14, 28 and 56 days for flexural strength. The laboratory tests were carried out in accordance with the *BS EN 12390-3:2009* and *BS EN 12390-5:2009*.

2.2.3 *Workability Test*

In this study, water content of all mixes was kept constant. Immediately after mixing, slump tests were conducted in accordance to the provisions of *(BS EN 12350, 2000)*.

2.2.4 *Compressive Strength Test*

The 72 Nos of cubes (150mm) were produced in accordance with *(BS EN 12350-6, BS EN 12390-3, 2009)*, cured and tested at 3, 7, 14, 21 and 28-days. Plates 1 shows the curing period for the cast specimen and Plate 2 shows the compressive strength test being carried out on the cube sample.

Plate 1: Curing of concrete cubes

Plate 2: Crushing of Cubes

2.2.5 *Tensile Strength Test*

The investigation of the tensile characteristic of concrete was conducted on thirty-six (36 Nos.) concrete cylinders (150dia x 300mm) using 1500kN Avery Universal Testing machine. The concrete cylinders were tested at 3, 7, 14, 21, and 28-days curing (BS EN 12390-6, 2009).

2.2.6 *Flexural Strength Test*

The specimens used for flexural tests were of size 150 × 150 x 750 mm, 18 beams were cast. The flexural test was performed according to BS EN12390-5 *(BSI, 2000)*. The test was carried out at 28-day (Flexural Strength testing machine) at the Concrete laboratory of Civil and environmental engineering department, University of Lagos. Plates 3 and 4 show the casting of the beams and the flexural strength test procedure respectively.

Plate 3: Casting of the Beams

Plate 4: Flexural strength test in process

2.2.7 Mathematical Modelling Method

The Coefficient Equations Approach is a modelling technique for Civil Engineering Data of low risk projects which is restricted to two independent variable data. Below are the steps on how to develop a mathematical model using Coefficient Equations Approach *(Komolafe et al., 2018*):

STEP 1:

For any set of two independent variable civil engineering data, the relationship will be given as:

$$y = f(x, z) \tag{1}$$

An arrangement of the data in tabular form is shown below:

Table 2. Sample of Two Variable Civil Engineering Data

Variable	Variable z					
x	0%	2%	4%	6%	8%	10%
0%	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}	y_{16}
2%	y_{21}	y_{22}	y_{23}	y_{24}	y_{25}	y_{26}
4%	y_{31}	y_{32}	y_{33}	y_{34}	y_{35}	y_{36}

The Coefficient Equations Approach will be more precise with higher number of rows and columns of values of y. Also, having equal set of intervals in variable x and equal set of intervals in variable y can improve the accuracy of the final equation generated using the Improved Coefficient Equations Approach.

STEP 2:

Generate equations for the base variable (selecting variable x as base variable) at intervals of variable z. This may involve splitting the main table into smaller tables. An example is shown below for values of y at 0% of variable x.

Table 3. Sample of Two Variable Civil Engineering Data in split form

Variable x	Variable z					
	0%	2%	4%	6%	8%	10%
0%	y_{11}	y_{12}	y_{13}	y_{14}	y_{15}	y_{16}

Continue the above process for all values of y at each interval of variable x. The equations can be generated using software such as Microsoft Excel®, MATLAB® or other similar tools. In this study, Microsoft Excel was employed in generating the equations. The preferable plot should be the scatter plot connected with lines for all graphs when using the Improved Coefficient Equations Approach to observe how the trend line behaves with the plot.
The general form of equation to be selected can be either linear, two-degree polynomial, three-degree polynomial or four-degree polynomial. The general form of equation selected should be consistent throughout step 2 (this step). Also, the form of the equation to be selected will depend on the behaviour of the trend line with the pattern of the plot from the research data.

STEP 3:
A Table of Coefficients should be generated for each interval of variable x. If the form of equation selected from step 2 is a three-degree polynomial, then the table of coefficients for the sample data is given as:

Table 3. Table of Coefficients

Variable	Coefficients			
x	a	b	c	d
0%	w_{11}	w_{12}	w_{13}	w_{14}
2%	w_{21}	w_{22}	w_{23}	w_{24}
4%	w_{31}	w_{32}	w_{33}	w_{34}

Where, w_{11}, w_{12}, … are the coefficients from the generated equation.

STEP 4:
Generate equations for each of the coefficients at intervals of variable x. This may involve splitting the table of coefficients into smaller tables (a similar process was done in step 2). Follow the remaining processes in step 2, but this time for all values of each coefficient at varying intervals of variable x. Therefore, there will be an equation for coefficient a, b, c and d respectively which may either be a linear, two-degree, three-degree polynomial or four-degree polynomial.

STEP 5:
Replace the coefficients (a, b, c and d) with their respective equations generated in step 4. Assuming that the form of equations generated for the coefficients are also three-degree polynomials. Therefore, superimposing the equations generated in step 4 with the equations generated in step 2, we will finally have:

$$y = (a_a x^3 + b_a x^2 + c_a x + d_a)z^3 + (a_b x^3 + b_b x^2 + c_b x + d_b)z^2 + (a_c x^3 + b_c x^2 + c_c x + d_c)z + (a_d x^3 + b_d x^2 + c_d x + d_d) \quad (2)$$

The equation above is the model developed using the Coefficient Equations Approach.

The validation of the model was done by determining the percentage difference and comparing the predicted values on the basis of the model and those data obtained from the experiment using simple percentage difference formula;

$$Percentage\ Difference = \frac{Actual\ Result\ -\ Model\ Result}{Actual\ Result} X\ 100\% \quad (3)$$

3.0 RESULTS AND DISCUSSION

3.1 Chemical Analysis on Binders

The chemical composition of the samples was determined by conduction Atomic Absorption Spectroscopy (AAS) test and all the results are reported in Table 4.

Table 4. Chemical composition of studied materials

Sample	Chemical Composition									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	L.O.I	Total SiO_2 + Al_2O_3	Total SiO_2 + Al_2O_3 + Fe_2O_3
Cement	2.85	5.26	1.35	64.12	2.72	0.48	1.2	0.1	8.11	9.46
POFA (Oyingbo)	55.3	11.0	6.1	4.6	3.3	10.20	0.87	5.8	66.3	72.40
POFA (Bariga)	53.4	10.91	6.4	4.9	5.0	11.21	1.64	6.1	64.31	70.71

The results show that the combining percentage masses of silica (SiO_2), alumina (Al_2O_3) and ferric oxides (Fe_2O_3) gives a total of 72.40% and 70.71% for the two POFA samples, which are similar to those of class N type pozzolans according to ASTM C618-12a. CaO known for providing strength in cement was observed to be low in palm oil fuel ash (POFA) leading to a lower strength gain and increase in setting time. The MgO was found to be within the limit range of less than 5% (BS 12, 1996; Marthong, 2012). The loss on ignition value for POFA are above the limits of 3.0% set by BS 12 (1996). The percentages of Na_2O and K_2O known as the alkali oxides were observed to be large when compared to the standard range (BS 12, 1996). This could be due to the soil and topography of the areas where the palm oil trees were planted. This high presence of alkali oxides resulted in difficulties in regulating the setting time of cement paste.

3.2 Physical Properties of Aggregates

Table 5 presents the results of the physical properties of the aggregates used in this research. It was observed that fine and coarse aggregates had uniformity coefficients (Cu) of 0.91 & 1.21 respectively, while they had a coefficient of curvature (Cc) of 1.80 & 1.35 respectively. According to Unified Soil Classification, the fine and coarse can be classified as poorly graded medium to coarse sand and fine to medium granite. The particle size distribution curve for the aggregates are presented in Figure 1. The specific gravity for the fine aggregate was lower than the allowable range of 2.65 to 2.67 for sand but coarse aggregate was within the allowable range of 2.60 to 2.70 for granite as depicted by relevant standards. Also, it was observed that the bulk densities of sand and granite were below the allowable range of 1520-1680 Kg/m^3 and 2630-2760 Kg/m^3 respectively for normal weight concrete.

Table 5. Physical Properties of Aggregates

Physical Property	Sand	Granite
Coefficient of Uniformity (Cu)	0.91	1.21
Coefficient of Curvature (Cc)	1.8	1.35
Specific Gravity	2.49	2.66
Dry Density (Kg/ m^3)	139.20	61.24
Bulk Density ((Kg/m3)	1423.95	1548.34
Moisture Content (%)	2.10	0.96
Aggregate Crushing Value	-	21.87
Aggregate Impact Value	-	8.12

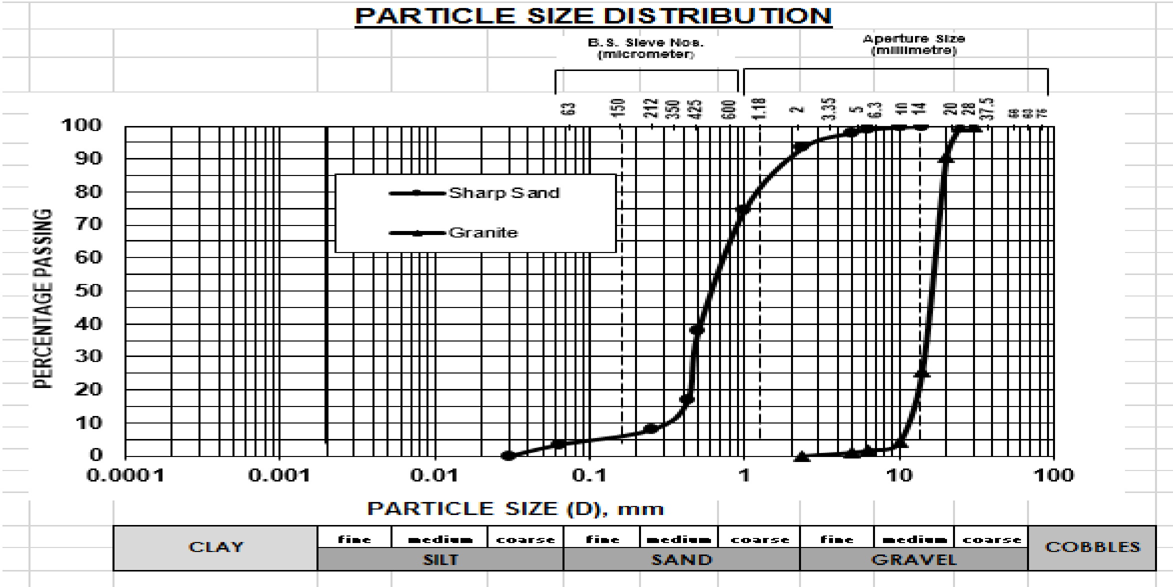

Figure 1: Aggregates Particle Size Distribution Curve

3.3 Effect of palm oil fuel ash (POFA) on workability of concrete

The measure of concrete's fluidity or workability can achieve using slump test. The results of the slump test value of concrete for control, 10% to 50% replacement of POFA at 10% interval are presented in Figure 2.

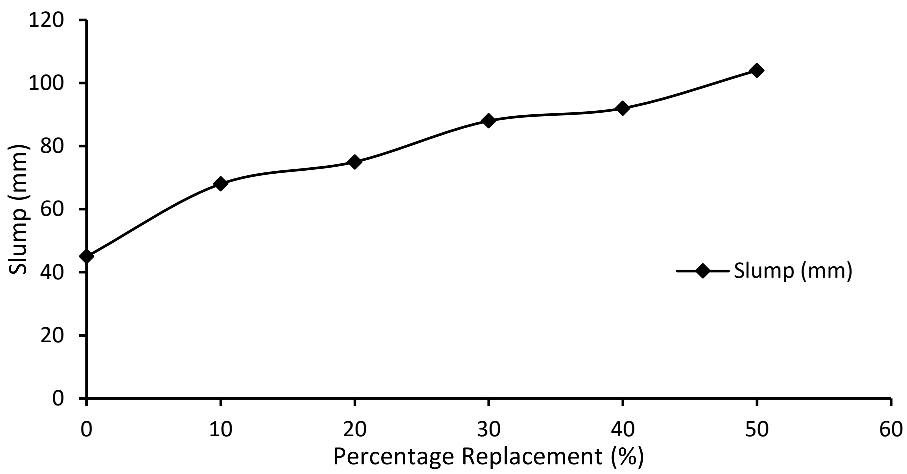

Figure 2: Variation of slump values at different POFA percentage replacement

From Figure 2, it was observed that the workability increases as the percentage replacement level of POFA was increasing. Cement replacement with POFA up to 50% by weight resulted in high workability. This increasing trend reveals the interaction of POFA with other constituents in the concrete matrix. More cementitious material will lead to available paste for coating the surface of aggregates and also filling the voids between. Hence, creating a smooth movement of the mix.

3.4 Effect of Palm Oil Fuel Ash (POFA) on Compressive Strength of Concrete

The compressive strength of POFA blended concrete at different curing age for different percentage replacement of POFA are presented in Figure 3. The results of the average compressive strength increased with increase in curing age which can be attributed to presence of moisture needed for continuous hydration leading to gain strength.

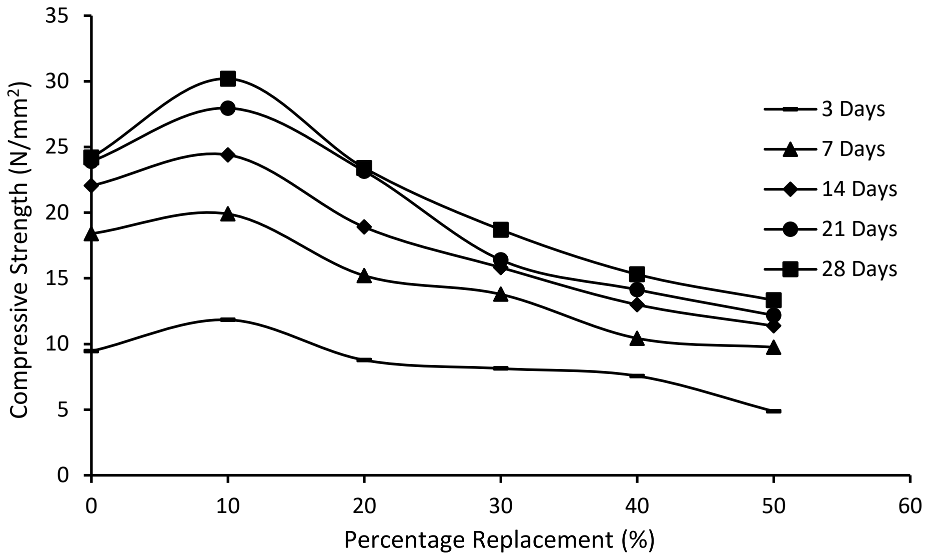

Figure 3: Variations of Compressive Strength at different Cement Fineness Zone

From Figure 3, it was observed that the compressive strength of concrete increased up to 10% replacement of POFA and further addition of POFA contents led to a decline in strength. At 10% replacement of POFA, compressive strength value of 30.2N/mm^2 was recorded and higher than the control specimen having 24.2N/mm^2. The compressive strength of the control mix was below the target designed strength of 25N/mm^2 as a result of some factors like mixing method and compaction. The increase at 10% replacement of POFA can be attributed to the presence of high silicon dioxide content in POFA which produces calcium silicate hydrate (C-S-H) during hydration acting as an interfacial bonding between the aggregates and pastes leading to improved strength. Further increase of POFA contents in the concrete mix resulted in excess silicon dioxide contents within the concrete matrix leading to reduction in the strength of concrete.

According to BS 8110 (1985), the minimum strengths for plain concrete, reinforced concrete with lightweight aggregate, reinforced concrete with normal aggregate, post tensioned concrete and pre-tensioned concrete are 7N/mm^2, 15N/mm^2, 20N/mm^2, 30N/mm^2, and 40N/mm^2 respectively. The POFA blended concrete produced with 30%, 20% and 10% replacement can be used for the production of reinforced concrete with lightweight aggregate, reinforced concrete with normal aggregate and post tensioned concrete respectively. 10% replacement of POFA is the optimum level and It can be concluded that POFA is a pozzolan which has potentials for improving the strength of concrete.

3.5 Effect of Palm Oil Fuel Ash (POFA) on Tensile Strength of Concrete

The results of the average split tensile strengths of concrete mixes without and with POFA at different curing ages are given in Figure 4. The curing age ranges from 3 to 28-day and it was observed that the tensile strength increased with increased curing age. This presents the effect of curing age on strength development in concrete when submerged in potable water leading to improved pore structure and reduces porosity.

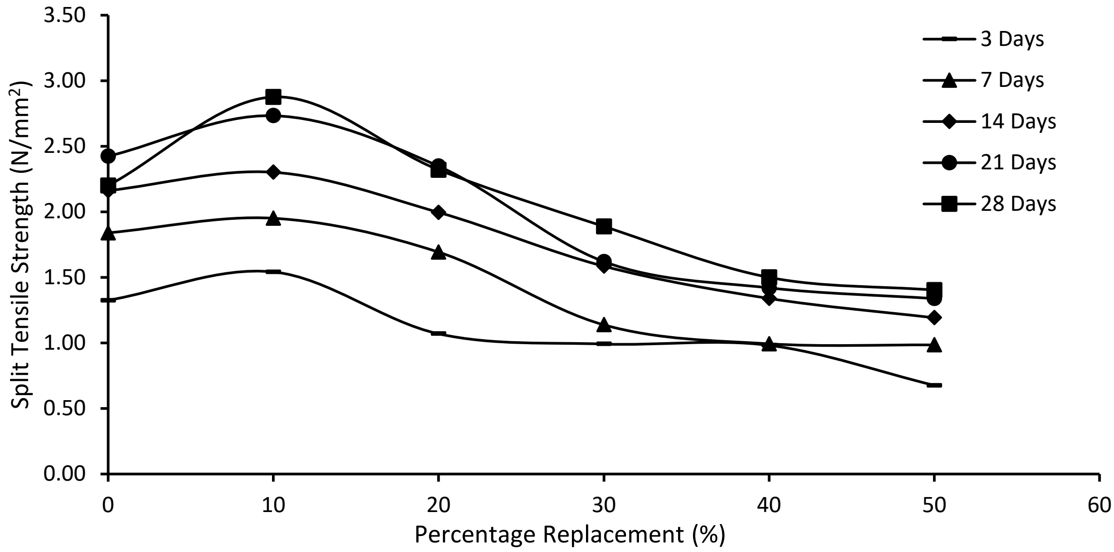

Figure 4: Variations of Tensile Strength at different Cement Fineness Zone

Figure 4 shows that the tensile strength increases up to 10% of POFA and further increase led to a decline in strength. At 28-day, it was observed that the tensile strength of the concrete was 2.20N/mm^2, 2.88N/mm^2, 2.32 N/mm^2, 1.89N/mm^2, 1.50N/mm^2 and 1.40N/mm^2 for control, 10%, 20%, 30%, 40% and 50% respectively. Generally, the results of the split tensile strength are about 10% of its compressive strength which reveals that concrete is strong in compressive but weak in tension as a result to its brittle nature.

3.6 Effect of POFA on the Flexural Strength of Concrete

The results documented from the experimental works on the flexural strength of POFA blended concrete at 7, 14, 28 and 56-curing days are presented in Figure 5. Flexural strength increased as curing age increased. The results reveal the capacity of unreinforced concrete beams to withstand load in bending and the impact of different percentage replacement of POFA on its flexural performance.

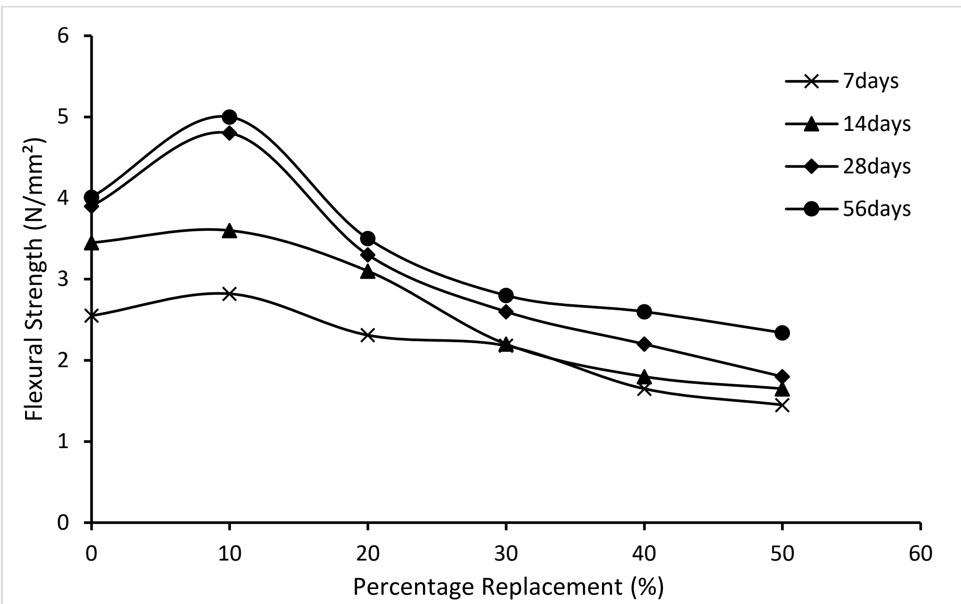

Figure 5: Variations of Cement Strength at different Cement Fineness Zone

From Figure 5, it was observed that the flexural strength increases from control up to 10% replacement of POFA and further increase resulted in decrease in flexural strength. The crack and failure patterns were similar for all samples as shown in Plate 5. The failure of the beams was seen to occur at 285 mm from the end of the beams and no cracks were observed prior to the failure of the beams. The failure was sudden without initial crack(s) preceding the ultimate failure of the beams. The sudden failure of the beams can also be attributed to the exclusion of steel reinforcement which contributes immensely to the flexural strength of concrete beams.

Plate 5. Failure pattern of the beams

3.7 Empirical Models using Coefficient Equations Approach

The experimental data were used to develop some mathematical models using equations coefficient approach which considered the pattern of the graph and the coefficient of determination value of the best fit function that clearly represent the experimental data. The final form of the mathematical models is shown in equations 4 and 5 for different structural strengths. The notation α represent the percentage replacement level (%) and β is the curing age (Days).

For Compressive Strength:

$$f_{cu} = (0.0000000000633547\alpha^5 - 0.00000000904564\alpha^4 + 0.000000440797\alpha^3 - 0.00000831302\alpha^2 + 0.0000512361\alpha - 0.000301006)\beta^4 + (-0.00000000162674\alpha^5 + 0.000000277517\alpha^4 - 0.0000152777\alpha^3 + 0.000312748\alpha^2 - 0.00215572\alpha + 0.0211919)\beta^3 + (-0.0000000235833\alpha^5 + 0.00000126909\alpha^4 + 0.0000197192\alpha^3 - 0.00153654\alpha^2 + 0.0209949\alpha - 0.539694)\beta^2 + (0.000000547545\alpha^5 - 0.0000545198\alpha^4 + 0.00176488\alpha^3 - 0.021462\alpha^2 - 0.000324617\alpha + 6.13487)\beta + (-0.000000743403\alpha^5 + 0.0000422529\alpha^4 + 0.000742625\alpha^3 - 0.0695299\alpha^2 + 1.01766\alpha - 4.64515) \quad (4)$$

For Tensile Strength:

$$f_{cu} = (0.0000000000342107\alpha^5 - 0.000000004369998\alpha^4 + 0.000000191513\alpha^3 - 0.00000328348\alpha^2 + 0.0000181227\alpha - 0.000023643)\beta^4 + (-0.00000000207118\alpha^5 + 0.00000026575\alpha^4 - 0.0000117043\alpha^3 + 0.000201755\alpha^2 - 0.00111813\alpha + 0.00144776)\beta^3 + (0.0000000426258\alpha^5 - 0.00000550758\alpha^4 + 0.000244629\alpha^3 - 0.00426342\alpha^2 + 0.0239824\alpha - 0.0324515)\beta^2 + (-0.000000344647\alpha^5 + 0.00004496\alpha^4 - 0.00202001\alpha^3 + 0.0357091\alpha^2 - 0.204721\alpha + 0.352508)\beta + (0.000000817603\alpha^5 - 0.000109415\alpha^4 + 0.00509087\alpha^3 - 0.0949545\alpha^2 + 0.581778\alpha + 0.52275) \quad (5)$$

Where, α is the percentage replacement level (%) and β is the curing age (Days)

Table 6. Comparison between developed models and experimental data for the compressive strength of POFA blended concrete at 7 and 28-day curing

	7 Days			28 Days		
Per. Rep. (%)	Exp. (N/mm^2)	Model (N/mm^2)	Per. Diff. (%)	Exp. (N/mm^2)	Model (N/mm^2)	Per. Diff. (%)
0	18.4000	18.4000	0.0002	24.2000	24.2006	0.0023
10	19.9000	19.9000	0.0002	30.2000	30.1989	0.0038
20	15.2000	15.2000	0.0002	23.4000	23.3989	0.0047
30	13.7800	13.1636	4.4731	18.7000	16.2297	13.2102
40	10.4300	10.4301	0.0009	15.3000	15.2957	0.0281
50	9.7500	9.7506	0.0060	13.3300	13.3334	0.0253

Table 7. Comparison between developed models and experimental data for the tensile strength of POFA blended concrete at 7 and 28-day curing

	7 Days			28 Days		
Per. Rep. (%)	Exp. (N/mm^2)	Model (N/mm^2)	Per. Diff. (%)	Exp. (N/mm^2)	Model (N/mm^2)	Per. Diff. (%)
0	1.8400	1.8400	0.0001	2.2000	2.1999	0.0039
10	1.9510	1.9510	0.0004	2.8762	2.8764	0.0083
20	1.6927	1.6927	0.0017	2.3204	2.3187	0.0717
30	1.1379	1.1381	0.0144	1.8889	1.8782	0.5660
40	0.9933	0.9937	0.0400	1.5000	1.4643	2.3771
50	0.9848	0.9855	0.0630	1.4032	1.3134	6.4001

The results presented in tables 6 and 7 reveals that the strengths properties of concrete can be affected by its curing age and percentage replacement of POFA. From the analysis, it was observed that the maximum percentage differences between experimental data and the predicted values were 13.21% & 6.40% for compressive, and tensile strengths respectively. Also, it was observed that the values of the mathematical models are in good agreements with the experimental results having reliability of the coefficient of determination (RR^2) of 1.0000 & 1.0000 for compressive and tensile strengths respectively. Therefore, these models can be used to estimate the value of structural strengths of POFA blended concrete within the dataset.

4.0 CONCLUSION

In this study, the effect of POFA on the structural performance of concrete were investigated and mathematically modelled. The following conclusions are drawn:

a) The chemical composition of POFA revealed that the combining percentage masses of silica (SiO_2), alumina (Al_2O_3) and ferric oxides (Fe_2O_3) was above 70% which are similar to those of class N type pozzolans according to ASTM C618-12a.

b) The application of POFA into the concrete matrix resulted to the increase in the workability of concrete.

c) An Increase in the curing age led to the increase in the structural strengths (Compressive, split tensile and flexural strengths) of concrete. The structural strengths of concrete increased up to 10% POFA replacement and further increase in POFA contents led to a decline in strength.

d) The POFA blended concrete produced with 30%, 20% and 10% replacement can be used for the production of reinforced concrete with lightweight aggregate, reinforced concrete with normal aggregate and post tensioned concrete respectively.

e) Mathematical models for predicting the structural strengths of concrete at varying percentage replacement level and curing age were developed through coefficient equation approach and found to be in good agreement with the experimental data with high level of significance.

The present study reveals that 10% replacement of POFA is the optimum level and It can be concluded that POFA is a pozzolan which has potentials for improving the structural performance of concrete for sustainable construction.

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REFERENCES

Adesogan, S. O. (2014). Strategies and techniques of providing adequate and affordable potable water in rural areas of Nigeria. *International Journal of Water Resources and Environmental Engineering*, 6(1): 32–39.

ASTM C618-12a (2012). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. *ASTM International, West Conshohocken, PA, US*.

Awal, A. A. and Hussin, M. W. (1997). The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction. *Cement and Concrete Composites*, 19(4), 367-372.

British Standard Code of practice (1985). Specifications for Minimum Concrete Strength. London. BS8110:1.

BS 12 (1996). Specification for Portland Cement. *British Standard Institution*, London.

BS EN 1008 (2002). Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. *389 Chiswick High Road*, London.

BS 882 (1992). Specification for aggregates from natural sources for concrete. *British Standard Institution*, London.

BS EN 12350: Part 2 (2000). A method for Determination of Slump. *British Standard Institution,* London.

BS EN 12350-6: (2009). Testing Fresh Concrete Density of Test Specimens. *British Standard Institution*, London.

BS EN 12390-3: (2009). Testing Hardened Concrete. Compressive Strength of Test Specimens. *British Standard Institution*, London.

BS EN 12390-6: (2009). Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens. *British Standard Institution*, London.

Donatello, S., Tyrer, M. and Cheeseman, C. R. (2010). Comparison of test methods to assess pozzolanic activity. *Elsevier: Cement and Concrete Composites*. Elsevier Ltd, 32(2): 121–127.

Deepak, T. J., Elsayed, A., Hassan, N., Chakravarthy, N., Tong, S. Y. and Mithun, B. M. (2014). Investigation on properties of concrete with palm oil fuel ash as cement replacement. *International Journal of Scientific and Research*, **3**, 138-142.

Ikponmwosa, E., Fapohunda, C. and Ehikhuenmen, S. (2014). SUITABILITY OF POLYVINYL WASTE POWDER AS PARTIAL REPLACEMENT FOR CEMENT IN CONCRETE PRODUCTION. *Nigerian Journal of Technology (NIJOTECH)*, 33(4): 504–511.

Islam, G. M. S., Rahman, M. H. and Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 6(1): 37–44.

Karim R., Zain M., Jamil M. and Islam N. (2011). Strength of Concrete as Influenced by Palm Oil Fuel Ash. *Australian Journal of Basic and Applied Sciences,* 5(5): 990–997.

Joshua, O. and Ogunde, A. (2015). Exploring the Pozzolanic Potential of Blend of Palm Kernel Nut Ash (PKNA) With Cement Towards a Sustainable Construction. *International Conference on African Development Issues*, 135–140.

Manjunath, B. T. A. (2016). Partial Replacement of E-plastic Waste as Coarse-Aggregate in Concrete', *Procedia Environmental Sciences,* 35, 731–739.

Marthong, C. (2012). Sawdust Ash (SDA) as Partial Replacement of Cement. *International Journal of Engineering Research and Applications*, 2(4): 1980–1985.

Mclellan, B. C. *et al.* (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Elsevier Journal of Cleaner Production*. Elsevier Ltd, 19(9–10): 1080–1090.

Michael, G. *et al.* (2014). The Effect of Population Explosion on Family Standard of Living in Calabar , Nigeria. *European Scientific Journal*, 10(20): 190–204.

Munir, A. *et al.* (2015). Utilization of palm oil fuel ash (POFA) in producing lightweight foamed concrete for non-structural building material. *Procedia Engineering*. Elsevier B.V., 125, . 739–746.

Oj, O., Lm, O. and Sp, A. (2015). Performance of coconut shell ash and palm kernel shell ash as partial replacement for cement in concrete. *Journal of Building Materials and Structures*, 2, 18–24.

Oyejobi D.O., Abdulkadir T.S. and Ahmed A.T. (2015). A Study of Partial Replacement of Cement with Palm Oil Fuel Ash in Concrete Production. *Journal of Agricultural Technology*, 12(4): 619–631.

Raheem, A. A., Olasunkanmi, B. S. and Folorunso, C. S. (2012). Saw Dust Ash as Partial Replacement for Cement in Concrete. *International Journal of Engineering Science Invention*, 4(2): 36–40.

Resch, E. *et al.* (2016). Impact of Urban Density and Building Height on Energy Use in Cities', *Energy Procedia*, 800–814.

Rezaul Karim, M. *et al.* (2011). Strength of concrete as influenced by palm oil fuel ash. *Australian Journal of Basic and Applied Sciences*, 5(5): 990–997.

Sata, V., Jaturapitakkul, C. and Kiattikomol, K. (2007). Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. *Construction and Building Materials- Elsevier*, 21, 1589–1598.

Sooraj V.M (2013). Effect of Palm Oil Fuel Ash (POFA) on Strength of Properties of Concrete. *International Journal of Scientific and Research Publications*, 3(6): 1-7.

Subramani, T. and Anbuchezuian A. (2017). Experimental Study of Palm Oil Fuel Ash As Cement Replacement of Concrete. *International Journal of Application or Innovation in Engineering & Management*, 6(3): 1–5.

Ukpong, E. C. (2012). ENVIRONMENTAL IMPACT OF AGGREGATE MINING BY CRUSH ROCK INDUSTRIES IN AKAMKPA LOCAL GOVERNMENT AREA OF CROSS RIVER STATE', *Nigerian Journal of Technology (NIJOTECH)*, 31(2): 128–138.

V, S. D., Gnanavel, B. K. and Murthi, P. (2015). Experimental Investigation on the mechanical properties of steel slag ceramic concrete', *International Journal of ChemTech Research*, 8(8): 152–160.