Nigerian Journal of Technology (NIJOTECH)
Vol. 42, No. 2, June, 2023, pp.167 - 174
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v42i2.2

MIX DESIGN OPTIMIZATION OF HIGH-PERFORMANCE CONCRETE USING LOCAL MATERIALS

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Article history: Received 17 April, 2023. Revised 15 May, 2023. Accepted 03 July, 2023. Published 31 July, 2023. ***CC BY-NC-ND Licence***

Abstract

In this paper, twelve different concrete mixes made from local materials were studied with a view to determining which of the mix designs will produce high-performance concrete. Varied water-cement ratios (w/c) of 0.3, 0.35, and 0.4 were studied with different combinations of particle sizes of coarse aggregates. Twelve concrete mixes were then produced, cast, and cured for 7, 14, 21, 28, 45, and 90 days. Superplasticizer was used to facilitate the workability of the concrete mixes. A slump test was first conducted on the fresh concrete to determine its workability, while compressive, flexural, and tensile strength were determined at the end of each curing age in accordance with relevant standards. The results shows that slump value increased with an increase in w/c ratio, while the concrete with 100% 10 mm particle size coarse aggregate had a minimum slump of 24, 37, and 50 mm at w/c of 0.3, 0.35 and 0.4 respectively, but higher slump values of 70, 76 and 83 mm were obtained with concrete containing larger particle sizes combination i.e. 25% of each of 10, 12, 15 and 19 mm sizes. But strengths reduced with an increase in w/c and aggregate particle sizes. Concrete produced with w/c of 0.3 and 10 mm coarse aggregates had a strength of 52.22N/mm^2 at 28 days, which was about 126% of other strengths obtained from other mixes. Statistical models were then proposed to predict the strength of the best-performed concrete mix. The study concluded that it was possible to produce high-performance concrete using local materials, if the mix is properly optimized.

Keywords: High performance concrete, Workability, Strength, Curing ages, Optimization.

1.0 INTRODUCTION

In the recent past, there has been significant increase in consumption of concrete as well as improvement in the properties of concrete. As the need for high rise buildings with reduced column sizes and increased space, long-span bridges as well as heavy hydraulic structures become more necessary in emerging cities, so also it is exigent to improve on the concrete performance. High performance concrete is one such modern concrete developed to meet the requirements of global challenges.

High performance concrete (HPC), according to Fares et. al. [1] is a specialized concrete made from high quality ingredients, optimized mixture designs with careful handling. In this type of concrete, strength, durability and workability are of essence. To produce concrete with these tripartite properties has been attracting the attention of many researchers in the last decades. Chemical admixtures have also been developed to reduce amount of water-cement ratio, to enhance workability and hence improve strength [2], [3], while some researchers improved concrete performance by incorporating supplementary cementitious materials (SCMs) such as fly ash, silica fume [4]–[6]. Another important approach to achieving HPC is to optimize the concrete ingredients based on available materials in the locality.

Rakesh and Mishra [7] developed an empirical method of mix design for high strength concrete using materials available in their locality. In the research work, nine different mixes were designed and their results indicated that a strength of more than 50 MPa with a mix ratio of 1:1.17:1.88 was possible. Vardhan et al. [8]. on the other hand, worked on 5 trial mixes with conventional aggregates with blended cement-silica fume as binder, while incorporating superplasticizer (Polycarboxylate ether based). It was reported that 28-day strength of about 110 MPa was achievable. Comparable results were also obtained by Samir and Dalya [9], even at higher proportion of silica fume of 15% but at low water-cement ratio of 0.3. Soliman and Tagnit-Hamou [10] equally replaced quartz powder and cement with glass powder to produce ultra-high performance glass concrete, whose strength was in the range of 220 MPa, while Mohamadreza et. al. [11] incorporated ductal (an industrial bye-product) to produce concrete with strength triple that of normal concrete. Apart from replacing cement with other powders, non-conventional aggregates are equally being used to improve concrete. Dolomite and steel fibres were used by Amin, et. al. [12] to replace aggregates to produce concrete with high strength.

Other techniques had earlier been developed to improve concrete strength. One such technique involved the use of densified small particles (DSF), where concrete with dense granular matrix was produced. This concept was introduced in the 1980s [13]. Meanwhile macro-defect free (MDF) approach was developed by Birchall et al. [14]. In this approach (MDF), polymer-modified mortar is used to fill the pore of the concrete to produce denser concrete with high compressive strength, though the ductility might not be enhanced [15]. Linear packing density model was another method used to produce HPC. This technique has potential to produce concrete of 236 MPa strength in 4 days when cured at 90 ℃ [16]. Compressible packing model (CPM) and solid suspension model (SSM) are relatively newly developed models. The details of these techniques are reported by [16], [17] respectively. The underlining principle in each of these models is to reduce the gel porosity as well as the capillary pores, which changes the chemistry of C-S-H to more crystalline phases, causing increase in strength [18].

In addition to packing techniques, careful combination of concrete ingredients could also be used to improve concrete performance. Aggregate size distribution, water-cement ratio as well as mix ratios are variables that have greater influence on the performance of concrete. In this study, therefore, effect of coarse aggregate sizes and varied water-cement ratio on the strength properties of concrete are studied with a view to producing concrete with higher strength far above strength of normal concrete.

2.0 MATERIALS AND METHODS

2.1 Materials

Ordinary Portland cement (OPC) of strength 42.5R was used as binder, while river sand of maximum nominal size of 3.81 mm was used as fine aggregate. Granite of varied sizes was used as coarse aggregate. Granite of various nominal sizes of 10, 12, 15 and 19 mm were used as coarse aggregates. Potable water was used for mixing the concrete. A Sulphonated Naphthalene polymers based superplasticizer with a brand name Conplast SP430 was used as water reducing admixture. It is supplied as a brown liquid instantly dispersible in water. The dosage used was 0.5 litres /50 kg cement.

Table 1: Concrete mix sample designation and constituent

Concrete Mix code name	Aggregate size (mm) (% proportion)	w/c	Sample Group
S1		0.30	
S2	10 (100%)	0.35	A
S3		0.40	
S4	10 (25%)	0.30	
S5	12(50%)	0.40	B
S6	15 (25%)	0.45	
S7	10 (25%)	0.30	
S8	12(25%)	0.35	C
S9	15 (25%)	0.40	
	19 (25%)		
S10	10 (25%)	0.30	
S11	12(25%)	0.35	D
S12	15 (50%)	0.40	

2.1.1 Preparation of concrete mixes, casting and curing

Twelve different concrete mixes were prepared and coded as S1 to S12. All mixes had a baseline mix ratio of 1:1:2 and the same cement content, while aggregate sizes were varied and combined in different proportions. For each of the mix, water cement ratios of 0.3, 0.35 and 0.4 were used separately. The samples were further grouped into four (A to D), depending on the content of the aggregates. For instance, concrete Sample S1 represent concrete containing 10 mm size aggregate with w/c of 0.3, while Sample group A indicates concrete samples that contain 10 mm size aggregate irrespective of the value of w/c. Table 1 shows the detail of the sample classification and their designation. In each mix, Conplast SP340 was added at a rate of 0.5 litres/50 kg of cement. The choice of dosage was based on the manufacturer's recommendation. Each concrete mix was cast in the steel mould of size 150 x 150 x 150 mm for the compressive strength test, while cylinder mould of diameter 150 mm and height 300mm was used for tensile strength test. For the flexural strength test, concrete beam of size 150 mm x 150 mm x 500 mm was cast. In each case, the fresh concrete was left in the mould for 24 hours and demoulded. The concrete samples were weighed and cured in water (by immersion) for 7, 14, 21, 28, 45 and 90 days.

2.2 Methods

2.2.1 Materials characterization

Physical properties of the materials used in this study were determined, following standard procedures. Specific gravities, bulk density, and crushing value of the aggregates were some of the parameters determined in accordance with the guidelines of BS 1377 -3 [19].

2.2.2 Determination of workability

Slump test was conducted to measure workability of each concrete sample. The procedure detailed in BS 1881-102 [20] was followed. Average of three readings was recorded.

2.2.3 Determination of compressive strength

Concrete cubes were placed in turn under the compression machine and crushed to failure. The compressive strength was then determined as the ratio of the crushing force obtained from the machine to the area of the cube.

2.2.4 Determination of tensile strength

Tensile strength of each of concrete sample was determined in accordance with the provision of ASTM C496 [21].

2.2.5 Determination of flexural strength

Flexural Strength is the theoretical maximum tensile stress reached in the bottom fibre of a test beam during a flexural strength test. The formula used to calculate the flexural strength of each of the beam specimen using the results of the two-point flexural test for a rectangular cross-section is given by equation (1)

$$R = \frac{3PL}{2bd^2} \quad (1)$$

Where R= Modulus of rupture or flexural strength (N/mm^2)
P = Failure load
b = Beam width (mm)
d = Beam depth (mm)
L = length of the concrete beam (mm)

3.0 RESULTS AND DISCUSSION

3.1 Material Properties

The fine aggregate used could be classified as well graded as its coefficients of uniformity (C_u) was 2.43, while curvature (C_c) was 0.84 and they were within the recommended boundaries [22]. The grading coefficients were obtained from the particle size distribution shown in Figure 1.

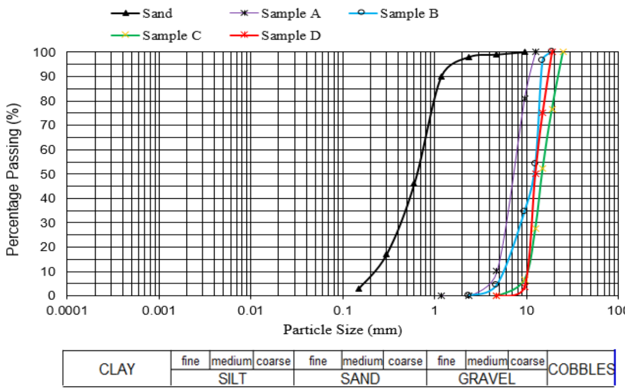

Figure 1: Particle size distributions of the aggregates

Other physical properties of the aggregates obtained are presented in Table 2. The specific gravities of the sand and granite were 2.63 and 2.66, respectively indicating that they were normal weight aggregate. This is further supported by the values of their bulk densities. There were difference in the moisture content and dry density of the aggregates. This may be due to the difference in their grain sizes, which make their surface areas also differ.

Table 2: Physical Properties of Aggregates

Physical Property	Sand	Granite
Specify Gravity	2.63	2.66
Uniformity Coefficient (Cu)	2.43	-
Coefficient of Curvature (Cc)	0.84	-
Moisture Content (%)	0.73	0.63
Bulk Density (Kg/m^3)	1331.57	1376.84
Dry Density (Kg/m^3)	769.69	844.64
Aggregate Crushing Value (%)	-	29.79
Aggregate Impact Value (%)	-	20

3.1.1 Workability of the concrete mixes

Figure 2 shows the effect of w/c ratio on the workability of the concrete mixes. It shows that slump value increased with increase in water content for all the mixes. This observation is similar to the what Vardhan et al. [8] reported in their work. The pattern was that about 50% slump was gained, when w/c ratio increased from 0.3 to 0.35 for concrete sample A, while it was increased by 35% and 25% for Samples B and D. For Sample C, there was slight increase (about 8%) in the slump as the w/c increased to 0.35. Similar trend was observed, when the w/c increased from 0.35 to 0.4 for all the samples. Considering the effect of aggregate size on the slump, there was significant influence of the aggregate size and combination of aggregates on the workability. Concrete specimen that contained smallest aggregate sizes of 10 mm only (Sample A) had the lowest slump value at all the w/c ratios, while Sample C (combination of aggregates sizes of 10, 12, 15 and 19mm) had the highest slump values at 0.3 and 0.35 w/c ratios and had equal slump value of 83 mm with Sample D at w/c of 0.4. What could be attributed to these trends is the variation in the particle sizes of the samples.

For Sample A, it contained only one type of aggregate size of 10 mm, it has more surface area than that of Sample D that contained about 50% of its aggregates of 15 mm. Thus, concrete that contain higher surface area will require more water to moisten the surface of its particles than aggregates with lower surface area. This is responsible for concrete with 10 mm aggregate size to flow less than concrete that contain aggregates of larger sizes. The general trend was that as the aggregates become coarser, the slump values increased. But there appeared to be slight deviation from this generalization in the slump values of concrete of sample C and Sample D. Sample D was expected to be less coarse as it did not contain aggregate size greater than 15 mm while Sample C had about 25% of its content to be 19 mm aggregate size. This could be the reason why Sample C initially had higher slump value but at higher water content (w/c=0.4), the slump value of both samples merged to 83 mm.

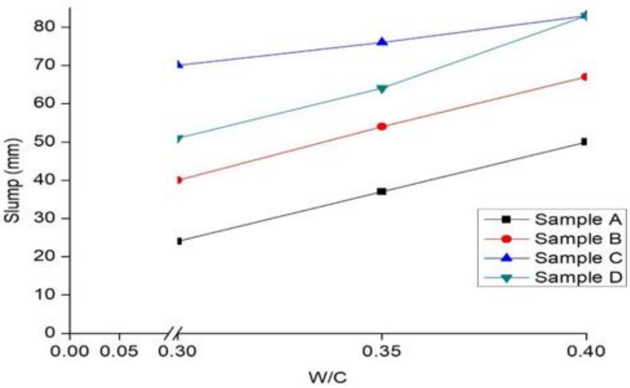

Figure 2: Slump value of concrete with different aggregate sizes at various water-cement ratio

3.1.2 Effect of water-cement ratio on the strength properties

Figure 3 shows effect of w/c on the compressive strength of the concrete mixes at different ages. It was observed that compressive strength of concrete reduced with increase in water-cement ratio for all the mixes and at all the ages. For concrete Sample A, compressive strength with w/c of 0.3 had strength of about 17% and 25% higher than the strength of concrete of w/c of 0.35 and 0.4, respectively at 28 days. Similarly, at the same age of 28 days and for concrete Samples B, the strength increased by 10 and 26%, when w/c increased from 0.3 to 0.35 and 0.4 respectively. As for Samples C, the corresponding increase in strength was 5% when w/c increased to 0.35 and 10% at w/c of 0.4. But for Sample D, the increase in strength was about 10% at w/c of 0.35 and 32% at w/c of 0.4. It is observed that the percentage increase varied with each sample of concrete, indicating that aggregate content also has attendant effect on the compressive strength. The same trend is observed in the flexural strength (Table 3) as well as tensile strength (Table 4). At 28 days for concrete Sample A, when w/c increased from 0.3 to 0.35, the flexural strength decreased from 9.78 N/mm^2 to 8.89 N/mm^2 representing 10% reduction.

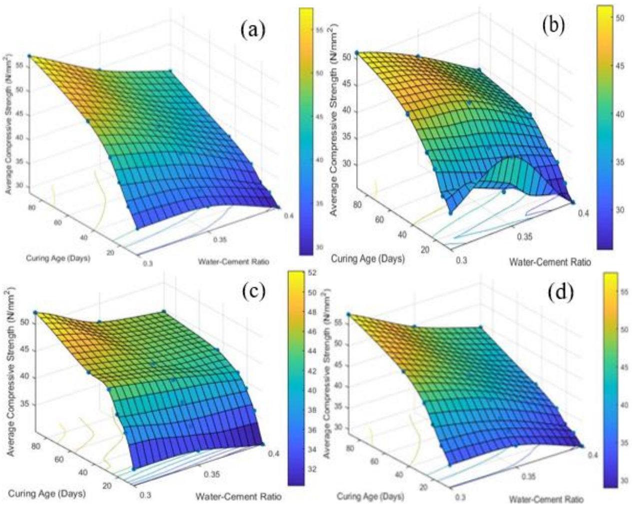

Figure 3: Compressive strength at different w/c ratios for (a) Sample A (b) Sample B (c) Sample C and (d) Sample D

A further increased in w/c to 0.4 also brought about 24% reduction in flexural strength. This results further showed that water content in concrete has influence on strength development of concrete when the pore size within the concrete matrix is increased as reported by [23]. However, there is a limit to which w/c ratio can be lowered because decrease in w/c could lead to concrete being less workable (Figure 2) and could cause honey comb in the hardened concrete, posing durability challenges. Thus, there is need to strike a balance between strength and workability. Definitely, in the absence of superplasticizer, concrete made with w/c 0.3 to 0.4 will not be workable. However, in the presence of superplasticizer, workable concrete can be achieved, while increased strength is obtained. From these results, w/c ratio of 0.3 would be appropriate for all the concrete samples to achieve high performance concrete.

Table 3: Flexural strength of the concrete mixes

Sample Name	Flexural strength (N/mm^2) Curing Ages (Days)					Concrete Sample
	7 days	14 days	28 days	45 days	90 days	
S1	8.56	8.89	9.78	9.89	10.45	
S2	7.56	8.22	8.89	9.34	9.56	A
S3	6.67	7.78	7.89	8.00	8.67	
S4	4.50	4.61	4.72	4.83	4.94	
S5	3.90	4.06	4.33	4.56	4.78	B
S6	3.36	3. 78	4.00	4.17	4.28	
S7	2.94	3.94	4.56	6.17	6.78	
S8	2.39	3.39	4.06	5.50	6.17	C
S9	2.06	2.89	3.72	5.17	5.72	
S10	3.20	3.33	3.87	4.22	4.49	
S11	2.11	3.07	3.51	3.73	4.09	D
S12	1.87	2.31	2.89	3.38	3.64	

Table 4: Tensile strength of the concrete mixes

Sample Name	Tensile strength (N/mm^2) Curing Ages (Days)						Concrete Sample
	7 days	14 days	21 days	28 days	45 days	90 days	
S1	2.16	2.37	2.62	2.73	3.08	3.29	
S2	2.19	2.19	2.37	2.48	2.76	2.80	A
S3	1.88	1.98	2.16	2.37	2.59	2.76	
S4	5.11	5.44	6.22	6.89	7.33	7.78	
S5	5.00	5.33	5.56	5.89	6.22	6.89	B
S6	4.56	5.00	5.22	5.67	6.22	6.44	
S7	5.00	5.22	5.56	6.11	6.89	7.11	
S8	4.78	5.11	5.33	6.44	6.56	7.00	C
S9	4.56	4.89	5.11	5.67	6.33	6.78	
S10	2.16	2.58	2.65	2.79	3.22	3.50	
S11	2.09	2.23	2.37	2.44	2.58	2.79	D
S12	1.80	2.09	2.12	2.30	2.33	2.55	

3.1.3 Effect of aggregates sizes on strength characteristics

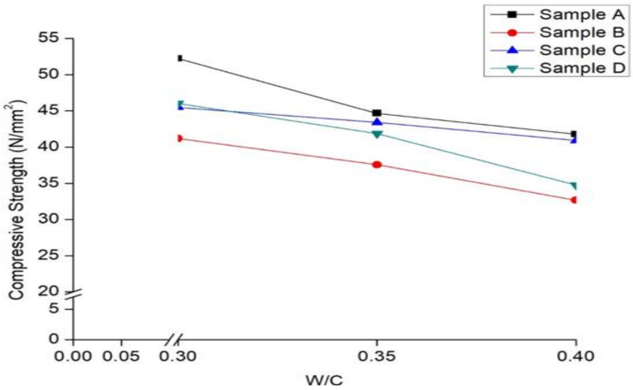

Figure 4: 28-day compressive strength of concrete with varied aggregate sizes

As observed earlier, the strength reduced with increase in w/c ratio for all the concrete samples, irrespective of the aggregates size. The Figure 4 (28-day strength) however, shows that aggregate sizes also influenced the trend of compressive strength, similar to what was obtained with different ages. It was that, compared to concrete with varying aggregate sizes, higher strengths were recorded for concrete with having lower aggregates size of 10 mm (Sample A) For instance, at 0.3 w/c (equally for other w/c ratios), Sample A had strength which was about 126% higher than that of Sample B and 114 and 113% higher than the strength of concrete Samples C and D, respectively. The same trend was found with flexural and tensile strength (Tables 3 and 4). However, there is tendency to use more cement paste due to relatively higher surface area occasioned by the relatively small size of the aggregate.

Furthermore, it may lead to high cost because higher cement content would be required, possibility of internal cracks is high due to autogenous shrinkage. Combination of aggregates in Sample B seem not to be a good combination for producing high performance concrete (HPC) due to lower strength obtained, compared to other concrete mixes. While, Sample D performed better at w/c of 0.3 but had lower strength compared to Sample C at other water cement ratios of 0.35 and 0.4. It can be deduced that to produce HPC at higher strength above 40 N/mm^2, it may not be appropriate to use aggregate combination as specified in sample B (Table 1), while others could be used at all w/c ratio except Sample D at w/c of 0.4.

3.2 Statistical Model for Strength Prediction

From foregoing, Sample A seems to be appropriate material combination that produced highest strength for use as HPC. Therefore, statistical analysis of the data obtained from the compressive strengths was carried out. Two approaches were adopted: coefficient equation approach and multiple linear regression techniques. In order to get the line of best fit, as required by Curve Expert Basic, two additional curing ages (60 days and 75 days) were determined and inserted between 45 days and 90 days (Table 5).

3.2.1 Coefficient equation technique

Equations (1 – 3) were generated for each of the water cement ratio considered,

At w/c = 0.3,

$$C = -0.0038082994a^2 + 0.6854939a + 34.184597 \quad (R^2 = 0.989) \quad (1)$$

At w/c = 0.35,

$$C = -0.0028385271a^2 + 0.51101106a + 31.484653 \quad (R^2 = 0.993) \quad (2)$$

At w/c = 0.4,

$$C = -0.002329554a^2 + 0.41931973a + 29.92164 \quad (R^2 = 0.971) \quad (3)$$

Where, 'a' represents curing age and C represent compressive strength

Considering w/c ratio as a variable (w), Equations (4-6) were generated,

$$C = -0.0921598w^2 + 0.0792993w - 0.0193037 \quad R^2 = 1.00 \quad (4)$$

$$C = 16.5583020w^2 - 14.2525531w + 3.4710127 \quad R^2 = 1.00 \quad (5)$$

$$C = 227.3862000w^2 - 201.7999100w + 74.259812 \quad R^2 = 1.00 \quad (6)$$

Where, w is water cement ratio

In the case where the variables (w and a) were merged, a general equation (Equation 7) was developed to predict compressive strength of the concrete mix.

$$C = (-0.092159w^2 + 0.0792993w - 0.0193037)a^2 + (16.5583020w^2 - 14.2525531w + 3.4710127)a + (227.386200w^2 - 201.7999100w + 74.259812) \quad (7)$$

3.2.2 Multiple linear regression method

The equation for the multiple linear regression model for Average compressive strength (y) from the water cement ratio (X_1), curing age (X_2) and bulk density (x 1000) (X_3) as variables is given in Equation 8.

$$y = \beta_0 + X_1\beta_1 + X_2\beta_2 + \cdots + X_K\beta_k \quad (8)$$

Regression analysis of the data showed that Equation (9) represent a best fit for the data,

$$C = (248.3721) + (-154.753)X_1 + (0.2306)X_2 + (-61.5047)X_3 \quad (9)$$

Table 5: Compressive Strength for all water cement ratios and curing ages

w/c ratio	CURING AGE							
	7 days	**14 days**	**21 days**	**28 days**	**45 days**	**60 days**	**75 days**	**90 days**
0.3	37.63	42.15	47.34	52.22	59.70	61.13	62.57	64.00
0.35	34.82	37.48	40.45	44.66	50.30	51.61	52.91	54.22
0.4	30.59	35.26	38.89	41.78	45.48	46.22	46.97	47.71

Table 6: Comparison of the Model and Experimental Compressive Strength for Each Modelling Method

Water Cement Ratio	Curing Age	Experimental Result	Coefficient Equation Approach		Linear Regression Model	
			Predicted Results	Percentage Difference (%)	Predicted Results	Percentage Difference (%)
0.3	**7**	37.63	38.80	3.11	43.45	15.47
	14	42.15	43.04	2.11	45.14	7.09
	21	47.34	46.90	-0.93	46.82	-1.10
	28	52.22	50.39	-3.50	48.50	-7.12
	45	59.7	57.32	-3.99	52.59	-11.91
	90	64	65.03	1.61	63.40	-0.94
0.35	**7**	34.82	34.92	0.29	38.18	9.65
	14	37.48	38.08	1.60	39.86	6.35
	21	40.45	40.96	1.26	41.54	2.69
	28	44.66	43.57	-2.44	43.22	-3.22
	45	50.3	48.73	-3.12	47.31	-5.94
	90	54.22	54.48	0.48	58.12	7.19
0.4	**7**	30.59	32.74	7.03	32.90	7.55
	14	35.26	35.34	0.23	34.58	-1.93
	21	38.89	37.70	-3.06	36.26	-6.76
	28	41.78	39.84	-4.64	37.95	-9.17
	45	45.48	44.07	-3.10	42.03	-7.59
	90	47.71	48.79	2.26	52.84	10.75

Average	**-0.27**	**0.61**
Standard Deviation	**3.07**	**7.97**

3.2.3 Comparison of the two approaches

From Tables 6, it is seen that the values of concrete strength obtained from the Coefficient Equations Approach compared very well with the values of experimental strength more than the values obtained from the Multiple Linear Regression Method. When expressed as a percentage of model strength, the predicted and experimentally observed strengths for Coefficient Equations Approach vary between -3% and 4% while that of the Multiple Linear Regression Method vary between -11.91% and 15.47% for concrete strength indices.

Statistical analysis also showed that the mean and the standard deviation value from the Coefficient Equations Approach were smaller, when compared with the values obtained from the Multiple Linear Regression Method. The lower value of standard deviation is an indication of the data clustering around the average. Thus, both strength-predicting method could be considered valid for high strength concrete but the Coefficient Equations Approach seem more precise than the multiple linear regression.

4.0 CONCLUSION

Optimization of mix design for high performance concrete from locally available materials was carried out. The properties investigated were workability (slump), density and compressive, tensile and flexural strength. The following were concluded from the study:

i. Slump value increased with increase in w/c but reduced as the particle size of the coarse aggregates reduced, due to increase in the surface area.
ii. Highest strength was obtained at w/c ratio of 0.3, when 100% coarse aggregate of maximum nominal size of 10 mm was used.
iii. Apart from concrete that contained aggregate of particle sizes 10 mm (25%), 12 mm (50%) and 15 mm (25%), at higher w/c above 0.3, all other mixes had their 28-day compressive strength higher than 40 N/mm^2.
iv. Model equation developed from Coefficient Equation approach seem to be more precise than obtained from the regression method.
v. The model equation could be used to predict compressive strength of HPC at a given age with varied w/c ratio.

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