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Optimization Of The Compressive Strength Of High Performance Recycled Coarse Aggregate Concrete

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Abstract:
Background: *This study applied recycled coarse aggregate in the production of high-performance concrete (HPC) by partially replacing the natural coarse aggregate in the high performance concrete mix with recycled coarse aggregate, and the resulting high performance concrete mix with the following constituents (water, cement, silica fume, high range water reducing admixture, natural coarse aggregate, recycled coarse aggregate, and fine aggregate) was optimized using some statistical approach.*
Materials and methods: *The mixture experiment approach was employed in this research. A selected reference mixture gave the guide for the selection of upper and lower bounds of the mixture components in terms of volume fractions. A total of 46 experimental runs were planned and carried out for the mixture experiment design. MINITAB 17 statistical software was employed in the design and analysis of the experiment. The experiment design was based on the extreme vertices design for mixture experiment, and was analyzed using analysis of variance (ANOVA), and least squares methodology. The mixture experiment was modeled on Scheffe's quadratic polynomial. The numerical optimization procedure based on desirability function methodology was used to obtain optimum components proportion meeting a desired response property. The response optimizer function of MINITAB 17 was used to perform the numerical optimization. The numerical optimization procedure produced optimized mixture component proportions that would meet a predetermined response property (specified strength).*
Results: *The range of predictable values of compressive strengths obtained in this study are 14.6 – 26.4(MPa) for 1-day compressive strength; and 36.2 – 57.4(MPa) for 28-day compressive strength.*
Conclusion: *The models developed from this study could predict compressive strength properties that are within the range obtained in the study, as it is common with regression models.*
Key words: *Model; High performance concrete; recycled coarse aggregate; High range water reducing admixture (Superplasticizer), Extreme vertices design.*

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I. Introduction

Concrete is a major construction material for civil engineering works. Today, the rate at which concrete is used is much higher than it was 40 years ago[1]. This assertion is also evident in the rate of infrastructural development in different parts of the world. Large quantity of construction waste is being produced in Nigeria almost on daily basis from demolition and renovation of old and worn-out structures, yet very little demolished concrete is currently recycled or reused in this country. The small quantity which is recovered is mainly reused as sub-base in highway construction. The rest is dumped or disposed into landfills[2]. In Nigeria and most of other developing countries where technological development is still growing, some regions especially large urban areas are already facing problems of obtaining adequate aggregate supplies at reasonable cost due to the distance to the source of the aggregate. The idea of recycling aggregates, become invaluable in such areas. For reasons of waste reduction and to save energy and cost in the production of natural aggregate, it is important for concrete from demolished structures to be reused for construction of new structures. Concrete debris is typically reclaimed as recycled concrete aggregate (RCA). For effective utilization of waste concrete, it is pertinent to use waste concrete as recycled aggregates for new concrete[3].

Though there have been previous researches on recycled aggregates, most have been on the production of conventional concrete. This research focuses on the development of prediction equations (models) for 1-day and 28-day compressive strengths of high-performance concrete (HPC) made with the natural coarse aggregate partially replaced with recycled coarse aggregate. The models can then be used subsequently to obtain optimal combinations of the mixture components for the HPC meeting a specified strength. Since the traditional method of concrete mixture proportioning is usually based on trial and error method, which most times do not give the best setting of components to meet a specific or several performance criteria simultaneously, it is relevant to have a method which is not only precise in meeting the required properties for a given concrete mixture proportion, but can also be used to optimize mixture proportions such that the most efficient component setting in terms of the desired response and cost are obtained. Statistical models find useful application in this. High-performance concrete (HPC) is usually characterized by high compressive strength and finds useful application in cases where very high strength is required. This study attempts to use statistical methods which incorporates the idea in Scheffe's regression technique to develop models to adequately predict the compressive strength property of HPC made with recycled coarse aggregate, and these models are further applied to optimize the HPC mixture (i.e. to obtain the most favorable combination of the mixture components obtainable, which produces the desired response or property). In the development of models, a general approach known as the Response Surface Methodology (RSM) was employed in the design of the experiments which were the basis for the development of models. Response Surface Methodology (RSM) is a set of statistical methods used to develop improved or optimized products. The aspect of RSM which found application in this research was the mixture experiment design, this is so because the material of study in this research which is concrete, is a mixture of different components in respective proportions. The mixture experiment design comprises three different types of designs which include the simplex centroid, simplex lattice, and the extreme vertices designs. While the simplex designs involve series of mixture design points, including some design points which may not contain proportions (I.e. zero proportions) of some of the mixture components, the extreme vertices design is a design which must contain proportions of all the mixture components of the mixture at any given design point. Hence, for a concrete mixture, it is necessary to include all the mixture components in respective proportions, thus, the extreme vertices design was the most suitable for the design of the mixture experiment in this research. The experiment design and analysis was performed using the MINITAB 17 statistical software. MINITAB 17 utilized regression analysis method, based on the analysis of variance (ANOVA) and least squares methodology to automatically analyze the data and fit the data to an obtained model.

II. Material and Methods

The materials used in this work to produce mixture samples in the laboratory are Water, cement, silica fume, high range water reducing admixture (HRWRA or superplasticizer), natural coarse aggregate, recycled coarse aggregate, and fine aggregate. Potable water obtained from the strength of materials laboratory at the Cross River State University of Technology, Calabar, was used for all concrete works including curing. Ordinary Portland cement obtained from a local supplier was used for all concrete casting. Silica fume in powdered form; was obtained from a local supplier of assorted concreting materials, having a specific gravity of 2.2. The high range water reducing admixture (superplasticizer) used for this work is called Conplast SP430. It is a chloride free superplasticising admixture based on selected sulphonated napthalene polymers. It is supplied as a brown solution which instantly disperses in water[4]. The natural aggregate used in this work is granite of intrusive igneous rock origin, with a maximum particle size of 20mm. The recycled coarse aggregate was obtained from a demolished concrete structure site in Calabar metropolis. It was free from impurities and dust, and was manually crushed to approximate maximum particle sizes in the range of 20mm – 25mm. The fine aggregate is river sand obtained from the Cross River, through local suppliers. The particle size distribution for the aggregates used in this work was conducted in accordance with BS 1377: Part 2: 1990[5], a summary of other physical properties of aggregates, conducted in accordance with relevant standards.[6,7], are as presented in Table 2.

The mixture experiment approach, which incorporates the extreme vertices design in the design of experiment, and Scheffe's second degree polynomial for mixture experiments, to model the seven (7) component mixture experiment was employed. For a seven (7) component mixture experiment, the Scheffe's second degree polynomial model for mixture experiment contains 28 constant terms and takes the form as shown in equation (1)[8].

$$y = \beta_1 x_1 + \ldots + \beta_7 x_7 + \ldots + \beta_{12} x_1 x_2 + \ldots + \beta_{67} x_6 x_7 + e \qquad (1)$$

Where: βi terms are constants, x terms are the mixture components proportions and, e is the random error, $x_i x_j$ are interaction terms, and y is the studied response property.

A reference mix proportion for the HPC used in the construction of main piers and T-beams of the Confederation Bridge in Canada[1] was selected, and formed the basis on which the upper and lower bounds of mixture components were selected for the extreme vertices design done with MINITAB 17 statistical software. The lower and upper bound volume fractions for the natural coarse aggregate was modified to accommodate the partial replacement with recycled coarse aggregate, and the constraint: 0.4 E + F 0.44 was imposed on the combined coarse aggregates to ensure that the combined volume fractions of both natural and recycled coarse aggregate was not less than 0.4 or more than 0.44 as specified for coarse aggregate in the conventional HPC mixture. Table 1 shows the upper and lower bounds of mixture components selected for this work. The volume fractions of both natural and recycled coarse aggregates were so selected so as to obtain random proportioning of both components in high and low percentages in the experiment design. MINITAB 17[9] produced a total of 81 candidate design points (in terms of volume fractions) from which a random set of 46 design points were

selected and used for the experiment design. The minimum number of design points is 28, according to the number of constant terms in the Scheffe's second degree polynomial for a seven component mixture experiment. In addition to the 28 distinct
mixes needed to estimate the model coefficients, 10 distinct mixes were added to check the adequacy of the model and 8 mixes from the augmented design were replicated mixes; 5 mixes replicated once to test the statistical significance of the fitted coefficients and 1 other mix replicated once for each week of experiment, to check statistical control of the fabrication and measurement process[10], making a total of 46 design points. Using the specific gravity of individual components, the volume fractions were converted to mass and used for batching.
Compressive cube strength test at ages 1 day and 28 days were performed on standard 100mm concrete cubes. The test cubes were prepared in accordance with BS EN 12390-1[11], and specimens were tested in accordance with BS EN 12390-3[12]. The tests were conducted for a total number of 46 mixes. Six cubes were produced for each mix proportion, three each for the 1 day and 28-days compressive strength test, making a total of 276 concrete cubes cast. The cubes were cured in a curing tank for the required days before they were crushed.

Table 1: Upper and Lower bounds of mixture components

Components	**ID**	**Minimum Volume fraction**	**Maximum Volume fraction**
Water	A	0.16	0.185
Cement	B	0.128	0.148
Silica fume	C	0.015	0.029
HRWRA	D	0.0121	0.0401
Natural Coarse aggregate	E	0.060	0.340
Recycled Coarse aggregate	F	0.060	0.340
Fine aggregate	G	0.28	0.3054

The forty-six (46) mix proportions of the HPC in Table 3 were prepared within a period of three weeks. Each batch of concrete was approximately 0.0032m^3 in volume and was prepared manually in a mixing pan.

After all concrete mixes were batched, compressive strength tests conducted, and data (results) obtained from the average of three crushed cubes for each concrete mix, the data were analyzed using MINITAB 17. In the analysis of the data, the first initial analysis performed with MINITAB 17, fitted the data to a quadratic model which included all 28 model terms including linear and quadratic (interaction terms). However, not all these terms were significant enough to be included in the model, hence, model reduction was performed. In order to reduce the model and obtain only significant terms in the model, a hypothesis testing was performed on the coefficients of the model terms. The null hypothesis "H_0" is that the coefficient of a model term is equal to zero ($H_0 = \beta_i = 0$) and should be removed from the model. The alternate hypothesis "H_A" is that the coefficient of the model term is not equal to zero (H_A β_i 0) and can be included in the model. The significance of a model term was judged by the magnitude of its p-value. The p-value is a probability level which was set at 0.05, a p-value less than this value indicated a significant model term whose inclusion in the model will improve it, and a p-value greater than 0.05, indicated a non-significant model term whose inclusion in the model will not improve or have any positive effect on it. Hence, for a p-value of a model term less than 0.05 the null hypothesis was rejected for the alternate hypothesis. The p-values were calculated and presented in the regression table, and the hypothesis tests were carried out by inspecting the p-value of each model term. The model was manually reduced by inspecting the p-values and removing any p-value of terms with insignificant coefficient in each analysis until such a model as there were only significant terms was obtained.

For the optimization procedure, the optimization function of MINITAB 17 was utilized. Optimizer function of MINITAB 17 is a function on MINITAB 17 that could be used to obtain optimum components proportions in mixture experiments. In this study, the optimization function of MINITAB 17 was utilized to obtain a HPC meeting a specified predetermined response property or a combination of response properties simultaneously. The response optimizer function of MINITAB 17 utilizes a mathematical or numerical approach to optimize response properties of mixtures. The mathematical or numerical optimization involves defining an objective function (called desirability or score function) that reflects the levels of each response in terms of minimum (zero) to maximum (one) desirability. For a set target, the desirability of the response is zero below the set target and one at the set target and above. It is an approach that is useful in optimizing multiple responses. An approach to optimization involves transforming each of the response values using a specific desirability function. The individual and composite desirability are used to assess how well a combination of input variables satisfies the goals that have been defined for the responses. Individual desirability (d) evaluates how the settings optimize a single response; composite desirability (D) evaluates how the settings optimize a set of responses overall. Desirability has a range of zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits.

III. Results

In the presentation of results for mixture experiment, the following letters were used to represent each mixture component for convenience: Water (A), Cement (B), silica fume (C), HRWRA (D), natural coarse aggregate (E), recycled coarse aggregate (F), fine aggregate (G).

Table 2: summary of other physical properties of aggregate

Physical Properties	**Aggregate**	
	Natural	**Recycled**
Specific Gravity	2.8	2.49
Aggregate Crushing Value (%)	23.64	28.91
Aggregate Impact Value (%)	20.73	25.17
Moisture Absorption Value (%)	0.0	4.6

Std Order	Run Order	Water (kg/m^3)	Cement (kg/m^3)	Silica Fume (kg/m^3)	HRWRA (l/m^3)	Natural Coarse agg. (kg/m^3)	Recycled Coarse agg.(kg/m^3)	Fine agg. (kg/m^3)	1-day compressive strength (MPa)	28day compressive strength (MPa)
2	1	151.8	382.6	41.5	11.5	159.4	803.3	728.0	18.9	44.2
67	2	151.8	382.6	31.3	11.7	479.8	518.5	740.1	20.5	41.2
78	3	152.2	391.1	32.2	11.9	717.9	307.6	729.1	20.5	46.2
80	4	152.2	383.8	32.2	11.9	717.9	307.6	735.4	23.9	50.5
72	5	152.2	391.1	32.2	11.9	345.9	638.4	729.1	19.2	42.6
26	6	151.8	382.6	41.5	11.5	531.4	472.6	728.0	22.0	51.0
47	7	154.2	382.6	31.3	11.5	903.4	141.8	734.4	22.3	52.6
10	8	156.5	382.6	31.3	11.5	903.4	141.8	728.0	24.7	48.4
46	9	154.2	382.6	31.3	11.5	159.4	803.3	734.4	18.3	42.6
27	10	152.2	383.8	32.2	11.9	352.5	638.4	729.1	19.8	39.4
17	11	151.8	382.6	31.3	13.8	159.4	803.3	734.4	16.7	38.1
69	12	152.6	385.0	33.0	12.3	532.5	473.5	730.1	19.9	40.1
5	13	151.8	382.6	31.3	11.5	159.4	803.3	740.7	19.9	36.5
21	14	151.8	382.6	31.3	16.1	531.4	472.6	728.0	17.7	38.7
35	15	151.8	397.2	31.3	11.5	531.4	472.6	728.0	20.2	47.0
4	16	156.5	382.6	31.3	11.5	159.4	803.3	728.0	19.6	38.2
7	17	151.8	382.6	31.3	11.5	172.4	803.3	728.0	19.9	37.1
73	18	154.5	383.8	32.2	11.9	345.9	638.4	729.1	17.4	40.6
74	19	152.2	383.8	32.2	11.9	345.9	638.4	735.4	22.4	36.2
17	20	151.8	382.6	31.3	13.8	159.4	803.3	734.4	17.9	37.0
60	21	153.4	382.6	34.7	13.0	903.4	141.8	728.0	24.1	47.7
8	22	151.8	382.6	41.5	11.5	903.4	141.8	728.0	26.4	57.4
34	23	151.8	389.9	31.3	11.5	165.9	803.3	728.0	19.5	39.3
1	24	151.8	382.6	31.3	11.5	903.4	153.3	728.0	25.1	53.7
16	25	151.8	382.6	31.3	11.5	531.4	472.6	740.7	22.1	42.3
72	26	152.2	391.1	32.2	11.9	345.9	638.4	729.1	19.7	42.1
12	27	151.8	382.6	31.3	16.1	903.4	141.8	728.0	16.3	44.5
75	28	152.2	383.8	32.2	14.2	345.9	638.4	729.1	14.6	40.1
22	29	151.8	382.6	36.4	11.5	159.4	803.3	734.4	14.9	40.7
38	30	151.8	382.6	31.3	13.8	903.4	141.8	734.4	20.2	47.3

Table 3: Batching weights of mixture components and results for average 1-day compressive strength, and average 28-day compressive strength.

Std Order	Run Order	Water (kg/m^3)	Cement (kg/m^3)	Silica Fume (kg/m^3)	HRWRA (l/m^3)	Natural Coarse agg. (kg/m^3)	Recycled Coarse agg.(kg/m^3)	Fine agg. (kg/m^3)	1-day compressive strength (MPa)	28day compressive strength (MPa)
8	34	151.8	382.6	41.5	11.5	903.4	141.8	728.0	23.8	55.5
79	35	154.5	383.8	32.2	11.9	717.9	307.6	729.1	16.9	42.5
35	36	151.8	397.2	31.3	11.5	531.4	472.6	728.0	20.2	47.0
3	37	151.8	397.2	31.3	11.5	159.4	803.3	728.0	17.9	43.1
50	38	156.5	382.6	31.3	11.5	531.4	472.6	728.0	20.2	44.7
70	39	152.2	383.8	32.2	11.9	717.9	313.4	729.1	18.9	45.5
69	40	152.6	385.0	33.0	12.3	532.5	473.5	730.1	18.8	43.2
69	41	152.6	385.0	33.0	12.3	532.5	473.5	730.1	20.0	43.1
9	42	151.8	397.2	31.3	11.5	903.4	141.8	728.0	22.5	49.2
51	43	153.4	382.6	34.7	13.0	159.4	803.3	728.0	17.0	36.7
24	44	152.2	383.8	32.2	14.2	717.9	307.6	729.1	18.9	43.1
77	45	152.2	383.8	37.3	11.9	717.9	307.6	729.1	22.0	51.7
33	46	151.8	389.9	31.3	11.5	903.4	147.6	728.0	23.0	48.6
Ref 1	0%	153	416	34	11.4	1030	0	737	27.1	60.7
Ref 2	100%	153	416	34	11.4	0	1030	737	22.1	38.7

Table 4: Final regression analysis for 1-day compressive strength

Estimated Regression Coefficients for 1-DAY(MPa)(component proportions)

Term	Coefficients	SE Coef	T	P	VIF
A	480266	99405	*	*	5822040572
B	-178902	138386	*	*	7245336979
C	26523	20319	*	*	2351174
D	25224	20322	*	*	1568435
E	26388	20316	*	*	480130349
F	26375	20316	*	*	471691841
G	-326970	81128	*	*	11832961790
A*B	-3546383	732574	-4.84	0	5253759178
B*G	2758789	761150	3.62	0.001	17306675666

S = 1.40587 PRESS = 113.854

R-Sq = 76.10% R-Sq(pred) = 61.75% R-Sq(adj) = 70.79%

Analysis of Variance for 1-DAY(MPa) (component proportions)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	226.541	226.541	28.318	14.33	0
Linear	6	179.817	226.099	37.683	19.07	0
Quadratic	2	46.724	46.724	23.362	11.82	0
A*B	1	20.759	46.319	46.319	23.44	0
B*G	1	25.965	25.965	25.965	13.14	0.001
Residual Error	36	71.153	71.153	1.976		
Lack-of-Fit	28	62.555	62.555	2.234	2.08	0.141
Pure Error	8	8.598	8.598	1.075		
Total	44	297.694				

Estimated Regression Coefficients for 28-DAY(MPa) (component proportions)

Term	Coefficients	SE Coef	T	P	VIF
A	-158734	64613	*	*	1157840390
B	30767	12330	*	*	27070388
C	31745	12332	*	*	409719
D	213038	86028	*	*	13198612
E	30335	12326	*	*	81531391
F	30298	12326	*	*	84067836
G	-85977	31469	*	*	838464896
A*D	-1146652	539851	-2.12	0.04	13438597
A*G	724715	272950	2.66	0.012	1631899100

S = 2.07153 PRESS = 235.506

R-Sq = 87.15% R-Sq(pred) = 80.95% R-Sq(adj) = 84.38%

Analysis of Variance for 28-DAY(MPa) (component proportions)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	1077.23	1077.23	134.654	31.38	0

Linear	6	1026.56	918.32	153.053	35.67	0
Quadratic	2	50.67	50.67	25.336	5.9	0.006
A*D	1	20.42	19.36	19.36	4.51	0.04
A*G	1	30.25	30.25	30.252	7.05	0.012
Residual Error	37	158.78	158.78	4.291		
Lack-of-Fit	29	136.59	136.59	4.71	1.7	0.221
Pure Error	8	22.19	22.19	2.773		
Total	45	1236				

Table 5: Final regression analysis for 28-day compressive strength

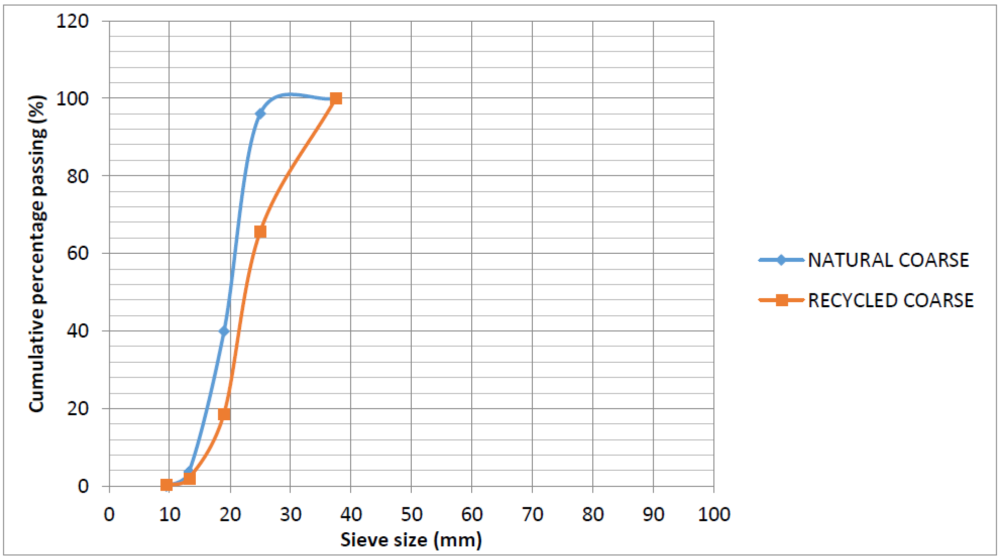

Figure 1: Gradation curves of natural and recycled coarse aggregates

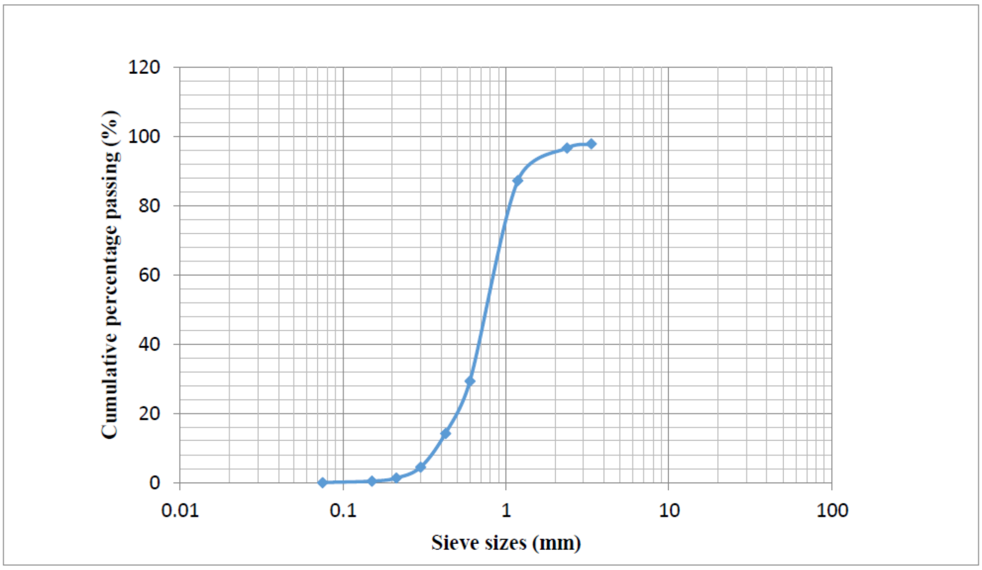

Figure 2: Gradation curve of fine aggregate

IV. Discussion

In Table 2, the aggregate crushing value of the recycled aggregate (28.91%) is higher than that of the natural aggregate (23.63%). This indicates that the recycled aggregate has lower compressive strength than the natural aggregate, however, both meet the limit of specification in BS EN 1097-2:2020.[13] of not greater than 30%. Similarly, the aggregate impact value for recycled aggregate is (25.17%) while that of the natural aggregate is (20.73%). Also, according to BS EN 1097-2:2020, the aggregate impact value of coarse aggregate for use in concrete production shall not exceed 30%, hence both meet the requirement. Also in Table 2, the recycled coarse aggregate has a moisture absorption of 4.6%, for this reason, the recycled coarse aggregate was soaked in water and air dried for a few minutes before being used to bring its moisture condition to the saturated surface dried (SSD) condition. It was necessary to bring the moisture conditions of aggregates to SSD condition so that the batching water will completely be utilized for the hydration of cement and not be absorbed into the pores of aggregates. The zero percent moisture absorption of natural coarse aggregates indicates that the natural aggregates cannot absorb moisture, hence, no need for it to be soaked before use. The moisture absorption of 4.6% for the recycled coarse aggregate, however, is still within the limits of 3.7% to 8.7% as observed by[14], for water absorptions of coarse recycled aggregates.

Figure 1 shows the gradation curves of the natural and recycled coarse aggregates used in this work. The natural coarse aggregate appears to be well graded, and the recycled coarse aggregate, though not as well graded as the natural coarse aggregate, still has an acceptable range of gradation. The fine aggregate on the other hand (Figure 2), gives an almost perfect gradation curve, indicating a well graded nature of particles of fines.

Table 3 shows the batching weights of mixture components and the results for 1-day compressive strength test, and 28-day compressive strength test. For reference purpose, it was observed that a 0% replacement of natural coarse aggregate (I.e. no replacement) in the reference mixture, gave a 1-day and 28-day compressive strength of 27.10MPa and 60.73MPa respectively, and a 100% replacement of natural coarse aggregate (I.e. total replacement) gave a 1-day and 28-day compressive strength of 22.10MPa and 38.66MPa respectively. These were shown in the last two rows of Table 3.

Table 4, and Table 5, show the final regression analysis for 1-day, and 28-days compressive strengths respectively, from the analysis of mixture experiment using the data (results) in Table 3. The coefficients in the final regression tables are the constants in the Scheffe's second degree polynomial for mixture experiment, and were used to formulate the models for 1-day, and 28-days compressive strengths in equations (2) and (3) respectively. The summary statistics S, R^2, R^2 (Pred.), and R^2 (adj.), in the final regression tables give the goodness of fit of the fitted models. The relatively low values of S and high percentage of R^2 (adj.), indicate that the model is a good fit to the data analyzed, and to an extent affirms the validity of the model.

In order to establish the conformity of the developed models to the least square's model assumptions on which the developed models are based, it is necessary to assess the residual plots for compressive strength. This is another and probably more reliable way of validating the developed model. The least square's model assumptions evolve mostly around the error terms in the generated data, and the residuals are the best estimates of error, hence, the assumptions are checked by assessing residual plots[15]. The validity of the model depends on the conformity of the residual plots to least square's model assumptions.

Figure 3 is the residual plot of 28-day compressive strength, the normal probability assesses the normality condition of the residuals, as could be seen, the normal probability plot is approximately linear, hence, the normality condition could be said to be satisfied. The residual versus fit plot is used to assess the linearity condition of the residuals as well as affirm the equal variance condition, and to check for outliers. As seen in the residual versus fit plot, the vertical average of the residuals remains close to 0 as we scan the plot from left to right (this affirms the linearity condition); the vertical spread of the residuals remains approximately constant as we scan the plot from left to right (this affirms the equal variance condition); and there are no excessively outlying points. The conclusions from these analyses indicate the validity of the model of the 28-day compressive strength. Similar analysis was also carried out and used to validate the model of the 1-day compressive strength. The models for 1-day compressive strength (y_1), and 28-day compressive strength (y_2), are given by equations (2), and (3) respectively.

$$y_1 = 480266*A - 178902*B + 26523*C + 25224*D + 26388*E + 26375*F - 326970*G - 3546383(A*B) + 2758789(B*G) \quad (2)$$

$$y_2 = -158734*A + 30767*B + 31745*C + 213038*D + 30335*E + 30298*F - 85977*G - 1146652(A*D) + 724715(A*G) \quad (3)$$

Where the terms A – G represent appropriate volume fractions of the mixture components.

The models developed could be used to obtain an optimized response property desired (i.e. the most favorable combination of mixture components obtainable, which produces the desired response property). However, the response property desired would have to be within the range of response property obtained from laboratory experiment in this work. The model was tested practically by using the response optimizer function of MINITAB 17. Using the model generated, the response optimizer function of MINITAB 17 could predict that when the following components proportions: A=0.160853, B=0.128879, C=0.01579, D=0.012842, E=0.223188, F=0.177639, G=0.28081 are used to prepare a mixture of HPC, the resulting HPC mixture will have a 1-day compressive strength of 20MPa, and a 28-day compressive strength of 45MPa, with individual and composite desirability of 1 respectively. The components proportions given by MINITAB 17 were converted to weights and used for batching in a laboratory experiment, and the laboratory experiments gave a 1-day compressive strength of 19.04MPa, and a 28-day compressive strength of 43.95MPa. As could be seen, the laboratory experimental results are quite close to the predicted strengths from response optimizer. This confirms a high degree of accuracy of the models.

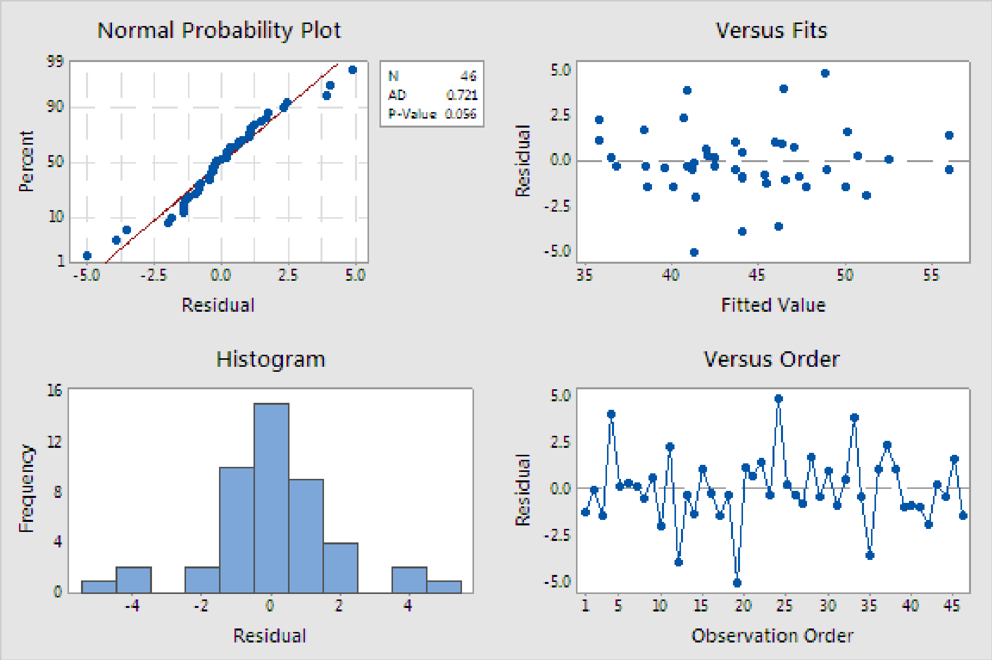

Figure 3: residual plot for 28-days compressive strength

V. Conclusion and Recommendation

Models were developed for 1-day compressive strength, and 28-day compressive strength of high performance recycled coarse aggregate concrete, and these models were used to optimize the HPC. These models are recommended for use in the production of high performance recycled coarse aggregate concrete, however, the range of desired response properties should be within the range of response properties obtained from laboratory experiments in this work, which is 14.6 – 26.4(MPa) for 1-day compressive strength; and 36.2 – 57.4(MPa) for 28-day compressive strength, and the mixture components should be of the same quality as those used in this work.

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