CONCRETE CHARACTERISTICS MODELLING FOR MINIMAL COST AND OPTIMUM PERFORMANCE OF ABUJA HOUSING INFRASTRUCTURES

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ABSTRACT

Abuja has experienced phenomenal infrastructural growth in the last two decades and concrete is at the heart of it. The cost of concrete has increased over the years due to the increased costs of its constituents like aggregates and cement. Many housing projects have slowed down due to the skyrocketing costs. A scientific approach in reducing concrete cost without compromising quality control is investigated. The compressive strength and workability characteristics of concrete mixes from different coarse aggregate sizes were determined in the laboratory. The cost of the mixes as determined from the market prices of the constituents were also determined. The intention was to use the Response Surface Methodology (RSM) to obtain a concrete cost predictive model that can be optimized to link the strength, workability and aggregate sizes to give a minimal cost of the concrete. Statistical packages like SPSS, WEKA and E-Views were used to verify the adequacy of the model. The results from the model show that for all concrete mixes of volume 0.041m$^3$, the optimum cost which is the least and most reasonable cost is made from 25mm size coarse aggregate at NGN29,942.49. It also has the least slump and highest strength for each of the mix ratios of 1:3:6, 1:2:4 and 1:1½:3 after 28 days of curing. This therefore provides the most economical option in terms of cost and quality. The integration of hardened concrete strength, wet concrete workability and aggregate sizes produced a predictive mathematical model for minimal cost, which is recommended for use in cost projection and quality control in Abuja Infrastructural development.

Keywords: Coarse aggregate, Compressive strength, Concrete, Cost, Housing, Model
INTRODUCTION

Abuja, the capital of Nigeria is one of the fastest-growing cities in Africa where massive housing and infrastructural development is ongoing (Abubakar, 2014, Mahmud et al., 2016, Ujoh, 2010). Most of the structures are concrete-based and so, require high quantities of constituents like aggregates. The cost of these materials tremendously increased in the last two decades leading to compromises in quality control. This is attested to by reported cases of building collapses (Ogbemudia et al., 2021). There is a need to scientifically formulate a more economical concrete without compromising quality.

Many works on the strength characteristics of concrete with different aggregate materials and brands of cement are available (Wu et al., 2001), (Waziri et al., 2011), (Abdullahi, 2012), (Ukpata & Ephraim, 2012) and (Meddah et al., 2010).

Aggregates are very important in concrete. They constitute 60% to 80% of concrete volume (Ghasemi, 2017), (Ajamu & Ige, 2015). Increasing the number of aggregates in concrete corresponds to less usage of cement which has several benefits, like. reduction in the cost of producing concrete, decrease in some of the durability problems of hardened concrete, like reducing shrinkage and cracking (And & Ezeagu, 2016). Previous works (Ahmed et al., 2016) show that the cost of concrete mix increases with workability, the maximum size of aggregate, the strength of concrete, and the reduced water-to-cement ratio. Estimating the cost of concrete requires many variables and will vary from location to location or from site to site (BS EN 1992-1-2:2004 ).

Away from the routine method, the adaptive approach here proposes that all elements of the building be modeled in their unit rate form. The various quantities are multiplied by their unit rate cost and subsequently summed up with prime cost items, giving the cost of the building. A major feature of this model is that it can be subjected to further mathematical treatment of change when variables are constrained (Samuel & Snapp, 2015). The cost model in this paper has been restricted to the concrete component used in the city of Abuja

RSM is a technique widely used to optimize various processes (Yolmeh & Jafari, 2017). Also, helpful for fitting the models and analyzing the problems in which quite a lot of independent parameters control the dependent parameter(s) (Khuri, Andre & Cornell, 1996). It has found application in the various areas of the chemical industry, physical and engineering sciences, biological, clinical, and social sciences (Khuri and Andre, 2001). It was used in optimizing the coagulation process (Trinh & Kang, 2010) and performance measures or quality characteristics of industrial products or processes (Dan et al., 2014) and (Myers et al., 2016). It is adopted in the modeling and optimization hereby reported.

This work presents an effort on the development of models for predicting the economical values of concrete mixes while considering the price regimes of the constituent materials in the Abuja environs.

MATERIALS AND METHODS

MATERIALS AND THEIR PREPARATIONS

Materials sourced and used for this research work included Ordinary Portland Cement (OPC) of 42.5R from the “Dangote” brand, water obtained from the distribution network of Abuja Water Board and coarse aggregate of
different sizes obtained from a crushing plant in Mpape, Abuja. In this research work, different sizes of coarse aggregate (10mm, 13mm, 19mm & 25mm) were used to prepare concrete of different mixes common in the study environment (1:1½:3, 1:2:4 and 1:3:6). Concrete cubes in four batches of these mixes were prepared using the four different aggregate sizes. The cost inherent in the preparation of the different concrete cubes was noted before the experimental procedures.

The fine aggregate was sourced from the Gurara River at Yaba, Abuja. Earlier work on the sand presented it as suitable for concreting (Sanusi et al., 2021). The Fine aggregate was washed to remove impurities before use in the dry state. The laboratory equipment used includes a steel cube mold, digital scale, set of BS sieves, Universal Testing Machine (UTM), and poker vibrator. The materials and their properties were characterized using the European Standards (BS EN 1990-2-2007, 2010) and (BS EN 196-3:2005 +A1:2008, 2005)

**TESTS**

**SIEVE ANALYSIS**

The coarse and fine aggregates used were measured and passed through mechanically operated sieves to obtain the coarse aggregate sizes 10.0mm to 25mm respectively. The fine aggregate was graded between 4.75mm (No.4) sieve and 150μmm (No.100). Both activities were in accordance with BS EN 196-6 (2018)

**PROPORTIONING AND MIX RATIOS**

Table 1 shows the proportioning of OPC, fine aggregate and coarse aggregates that gave the various mix ratios. The volume and weight values show that the concrete density is approximately 2,370.73kg/m³.

**Table 1:** Proportioning of mixes for different coarse aggregate sizes

| S/N | Aggregate Size (mm) | Mix-ratio | No. of cubes | Vol. (m³) | Eqwiv. Wt. (kg) | Cement Qty. | Fine-Agg. Qty. (kg) | Coarse-Agg. Qty. (kg) | Water Cont. (kg) |
|-----|---------------------|-----------|--------------|-----------|-----------------|--------------|---------------------|----------------------|-----------------|
| 1   | 10                  | 1 3 6     | 12           | 0.041     | 97.2            | 9.72         | 29.16               | 58.32                | 5.35            |
| 2   | 10                  | 1 2 4     | 12           | 0.041     | 97.2            | 13.89        | 27.77               | 55.54                | 7.64            |
| 3   | 10                  | 1 1.5 3   | 12           | 0.041     | 97.2            | 17.67        | 26.51               | 53.02                | 9.72            |
| 4   | 13                  | 1 3 6     | 12           | 0.041     | 97.2            | 9.72         | 29.16               | 58.32                | 5.35            |
| 5   | 13                  | 1 2 4     | 12           | 0.041     | 97.2            | 13.89        | 27.77               | 55.54                | 7.64            |
| 6   | 13                  | 1 1.5 3   | 12           | 0.041     | 97.2            | 17.67        | 26.51               | 53.02                | 9.72            |
| 7   | 19                  | 1 3 6     | 12           | 0.041     | 97.2            | 9.72         | 29.16               | 58.32                | 5.35            |
| 8   | 19                  | 1 2 4     | 12           | 0.041     | 97.2            | 13.89        | 27.77               | 55.54                | 7.64            |
| 9   | 19                  | 1 1.5 3   | 12           | 0.041     | 97.2            | 17.67        | 26.51               | 53.02                | 9.72            |
| 10  | 25                  | 1 3 6     | 12           | 0.041     | 97.2            | 9.72         | 29.16               | 58.32                | 5.35            |
| 11  | 25                  | 1 2 4     | 12           | 0.041     | 97.2            | 13.89        | 27.77               | 55.54                | 7.64            |
| 12  | 25                  | 1 1.5 3   | 12           | 0.041     | 97.2            | 17.67        | 26.51               | 53.02                | 9.72            |
WORKABILITY
The slump test on fresh concrete was carried out by the standard test method for slump hydraulic-cement concrete as outlined in the relevant codes (BS EN 12350-2:2009-Testing Fresh Concrete, Part 2: Slump Test, 2009) for the different mixes used for this research work. Measurements of the corresponding reduction in height of the compacted volume of fresh concrete immediately after removing the slump cone were recorded as slump values for the mix.

COMPRESSIVE STRENGTH TESTS
A compressive strength test was conducted on each of the 150x150x150mm cube samples produced from the three mix ratios respectively. The water-cement (w/c) ratio adopted was 0.55 based on the concrete mix design manual of COREN (COREN, 2017). The UTM by BS EN (BS-EN 12390-3-2009, 2009) was used to crush the cubes after 28 days of curing by ponding.

COST OF CONCRETE
The cumulative unit cost of producing batches of 150x150x150mm concrete cubes was computed from the cost of laboratory inputs and recorded per cubic meter. The cost of production of concrete used in this research work is a function of the constituent materials (cement, fine aggregate, coarse aggregate, and water) as well as 15% provision (which generally represents the mark-up rate in the Abuja area but excludes tax) for handling which encompasses production cost and fees associated with preparing the surface. The observed cost values obtained for each concrete mix were required for modeling cost variabilities to aggregate sizes, compressive strength, and workability values. Tables of mix ratios to cost are presented in Tables 1, 2, and 3: These values represent the market rates of the time (2020) and can be applied to all the coarse aggregates.

Table 1: Determination of Cost of 1:3:6 Mix Design.

| Material       | Ratio | Weight (Kg) | Rate (NGN) | Amount (NGN) | Cube Volume (m$^3$) | Rate/m$^3$ (NGN) |
|----------------|-------|-------------|------------|--------------|---------------------|------------------|
| Cement         | 1.0   | 0.806       | 51.00      | 41.12        | 0.003375            | 12,183.70        |
| Fine-Aggregate | 3.0   | 2.418       | 3.10       | 7.50         | 0.003375            | 2,222.22         |
| Coarse-Aggregate | 6.0 | 4.837       | 3.00       | 14.52        | 0.003375            | 4,302.22         |
| Water          | 0.55  | 0.443       | 0.15       | 0.07         | 0.003375            | 20.74            |
| Handling       |       |             |            | 9.48         | 0.003375            | 2,809.33         |
| Total          |       | 8.505       |            | 72.69        | 0.003375            | 21,538.22        |

Note: NGN denotes Nigerian Naira

Table 2: Determination of Cost of 1:2:4 Mix Design.

| Material       | Ratio | Weight (Kg) | Rate (NGN) | Amount (NGN) | Cube Volume (m$^3$) | Rate/m$^3$ (NGN) |
|----------------|-------|-------------|------------|--------------|---------------------|------------------|
| Cement         | 1.0   | 1.124       | 51.00      | 57.46        | 0.003375            | 17,025.19        |
| Fine-Aggregate | 2.0   | 2.253       | 3.10       | 6.99         | 0.003375            | 2,071.11         |
| Coarse-Aggregate | 4.0 | 4.506       | 3.00       | 13.52        | 0.003375            | 4,005.93         |
| Water          | 0.55  | 0.55        | 0.15       | 0.10         | 0.003375            | 29.63            |
| Handling       |       |             |            | 11.71        | 0.003375            | 3,469.78         |
| Total          |       | 89.78       |            | 26,601.63    | 0.003375            | 26,601.63        |

Note: NGN denotes Nigerian Naira
Table 3: Determination of Cost of 1:1½:3 Mix Design.

| Material       | Ratio | Weight (Kg) | Rate (NGN) | Amount (NGN) | Cube Volume (m³) | Rate/m³ (NGN) |
|----------------|-------|-------------|------------|--------------|------------------|---------------|
| Cement         | 1.0   | 1.406       | 51.00      | 71.70        | 0.003375         | 21,224.44     |
| Fine-Aggregate | 1.5   | 2.109       | 3.10       | 6.54         | 0.003375         | 1,937.78      |
| Coarse-Aggregate | 3.0   | 4.217       | 3.00       | 12.66        | 0.003375         | 3,751.11      |
| Water          | 0.55  | 0.773       | 0.15       | 0.12         | 0.003375         | 35.56         |
| Handling       |       | 8.505       | 104.67     |              |                  | 31,014.22     |

Note: NGN denotes Nigerian Naira

PREDICTIVE COST MODEL DEVELOPMENT

Results obtained from the laboratory were combined by procedures of multiple regression. Independent variables used in the cost-model formulation were compressive strength, aggregate size, and slump value. Multiple regression method based on the RSM was implemented by using software applications “E-views” and “Weka”. The resulting model for 28th-day strength values was tested using recommended slump values in BS EN 12350-2:2009). Four models were developed for the 28-day concrete using E-Views, SPSS, Weka, and Microsoft Excel. The cost of production was taken as the dependent variable. The values of the coefficient of determination of the various models were recorded for each model.

RESULTS AND DISCUSSIONS

PRELIMINARY MATERIAL ANALYSIS

Particle size distribution plot of the fine aggregate indicates values of uniformity coefficient $C_u$ and coefficient of curvature $C_z$ of 8.10 and 3.07 respectively. With $C_u$ above 8 and the absence of particles lower than 0.02mm (clay), it is considered well-graded and suitable for use by British standards (BS, 1990). Figure 1 shows the grading plot. The grading Tables are available on demand.

![Particle Size Distribution Curves of Fine and Coarse Aggregate Samples.](image-url)
RELATIONSHIP BETWEEN COMPRESSION STRENGTH AND WORKABILITY OF SAMPLES

Table 4 shows the values of the slump, and compressive strength ($\sigma$) for each of the concrete mixes at 28 days and with the different aggregate sizes. It also presents the cost of concrete samples per volume.

Table 4: Slump, compressive strength, and cost values of concrete mixes with various coarse aggregate sizes

| Mix ratio | 1:3:6 | 1:2:4 | 1:1½:3 |
|-----------|-------|-------|--------|
| Aggregate Size (mm) | Slump | $\sigma$ | cost | Slump | $\sigma$ | cost | Slump | $\sigma$ | cost |
| 10        | 31.5  | 14.1  | 21.54  | 23.5  | 22.1  | 26.61  | 18.6  | 24.0  | 31.02 |
| 13        | 28.4  | 15.6  | 21.54  | 20.8  | 22.8  | 26.61  | 16.2  | 27.6  | 31.02 |
| 19        | 26.0  | 16.6  | 21.54  | 18.5  | 23.8  | 26.61  | 14.6  | 29.4  | 31.02 |
| 25        | 23.3  | 17.4  | 21.54  | 16.7  | 25.5  | 26.61  | 13.1  | 30.6  | 31.02 |

Table 4 shows compressive strength decreased generally as the slump increased, in a linear relationship. There is also a general decline in a slump with a corresponding increase in coarse aggregate sizes. This is not unexpected because of the higher water content associated with less rich concrete mixes and smaller size coarse aggregates (Neville, 2003).

COMPRESSIVE STRENGTH AND COARSE AGGREGATE SIZE

From Table 4, a plot of the relationship between compressive strength and coarse aggregate size for the 1:1½:3 mix is a non-linear logarithmic one as shown in Figure 2. This is the trend in the three mixes. There is an increase in compressive strength with a corresponding increase in aggregate sizes. Regression analysis produced a logarithmic curve with a coefficient of determination ($R^2$) of 91.88%. These results are by the standards of the American Concrete Institute (ACI, 2002).

\[
y = 6.8419\ln(x) + 9.0676
\]

\[
R^2 = 0.9188
\]

Figure 2: Relationship of compressive strength with aggregate size for 1:1½:3 mix

COST ANALYSIS OF MIXES WITH VARIATION IN AGGREGATE SIZE AND COMPRESSION STRENGTH

From Table 4, it is observed that the cost only varies with mixed proportions and not with aggregate sizes, as presented in Tables 1 – 3. Compressive strength also increased with richer mixes.
A plot of compressive strength against the cost of concrete production as shown in Figure 3 for 1:1½:3 mix indicate the higher financial implication of producing richer mixes and by implication, higher grades of concrete. The increase is in a non-linear manner with an $R^2$ of 99.89%. The trend is the same for the other two mixes.

![Graph showing compressive strength vs cost for 1:1½:3 mix](image)

Figure 3: Relationship of compressive strength with the cost for 1:1½:3 mix

**COMPARATIVE COST DISTRIBUTION OF AGGREGATE SIZES IN CONCRETE.**

Analysis of the cost of representative aggregate quantities required for the production of sample cubes was obtained from the coarse aggregate size distribution of the whole all-in-aggregate from the open market. Table 5 shows the breakdown of size distribution and equivalent cost while Figure 4 shows the graphical representation. The cost of aggregate sizes below 10mm was redistributed among the four aggregate sizes. The regression curve follows a quadratic pattern with $R^2$ of 97.38%. Optimisation computations on the regression model showed that 16mm aggregate size presented the highest cost in all mixes as seen in Figure 4. The implication of this is to minimize the use of 16mm coarse aggregates in Abuja if cost is in consideration.

**Table 5: Cost Distribution of Aggregate Sizes in Concrete**

| Aggregate Size (mm) | Wt. Retained (g) | % Completion | Rate (NGN/kg) | Rate (NGN/kg) Actual Rate (NGN) | Rate |
|---------------------|------------------|--------------|---------------|-------------------------------|------|
| 25                  | 46.1             | 4.39%        | 0.14          | 0.0017                        | 0.14 |
| 19                  | 331.97           | 31.62%       | 0.98          | 0.0120                        | 0.99 |
| 13                  | 405.28           | 38.60%       | 1.20          | 0.0147                        | 1.21 |
| 10                  | 253.92           | 24.18%       | 0.75          | 0.0092                        | 0.76 |
| Below 10            | 12.73            | 1.21%        | 0.04          | Cost of aggregate size below 10mm redistributed |      |
|                     | 1050             |              | 3.10          |                               | 3.10 |
MODELLING OF COST

EViews, SPSS, Weka, and Microsoft Excel applications were used in procuring an empirical model that incorporates cost per volume as the dependent variable and compressive strength, aggregate size, and workability as independent variables for use in determining the cost of concrete. In general, the surface response model analysis of selected concrete parameters takes the form shown in equation (1):

\[
\text{cost per unit volume} = \gamma_0 + \gamma_1(\text{slump value}) + \gamma_2(\text{compressive value}) + \gamma_3(\text{aggregate size})
\]

Where; \(\gamma_0, \gamma_1, \gamma_2, \gamma_3\) represent modification factors.

Table 6 shows the coefficients from the modeling applications.

**Table 6**: Summary of Coefficients obtained from Different Cost Predictive Models on 28-day Strength.

| Modeling Application | Compressive Strength | Aggregate Size | Slump Value | Constant     |
|----------------------|----------------------|----------------|-------------|--------------|
| E-Views              | 114.96               | -315.91        | -665.62     | 43,038.39    |
| SPSS                 | 115.10               | -315.89        | -665.48     | 43,032.29    |
| WEKA                 | 115.10               | -315.89        | -665.48     | 43,032.29    |
| Microsoft-Excel      | 115.10               | -315.89        | -665.48     | 43,032.29    |

With equation (1) and the coefficients in Table 6, equation (2) is derived using SPSS, WEKA, and Microsoft Excel. They also have coefficients of determination, \(R^2 = 97.0, 96.99, \text{and } 96.7\) respectively.

\[
\frac{\text{Cost}}{\text{m}^3} = 115.1 \text{ Compressive Strength} - 315.89 \text{ Aggregate Size} - 665.48 \text{ Slump Value} + 43,032.29
\]

(2)

With the use of the E-Views Software Application, a second equation (3) is derived with coefficients of determination, \(R^2 = 96.7\)
\[
\text{Cost} = 114.96 \text{ Compressive Strength} - 315.91 \text{ Aggregate Size} - 665.62 \text{ Slump Value} + 43,038.39
\]

Model (2) may be adopted over (3) due to higher values of R². When sample laboratory results in values were inputted into equation (2), the predicted costs from the model are shown in Table 7. The values are very close to the manually determined costs that are shown in Tables 1, 2, and 3. This validates the predictive model as a useful tool for cost and quality control forecasting in concrete production.

**Table 7: Summary of Model-Generated Costs for All Concrete Mixes**

| Mix ratio | 1:3:6 | 1:2:4 | 1:1½:3 |
|-----------|-------|-------|--------|
| Aggregate size | Slump (mm) | \(\sigma\) (N/mm\(^2\)) | Predicted cost from model (NGN) | Slump (mm) | \(\sigma\) (N/mm\(^2\)) | Predicted cost from model (NGN) | Slump (mm) | \(\sigma\) (N/mm\(^2\)) | Predicted cost from model (NGN) |
| 10 | 31.50 | 14.10 | 20,533.30 | 23.50 | 22.10 | 26,777.94 | 18.60 | 24.00 | 30,257.90 |
| 13 | 28.40 | 15.60 | 21,821.46 | 20.80 | 22.81 | 27,709.03 | 16.20 | 27.67 | 31,329.59 |
| 19 | 26.00 | 16.57 | 21,635.06 | 18.50 | 23.77 | 27,454.92 | 14.60 | 29.43 | 30,701.51 |
| 25 | 23.30 | 17.44 | 21,636.85 | 16.70 | 24.87 | 26,884.09 | 13.10 | 30.63 | 29,942.49 |

**CONCLUSIONS**

Many laboratories and computational efforts invested in this research produced a mathematical model that gives a scientific approach to predicting the minimized cost of concrete if certain variables are known. The conclusion can therefore be presented as follows:

1. A mathematical model developed from the Response Surface Methodology (RSM) was formulated and optimized to compute the minimized cost of concrete when the size of the coarse aggregate, the slump of the fresh concrete, and the compressive strength of the hardened concrete are known.
2. The size of coarse aggregates has an impact on the compressive strength and cost of concrete. Also, the optimum cost which is the least and most reasonable cost is made from 25mm size coarse aggregate at NGN29,942.49. It has the least slump and highest strength for each mixing ratio respectively. This, therefore, provides the most economical option in terms of cost and quality.
3. Promoters of infrastructural development with concrete as a major input in Abuja, Nigeria may use the predictive model so formulated to address quality of work and cost minimization.

**RECOMMENDATIONS**

1. More work could be done by incorporating more quality control parameters and reducing or varying the assumed 15% provision for handling which encompasses production cost and fees for more exact cost values.
2. Similar work could be done on other concrete mixes, mortar, and other construction composite materials.
CONFLICT OF INTEREST
There is no conflict of interest in the course of this research and the manuscript preparation

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