Optimizing the compressive strength of binary mixtures of laterite-sand cement mortar

Adeshina Adetona[1] and Timothy Alao[2]

[1, 2]*Department of Building, Federal University of Technology, Minna*
[1]tonadayox@gmail.com [2]timothy.alao@futminna.edu.ng

Abstract:
The use of conventional cement-sand material for the production of mortar for permanent ferro-cement formworks and bedding & jointing sandcrete block walls has been in use as traditional material. An attempt to substitute partially, with binary mixtures of laterite to introduce both cement and plastic bonds as a property of the composite material is proposed to reduce the cost of cement, the binder. A methodology for specification writing procedure using a computational approach is introduced using the Central Composite Design mixture experimental design (CCD). The properties of the composite material were investigated and found to satisfy basic NIS standards. It enabled lower cement contents with corresponding higher minimum compressive strength to be achieved, which is well above the minimum requirement of 2.8 N/mm^2 NIS standards, thus making the replacements suitable for permanent ferro-cement and bedding & jointing masonry works.

Keywords: mortar, binary, compressive, bedding and jointing

1.0 Introduction

Conventional cement-sand mortar for bedding and jointing block walls or for permanent ferro-cement formworks is a composite material obtained by mixing cement, fine aggregate and water. Introducing alternative materials or blending are primarily aimed at improving the properties or for cost reduction, and it requires developing basis to confirm the acceptability of its properties for a series of acceptance criteria (Biju et al., 2018; BS EN 771-1: 2011). Cement-sand mortar for bedding and jointing is an integral total of the cost of block wall per square metre. Apart from bedding and jointing purposes, the composite material is also responsible for creating a uniform stress distribution of dead loads from the block walls and therefore the knowledge of both its wet and hardened properties is fundamental (Vladimir et al., 2011). The uniqueness in the use of laterite as a partial replacement of sand is its plasticity characteristics, thereby introducing both cement and plastic bonds in the composite material, to obtain high workability, plastic and cheaper mix at low cement content. Cement-sand mortars are also used as a basic finishing material on block walls such as plastering, rendering and/or on screeded beds, as a ferro-cement material and also blended with laterites for moulding sandcrete blocks (Kolapo et al., 2007; Joshua et al., 2014). Its usage is tied to good sound insulation and resistibility to water penetration. A specifications writing procedure is presented in order to obtain this improved characteristic properties of introducing 'plastic and cement bonds'

Constituent proportions selection for cement-sand mortar is necessary to achieve expected properties. Such properties include particle size distribution, specific gravity, shape and surface texture. They influence both the properties of the mortar in both their fresh and hardened states (BS EN 933-1: 2012).

2.1 Grading and sources of sand for cement-sand mortar production

Fine aggregates referred to as sand is generally described as aggregates passing 4.75 mm aperture size openings and retained on 75 microns sieve openings irrespective of their source. The requirement is that it should generally be free from silt, clay and deleterious substances. It can be sourced from a river bed or erosion sand, crushed stones or naturally deposited (Neville, 1993). The result of sieve analysis, otherwise called gradation describes the distribution of the particle sizes usually represented on a log-linear graph. The vertical scale, called the ordinate represents the percentage passing, and the horizontal scale called the abscissa on a log scale, represents the size. Visually, the continuous curve represents a well-graded deposit with all the size ranges present in the deposit.

BS 812 (1990) classification uses four grading bandwidths called grading zones over which a grading curve should lie within it. The zones are 1, 2, 3 and 4. Plaster sand called Zone 4 is almost naturally occurring while others can be sourced from river beds or as erosion soil (Neville, 1993). In contrast, BS EN 933-1: 2012 uses three classifications for sand. These include coarse sand with grain size within 2 to 4.75 mm range, medium sand with grain size within 0.425 to 2 mm range and fine sand with a grain size up to 0.425 mm.

Fine aggregates are classified primarily based on gradation requirements which are a reflection of the specific surface, which represents the surface area per unit weight of aggregate. Specific surface increases with the reduction in the size of the aggregate particle. This is a reflection of the fundamental proposition that the surface area of an equivalent sphere is proportional to the second power of its diameter. The volume is therefore proportional to the third power of its diameter, which implies that the specific surface is inversely proportional to its diameter, that is:

$$A \propto d^2 \qquad (1a)$$

$$V \propto d^3 \qquad (1b)$$

$$SP \propto \frac{1}{d} \qquad (1c)$$

$$where\ d = diameter, A = surface\ area, V = volume\ and\ SP = specific\ surface$$

This proposition, however, does not hold with laterite soils and its composites because the cementing materials themselves depend on the mineralogical composition. This implies that the finer the particle size, the higher the specific surface.

The ASTM method of classification of soil grades uses the fineness modulus, which is a dimensionless quantity obtained as a total cumulative percentage passing divided by 100. The higher the value of a fineness modulus, the coarser the grading.

2.2 Blending laterites for cement-sand mortar production

Earlier definition of laterite according to Gidigasu (1976) is described as a light to dark homogeneous, vesicular, unstratified and clinker-like soil material consisting mainly of oxides and hydroxides of aluminium, iron, manganese and silica. It hardens on extraction and exposure. It is described as a class of pedogenics where the cementing materials are the sesquioxides content and should typically constitute not less than 50 per cent of the mineralogical composition (Singh, 2006; Aguwa, 2009). The process called blending is primarily used in road works where lateritic materials from different sources with different properties are used. The combination from two different sources are aimed at re-confirming if desired specification requirement such as plasticity or grading are met. In road base and sub-base designs, a graphical method for proportioning laterite materials from sources have been well developed, (Singh, 2006). Here, laterite material is used to replace a percentage of sand in the composite material.

This lateritic material in its natural form is cementitious possessing plastic bonds in itself even without the addition of cement. However, where the plasticity index, a physical property of the material is in excess of 20 per cent, it is suggested that lime should be added to allow for flocculation of the clay particles (Singh, 2006).

Among notable reference classification systems of laterites are the Unified Soil Classification System (USCS) and the American Association of State Highways and Transport Officials (AASHTO) soil classification reference data. The BS 1377 (1990) is a commonly used laboratory method for carrying out physical properties of laterites to obtain the level of plasticity of the sample, notably the liquid limit, plastic limit, plasticity index and shrinkage limit tests.

2.3 Workability of mortars

Workability of mortars, a wet property of the mixture influences the ease with which masons carry out both mixing and placing as well as the property of the hardened property such as compressive strength, bond strength and durability. Plasticity and cohesion are difficult to measure in-situ; consistency test is therefore frequently used as a measure of the workability (Neville, 1993).

2.4 Cement

Cement, a binder is generally a calcareous (lime) and an argillaceous (silica and alumina) material (Neville, 1993). It is the most used material for bonding aggregates and fragments together in cement-sand composite material. Portland cement products are manufactured in a carefully controlled process. However, as a result of environmental pollution, a modification in the manufacturing process to reduce carbon emission has evolved by adding up to 5% limestone in the course of clinker grinding to produce what is known as a Portland limestone cement in accordance with BS EN 197-1: 2016.

2.4 The central composite design (ccd) quadratic model

This is a mixture experimental design employed for modelling responses of interest as a second-order quadratic model and has gained increasing wider application in mix design for concrete composites (Simon et al,. 1999). The second-order quadratic model takes the form (Montgomery, 2001)

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum\sum_{i<j} \beta_{ij} x_i x_j + \sum_{i}^{k} \beta_{ii} x_i^2 \qquad (2)$$

where *"y"* is the response of interest. The values x_i and x_j are the components. The value β_0 is the intercept, and the parameters β_i and β_{ij} represent the linear and quadratic coefficients fitting the mixture experimental data for both the linear and interactive terms, respectively. The technique is commonly used in mixture proportioning, particularly to develop, improve and also optimize the constituent mixture proportions.

There CCD is a scheme with a characteristic rotatability design which implies that predicted values should have equal variance at locations equidistant from the origin (Montgomery, 2001). A CCD run specifies a $2^n + 2n + 1$ design points for a full quadratic model with n factors, representing the factorial, the axial and centre points. The inclusion of the axial points, alpha (α) is primarily to account for any missing linear expression in the second-order quadratic model.

The experimental region can be designed by a simple lower and upper limits on the design variables of the type:

$$x_{\boldsymbol{il}} \le x_i \le x_{\boldsymbol{iu}} \qquad i = 1, \dots, n$$

where x_{il} and x_{iu} represent lower and upper bound of the variables. The coded variable x_i is represented as

$$x_i = \frac{2x_i' - x_{il} - x_{iu}}{x_{iu} - x_{il}} \tag{3}$$

and the normalized coded variable $\boldsymbol{x_i}$ can now be bonded within the cube as

$$-1 \le x_i \le 1$$

This represents a dimensionless coded variable which can also be translated to actual variables using the expression:

$$x_{\boldsymbol{actual}} = x_{min} + \frac{(x_{coded} + 1)}{2} * (x_{max} - x_{min}) \tag{4}$$

where x_{actual} is the uncoded value, and x_{min} and x_{max} represent the uncoded lower and upper values corresponding to ±1 coded values. The construction of this design matrix is also implementable using the Design Expert statistical software (Design Expert, 2000). The advantage of this type of experimental design procedure is that it has an important implication for specification writing, especially in site production. It can yield a target strength which implies that at least 95 per cent of the results are expected to fall within the normal distribution curve, with probability $p \le 0.05$

3.1 Methodology

The samples were produced using 50mm x 50mm x 50mm cube mould specimen samples preparation. The specimen sample size corresponding to the design points which corresponds to 20 runs of centre and non-centre points.

3.2 Portland cement

Ordinary Portland Limestone Cement Grade 42.5 produced by Dangote Cement Company was purchased from within the Minna building materials market, Niger State, and was used as the binder.

3.3 Fine aggregate

The fine aggregate used for the investigation was medium sand complying with BS EN 933-1: 2012. These characterization tests were conducted to classify the sample such as sieve analysis, specific gravity and bulk density. The fine aggregate sample is continuously graded and in air-dry condition

3.4 Estimation of constituent proportions

The absolute volume method was used for estimating the mixture proportions using Equation 5 (Neville, 1993)

$$\frac{water}{Gs_{water} \times 1000} + \frac{cement}{Gs_{cement} \times 1000} + \frac{sand + laterite}{Gs_{sand+lat} \times 1000} = 1 \qquad (5)$$

$\boldsymbol{w}here\ Gs = specific\ gravity\ of\ 1.0, 3.15\ and\ 2.62\ for\ water, cement\ and\ 'sand + laterite'\ respectively$

A starting water-cement ratio of 0.5 was used for the estimation of the quantities. It was later revised to reflect the mixing water required to obtain the needed workability using the flow metre apparatus. The mixing water was used to recalculate the proportions in Equation 5. The resulting proportions for the lower and upper limits on water, cement and aggregates are shown in Equation 6

$$\left.\begin{array}{l} 0.263 \leq x_1 \leq 0.277 \\ 0.056 \leq x_2 \leq 0.090 \\ 0.647 \leq x_3 \leq 0.668 \end{array}\right\} \quad CCD_{CONTROL}; \quad (6a)$$

$$\left.\begin{array}{l} 0.340 \leq x_1 \leq 0.377 \\ 0.051 \leq x_2 \leq 0.076 \\ 0.547 \leq x_3 \leq 0.609 \end{array}\right\} \quad CCD_{BINARY}; \quad (6b)$$

4.0 Results and discussion

The mixture proportions both in coded and actual variables for cement-sand mortar mixes for the control, and binary mixtures are shown in Tables 1 and 2. Columns 1, 2 and 3 represent the experimental numbers in the standard order, the corresponding factorial point and the value of the coded variables, respectively. Similarly, columns 4, 5 and 6 represent the value of the actual variables corresponding to the design points, the responses at 7 and 28 days, respectively.

Table 1: Mixture proportions in coded and actual variables for cement-sand control mixture

(1)	(2)	(3)			(4)			(5)	(6)
The design matrix		x_1=water; x_2=cement			x_3=sand (control)			$Y_1=f_{c7}$	$Y_2=f_{c28}$
		Variables						Response	
		coded			actual (kg)			N/mm^2	N/mm^2
Experiment no.	Point	x_1	x_2	x_3	x_1	x_2	x_3	Y_1	Y_2
1	Factorial	-1	-1	-1	262.89	175.00	1696.10	6.88	7.47
2	Factorial	1	-1	-1	276.50	175.00	1696.10	3.31	4.96
3	Factorial	-1	1	-1	262.89	282.68	1696.10	6.51	8.56
4	Factorial	1	1	-1	276.50	282.68	1696.10	6.44	7.92
5	Factorial	-1	-1	1	262.89	175.00	1750.01	2.93	4.59
6	Factorial	1	-1	1	276.50	175.00	1750.01	3.84	6.16
7	Factorial	-1	1	1	262.89	282.68	1750.01	9.00	10.41
8	Factorial	1	1	1	276.50	282.68	1750.01	9.29	11.32
9	Axial	-1.682	0	0	258.25	228.84	1723.05	5.00	7.52
10	Axial	1.682	0	0	281.14	228.84	1723.05	4.41	9.36
11	Axial	0	-1.682	0	269.70	138.28	1723.05	2.93	4.48
12	Axial	0	1.682	0	269.70	319.40	1723.05	11.61	15.76
13	Axial	0	0	-1.682	269.70	228.84	1677.71	7.56	12.00
14	Axial	0	0	1.682	269.70	228.84	1768.39	5.87	7.77
15	Centre	0	0	0	269.70	228.84	1723.05	5.21	8.37
16	Centre	0	0	0	269.70	228.84	1723.05	5.23	8.36
17	Centre	0	0	0	269.70	228.84	1723.05	5.37	8.36
18	Centre	0	0	0	269.70	228.84	1723.05	5.32	8.37
19	Centre	0	0	0	269.70	228.84	1723.05	5.37	8.37
20	Centre	0	0	0	269.70	228.84	1723.05	5.32	8.37

Table 2: Mixture proportions in coded and actual variables for binary cement sand mixture

(1)	(2)	(3)			(4)			(5)	(6)
The ccd design matrix		x_1=water; x_2=cement			x_3=sand + laterite (binary)			$Y_1=f_{c7}$	$Y_2=f_{c28}$
		Variables						Response	
		coded			actual (kg)			N/mm^2	N/mm^2
Experiment no.	Point	x_1	x_2	x_3	x_1	x_2	x_3	Y_1	Y_2
1	Factorial	-1	-1	-1	340.03	159.64	1432.82	3.76	6.68
2	Factorial	1	-1	-1	377.31	159.64	1432.82	3.36	6.15
3	Factorial	-1	1	-1	340.03	238.80	1432.82	4.44	6.75
4	Factorial	1	1	-1	377.31	238.80	1432.82	5.04	7.33
5	Factorial	-1	-1	1	340.03	159.64	1596.36	3.77	6.07
6	Factorial	1	-1	1	377.31	159.64	1596.36	3.44	5.97
7	Factorial	-1	1	1	340.03	238.80	1596.36	5.47	8.36
8	Factorial	1	1	1	377.31	238.80	1596.36	4.96	8.19
9	Axial	-1.682	0	0	327.31	199.22	1514.59	4.32	7.80
10	Axial	1.682	0	0	390.02	199.22	1514.59	3.72	7.15
11	Axial	0	-1.682	0	358.67	132.64	1514.59	2.72	5.84
12	Axial	0	1.682	0	358.67	265.80	1514.59	5.16	7.80
13	Axial	0	0	-1.682	358.67	199.22	1377.06	3.67	6.44
14	Axial	0	0	1.682	358.67	199.22	1652.12	4.00	6.21
15	Centre	0	0	0	358.67	199.22	1514.59	4.04	7.05
16	Centre	0	0	0	358.67	199.22	1514.59	4.05	7.03
17	Centre	0	0	0	358.67	199.22	1514.59	4.05	6.97
18	Centre	0	0	0	358.67	199.22	1514.59	4.05	7.03
19	Centre	0	0	0	358.67	199.22	1514.59	4.05	7.15
20	Centre	0	0	0	358.67	199.22	1514.59	4.04	7.04

The models that explain the fitted data are as shown in Equations 7 and 8, which represents the response predictions for mortar strength at 7 and 28 days for cement sand mortar and binary mixtures of sand/laterite mixtures. By default, the CCD model consists of a constant term and a coefficient of the variable term which describes the responses from input data. This model represents the statistical significance with a low probability value of $p \leq 0.05$ and shows that both the model, the coefficient and the intercept are significant and should be included in the model.

$$f control; \qquad fc7 = -3.11682 + 0.039274 * Cement \qquad (7a)$$

$$f control; \qquad fc28 = -2.16033 + 0.046255 * Cement \qquad (7b)$$

$$f binary; \qquad fc7 = 0.54007 + 0.017899 * Cement \qquad (8a)$$

$$f binary; \qquad fc28 = 3.61276 + 0.016751 * Cement \qquad (8b)$$

Contour plots for the response predictions can also be produced, which can then be used to identify the conditions that give the extremum visually in one-dimensional view. A contour plot is a graphical representation which shows only two (2) components at a time by default. In these models, the interaction terms are not included because they are not significant in the model. The general form of the second-order quadratic model is of the form: $a + bx$. Sample contour plot 28-day compressive strength result for the control mix is shown in Figure 1

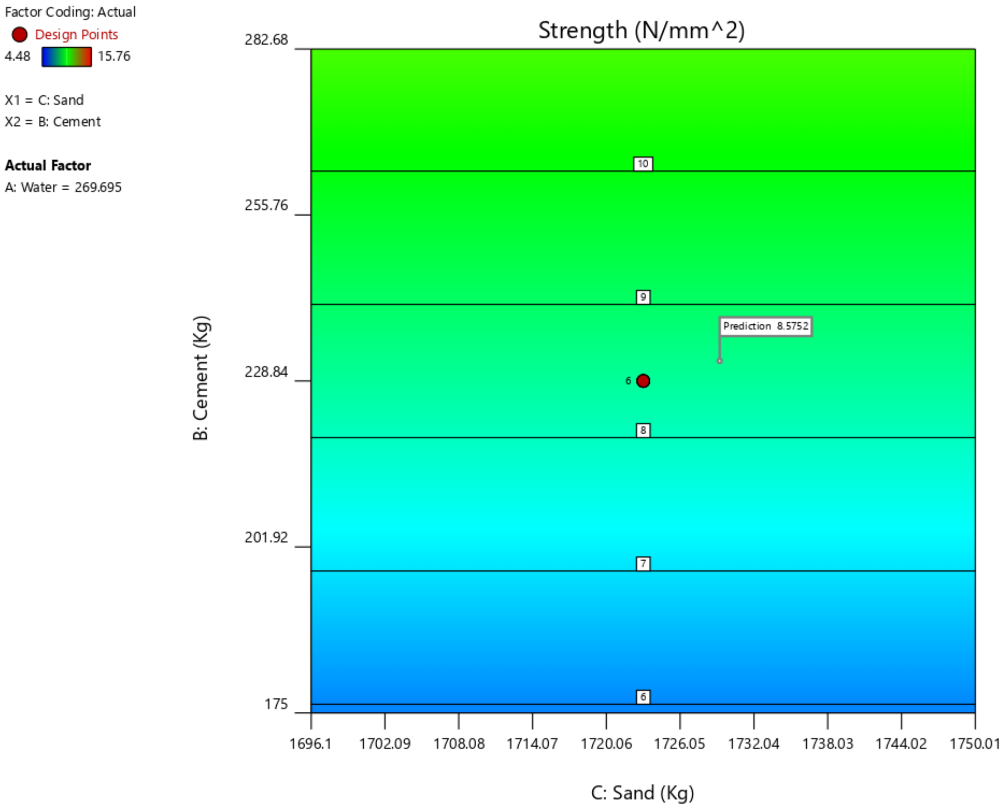

Figure 1: Sample contour plot for compressive strength at 28 days

The mortar strength for bedding and jointing block walls should not be less than the block strength. In accordance with NIS 87 (2004), this is suitable because the mortar can be produced far above the value of 2.8N/mm^2 specified.

4.1 Mixing water requirement and cement quantity

A simple linear relationship can be written for mixing water requirement and the quantity of aggregate for the composite mix. The limits in equations 6(a) and 6(b) was used to generate the points within an augmented [3,2] Simplex lattice design representing 10 design points. By multiplying the relative absolute volumes of the component mixes by their densities, the proportions can be obtained for all the design points. This method also enables fitting points that can yield a second order-quadratic polynomial expression, (Montgomery, 2001) and thus obtain a linear mathematical relationship connecting water requirement to the cement:sand/laterite ratio per one cubic meter of the mix. Similarly, the fine aggregate quantity can be regressed in a similar manner thus yielding the linear expression in Equations 6 and 7 using a probability $p < 0.05$ statistical significance,

$$Water_{control}; \qquad W_{control} = 291.267 - 159.860 * \left(\frac{Cement}{sand}\right) \qquad (9a)$$

$$Water_{binary}; \qquad W_{binary}Y = 335.063 + 166.076 * \left(\frac{Cement}{sand\text{:} Laterite}\right) \qquad (9b)$$

$$Aggregate_{control}; \qquad A_{control} = 1849.236 - 0.555 * Cement \qquad (10a)$$

$$Aggregate_{binary}; \qquad A_{binary} = 1717.380 - 0.992 * Cement \qquad (10b)$$

4.2 Example of component mix selection

This method starts as an iterative process by selecting a cement quantity within the limits to obtain the desired strength. The procedure is stated thus:

i) Calculate the quantity of cement from within the limits suggested
ii) Substitute the cement quantity in the equation expressing the compressive strength of mortar cube
iii) Estimate the quantity of fine aggregates from the equation relating the calculated cement quantity
iv) Estimate the quantity of water from the equation relating the ratio of cement/fine
v) Calculate cement: laterite ratio

Using the same problem statement:

i) Starting with the lowest limit of cement in Equation 6(a) (absolute volume = 0.056) represents 176.4 kg of cement, that is (0.056 x 3150 = 176.4 kg), where unit weight of cement is 3150 kg/m^3.
ii) Substituting the cement quantity in Equation 7(b) $fc = -2.16033 + 0.046255 * 176.4$
iii) This yields a compressive strength value of 6.0 N/mm^2.

iv) The corresponding quantity of fine aggregates from equation 10(a) relating the calculated cement quantity is: $i.e = 1849.236 - 0.555 * cement$; gives (1849.236 - (0.555*176.4)) = 1751.334 kg/m^3.

v) The corresponding quantity of water from equation 11(a) relating the calculated cement/laterite ratio is: $water = 291.267 - 159.860 * \frac{cement}{sand}$. This substitution gives = (291.267 - (159.267*(176.4/1751.334))) = 275.23 kg/m^3

vi) The cement:sand ratio is 176.4/1751.334 ≈ 1:6

At the same cement content and substituting the values in the example, the compressive strength of binary mixture yields higher strength i.e, 6.6 N/mm^2 > 6.0 N/mm^2.

5.0 Conclusions and Recommendations

Based on the CCD method, it has been shown that cement-sand mortar mixes blended with binary replacement of silica sand with laterite can be designed to meet a specified requirement. It allows the use of lower cement quantities to get the required flow or workability because of the cement and plastic bonds. This makes it suitable for ferro-cement formwork construction and bedding & jointing blockwalls. Specification writing for site production is possible, using this approach.

References

Biju, M., Freeda, C. and Benny, J. (2018). *An investigation of laterites as fine aggregate to develop eco-friendly mortar*. 14th International Conference on Concrete Engineering and Technology. IOP Materials Science and Engineering Conference Series. IOP Publishing.

BS 812 (1990). “Method of Sampling and Testing of Mineral Aggregates, Sands and Fillers. British Standard Institute

BS 1377 (1990). *Methods of Testing Soils for Civil Engineering Purposes*. British Standard Institute, London.

BS EN 197-1: (2016). Specifications for common cements. British Standard Institute London

BS EN 771-1: (2011). Specification for Masonry Units. British Standard Institute London.

BS EN 933-1: (2012). Tests for geometrical properties of aggregates: British Standard Institute London.

Design-Expert (2000). Design-Expert User Guide. *Stat-Ease Corporation*, www.stat-ease.com

Gidigasu, M. D., (1976). *Laterite Soil Engineering*. Elsevier Scientific Publishing Company. Amsterdam. 360-450

Joshua, O., Amusan, L. M., Fagbenle, O. I., Kukoyi, P. 0. (2014). *Effects of partial replacement of sand with lateritic soil in sandcrete blocks*. Covenant Journal of Research in the Built Environment (CJRBE). 1(2). 91-102

Kolapo O. A., Oludare, O. and Abiodun, O. (2007). *A study of compressive strength characteristics of laterite/sand hollow blocks*. Civil Engineering Dimension. 9(1): 26-29.

Montgomery, D. C., (2001). *Design and Analysis of Experiments*. 5th Edition, John Wiley & Sons, New York, 427 – 473.

Neville, A. M. (1993). *Properties of Concrete*. Third Edition. Pitman Publishing Limited, London, 648-711.

NIS 87 (2004). "*Standards for sandcrete blocks*". Standard Organization of Nigeria, Lagos, Nigeria.

Singh, A. (2006). *Soil Engineering in Theory and Practice*. Volume 1, Fourth Edition. CBS Publishers and Distributors. 725-759.

Simon, M.; Snyder, K. and Frohnsdorff, G. (1999), *Advances in Concrete Mixture Optimization*. Advances in Concrete Durability and Repair Technology Conference, University of Dundee, Scotland, UK. Thomas Telford Publishing. 21 – 32.

Vladimir, G. H., Paulo, B. L. and Graca, V. (2011). *Influence of aggregates grading and water cement ratio in workability and hardened properties of mortars*. Construction and Building. Materials. 25(6). 2980 – 2987