IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Optimizing the Rheology of Concrete modified with High Silica and Alumina Precursor for Normal Workability in the Built Environment

To cite this article: S. O. Oyebisi *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1107** 012211

View the article online for updates and enhancements.

You may also like

- AtomicNet: a novel approach to identify the crystal structure of each simulated atom
Yuexing Han, Leilei Song, Bing Wang et al.

- Transmural recordings of gastrointestinal electrical activity using a spatially-dense microelectrode array
Nipuni D Nagahawatte, Niranchan Paskaranandavadivel, Timothy R Angeli-Gordon et al.

- Strength and weaknesses of modeling the dynamics of mode-locked lasers by means of collective coordinates
M Alsaleh, C B L Mback, E Tchomgo Felenou et al.

The Electrochemical Society
Advancing solid state & electrochemical science & technology

243rd ECS Meeting with SOFC-XVIII

Boston, MA • May 28 – June 2, 2023

Abstract Submission Extended
Deadline: December 16

Learn more and submit!

This content was downloaded from IP address 165.73.223.226 on 30/11/2022 at 11:06

Optimizing the Rheology of Concrete modified with High Silica and Alumina Precursor for Normal Workability in the Built Environment

S. O. Oyebisi[1*], A. N. Ede[1], H. I. Owamah[2], J. O. Oluwafemi[1], R. O. Sani[1], A. O. Odetoyan[1], A. I. Akpabot[1]

[1]Civil Engineering Department, Covenant University, Ota, Ogun State, Nigeria
[2]Civil Engineering Department, Delta State University, Oleh Campus, Abraka, Delta State, Nigeria
[*]Corresponding author: solomon.oyebisi@covenantuniversity.edu.ng +234(0)7030110003

Abstract

Concrete performance in its fresh state is not only pertinent for proper concrete placement, consolidation, and finishing but also its properties in its hardened state. Thus, this study optimized the rheology of concrete modified with high silica and alumina precursor (cashew nutshell ash (CNA)). Cashew nutshell was recycled, and the ash obtained was used at 5, 10, and 15 wt.% of cement using the concrete mix designs of grades C 25-40 to attain the target strengths of 25-40 MPa at 28 days. Both slump and its corresponding compressive strength were determined. Moreover, the concrete slump was optimized using the experimental mix design properties (EMDPs) such as cementitious materials, water/cementitious materials, and cementitious materials/aggregate ratios, as independent (continuous variables). The findings showed that EMDPs influenced the rheology of fresh concrete, significantly, hence yielding an optimized high precision with 99 % R^2. Therefore, the model can be used to predict the normal workability of the concrete incorporating CNA in the built environment.

Keywords: Optimization, concrete, supplementary cementitious materials, slump, compressive strength, sustainability, built environment, modelling.

1. Introduction

The role of rheology in attaining successful performance of concrete cannot be over-emphasized. A fundamental understanding of concrete workability can be gained by the mechanism of rheology [1]. Achieving the goals of limiting segregation, excellent surface finishes, mix design and quality control, minimizing pump pressure, and formwork pressure control can be balanced via the rheological characteristics of concrete [1]. However, adjusting a property to attain one objective can have negative influences on other goals. Therefore, the rheological characteristics of any concrete must be balanced to manage the purposes earlier stated. The rheological characteristics of concrete are tailored via the process of mix designs [2]. Cementitious content, water/cementitious materials ratio, SCMs content, and aggregate properties and content play a vital role in the rheological properties of the concrete [2]. Furthermore, apart from providing to the energy and environmental preservation, and sustainable development, the incorporation of SCMs as mineral admixtures were designed to enhance the concrete quality due to rapid concrete construction and the need for new properties [2-4]. Notwithstanding, the behaviour of concrete is complex and the rheology of fresh concrete is a vital property that influences the strength [5-7], durability [8-10], and cost [11, 12] of concrete in its hardened state.

In recent times, the reality of material science as a subject area is still of interest considering the behavioural mechanisms of materials and the suitable modelling of their mathematical relationships [13]. A concrete mix is optimized to reduce the constituents' costs and expended

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

time on conducting the concrete trial mixes without compromising the quality and performance of concrete under an applied loading condition [14]. Therefore, the optimization of a concrete mix can be performed by adjusting the critical levels of mix factors such as cement/aggregate ratio, water/cement ratio, and cementitious material contents and the ratio [15, 16].

Cashew nutshell is a waste product obtained from agricultural products with an estimated global generation of about 4.5 million metric tonnes (MMT) in 2017, while Nigeria generated about 100 MMT in the same year [17]. However, it is perturbed to notice that this material is usually discarded as wastes, hence causing environmental problems.

Chiara et al. [1] examined the role of rheology in attaining adequate performance of concrete. It was established that yield stress and plastic viscosity influence the concrete rheological properties such that sufficient yield stress and plastic viscosity result in segregation control and functional surface finishing. *Guoming et al.* [18] investigated the rheological properties of fresh concrete and its applications on shotcrete by reviewing the rheological models and measurements. The findings revealed that the optimization and adjustment of shotcrete workability are attainable based on the rheological variables, indicating that the Bingham model provides better precision. Also, *Girish and Ajay* [2] reviewed the importance of rheological properties of fresh concrete. It was revealed that workability is a function of concrete's flow properties; besides, new methods are required to solve the inadequacies of experimental tests based on the mechanism of material science. Despite the outcomes of these previous studies, as earlier highlighted, the rheological optimization of concrete incorporating cashew nutshell ash (CNA) is rare.

In this present study, an effort was made to use the application of a Box-Behnken Design (BBD) of Response Surface Methodology (RSM) to obtain an optimized rheological property of concrete flow using the slump values obtained from an experimental design. Design factors such as cementitious contents, water/cementitious materials ratio, and cementitious materials/aggregate ratio were selected as independent (continuous) variables while slump value was considered as a response variable. The experimental data were statistically analyzed via Minitab 17 software, and the regression model was developed for concrete slump as a function of mixture variables.

2. Experimental Methods

Valorizing cashew nutshells obtained cashew nutshell ash (CNA) at the pyrolysis section of the Federal University of Agriculture, Abeokuta, Nigeria. Afterwards, about 23 wt.% of processed hulls were obtained as CNA. The oxide elements of both CNA and a 42.5R Portland limestone cement (PLC) used as cementitious materials are shown in Table 1. From Table 1, it was revealed that CNA satisfied a 70% minimum required specification of SiO_2 + Al_2O_3 + Fe_2O_3, stipulated by *BS EN* [19] and the oxide compositions of PLC are in good agreement with *BS EN* [20]'s specification. Also, the fineness, specific gravity, and specific surface area were obtained for both CNA and PLC as 8.10 and 7.64 %, 2.85 and 3.15 g/cm^3, and 505 and 375 m^2/kg, respectively, following the procedure outlined in *BS EN* [20].

Table 1: Chemical compositions of materials used.

Binding	Chemical compositions (%)										
materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	TiO_2	P_2O_5	LOI
CNA	2.04	65.02	16.28	10.16	1.53	0.52	0.45	1.32	0.01	0.01	2.95
PLC	64.50	21.55	5.50	3.08	1.52	0.61	-	2.03	-	-	1.20

Sharp sand and granite were used as both fine and coarse aggregates and obtained from an aggregate dealer in Ota, Nigeria. The physical properties were determined based on the procedure outlined in *BS EN* [21]. The results indicated 2.60 and 2.64 g/cm^3 as specific gravity, 0.7 and 0.8 % as water absorption, and 0.3 and 0.2% as moisture content for fine aggregate (FA) and coarse aggregate (CA), respectively.

The concrete mix was designed based on the standard specification [22], putting into considerations, the physical properties, air content, specific gravity, moisture content and water absorption capacity of the concrete constituents. A 15% optimum replacement of PLC by CNA was proportioned at 5, 10, 15 wt.% following the previous studies [4, 23] that 15 wt.% of CNA replacement by PLC yielded the optimum compressive strength for structural applications. Besides, the adoption of concrete grades 25-40 was as a result of their more extensive and broad uses in the building construction. The mix design results indicated cementitious, FA, and CA contents as 340, 715, and 1035 kg/m^3 for concrete grade 25 (C 25); 390, 675, and 1031 kg/m^3 for concrete grade 30 (C 30); and 500, 585, and 1030 kg/m^3 for concrete grade 40 (C 40), respectively.

2.1 Tests

The slump and compressive strength tests were performed on the fresh mixes and 150 mm^3 standard cubes, respectively based on the respective standards specified in *BS EN* [24] and *BS EN* [25]. The samples were prepared at 28 °C and 65% relative humidity.

2.2 Box-Behnken design (BBD) for the optimization process

The BBD was applied to evaluate the interaction between the three selected continuous variables and the response variable via Minitab statistical software, as shown in Table 2. Thus, the number of the experimental run was estimated using the illustration presented in Equation (1) [26].

$$N = 2v(v-1) + c_p \qquad (1)$$

where
N: number of the experimental run,
v: total continuous variables,
c_p: total applied central point.

Table 2: 3-continuous variable in a 3-different level for BBD

Variables	Symbol	Coded values		
		Low -1	Centre 0	High +1
Water/cementitious materials	A	0.42	0.54	0.62
Cementitious materials/aggregate	B	0.19	0.23	0.31
CNA/PLC	C	0.05	0.10	0.15

Following Equation (1), the number of the experimental run based on three (3) continuous variables and three (3) applied central points, as shown in Table 1, was fifteen (15) base runs. Besides, full quadratic term, as illustrated in Equation (2), accurately optimizes the relationship between the continuous variables and the response variable, hence yielding a high precision [26].

$$Y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i<j} a_{ij} x_i x_j \qquad (2)$$

where
Y: response variable (f_c),
a_0: model coefficient constant,
x_i and x_j: continuous variables,
a_i: linear coefficient,
a_{ii}: square coefficient,
a_{ij}: interaction coefficient.

The experimental data were analyzed via Analysis of variance (ANOVA) to evaluate the three continuous variables, as presented in Table 2 and to consider the concrete rheology that would fit the statistical model using the best fit terms. P-value represents a significance level compared with the α-value of 0.05. Considering the null hypothesis, if P-value ≤ α -value, there is a significant effect; if P-value > α-value, then no significant impact [14].

2.3 Optimization

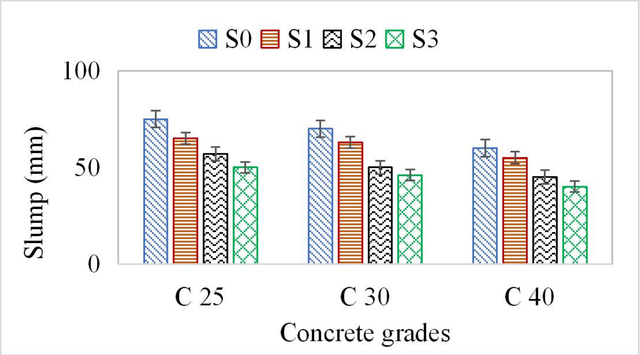
The three independent variables, A, B, and C, were optimized while minimizing the response variable (slump) via the optimization concept. Based on this concept, the slump was converted into a composite desirability function (D) over the range of 0-1, as illustrated in Equation (3), hence asserting that the closer the composite desirability to 1, the better the optimization [26]. From Equation (3), D = 1 if the slump is at its goal or target. Also, D = 0 if the slump is outside an acceptable region.

$$0 \leq D \leq 1 \qquad (3)$$

3. Results and Discussion

3.1 Slump and compressive strength

Figures 1 and 2 present the results of both slump and compressive strength (fc) in fresh and hardened states, respectively. It was evident, as shown in Figure 1 that the slump values reduced as CNA content increased because CNA exhibited higher fineness and specific surface area than PLC, hence requiring more volume of CNA and water in the mix and reducing the concrete rheology [27]. Therefore, the slump results yielded by the incorporation of CNA in the concrete mix can be beneficial in the humid environment in that hydrating process would be accelerated, hence resulting in better performance of the concrete's hardened state. On the other hand, the compressive strengths, as indicated in Figure 2, increased with increasing CNA content due to the substantial contents of silica and alumina oxides in CNA compared with PLC; the oxides reacted with the hydrating agents of PLC, hence increasing the strengthening paste and bond of the concrete [27].



SO (100 % PLC); S1 (5 % CNA + 95 % PLC); S2 (10 % CNA + 90 % PLC); S3 (15 % CNA + 85% CNA)

Figure 1: Slump values for concrete grades C 25-40

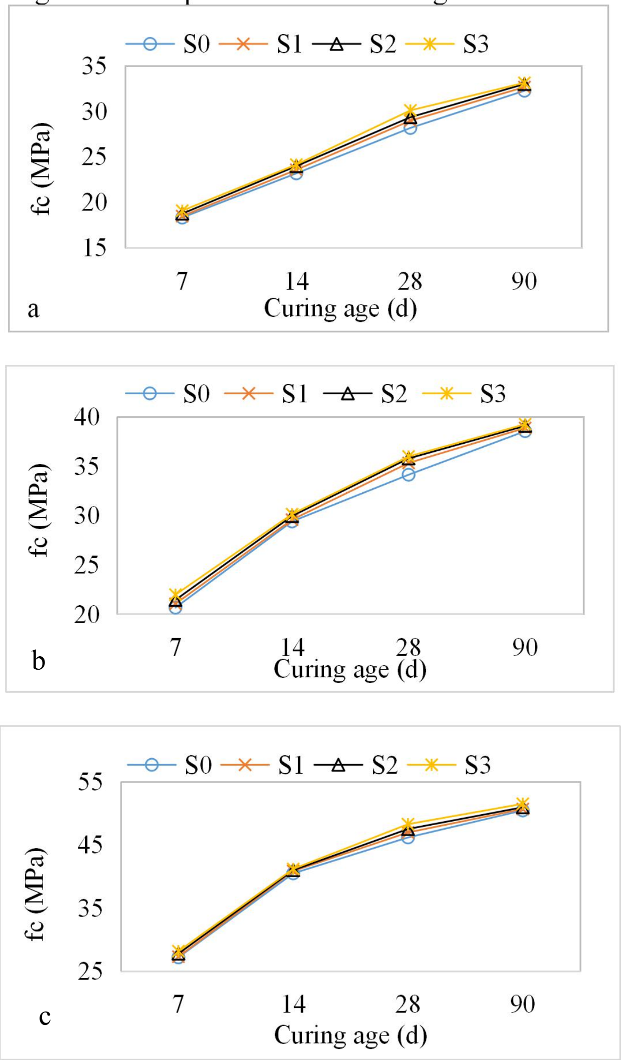


Figure 2: Compressive strengths for (a) C 25, (b) C 30, and (c) C 40

3.2 *Design of experiment (DOE)*

Tables 3 presents the fitted model analysis to a response surface design following the creation of response surface design with three continuous variables, as presented in Table 2.

Table 3: ANOVA for the regression model using linear and squared terms

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	4	783.733	195.933	198.58	0.000
Linear	3	783.689	261.230	264.76	0.000
A	1	4.629	4.629	4.69	0.050
B	1	0.758	0.758	0.77	0.401
C	1	490.889	490.889	497.52	0.000
Square	1	21.429	21.429	21.72	0.001
C^2	1	21.429	21.429	21.72	0.001
Error	10	9.867	0.987	-	-
Lack-of-Fit	4	9.867	2.467	-	-
Pure Error	6	0.000	0.000	-	-
Total	14	793.600	-	-	-

Compared to the full quadratic terms, the linearly squared terms yielded the best precision and significant effect, hence used for the modelling analysis. During the modelling processes, both A^2 and B^2 were adjudged as non-significant terms and thus, removed from the model. From Table 3, all conditions, except B, exhibited significant effects on the slump because P-value was less than α-value (0.05). Consequently, the regression model between the response variable (slump) and the continuous variables (A, B, and C) is developed, as illustrated in Equation (4), ranging from 14-90 d curing for concrete grades C 25-40. Statistically, the model's goodness of fits yielded standard distance (S) and coefficient of determination (R^2) as 0.993311 and 99 %, respectively, hence signifying that the equation fits the regression line and the model is 99 % suited to optimize all designed variables. Therefore, this proposed model equation (Equation 4) can be applied in the prediction of the rheology of fresh concrete incorporating CNA.

$$Slump = 14.3 + 90\,\mathrm{A} + 60\,\mathrm{B} - 356.7\,\mathrm{C} + 1000\,\mathrm{C}^2 \qquad (4)$$

For a balanced design, a normally distributed residuals, as shown in Figure 3, is required [26]. Thus, the residuals generally followed a straight-line pattern; this showed evidence of normality or known variables in the model. Also, in a designed experiment, the order of observations influences the response variable if the residuals fluctuate in a random pattern around the centre line [26]. Thus, Figure 4 shows the result of versus order for the response variable and exhibits a randomly scattered pattern about zero, hence signifying evidence that the error terms are not correlated with one another.

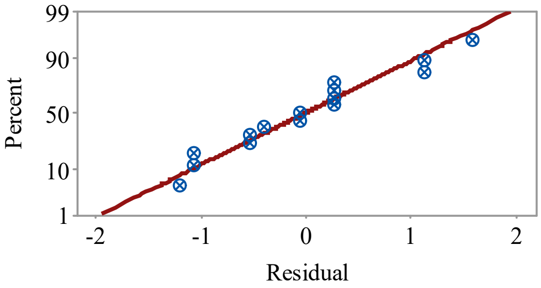


Figure 3: Normal probability plots for the slump

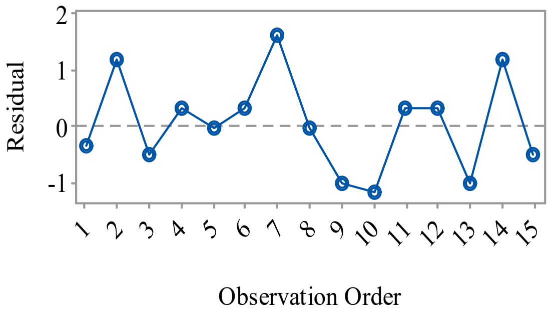


Figure 4: Residual versus order plots for the slump

3.3 *Optimization*

Figure 5 shows an optimized value for the response (slump) based on the stored models. The vertical brown and horizontal blue lines signified a current setting and a current response (slump), respectively. The current setting showed A, B, and C as 0.42, 0.190, and 0.15, respectively, yielding a minimized slump (rheology) of 33 mm at 1.0000 composite desirability (D). Therefore, the rheological optimization of fresh concrete modifying with high contents of SiO_2 and Al_2O_3 (CNA) supported a relationship, as illustrated in Equation (3) in that D = 1 because the current slump (33 mm) is lower than 40 and 65 mm for target and upper slump obtained from the empirical results (Figure 1), respectively.

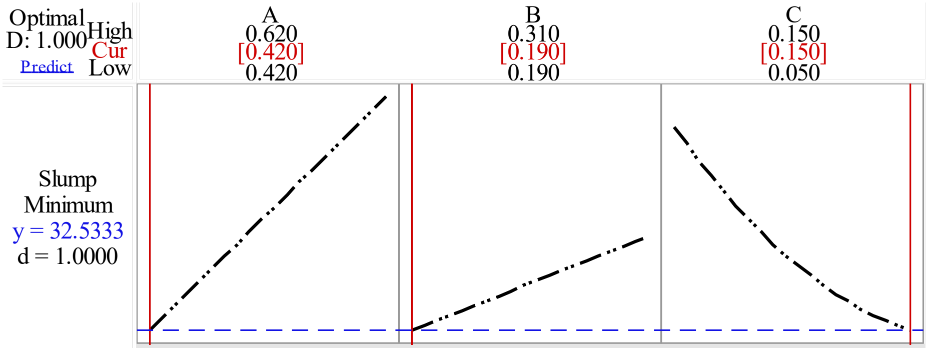


Figure 5: Optimization plot for the rheology of fresh concrete produced

4. Conclusions

This study optimized the rheology of fresh concrete modified with high silica and alumina oxides. Empirical works were conducted to generate data for statistical analysis. The key design mix properties were considered as continuous variables, while slump was selected as the response factor. Consequent upon the study findings, the following conclusions are drawn:

i. The slump of fresh concrete incorporating CNA increases with increasing water/cementitious materials and cementitious materials/aggregate ratios; however, it reduces with increasing CNA/PLC ratio.

ii. There was about 13-33 %, 10-34 %, and 8-33 % decrease in the slump as CNA content increased from 5-15% for C 25, C 30, and C 40, respectively, compared with 100 % PLC mix.
iii. Compared with the empirical slump, an optimization of about 18-49 % decrease in a slump was obtained as concrete grades increased from C 25- C 40.
iv. A strong correlation exists between the slump and the independent variables at 99% R^2.

Acknowledgement

The authors acknowledge the Covenant University Centre for Research, Innovation and Discovery (CUCRID) for financial support.

References

[1] Chiara F F *et al* 2017 *ACI Committee* **238** 43-51.
[2] Girish S and Ajay N 2017 *Indian Concr. J.* **91**(9) 9-17.
[3] **Mark O G *et al*** 2019 *IOP Conf. Series: Mater. Sci. Eng.* **640** 012071.
[4] Oyebisi S *et al* 2019 *Case Studies Constr. Mater.* **11** e00293.
[5] **Ede A N *et al*** 2019 *J. Phys.: Conf. Series* **1378** 032037.
[6] Oyebisi S *et al* 2020 *Constr. Build. Mater.* **256** 119390.
[7] Oyebisi S *et al* 2020 *Case Studies Constr. Mater.* **13** e00393.
[8] Oyebisi S *et al* 2020 *Constr. Build. Mater.* **258** 119604.
[9] Oyebisi S *et al* 2020 *Case Studies Constr. Mater.* **13** e00394.
[10] Oyebisi S *et al* 2020 *Case Studies Constr. Mater.* **11** e00293
[11] Thaarrini J and Dhivya S 2016 *Int. J. Civ. Eng. Res.* **7** (2) 117–124.
[12] Oyebisi S *et al* 2019 *10th Int. Struct. Eng. Constr. Conf.* ISBN: 978-0-9960437-6-2.
[13] Angelo M D *et al* 2020 *Mech. Res. Comm.* **103** 103462.
[14] Ahmad S and Alghamdi S A 2014 *Sci. World J.* **561539** 1-7.
[15] Chang P K 2004 *Cem. Concr. Res.* **34**(4) 623-629.
[16] Ozlem A *et al* 2010 *ACI Mater. J.* **107**(4) 357-364.
[17] Food and Agriculture Organization of the United Nations 2017 *Food and Agriculture Organization Statistical Pocketbook World Food and Agriculture* Rome Italy.
[18] Guoming L *et al* 2020 *Constr. Build. Mater.* **243** 118180.
[19] British Standard EN 450-1, 2012 *Pozzolan for Use in Concrete: Definitions, Specifications and Conformity Criteria BSI*, London.
[20] British Standard EN 196-3, 2016 *Method of Testing Cement: Physical Test* BSI, London.
[21] British Standard EN 12620, 2013 *Aggregates from Natural Sources for Concrete* BSI, London.
[22] British Standard EN 206, 2016. *Concrete Specifications, Performance, Production and Conformity* BSI, London.
[23] Pandi K and Ganesan K 2015 *Australian J. Basic Appl. Sci.* **9**(23) 311-316.
[24] British Standard EN 12350-2, 2009 *Testing Fresh Concrete: Method for Determination of Slump* BSI, London.
[25] British Standard EN 12390-3, 2009 *Testing Hardened Concrete: Compressive Strength of Test Specimens* BSI, London.
[26] Myers R H *et al* 2009 *Response Surface Methodology: Process and Product Optimization using Designed of Experiments* 3rd ed. New Jersey: John Wiley and Sons, Inc.
[27] Khan *et al* 2014 *Sci. World J.* **986567**, 1-11.