FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 24, December, 2026, pp 333 – 341
DOI: https://doi.org/10.33003/fjs-2026-1024-6051

Response Surface Optimization of Coconut-Shell Aggregate Concrete for Compressive Strength and Water Absorption

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ABSTRACT
Coconut shell (CS) is an abundant agricultural residue that has been proposed as a partial substitute for coarse aggregate in concrete. This study used a central composite design (CCD) within response surface methodology (RSM) to examine how CS replacement ratio (5–25 %), CS particle size (3.35–14 mm) and curing age (7–35 days) affect the compressive strength and water absorption of concrete (cement: sand: coarse aggregate = 1: 1.5: 3 by absolute volume; water/cement ratio 0.5). Twenty experimental runs (one 150 mm cube per run, including five centre-point replicates) and one control cube without CS were produced. Measured compressive strength of the CS concretes ranged from 16.23 to 20.21 N/mm^2 (control: 24.36 N/mm^2) and water absorption from 1.5 to 3.9 %. The quadratic models were significant for both responses ($p < 0.0001$; $R^2 = 0.980$ and 0.958), although the lack-of-fit test for compressive strength was borderline ($p = 0.051$). Numerical optimisation (maximise strength, minimise absorption) predicted 20.46 N/mm^2 and 1.50 % at 5.27 % replacement, 3.42 mm particle size and 9.2 days of curing; the desirability of 1.000 is a model output that reflects the chosen goal limits and is not evidence of performance. Two confirmation specimens made at these settings gave 18.98 and 19.10 N/mm^2 (mean 19.04 N/mm^2) and 1.95 and 1.98 % (mean 1.97 %). The two cubes agreed within 0.12 N/mm^2, but the mean strength was 6.9 % lower than predicted and both values fell below the 95 % prediction interval (19.57–21.36 N/mm^2), whereas both absorption values lay within their interval (0.59–2.40 %). The two confirmation cubes had masses of 6.47 and 6.49 kg, corresponding to densities of 1,917 and 1,923 kg/m^3 (mean 1,920 kg/m^3) after air-drying following ASTM C567. This exceeds the 1,840 kg/m^3 air-dry limit that ASTM C330 sets for structural lightweight concrete, so the concrete is not classified as lightweight or structural, and the findings apply only to the tested formulations and properties.

Received: 25 Sep. 2026
Accepted: 14 Nov. 2026
Published: 17 Nov. 2026

Keywords: Coconut Shell Aggregate, Concrete, Compressive Strength, Water Absorption, Central Composite Design, Response Surface Methodology

INTRODUCTION

Concrete remains the principal construction material in civil and agricultural infrastructure because of its compressive strength, adaptability, workability and durability. The growing demand for conventional concrete has, however, intensified the extraction of natural aggregates, with consequences such as land degradation, biodiversity loss and resource depletion. Aggregate extraction and processing account for a significant share of the environmental burden of concrete, which has motivated the search for alternative aggregates that support resource conservation and circular-economy principles (Pordesari et al., 2025).

Agricultural residues have therefore attracted attention as aggregate substitutes. Valorising such residues can turn waste streams into construction materials while reducing landfill disposal and the demand for quarried aggregate (de Bortoli, 2025; Oppon et al., 2025). Among these residues, coconut shell (CS) is regarded as a promising lightweight coarse aggregate because of its low specific gravity, toughness and wide availability in tropical and subtropical regions. Reviews describe CS as having physical and mechanical characteristics comparable to some commercial lightweight aggregates, although the reported concrete strengths vary widely with replacement level, water–cement ratio and curing conditions (Dwarampudi & Venkateshwari, 2024; Pordesari et al., 2025). Boakye et al. (2025) reported that concrete containing up to 15 % CS aggregate retained acceptable compressive strength, and other studies have examined CS as a coarse-aggregate replacement in lightweight and conventional concrete (Natarajan et al., 2022; Pratiwi et al., 2022). Other agricultural shell residues have been examined in the same way; for example, Liman et al. (2021) reported 28-day strengths of 28.0 and 20.2 MPa for concrete in which 5 % and 10 % of the coarse aggregate was replaced by crushed doum palm shell. Such locally available, low-cost materials are of interest for agricultural structures, but their suitability for any particular structural use has to be established by testing, as discussed in Sections 3.7 and 4.

The studies cited above mostly evaluate the effect of replacement ratio on strength at fixed ages. Considering replacement ratio, shell size and curing duration together is needed for three reasons. Firstly, CS is highly absorptive and porous, so the effect of the replacement ratio on strength and absorption may depend on the size of the shell particles. Secondly, strength development depends on curing duration, and its effect may differ with the proportion of porous shell

in the mix. Thirdly, interactions of this kind cannot be detected by varying one factor at a time. Response surface methodology (RSM) estimates linear, quadratic and interaction effects from a limited number of runs and allows the factor settings to be optimised numerically, but a predicted optimum is a model result that must be confirmed by independent measurement.

The aim of this study was to model and optimise the compressive strength and water absorption of coconut-shell aggregate concrete as functions of CS replacement ratio, particle size and curing age using a central composite design, and to test the predicted optimum with replicate confirmation specimens.

Abbreviations

ACI, American Concrete Institute; ANOVA, analysis of variance; ASTM, ASTM International; BS, British Standard; CCD, central composite design; CS, coconut shell; CV, coefficient of variation; Df, degrees of freedom; PI, prediction interval; RSM, response surface methodology; WA, water absorption.

MATERIALS AND METHODS

Materials

Ordinary Portland cement (Dangote Cement) was obtained from SRS Junction, North Bank, Makurdi. Coconut shells from local agricultural processing centres were cleaned, dried, crushed manually with a hammer into small chips and graded into five particle sizes (Figure 1) before being incorporated into the mixes. The shell was used as received, without pre-soaking, at a moisture content of 5.4 % (Section 3.1). Because CS absorbs about 24 % of its dry mass, the dry shell can withdraw water from the mix. The fine aggregate was sand from the Engineering Complex, Joseph Sarwuan Tarka University, Makurdi. The coarse aggregate was gravel of 20 mm nominal size collected from a site close to the River Benue. Potable water from the Engineering Complex, free from oil, acid, alkali, salt, sugar, silt and organic matter, was used throughout.

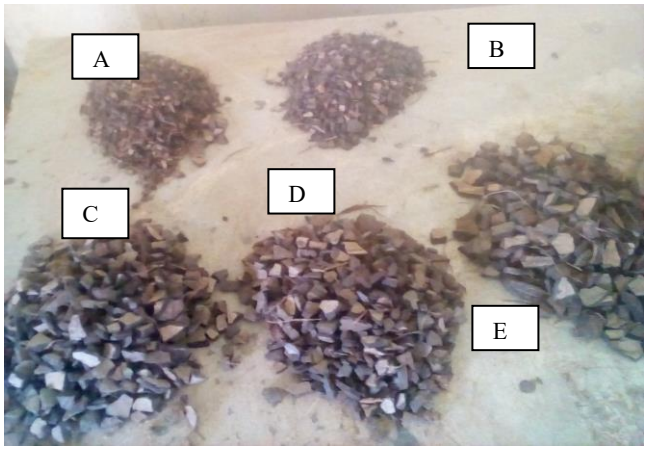


Figure 1: Coconut shell separated into five size fractions (A = 3.35 mm, B = 5.0 mm, C = 6.3 mm, D = 10.0 mm and E = 14.0 mm)

Material Characterisation

Specific gravity, particle size distribution, bulk density, moisture content and water absorption of the constituent materials were determined before concrete production, with references to ASTM C127, ASTM C128, ASTM C29 and BS EN 1097-6 (results in Section 3.1).

Mix Proportions

The mix notation 1 : 1.5 : 3 : 0.5 denotes cement : sand : coarse aggregate : water. The first three terms are proportions by absolute volume, converted to masses with the specific gravities of the materials, and the last term is the water/cement ratio by mass (0.5). The proportions are close to the 1 : 1.51 : 3.06 control mix used for coconut-shell concrete by Osei (2013), although Osei replaced the granite by volume rather than by mass. For one 150 mm cube plus 5 % allowance for wastage, the control batch (100 % gravel) contained 2.03 kg cement, 2.40 kg sand, 5.41 kg gravel and 1.01 kg water (Table 1). In the CS mixes, the stated percentage of the gravel was replaced by CS of the stated size. The replacement was made by mass of gravel. Because the CS is much less dense than gravel (specific gravity 1.21 against 2.80), replacement by mass increases the volume of coarse aggregate in the mix as the replacement ratio rises.

Table 1: Batch Quantities for One 150 mm Cube (Control Mix, including 5 % Allowance for Wastage)

Material	Proportion	Quantity per batch (kg)
Cement	1	2.03
Sand	1.5	2.40
Gravel (100 % in control)	3	5.41
Water	0.5 (water/cement, by mass)	1.01

Experimental Design

A five-level, three-factor central composite design (CCD) was generated with Design-Expert software (version 10, Stat-Ease Inc.). The factors were CS replacement ratio (A, %), CS particle size (B, mm) and curing age (C, days); the responses were compressive strength and water absorption. Coded and actual levels are given in Table 2. The axial levels were set at the extreme experimental values (5 and 25 %, 3.35 and 14 mm, 7 and 35 days).

Table 2: Coded and Actual Levels of the Experimental Factors

Factor	−α	−1	0	+1	+α
A: Replacement ratio (%)	5	10	15	20	25
B: Particle size (mm)	3.35	5	6.3	10	14
C: Curing age (days)	7	14	21	28	35

The design comprised 20 runs (Section 3.2, Table 4): six factorial points, six axial points, five centre-point replicates (runs 9, 11, 16, 17 and 19) and three additional points (runs 12, 13 and 15). The centre-point replicates provide four degrees of freedom for pure error and the lack-of-fit test. One cube was cast and tested per run, giving 20 specimens, plus one control cube without CS cured for 28 days; replication therefore exists only at the centre point. The runs were carried out in random order according to the design matrix.

Specimen Preparation and Curing

Cement, sand and aggregate were mixed dry with a hand trowel; water was added after the CS had been incorporated. Concrete was placed by hand in oiled 150 mm × 150 mm × 150 mm steel moulds and compacted on a vibrating machine. The moulds were covered with plastic sheets, and the cubes were demoulded after 24 h and cured fully immersed in water in a drum (Figure 2) for the age specified for each run. Curing was carried out at normal room temperature.



Figure 2: Curing of concrete cubes in water

Compressive Strength Test

Cubes were tested at the end of their curing period in an ELE electro-hydraulic compression testing machine (capacity 1560 kN) at the Civil Engineering Laboratory, Joseph Sarwuan Tarka University, Makurdi. Each cube was placed singly between the machine plates and loaded gradually, without shock, to failure. Compressive strength was calculated as the failure load divided by the loaded area (22 500 mm^2):

$$f_c = P_{max} / A \quad (1)$$

where f_c is the compressive strength (N/mm^2), P_{max} is the failure load (N) and A is the loaded area (mm^2).

The density of the two confirmation cubes of the optimised mix was determined after air-drying following ASTM C567/C567M-19, as the mass of the cube divided by its nominal volume (0.150^3 m^3 = 0.003375 m^3).

Water Absorption Test

A small sample of each concrete (36–90 g) was oven-dried at 105 °C for 24 h and weighed (M_1), immersed in water for 24 h, surface-dried with a towel and weighed again (M_2). Water absorption was calculated as:

$$WA\ (\%) = [(M_2 - M_1) / M_1] \times 100 \quad (2)$$

This is a simplified 24-h immersion procedure. It is not the full ASTM C642 procedure (which prescribes longer immersion and boiling) or the BS 1881-122 method.

Regression, ANOVA and Optimisation

A second-order polynomial model was fitted to each response by least squares in Design-Expert (no transformation was applied):

$$Y = \beta_0 + \Sigma\beta_i x_i + \Sigma\beta_{ii} x_i^2 + \Sigma\Sigma\beta_{ij} x_i x_j \quad (3)$$

where Y is the response, x_i the factors (A, B, C in actual units) and β the regression coefficients. Model significance was assessed by analysis of variance (ANOVA, Type III sums of squares, $\alpha = 0.05$). Lack of fit was tested against the pure error from the five centre-point replicates. Model adequacy was assessed with R^2, adjusted and predicted R^2, adequate precision and the coefficient of variation (CV), and by residual diagnostics (studentised residuals against predicted values, normal probability plot and predicted-versus-actual plot; Figure 3). The 95 % prediction interval (PI) of a single new observation at the optimum was calculated as the predicted value $\pm\ t_{0.975,10}\ \sqrt{[\mathrm{MSE}(1 + x'(X'X)^{-1}x)]}$.

Numerical optimisation used the desirability function with the goals "maximise compressive strength" (limits 16.23–20.21 N/mm^2) and "minimise water absorption" (limits 1.5–3.9 %), with all three factors kept within their experimental ranges (Section 3.6); up to 30 solutions were requested. The solution selected was then reproduced experimentally with two confirmation cubes and compared with the model prediction and its PI.

RESULTS AND DISCUSSION

Properties of the Constituent Materials

The sand was uniformly (poorly) graded, with a uniformity coefficient (C_u) of 2.86, below 4 (Table 3). Its specific gravity was 2.48, bulk density 1630 kg/m^3, water absorption 4 % and moisture content 1.3 %; the gravel had a specific gravity of 2.80 and a water absorption of 1.4 %. In contrast, the CS had a specific gravity of 1.21, a bulk density of 515 kg/m^3, a water absorption of 24 % and a moisture content of 5.4 %, reflecting its porous lignocellulosic structure. The specific gravity lies within the 1.03–1.56 range reported for CS aggregates by

Pordesari et al. (2025) and is consistent with Gunasekaran et al. (2011). The bulk density of the CS is below the 880 kg/m^3 maximum loose bulk density that ASTM C330 sets for coarse lightweight aggregate, which is an aggregate-level criterion only. The high absorption means that CS can withdraw mixing water from the paste, so the effective water/cement ratio of the CS mixes may differ from the nominal value of 0.5.

Table 3: Physical Properties of the Constituent Materials

Material	Specific Gravity	Water absorption (%)	Moisture content (%)	Bulk density (kg/m^3)
Sand	2.48	4	1.3	1630
Gravel (20 mm)	2.80	1.4	–	–
Coconut shell	1.21	24	5.4	515

– = not determined. Sand uniformity coefficient C_u = 2.86.

Design Matrix and Measured Responses

Table 4 gives the complete design matrix and the measured responses. Compressive strength of the CS concretes ranged from 16.23 N/mm^2 (run 1; 25 % CS, 6.3 mm, 21 days) to 20.21 N/mm^2 (run 14; 5 % CS, 6.3 mm, 14 days), that is 33 % and 17 % below the 28-day control cube (24.36 N/mm^2), respectively. Water absorption ranged from 1.5 % (runs 3, 7 and 18; 10 % CS) to 3.9 % (run 1), compared with 1.4 % for the control.

The five centre-point cubes (15 % CS, 6.3 mm, 21 days) gave a mean compressive strength of 18.32 N/mm^2 with a standard deviation of 0.083 N/mm^2 (CV 0.46 %), and a mean water absorption of 2.12 % with a standard deviation of 0.22 % (CV 10 %). These pure-error estimates are the main direct measure of repeatability available in this study; they correspond to an expanded uncertainty (95 %, t = 2.776, 4 df) of about ±0.23 N/mm^2 for a single cube strength and ±0.60 % for a single water-absorption value. The absorption values were obtained from small samples (36–90 g) and are reported to one decimal place, so their resolution is coarse. The 2.5 % obtained for run 19 is about 0.5 percentage points above the mean of the other four centre-point values and inflates the pure-error estimate for absorption.

Table 4: Complete Design Matrix (Actual Levels, Coded Levels in Brackets) and Measured Responses. One Cube Per Run

Run	Point type	A: Replacement (%)	B: Particle size (mm)	C: Curing age (days)	Compressive strength (N/mm^2)	Water absorption (%)
Control	No CS	–	–	28	24.36	1.4
1	Axial	25 (+α)	6.3 (0)	21 (0)	16.23	3.9
2	Axial	15 (0)	6.3 (0)	7 (−α)	18.89	2.1
3	Factorial	10 (−1)	5 (−1)	14 (−1)	18.99	1.5
4	Axial	15 (0)	14 (+α)	21 (0)	18.32	2.0
5	Factorial	20 (+1)	10 (+1)	14 (−1)	17.32	2.5
6	Axial	15 (0)	3.35 (−α)	21 (0)	18.11	2.1
7	Factorial	10 (−1)	10 (+1)	28 (+1)	19.21	1.5
8	Factorial	20 (+1)	5 (−1)	14 (−1)	17.42	2.5
9	Centre	15 (0)	6.3 (0)	21 (0)	18.30	2.0
10	Axial	15 (0)	6.3 (0)	35 (+α)	18.86	2.5
11	Centre	15 (0)	6.3 (0)	21 (0)	18.20	2.1
12	Additional	15 (0)	6.3 (0)	28 (+1)	18.66	2.0
13	Additional	20 (+1)	10 (+1)	21 (0)	17.56	2.5
14	Axial	5 (−α)	6.3 (0)	14 (−1)	20.21	2.2
15	Additional	10 (−1)	10 (+1)	21 (0)	19.02	1.9
16	Centre	15 (0)	6.3 (0)	21 (0)	18.32	2.0
17	Centre	15 (0)	6.3 (0)	21 (0)	18.43	2.0
18	Factorial	10 (−1)	5 (−1)	28 (+1)	18.76	1.5
19	Centre	15 (0)	6.3 (0)	21 (0)	18.35	2.5
20	Factorial	20 (+1)	5 (−1)	28 (+1)	17.34	3.5

Runs were carried out in random order according to the design matrix (run numbers as in the design layout). Each cube was tested at its own curing age. Centre-point pure-error standard deviation: 0.083 N/mm^2 (compressive strength) and 0.22 % (water absorption).

Effects on Compressive Strength

ANOVA of the full quadratic model (Table 5) shows that replacement ratio (A), curing age (C), the A×C interaction and the quadratic terms A^2 and C^2 were significant ($p \leq 0.05$), whereas particle size (B) and its terms were not (B: p = 0.945). Strength fell as the replacement ratio increased, from 20.21 N/mm^2 at 5 % (run 14) to 16.23 N/mm^2 at 25 % (run 1), although these two runs also differ in curing age. This trend is consistent with the higher porosity and lower stiffness of the shell relative to gravel. The effect of curing age was small and not monotonic: in the 15 % CS, 6.3 mm series the strengths were 18.89 N/mm^2 at 7 days, 18.32 N/mm^2 (mean) at 21 days, 18.66 N/mm^2 at 28 days and 18.86 N/mm^2 at 35 days, which the model describes as a shallow minimum near 21 days. This is not the steady gain expected from continued hydration, and the present data do not identify its cause. Each age was represented by a separately cast cube, so batch-to-batch variation cannot be separated from a true age effect, and

the curing terms should be regarded as empirical descriptors of this data set. The strengths are of the same order as the values near 20 MPa reported for CS concrete at comparable replacement levels (Kumar & Pawar, 2022; Pratiwi et al., 2022).

Table 5: ANOVA for the Full Quadratic Model of Compressive Strength

Source	Sum of squares	Df	Mean square	*F*-value	*p*-value	Significant ($p \leq 0.05$)
Model	**13.73**	**9**	**1.53**	**54.18**	**< 0.0001**	**Yes**
A: Replacement ratio	0.19	1	0.19	6.79	0.0262	Yes
B: Particle size	1.39×10^{-4}	1	1.39×10^{-4}	0.0049	0.9454	No
C: Curing age	0.53	1	0.53	18.75	0.0015	Yes
AB	3.42×10^{-3}	1	3.42×10^{-3}	0.12	0.7346	No
AC	0.17	1	0.17	6.13	0.0328	Yes
BC	0.047	1	0.047	1.66	0.2270	No
A^2	0.20	1	0.20	7.16	0.0232	Yes
B^2	0.088	1	0.088	3.12	0.1078	No
C^2	0.48	1	0.48	17.13	0.0020	Yes
Residual	0.28	10	0.028			
Lack of fit	0.25	6	0.042	6.09	0.0510	No (borderline)
Pure error	0.028	4	6.95×10^{-3}			
Corrected total	14.02	19				

Df = degrees of freedom. The lack-of-fit test is marginal ($p = 0.051$ against $\alpha = 0.05$).

Effects on Water Absorption

For water absorption (Table 6), the replacement ratio (A), particle size (B), the AB, AC and BC interactions and the quadratic term A^2 were significant, whereas curing age alone was not ($p = 0.270$). The lowest absorption (1.5 %) occurred at 10 % replacement and the highest (3.9 %) at 25 % replacement (run 1), in line with the high absorption of the shell itself (24 %, Table 3). The measured values are low in absolute terms, but they come from a 24-h immersion of small samples and should not be read as evidence of durability or low permeability: the test is not an accepted standard method (Section 2.7) and no permeability or durability test was carried out.

Table 6: ANOVA for the Full Quadratic Model of Water Absorption

Source	Sum of squares	Df	Mean square	*F*-value	*p*-value	Significant ($p \leq 0.05$)
Model	**6.50**	**9**	**0.72**	**25.08**	**< 0.0001**	**Yes**
A: Replacement ratio	0.17	1	0.17	5.85	0.0361	Yes
B: Particle size	0.27	1	0.27	9.24	0.0125	Yes
C: Curing age	0.039	1	0.039	1.37	0.2696	No
AB	0.31	1	0.31	10.76	0.0083	Yes
AC	0.57	1	0.57	19.68	0.0013	Yes
BC	0.21	1	0.21	7.15	0.0233	Yes
A^2	0.62	1	0.62	21.41	0.0009	Yes
B^2	2.11×10^{-3}	1	2.11×10^{-3}	0.073	0.7920	No
C^2	0.059	1	0.059	2.05	0.1828	No
Residual	0.29	10	0.029			
Lack of fit	0.10	6	0.017	0.35	0.8761	No
Pure error	0.19	4	0.047			
Corrected total	6.79	19				

Df = degrees of freedom.

Fitted Models and Adequacy

The coefficients of the full quadratic models, in actual units, are given in Table 7; these are the models that were used for the optimisation. They reproduce the ANOVA in Tables 5 and 6 and the predictions of the numerical optimiser. Both models were significant ($p < 0.0001$). Their adequacy statistics are given in Table 8: predicted R^2 is within 0.2 of adjusted R^2 for both responses and adequate precision is well above 4. The lack-of-fit test was clearly insignificant for water absorption ($p = 0.876$) but only marginally so for compressive strength ($p = 0.051$), so the strength model should be regarded as a good description of the design points rather than a guarantee of accuracy elsewhere, in particular at the edge of the design space. No studentised residual exceeded ±3 (largest: 2.53 for strength, run 14; 2.73 for absorption, run 19), the points in the normal probability plots lie close to a straight line, and the residuals show no systematic pattern against the predicted values (Figure 3).

Table 7: Regression Coefficients of the Full Quadratic Models (A in %, B in mm, C in days)

Term	Compressive strength: coefficient	*p*-value	Water absorption: coefficient	*p*-value
Intercept	22.860	< 0.0001	0.93273	0.4841
A	−0.15323	0.0262	−0.14385	0.0361
B	0.013535	0.9454	0.59206	0.0125
C	−0.23042	0.0015	−0.062883	0.2696
AB	0.0019398	0.7346	−0.018461	0.0083
AC	0.0045087	0.0328	0.0081699	0.0013
BC	0.0067177	0.2270	−0.014115	0.0233
A^2	−0.0039290	0.0232	0.0068679	0.0009
B^2	−0.0091975	0.1078	−0.0014265	0.7920
C^2	0.0028387	0.0020	0.00099276	0.1828

Coefficients were recomputed by least squares from the data in Table 4 and reproduce the ANOVA sums of squares in Tables 5 and 6 and the optimiser predictions in Table 9.
The fitted equations in actual units (*A* in %, *B* in mm, *C* in days) are:

$$\text{Compressive strength (N/mm}^2) = 22.860 - 0.15323A + 0.013535B - 0.23042C + 0.0019398AB + 0.0045087AC + 0.0067177BC - 0.0039290A^2 - 0.0091975B^2 + 0.0028387C^2 \quad (4)$$

$$\text{Water absorption (\%)} = 0.93273 - 0.14385A + 0.59206B - 0.062883C - 0.018461AB + 0.0081699AC - 0.014115BC + 0.0068679A^2 - 0.0014265B^2 + 0.00099276C^2 \quad (5)$$

Table 8: Adequacy Statistics of the Full Quadratic Models

Statistic	Compressive strength	Water absorption
R^2	0.9799	0.9576
Adjusted R^2	0.9618	0.9194
Predicted R^2	0.8715	0.8999
Adequate precision	31.58	20.57
Coefficient of variation (%)	0.92	7.58
Residual standard deviation	0.168 N/mm^2	0.170 %
Pure-error standard deviation (5 centre points)	0.083 N/mm^2	0.217 %
Lack-of-fit *p*-value	0.0510	0.8761
Largest |studentised residual|	2.53 (run 14)	2.73 (ru n 19)

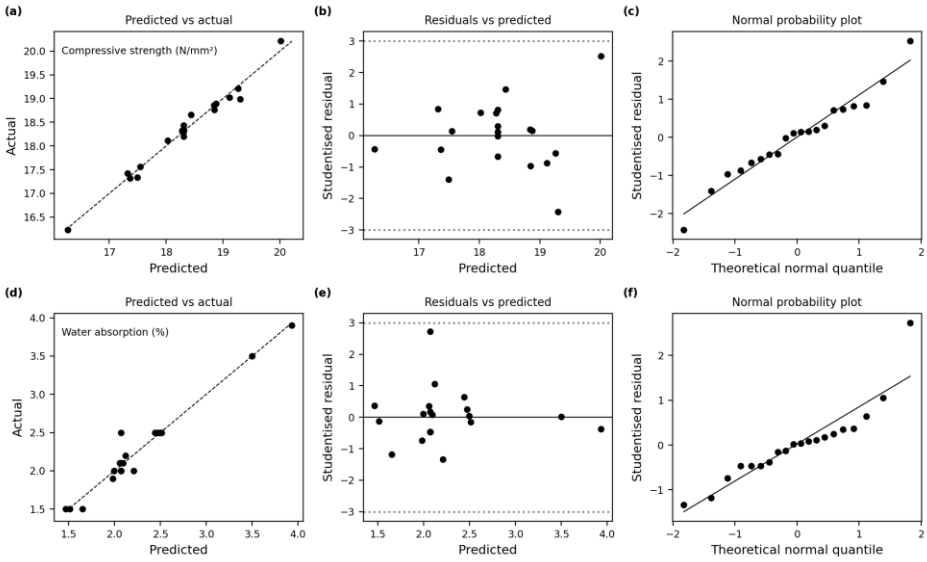


Figure 3: Diagnostic plots of the full quadratic models. (a–c) Compressive strength; (d–f) water absorption: predicted versus actual values, studentised residuals versus predicted values, and normal probability plot of studentised residuals

Numerical Optimization and Confirmation

The optimisation goals and limits are listed in Table 9. All 30 solutions returned by the optimiser had a desirability of 1.000. This does not indicate that the solutions are equivalent to an ideal mix: the goal limits were set at the extreme observed responses (20.21 N/mm^2 and 1.5 %), and any prediction at or beyond a limit receives a desirability of 1. Desirability therefore could not discriminate between solutions and is a model-optimisation output, not independent evidence of performance. The 30 solutions cluster at low replacement

ratios (5.03–8.40 %), small shells (3.35–3.70 mm) and short curing (7.05–11.35 days), that is, close to the lower boundaries of the design space (the 5 % and 3.35 mm axial levels), and their predicted strengths (20.21–20.46 N/mm^2) are at or above the highest strength actually measured (20.21 N/mm^2). Solution 19 (5.274 %, 3.419 mm, 9.243 days), which had the highest predicted strength, was selected for confirmation.

Table 9: Solutions of Numerical Optimization for Compressive Strength and Water Absorption

		Constraints				
Name	**Goal**	**Lower Limit**	**Upper Limit**	**Lower Weight**	**Upper Weight**	**Importance**
A: Ratio	is in range	5	25	1	0.1	3
B: Particle size	is in range	3.35	14	1	1	3
C: Curing age	is in range	7	35	1	1	3
Compressive strength	Maximize	16.23	20.21	1	1	3
Water absorption	Minimize	1.5	3.9	1	1	3

	Solutions						
No.	**Replacement Ratio (%)**	**Particle Size (mm)**	**Curing Age (days)**	**Compressive Strength (N/mm^2)**	**Water Absorption (%)**	**Desirability**	
1	5.230	3.426	10.609	20.294	1.434	1.000	
2	5.912	3.697	10.491	20.219	1.497	1.000	
3	6.069	3.627	10.308	20.216	1.476	1.000	
4	7.872	3.633	8.001	20.211	1.495	1.000	
5	6.916	3.350	8.598	20.290	1.418	1.000	
6	6.699	3.525	8.721	20.313	1.481	1.000	
7	5.344	3.480	10.533	20.289	1.450	1.000	
8	5.205	3.585	11.353	20.212	1.452	1.000	
9	5.158	3.382	10.826	20.275	1.412	1.000	
10	6.872	3.442	9.261	20.216	1.426	1.000	
11	5.338	3.389	9.997	20.354	1.445	1.000	
12	6.410	3.451	9.186	20.298	1.450	1.000	
13	6.302	3.519	8.970	20.344	1.487	1.000	
14	6.481	3.392	8.758	20.340	1.445	1.000	
15	5.452	3.557	10.088	20.331	1.492	1.000	
16	7.991	3.511	7.272	20.281	1.475	1.000	
17	5.030	3.557	11.342	20.236	1.452	1.000	
18	7.165	3.490	7.754	20.360	1.486	1.000	
19	5.274	3.419	9.243	20.461	1.496	1.000	Selected
20	6.550	3.571	9.503	20.240	1.471	1.000	
21	5.048	3.402	10.707	20.306	1.430	1.000	
22	5.195	3.635	10.778	20.284	1.497	1.000	
23	5.402	3.640	10.637	20.273	1.496	1.000	
24	8.147	3.510	7.239	20.258	1.469	1.000	
25	5.324	3.492	10.822	20.257	1.442	1.000	
26	7.076	3.561	8.298	20.306	1.493	1.000	
27	8.399	3.365	7.050	20.235	1.418	1.000	
28	6.152	3.433	9.615	20.283	1.438	1.000	
29	5.701	3.379	9.402	20.376	1.450	1.000	
30	5.859	3.612	9.935	20.292	1.497	1.000	

Selected solution (no. 19): A = 5.274 %, B = 3.419 mm, C = 9.243 days; predicted compressive strength 20.461 N/mm^2, predicted water absorption 1.496 %, desirability 1.000. Range over the 30 solutions: A 5.03–8.40 %, B 3.35–3.70 mm, C 7.05–11.35 days, strength 20.21–20.46 N/mm^2, absorption 1.41–1.50 %, desirability 1.000 for all.

The confirmation results are given in Table 10. Two cubes were made at the selected settings. Their compressive strengths (18.98 and 19.10 N/mm^2; mean 19.04 N/mm^2) agreed within 0.12 N/mm^2, which is inside the ±0.23 N/mm^2 repeatability suggested by the centre-point cubes, so the measured strength of the optimised mix is repeatable. However, the mean was 1.42 N/mm^2 (6.9 %) lower than predicted and both cubes were below the lower limit of the 95 % PI (19.57 N/mm^2), so the model over-predicted strength at the optimum. The measured water absorption values (1.95 and 1.98 %; mean 1.97 %) were about 0.47 percentage points (31 %) higher than predicted but both were within the PI (0.59–2.40 %). The optimum is therefore confirmed as a repeatable measured result but not as a model prediction: for absorption the model is consistent with the measurements, whereas for strength it over-predicted by about 7 %. The measured values (about 19.0–19.1 N/mm^2 and 1.95–1.98 %), not the predicted 20.46 N/mm^2 and 1.50 %, are the

performance figures for the optimised mix. Only two cubes were made, and they were cured for only about 9 days, so the 28-day strength of the optimised mix is unknown.

Table 10: Confirmation of the Optimum (A = 5.274 %, B = 3.419 mm, C = 9.243 days).

Response	Predicted (full model)	95 % PI	Measured (cube 1 / cube 2; mean)	Difference	Within PI
Compressive strength (N/mm^2)	20.46	19.57–21.36	18.98 / 19.10; mean 19.04	−1.42 (−6.9 %), mean	No (both cubes)
Water absorption (%)	1.50	0.59–2.40	1.95 / 1.98; mean 1.97	+0.47 (+31 %), mean	Yes (both cubes)

PI = prediction interval for a single new observation, calculated from the full quadratic model (Section 2.8); each cube is compared with it individually. Both confirmation cubes were made at the settings of the selected optimiser solution (no. 19).

Classification and Suitability

Structural lightweight concrete is defined by a minimum 28-day compressive strength of about 17 MPa (ACI 213R-14; ASTM C330/C330M-23, ≈ 17.2 MPa) together with an upper limit on density: ASTM C330 sets an air-dry density limit of 1,840 kg/m^3, to be determined by ASTM C567/C567M-19, and design under ACI 213R-14 relies on the equilibrium density defined in ASTM C567. Table 11 sets the evidence from this study against these criteria. Density was determined on the two confirmation cubes of the optimised mix, which were air-dried following ASTM C567/C567M-19 before weighing (Section 2.6). Their masses were 6.47 and 6.49 kg, which give air-dried densities of 1,917 and 1,923 kg/m^3 (mean 1,920 kg/m^3) for the 150 mm cube (nominal volume 0.003375 m^3). These densities exceed the 1,840 kg/m^3 limit of ASTM C330, so the concrete is not classified as lightweight or structural lightweight concrete in this paper and is described as coconut-shell aggregate concrete. The confirmation cubes gave 18.98 and 19.10 N/mm^2 (predicted: 20.46 N/mm^2), above the 17 MPa minimum, and the 28-day cubes made with 10–20 % CS (runs 7, 12, 18 and 20) gave 17.34–19.21 N/mm^2. These strength values are only indicative, because the criteria apply to cylinders whereas cube strengths are generally higher, the strength data come from single cubes (two for the optimum), and the confirmation cubes were cured for about 9 days rather than 28 days.

Table 11: Criteria for Structural Lightweight Concrete Compared with the Evidence Available in this Study

Criterion	Source	Evidence in this study	Status
28-day compressive strength ≥ 17 MPa	ACI 213R-14; ASTM C330/C330M-23 (≈ 17.2 MPa)	Cubes cured 28 days (runs 7, 12, 18, 20; 10–20 % CS): 17.34–19.21 N/mm^2. Confirmation cubes (about 9 days): 18.98 and 19.10 N/mm^2. Cube vs. cylinder strength not compared.	Indicative only
Air-dry density ≤ 1,840 kg/m^3 (equilibrium density used in design)	ASTM C330/C330M-23 with ASTM C567/C567M-19; ACI 213R-14	Confirmation cubes (150 mm; 6.47 and 6.49 kg): 1,917 and 1,923 kg/m^3 (mean 1,920), air-dried following ASTM C567	Exceeded (two cubes)
Loose bulk density of coarse lightweight aggregate < 880 kg/m^3	ASTM C330	CS bulk density 515 kg/m^3 (Table 3)	Aggregate only

Limitations

The conclusions are subject to the following limitations: (i) one specimen per run, with replication only at the centre point, and a separately cast cube for each curing age; (ii) only two confirmation specimens, both cured for about 9 days; (iii) the 28-day strength of the optimised mix was not measured; (iv) the water-absorption procedure was a simplified 24-h test on small samples; (v) the optimum lies at the edge of the design space, where the borderline lack-of-fit of the strength model matters most; (vi) no durability, permeability, shrinkage or structural-performance tests were carried out; and (vii) density was determined on two cubes of the optimised mix only, so the density of the other mixes is unknown.

Conclusion

The conclusions apply only to the tested formulations (5–25 % CS replacement of the gravel, CS size 3.35–14 mm, water/cement ratio 0.5, curing 7–35 days) and to the properties measured (compressive strength of 150 mm cubes and water absorption by 24-h immersion).

Compressive strength of the CS concretes was 16.23–20.21 N/mm^2 and water absorption 1.5–3.9 %; the 28-day control cube without CS reached 24.36 N/mm^2.

Replacement ratio and curing age (with the A×C interaction and curvature) significantly affected compressive strength, whereas particle size did not. Replacement ratio, particle size and their interactions significantly affected water absorption. The curing-age effect on strength was small and not monotonic and is not explained by these data.

The quadratic models were significant for both responses; the lack-of-fit for compressive strength was borderline ($p = 0.051$).

The model-predicted optimum (5.27 % CS, 3.42 mm, 9.2 days) was 20.46 N/mm^2 and 1.50 %. Two confirmation specimens gave 18.98 and 19.10 N/mm^2 and 1.95 and 1.98 %. The two cubes agreed closely, so the measured performance of the optimised mix is repeatable, but the mean strength was 6.9 % below the prediction and both cubes were outside the 95 % PI, whereas the absorption values were within it. The strength model therefore over-predicts at the optimum, and the measured values, not the predicted ones, should be taken as the performance of the optimised mix.

The two confirmation cubes of the optimised mix had air-dried densities of 1,917 and 1,923 kg/m^3 (mean 1,920 kg/m^3), which exceed the 1,840 kg/m^3 air-dry limit of ASTM C330, so the concrete is not classified as lightweight or structural lightweight concrete. Its 28-day strength, durability and

structural performance were not measured, so the results do not establish its suitability for agricultural structures.

Recommendations

Future work should (i) make further replicate confirmation cubes, test the optimised mix at 28 days, ideally on cylinders as well as cubes, and repeat the density determination (ASTM C567/C567M-19) on further cubes; (ii) measure water absorption on whole specimens by ASTM C642 or BS 1881-122 and add permeability tests; (iii) examine durability aspects such as alkali–silica reaction, shrinkage and sulphate resistance; (iv) evaluate chemical pre-treatment of the shell (for example hexamine or sodium silicate) to reduce its absorption; and (v) compare the RSM models with artificial neural network and genetic-algorithm approaches.

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