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RESEARCH ARTICLE OPEN ACCESS

Model Development for Prediction of Concrete Compressive Strength: Advancing Construction Industry Practices and Quality Control Standards

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Abstract:

In construction, the selection of concrete mix grades centres on the specified strength outlined in the design. However, achieving the desired strength necessitates laborious and costly experimental investigations. This inspires the current study, which seeks to establish an equation to predict concrete compressive strength (CS) based on water to cement ratio (WCR), reducing the need for costly experimental investigations. 90 concrete cube samples were made using Portland limestone cement of 42.5 N grades, with WCR ranging from 0.45 to 0.65 and two different mix ratios. Strength was tested at 7, 14, and 28 days, with statistical analysis focusing on the 28-day CS. Models developed using Design Expert software exhibited over 94% accuracy in predicting 28-day compressive strength, indicating strong alignment with experimental data. Fit Statistics indicated a satisfactory fit with adjusted R^2 of 0.9932 and predicted R^2 of 0.9715. Adequacy precision, signalling the signal-to-noise ratio, exceeded 4, indicating a robust model. P-value was significant (<0.05), and the F-value (583.28) suggested the model's significance in predicting CS. The findings imply the model's potential for guiding design decisions effectively.

Keywords — **Model, Water, Cement, Strength, Concrete, Statistical**

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I. INTRODUCTION

Water is the most widely used natural resource on our planet, followed closely by concrete, which ranks as the second most commonly employed building material worldwide (Alhaji, 2016: John et al 2019). Concrete, a composite construction material, is constituted of sand, cement, water and, gravel in precise proportions. To produce concrete that possesses qualities of robustness, durability, and cost-effectiveness, it is imperative that the aggregates, constituting 75 percent of an ideal concrete mix, conform to established criteria (Alhaji, 2016). The strength of concrete stems from cement's capacity to retain water (John et al 2019a). As a result of its early retention of moisture, the cement particles are bonded together inside an unstable framework surrounded by a moisture-saturated region. An increase in the water-to-cement ratio (WRC) will further increase the average spacing between the cement grains (Harrison, 1992). Concrete hardens as a result of an action known as hydration caused by water. According to Fayaz and Chidiac (2015), the WCR should be referenced when studying the compressive strength (CS) of concrete. The water-to-cement ratio is contingent on the concrete's grade and is crucial for upholding its durability (Nduka at al., 2018; Basheer et al., 2017). To enhance strength, high-grade concrete may incorporate plasticizers to lower the WCR (Xiao 2017; Gupta et al., 2021).

II. REVIEW OF EXISTING MODELS

The CS of concrete is the main mechanical property that may be assessed by studying a 7 to 28-day-cured concrete cylindrical or cube specimen. As noted by Noorzaei et al. (2007), factors such as WCR, aggregate quality, and the strength of the cement significantly influence the overall strength of concrete. There has been a great deal of research into developing a model for predicting the CS of concrete. In 1892, Feret was the first to propose a formula as shown in equation (1) for predicting the CS of concrete (Popovics 1985). The author anticipated that the cement-to-paste-to-air ratio governed the CS of concrete; nevertheless, experimental evidence revealed that these predicted CS values were not substantiated by facts.

$$CS = A\left(\frac{V_{oc}}{V_{oc} + V_{oa} + V_{ow}}\right)^{B} \qquad (1)$$

where,
V_{ow} = volume of water
V_{oa} = volume of air
CS = concrete compressive strength
A, B = calibration constants
V_{oc} = volume of cement.

Abrams (1919) proposed a ground breaking method for assessing concrete strength by introducing the concept of the WCR in the prediction of CS. This innovative approach marked Abrams as one of the pioneering figures to recognize and emphasize the paramount importance of this ratio in determining concrete's structural integrity and durability. His forward-thinking insight revolutionized the field of concrete technology and laid the foundation for modern concrete mix design methodologies, profoundly influencing the construction industry's approach to achieving optimal concrete performance. Based on this ratio, he developed a model as presented in Equation 2, that was thought to be simpler and had better agreement with the strength data for non-air embedded concrete. Nevertheless, Fayez and Chidiac (2015) pointed out that the calibration coefficients A and B of this model presented challenges.

$$CS = \frac{A}{B^{w/c}} \qquad (2)$$

where,
CS = concrete compressive strength
A, B = calibration constants
w = quantity of water
c = quantity of cement

Popovics (2008), modified Abrams (1919) empirical model by introducing cement parameter into Equation (2.0). The modified model according to Fayez and Chidiac, (2015) takes into consideration cement content and air parameters. The modified equation is presented in Equation 3.

$$CS = \frac{A}{B^{[(^{w}/_{c})+mc]}} \times 10^{-0.038V_a} \qquad (3)$$

where,
CS = compressive strength of concrete
A, B, m = calibration constants
c, w = quantity of cement and water
V_a = volume fractions of air

Pann et al. (2003) studied Abrams' equation and developed a model which contains WCR as presented in Equation (3) by integrating through empirical observation the binder pastes capillary porosity (CP). According to authors, CP depend the level of hydration.

$$CS = \frac{A}{B^{w/c}} + \frac{C}{D^{CP}} \qquad (4)$$

CS = concrete compressive strength
A, B, C, D = calibration constants
W/C = Water to Cement Ratio
CP = Capillary porosity

Fayez and Chidiac (2015) investigated compressive strength prediction models and reported that almost all the models give a satisfactory prediction since strength is typically influenced by WCR compared to gradation and properties of aggregates.

In construction, the selection of concrete mix grades centres on the specified strength outlined in the design (Wilby,2013). However, achieving the desired strength necessitates laborious and costly experimental investigations (Shi, et al 2015). This motivates the current study, which seeks to establish an empirical model for predicting the CS of concrete based on its WCR. This endeavour holds significant promise, as an accurate empirical model for determining concrete strength could alleviate the immediate need for extensive and resource-intensive experimentation in subsequent projects.

By formulating a reliable predictive model, this research aims to streamline the process of ascertaining concrete strength, offering an effective tool for engineers and construction professionals. Such a model would not only expedite decision-making in material selection and mixture design but also enhance the overall efficiency and cost-effectiveness of construction projects (Mehta, 2002). Additionally, it could pave the way for more innovative and sustainable approaches to concrete utilization, ultimately contributing to advancements in construction technology and the broader field of civil engineering. This study thus represents a fundamental step towards optimizing concrete performance and ushering in a new era of efficiency in construction practices.

III. MATERIALS AND METHODS

A. Materials

The study employed Portland limestone cement of grade 42.5 N, which adheres to the standards set forth in BS EN 197-1 (2011) and, both coarse and fine aggregates, in accordance with EN 932, were used. These aggregates were procured from sources within the Niger Delta University Campus, situated in Bayelsa State. The physical properties of the aggregates were examined to determine their suitability. It's noteworthy that the water utilized for the concrete mixture was devoid of any impurities, ensuring the integrity of the mixture. This meticulous selection of materials and stringent quality control measures underscores the precision and reliability of the experimental setup.

B. Method

1) Preparation of the test specimen

Portland limestone cement of 42.5 N grades was used to produce a total of ninety (90) concrete cube samples of 150 mm x 150 mm x 150 mm, with WCRs of 0.45, 0.50, 0.55, 0.60, to 0.65. A 1:1.5:3 and 1:2:4 by weight were chosen for this investigation. The cubes were then put through a curing process and examined for the effect of WCR on the CS at 7, 14, and 28 days.

2) Statistical Data Analysis, Model Development, Optimization and Test Results Application

Having considered five WRCs of 0.45, 0.50, 0.55, 0.60 and 0.65 experimentally, only CS at 28 days' response was statistically analysed using Design Expert. A number of models were chosen from the Design Expert software and examined for their appropriateness in modelling the CS equation. Cubic, special cubic, quadratic, and linear models are among those available as shown equations (5), (6), and (7). These types of models are clearly distinguishable from response surface approaches by the absence of an intercept term.

$$Y = b + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n \quad (5)$$
$$Y = b + \beta_1 x_1^2 + \beta_2 x_2^2 + \beta_3 x_3^2 + \cdots + \beta_n \quad (6)$$
$$Y = b + \beta_1 x_1^3 + \beta_2 x_2^3 + \beta_3 x_3^3 + \ldots + \beta_n x_n^3 \quad (7)$$

Generally, the software's built-in algorithm uses each model to choose design points. By default, higher-order models, for example, will normally necessitate more points. Experimental results obtained were analysed statistical with Design Expert software. Analysis of variance (ANOVA) was considered to evaluate the implication of the equations. The ANOVA values were examined in terms of standard deviation, p value, sum of squares, F value, coefficient of variation, adjusted (R^2), coefficient of determination (R^2), and adequate precision.

IV. RESULTS AND DISCUSSION

The findings of this investigation are elaborated upon and analysed in section A to **3.4**. This segment provides a comprehensive overview of the results, offering a detailed examination and interpretation of the data gathered during the course of the study. Through thorough presentation and discussion, this section aims to shed light on the key insights and implications derived from the experimental outcomes, contributing to a deeper understanding of the relationship between WCR and concrete CS, and also the developed empirical model.

A. Results for Physical Properties of Aggregates

The results of the physical properties examination carried out on the aggregates are illustrated in Table 1 and Figures. 2 and 3. The results of specific gravity and water absorption are within the stated limits of ASTM. Also, the particle distribution as illustrated in Figures 1 and 2 confirm that the coarse and fine aggregates, respectively, are well-graded.

TABLE 1. PHYSICAL PROPERTIES

Test conducted	Results	Code referenced	Code
Coarse Aggregate			
Specific gravity	2.58	ASTM C128, (2001)	2.55 -2.75
Water absorption (%)	0.6	BS 812 part 2, (1995)	< 3.5%
Fine Aggregate			
Specific gravity	2.72	ASTM C128, (2001)	2.55 - 2.75
Water absorption (%)	0.80	BS 812 part 2, (1995)	< 15%

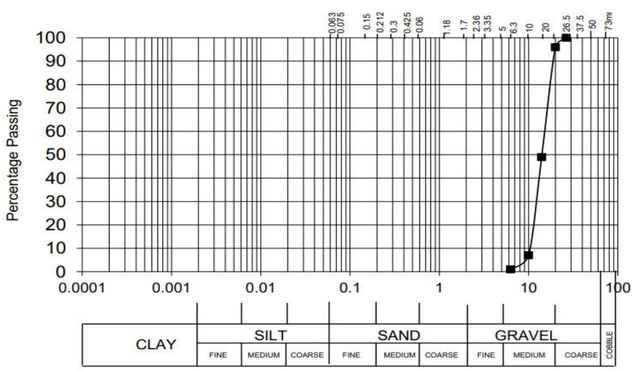

Fig. 1 Sieve analysis graph for coarse aggregate

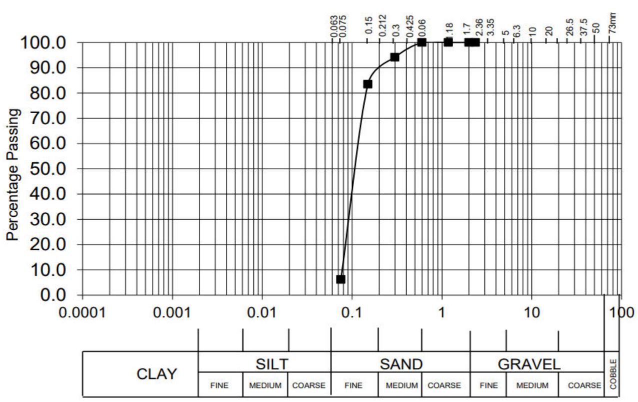

Fig. 2 Sieve analysis graph for fine aggregate

B. Concrete strength results

Table 2, Fig. 3 and Fig.4 present the CS results for mix ratios of 1:2:4 and 1:1.5:3, encompassing a range of WCR ranging from 0.45 to 0.65. Notably, Fig. 3 and Fig.4 and Table 2 both demonstrate a remarkable trend. The CS experiences a steady ascent up to a WCR of 0.55, where it reaches its maximum. However, once the WCR surpasses 0.55, the CS begins to decline. Specifically, for concrete with a mix ratio of 1:2.4, the CS values stand at 22.67 MPa, 23.33 MPa, 28.30 MPa, 24.78 MPa, and 23.48 MPa corresponding to WCRs of 0.45, 0.50, 0.55, 0.60, and 0.65, respectively. Meanwhile, for concrete with a mix ratio of 1:1.5:3, the CS figures are 16.30 MPa, 32.30 MPa, 33.41 MPa, 28.89 MPa, and 22.07 MPa with matching WCRs of 0.45, 0.50, 0.55, 0.60, and 0.65, respectively. Referring to Table 2, the reduction in CS observed beyond the 0.55 WCR ratio can be attributed to the phenomenon of concrete bleeding and the subsequent separation of aggregates. This insightful data illuminates the critical role that the WCR plays in determining the compressive strength of the concrete mixes, offering significant understandings for optimizing concrete preparations in future construction endeavours.

TABLE 2: CS OF CONCRETE FOR A 1:2:4 AND 1:1.5: 3 MIXES WITH VARIOUS WCR

Water/cement Ratio	7 days CS (MPa)	14 days CS (MPa)	28 days CS (MPa)
1:2:4 mix			
0.45	14.30	20.44	22.67
0.50	15.85	22.33	23.33
0.55	21.48	28.22	28.30
0.60	16.11	20.37	24.78
0.65	15.48	19.78	23.48
1:1.5:3 mix			
0.45	14.83	25.89	16.30
0.50	24.44	29.67	32.30
0.55	25.33	28.52	33.41
0.60	19.48	23.00	28.89
0.65	17.44	17.11	22.07

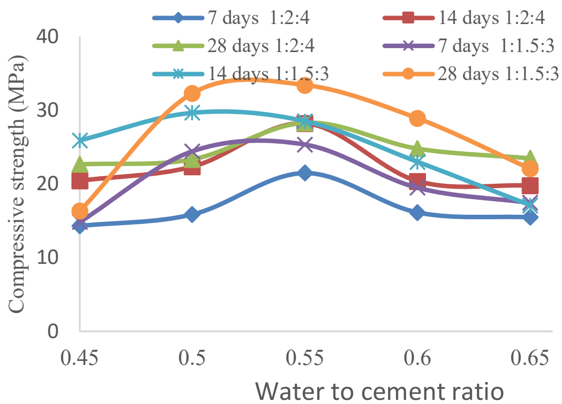

Fig. 3 CS vs water-to-cement ratio

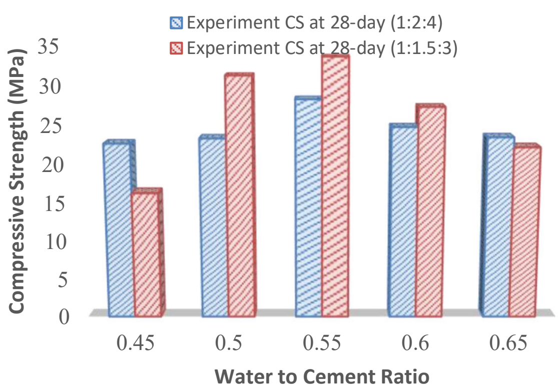

Fig. 4 Bar Chart Showing Strength Variation

C. Model Results and ANOVA

The transform used was Logit, with 22.66 and 181 as lower and upper bounds, respectively, for a 1:2:4 mix and 16.29 and 35 as lower and upper bounds, respectively, for a 1:1.5:3 mix. When the P-value is lower than 0.0500 and the F-value is higher than 0.1000, model terms are deemed substantial. Otherwise, they are deemed inconsequential. Table 3 shows that the P-value is less than 0.0500, which is significant. The F-value of the statistical model (583.28) shows that it could be significant. An F-value this high could have been caused by noise only 0.01% of the time.

Referring to Table 4, it is clear that the difference between the adjusted R^2 (0.9932) and the predicted R^2 (0.9715) the is absolutely below 0.2, it is satisfactory to conclude that these two values are in good alignment. When the adequacy precision, which measures the signal-to-noise ratio, surpasses 4, it is desirable. In this scenario, the signal is more than adequate, with a ratio of 50.340. As a result, this model may successfully guide design decisions within the confines of the available area. The empirical models for CS as a response and WCR as a factor from the ANOVA study is of the form Equations (8) and (9). Equations (8) and (9) were developed to predict the CS of concrete produced from 1:2:4 and 1:1.5:3, respectively.

TABLE 3: ANNOVA SUMMARY FOR THE CS

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	87.42	3	29.14	583.28	< 0.0001	significant
A-WCR	0.1857	1	0.1857	3.72	0.0860	
A^2	45.24	1	45.24	905.58	< 0.0001	
A^3	0.5045	1	0.5045	10.10	0.0112	
Residual	0.4496	9	0.0500			
Lack of Fit	0.4496	1	0.4496			
Pure Error	0.0000	8	0.0000			
Cor Total	87.87	12				

TABLE 4: FIT STATISTICS

Std. Dev.	0.2235	R^2	0.9949
Mean	-5.95	Adjusted R^2	0.9932
C.V. %	3.75	Predicted R^2	0.9715
		Adeq Precision	50.3403

Referring to Table 4, it is clear that the difference between the adjusted R^2 (0.9932) and the predicted R^2 (0.9715) the is absolutely below 0.2, it is satisfactory to conclude that these two values are in good alignment. When the adequacy precision, which measures the signal-to-noise ratio, surpasses 4, it is desirable. In this scenario, the signal is more than adequate, with a ratio of 50.340. As a result, this model may successfully guide design decisions within the confines of the available area. The empirical models for CS as a response and WCR as a factor from the ANOVA study is of the form

Equations (8) and (9). Equations (8) and (9) were developed to predict the CS of concrete produced from 1:2:4 and 1:1.5:3, respectively.

$$CS = \frac{181e^{\beta_0+\beta_1+\beta_2+\beta_3} + 22.66}{1 + e^{\beta_0+\beta_1+\beta_2+\beta_3}} \quad (8)$$

where,
CS = compressive strength (MPa)
β_0 = -360.94055,
β_1 = 1711.45466WCR,
β_2 = -2692.96169WCR2.
β_3 = 1387.26871WCR3
WCR = water-to-cement ratio

$$CS = \frac{35e^{\alpha_0+\alpha_1+\alpha_2+\alpha_3} + 16.29}{1 + e^{\alpha_0+\alpha_1+\alpha_2+\alpha_3}} \quad (9)$$

where,
CS = compressive strength
α_0 = -1167.17269
α_1 = 6063.35668WCR
α_2 = -10402.08959WCR2
α_3 = 5899.31862WCR3
WCR = water-to-cement ratio

1) Model Validity

By contrasting the compressive strength of concrete produced from the experiment with that anticipated by the model, the developed model was proven to be accurate. Numerous analytical techniques, including mathematical and pictorial analysis, were used to validate the model. Table 5 reveals that the CS prediction made by the empirical model is significant.

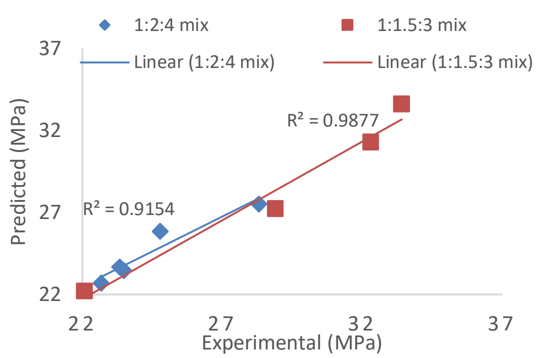

Fig. 5 Predicted v experimental

The values shown in Table 5 demonstrate how conservatively Equations (8) and (9) predicts the CS of 1:2:4 and 1:1.5:3 concrete mixes.

TABLE 5: ANALYTICAL MODEL FOR COMPRESSIVE STRENGTH

Water/cement Ratio	Experimental CS at 28 days (MPa)	Predicted CS at 28-day Equations (MPa)
	1:2:4 mix	
0.45	22.67	22.67
0.50	23.33	23.67
0.55	28.30	27.51
0.60	24.78	25.85
0.65	23.48	23.45
	1:1.5:3 mix	
0.45	16.30	16.30
0.50	32.30	31.29
0.55	33.41	33.63
0.60	28.89	27.23
0.65	22.07	22.20

2) Statistical Analysis

Correlation: Design Expert provided the correlation factor relating to the WRC and the CS of concrete. For the corrected and projected models, these findings are 0.9932 and 0.9715, respectfully. It is acceptable to state that the projected R2 of 0.9715 and the corrected R2 of 0.9932 are reasonably in conformity since the variation between the two is less than 0.2. Less than 2 MPa of standard error was recorded while predicting the model-based CS over a 28-day period. Excel from Microsoft 2019 was used to assess the standard error.

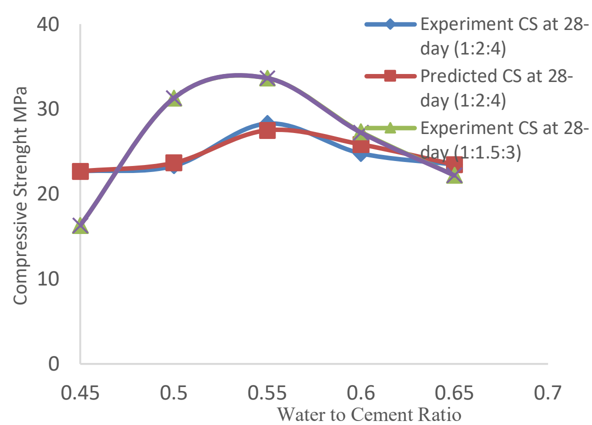

Fig. 6 Strength vs Water-to-Cement Ratio

The model's validity was further confirmed by plotting values of the experimental CS and the predicted CS against the different water-to-cement ratios. Fig. 5 shows the predicted strength of Eq. (8) and ((9). The coefficient of regressions was found to be 0.9154 for 1:2:4 mix and 0.9877 for 1:1.5:3 mix. Fig. 6 illustrates a strong trend in the curves and patterns, indicating a notably similar trend in the distribution of data points for both the experimentally measured and predicted CS. This trend in the graphical representation confirms the agreement observed in Table 5 between the two sets of results.

V. CONCLUSION

Empirical models to predict the 28-day compressive strength in relation to its water-to-cement ratio for 1:2:4 and 1:1.5:3 mixes were developed. The idea of using water-to-cement ratio as the only variable in developing the empirical model as seen in this investigation was conducted because water has a significant effect on the strength.

From the finding, the following conclusions were established:

i. the developed models exhibit an impressive accuracy of over 94% in predicting the 28-days compressive strength. This high level of precision is attributed to their exceptional fit with the experimental data, affirming their reliability and robustness in estimating concrete strength over an extended period;

ii. for the predicted for 28-day compressive strength, the standard error is less than 2 MPa, underscoring the remarkable precision and reliability of the predictive models;

iii. the models are developed to only predict 28-days compressive strength; Unfortunately, they lack the capability to provide accurate predictions for compressive strengths at 7 or 14 days, highlighting their limited applicability in those contexts; and

iv. Both the models and experimental findings clearly indicate that the optimal mix attains its maximum strength at a water-cement ratio (WCR) of 0.55. This ratio proves to be the most conducive for achieving peak strength.

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