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Optimization of Binary Superplasticized Concrete Using Taguchi Approach

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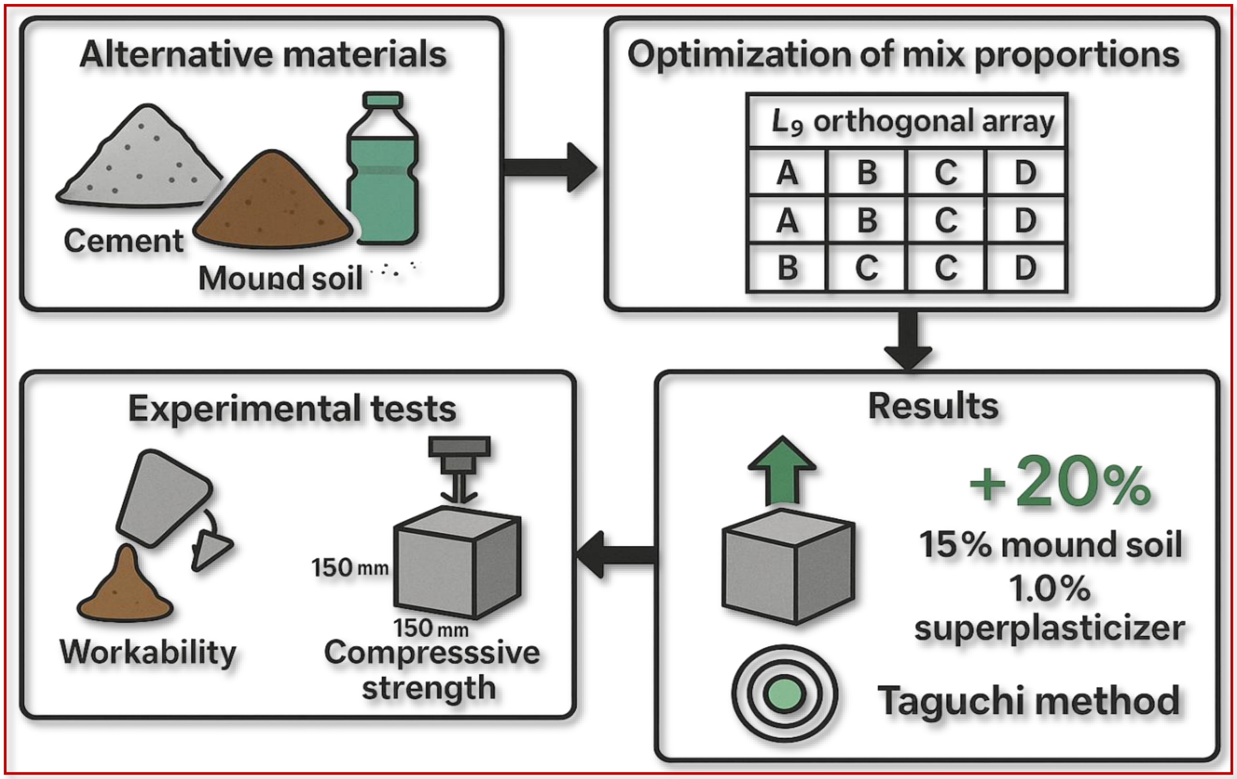
Abstract

Several materials are being considered as replacements for cement and the other basic known ingredients of concrete, which would help to reduce cost and environmental hazards. This research involved investigating mix proportion parameters of binary superplasticized concrete comprising chemical superplasticizer and mound soil to develop an optimum design using the Taguchi Experimental design approach for high strength concrete. To achieve this objective, an L9 orthogonal array was employed, involving four key variables: water-to-cement ratio, cement quantity, mound soil proportion, and superplasticizer dosage. Each factor was assessed at three distinct levels. Concrete samples were molded into standard 150 mm cubes and evaluated in both fresh and hardened states. In the fresh condition, workability was analyzed, whereas the hardened samples were subjected to compressive strength testing at 7 and 28 days. The goal was to meet structural and functional standards for superplasticized concrete. Findings indicated that the optimal mix configuration—featuring 15% mound soil substitution and 1.0% chemical superplasticizer—yielded a compressive strength improvement of approximately 20% at 28 days. The result of a verification experiment conducted using the optimum mixture proportions compared favourably with the model predicted by Taguchi method which shows that Taguchi model is a suitable approach that can enhance the properties of binary superplasticized concrete.

***Keywords**: Concrete, Superplastizer, Optimization, Compressive strength, Taguchi*

Graphical Abstract



1.0 INTRODUCTION

Concrete plays a vital role in the development of modern infrastructure due to its diverse range of structural applications. From road pavements and staircases to residential buildings, office complexes, warehouses, and high-rise structures, its usage spans virtually every aspect of the construction industry. This composite material consists primarily of cement, fine and coarse aggregates, water, and various admixtures. As one of the most utilized materials in civil engineering, it is essential not only to select appropriate constituents for each specific application but also to proportion them accurately to achieve targeted performance characteristics with optimal material consumption.

Current literature extensively documents the incorporation of superplasticizers (SPs) in concrete technology to reduce the water-cement ratio and enhance the strength of high-performance concrete mixes. However, there remains a significant research gap concerning the use of mound soil in such advanced formulations [1]. The idea of integrating both superplasticizers and mound soil in high-strength concrete is yet to be fully explored within the industry. Consequently, this study aims to determine an optimal dosage of chemical superplasticizer that, when combined with mound soil, can significantly improve the mechanical properties of high-strength concrete.

The research carried out by [2] applied the Taguchi method for optimizing conventional concrete mixtures, whereas [3] focused on fly ash in superplasticized concrete, but also limited to standard strength grades. In contrast, the present study demonstrates the application of Taguchi's robust design methodology in optimizing mechanical performance parameters for binary superplasticized high-strength concrete mixes. The research outlines a framework and predictive model capable of guiding the selection of optimal material combinations for binary superplasticized concrete suitable for construction-grade mixes. Employing Taguchi's Optimization Approach can drastically reduce trial-and-error experimentation on construction sites, thereby lowering project costs. The model's procedural simplicity and systematic framework allow for efficient tuning of mix parameters.

Emerging evidence has shown that cement can be partially or fully replaced with materials like waste concrete and limestone powder, without compromising sometimes even enhancing the compressive strength of the resulting concrete mix [4]. Additionally, there is a growing shift toward

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incorporating indigenous and locally sourced materials in construction practices. Such approaches promote sustainability by minimizing material waste and contributing to environmentally friendly construction practices. For instance, materials such as recycled glass and plastic have been introduced into concrete production with promising outcomes, achieving performance metrics that rival traditional concrete. In one such example, pre-sorted glass fragments were utilized with favorable mechanical results [5], while another study used recycled glass in mortar production [6].

Further investigations by [7] explored the replacement of cement with Calcined Termite Mound (CTM), supplemented with Sikament NN superplasticizer at varying proportions. The research revealed enhanced workability and compressive strength at 5%, 10%, and 15% substitution levels. Likewise, [8] evaluated the use of both calcined and uncalcined termite mound soil as pozzolanic additives in concrete mixes. Termite mound soil was extracted from within Akure metropolis at a depth of 20 cm, processed in a laboratory setting, and subjected to calcination at 650°C for one hour in a muffle furnace. The material was then cooled over six hours, ground to a fine powder, and sieved through a 150 µm mesh. The resulting powder underwent chemical analysis using an Atomic Absorption Spectrophotometer (AAS), characterizing both CTM and uncalcined termite mound (UTM) samples. Additional materials used included Grade 42.5 Dangote Ordinary Portland Cement, potable water, fine aggregates, and 19 mm coarse granite aggregates.

The inclusion of admixtures in concrete technology has seen broad usage as a strategy for improving mechanical behavior. Admixtures—substances introduced into the concrete mix other than cement, water, and aggregates—are typically added either during or immediately before the mixing process. These chemical additives are tailored to enhance specific properties of concrete, whether in its fresh or hardened state, and are integral to transforming ordinary concrete into high-strength composites [10].

One of such admixtures are superplasticizers. Superplasticizers has been considered to be a new category and improved version of plasticizer as they have been found to permit the reduction of water content in concrete up to 30 percent without reducing the workability unlike the conventional plasticizers that can only reduce water content up to 15 percent. The application of superplasticizers has become essential in the formulation of highly flowable, self-compacting, and self-leveling concrete, as well as in the production of high-strength mixes. Their inclusion has enabled the effective incorporation of supplementary cementitious materials such as fly ash, slag, and notably silica fume, in the development of high-performance concrete. Many nations are actively adopting superplasticizers in large-scale civil engineering projects—including skyscrapers, long-span bridges, and ready-mix concrete operations—due to their ability to significantly improve concrete workability without increasing the water-cement ratio. These admixtures facilitate the reduction of water content, allow for lower cement usage while preserving strength, and contribute to cohesive and uniform concrete mixes with minimal bleeding or segregation issues.

Superplasticizers are generally classified into three main categories: Sulphonated Melamine Formaldehyde (SMF), Sulphonated Naphthalene Formaldehyde (SNF), and Modified Lignosulphonate (MLS) condensates. Additionally, a newer generation of high-performance superplasticizers has emerged in some countries. These include Acrylic Polymer-based (AP), Copolymers of Carboxylic Acrylic Acid with Acrylic Ester (CAE), Cross-linked Acrylic Polymers (CLAP), Polycarboxylic Esters (PC), and Multicarboxylate Ethers (MCE), either in isolation or in hybrid combinations. The integration of these additives has been associated with enhancements in key properties of concrete, including acceleration, retardation, water reduction, air entrainment, shrinkage minimization, and increased plasticity. Their versatility makes them suitable for advanced concrete types such as high-strength and high-performance concrete (HPC and HSC).

The dosage of superplasticizers significantly impacts concrete characteristics, as demonstrated by [11], whose research identified direct correlations between dosage and performance. According to [12], experimental results confirmed that combining superplasticizers with crushed sand led to marked improvements in both fresh and hardened states of concrete. Additional insights by [13] showed that using different superplasticizer ratios improved concrete workability and reduced the water-cement ratio. In a related study, [14] evaluated three types of superplasticizers at a constant water-cement ratio and discovered unique effects on concrete properties. All three admixtures enhanced the compacting factor beyond 0.84, with each yielding noticeable increases in workability. Meanwhile, [15] studied the performance of normal concrete modified with varying superplasticizer dosages—500, 750, and 1,000 ml per 1,000 kg of cement—using the Department of Environment method to design mixes for Grades 25 and 30, ensuring accurate proportions of ingredients.

Concrete mix design, at its core, involves selecting appropriate raw materials and determining their relative quantities to produce concrete that meets

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specific strength and durability criteria while optimizing material cost. Research by [16] emphasized that a reduced cement content could still yield effective mixes if the water-cement ratio is maintained, thus ensuring improved concrete quality. Similarly, [17] focused on optimizing high-performance concrete mixes using locally sourced materials, highlighting the need to balance strength, durability, and sustainability.

Optimization itself is a critical process in engineering—defined as the act of selecting the best possible alternative under specific constraints. Techniques such as Scheffe's optimization model have been utilized by [18] and [19] for concrete mix design. Among the simpler and more practical strategies is the Taguchi method, which has found widespread use across various engineering disciplines [20]. In the context of concrete, [21] employed the Taguchi technique to optimize mixes containing unconventional materials, reinforcing the importance of considering all mix parameters when working with novel components. This approach also minimizes costs by reducing the number of experimental combinations needed.

For high-strength concrete (HSC), maintaining a low water-cement ratio is vital, as this ratio predominantly governs the strength development. Such low-ratio mixes, especially when combined with additional cementitious materials, typically require polycarboxylate-ether-based superplasticizers to achieve the desired water reduction and workability. However, increasing the cement content alone does not guarantee higher strength, as beyond a certain threshold, further cement addition yields diminishing returns.

This study utilized the orthogonal array experimental design method L9 (3^4), a standard Taguchi configuration well-suited for testing four parameters at three levels each. This methodology allowed for the systematic optimization of both the workability and compressive strength properties of high-strength concrete.

The structure of the remaining paper is as follows: Section II outlines the methodology employed; Section III presents the experimental results; and Section IV discusses the findings, with attention to their practical implications in construction.

2.0 MATERIALS AND METHODS

This experimental study utilized several construction materials. Ordinary Portland Cement (OPC) of 42.5 grade, manufactured by Dangote, was used in accordance with BS 12 standards [22]. Crushed granite, obtained from a local quarry, served as the coarse aggregate, with a nominal maximum particle size of 20 mm. The fine aggregate used was quartzite-rich river sand collected from the Okhuahe River, whose physical properties and gradation satisfied the requirements specified in [23]. Termite mound soil sourced from Edo State functioned as a partial replacement for cement. Clean, potable water free from harmful impurities was employed throughout the mixing process. Additionally, a chemical superplasticizer, Hydroplast 500, was introduced into the mix to enhance the performance characteristics of the concrete.

Concrete mix proportions were determined using the Department of Environment (DOE) method for Grade 50 concrete, which served as the control formulation. Variations in the quantities of the individual components were introduced in subsequent mixes to evaluate the influence of mix parameters on concrete behavior.

To assess the fresh properties of the concrete, the slump test was conducted in accordance with the procedure outlined in [24]. Compressive strength was measured at 7 and 28 days using a standard compression testing machine, following the protocol specified in [25]. 2.1. Model Architecture

To ensure a statistically valid investigation, the study employed the Taguchi experimental design approach using an L9 orthogonal array (3^4), which is one of the standard configurations optimized by Taguchi. This design was chosen as it best matched the conditions under investigation, namely four independent parameters, each with three levels. The variables were as follows: cement content (A), water-to-cement ratio (B), mound soil content (C), and superplasticizer content (D). Detailed combinations of levels and parameters are presented in Table 1. A preliminary trial mix was carried out using the Grade 50 concrete as a baseline before proceeding with the full experimental plan based on the orthogonal array.

2.1.1. Taguchi Signal – to- Noise Ratio (S/N)

In the Taguchi method, the Signal-to-Noise (S/N) ratio is employed to evaluate performance consistency and to quantify the impact of uncontrollable factors, known as noise. Unlike simple mean values, the S/N ratio provides a more robust assessment of how reliably the process or product maintains its target performance level under varying conditions [2].

Noise in this context refers to any external or internal factor that may cause a deviation in the measured performance outcome.

According to [20], three distinct performance characteristic models are used in S/N analysis:

a. Smaller – the – Better: This is chosen when the goal is to minimize the response.

$$S/N = -10 \log \left(\frac{1}{n}\sum Y^2\right) \quad (1)$$

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b. Larger – the – Better: This is chosen when the goal is to maximize the response.

$$S/N = -10\log\left(\frac{1}{n}\sum\frac{1}{Y^2}\right) \quad (2)$$

c. Nominal – the – Better:

$$S/N = -10\log\left[\frac{1}{n}\sum(Y_i - Y_0)^2\right] \quad (3)$$

Where Y_i is the performance value of the i^{th} trial and n is the number of repetitions for an experimental combination.

The overall objective is to determine the most effective combination of control parameters to ensure that the output remains stable and reliable, even in the presence of variations or uncertainties introduced by external influences.

A preliminary control mix was developed and tested to validate the design before proceeding with the Taguchi orthogonal array experimentation, as summarized in Table 1.

Table 1: Mix Design for Control Mixes for Grade 50 Concrete

Grade of Concrete	Water Cement Ratio	Cement Content (Kg/m³)	Water Content (Litre)	Fine Aggregate Content (Kg/m³)	Coarse Aggregate Content (Kg/m³)	Target Strength
50	0.35	645	226	460	1172	56.56 N/mm²
Per trial Mix of 0.07m³	0.35	45.15	15.82	32.2	82.04	

From the results obtained from control mix parameters and levels decided, the chosen parameters were varied by reducing the water-cement ratio and cement content were while increasing superplasticizer and mound soil contents. The experiments were carried out using 150mm x 150mm x 150mm cubes in accordance with BS 1881 to evaluate the influence of the various mix parameters and thereby to optimize the cement content in concrete.

2.1.2. Procedure for Taguchi's Approach

The Taguchi's Approach involves the following procedure:

1. Identification of the main function and its side effects.

• Considering compressive strength;
• Main function: Compressive strength test using Universal Testing Machine. (UTM)
• Side effects: Variation in compressive strength. The main function and side effects are shown in Table 2

Table 2: Factors Affecting Compressive Strength

Control Factors	Noise Factors
Cement Content	Temperature
Water/cement ratio	Operational skills
Mound soil content	Aggregate size
Superplasticizer content	Site control
	Machine conditions
	Material properties
	Measuring tools

Table 3: Testing Conditions and Quality Characteristics

Quality characteristics	Strength (compressive)
Work piece material	Binary SP concrete
Operating machine	Concrete mixer
Curing medium	Curing tank
Testing machine	Universal Testing Machine (UTM)

3. Identification of the objective function

Objective function for the compressive strength is larger-the better

S/N Ratio for this function is given from [20] in equation 2:

$$S/N = -10\log\left(\frac{1}{n}\sum\frac{1}{Y^2}\right)$$

where S/N = Signal to Noise ratio

n = number of trials for experiment

y = performance parameter mean (compressive strength in that run)

4. Identification of control factors and their levels.

The variation in factors is determined by recommendations from literature and manufacturer's manual. Table 4 shows the various levels and factors considered while Table 5 a Grade 50.

https://doi.org/10.60787/ijtec.vol1no1.33

Table 4: Control Factors and Levels

Factors	Levels		
	1	2	3
Cement content (A) kg	A_1	A_2	A_3
Water-cement ratio (B)	B_1	B_2	B_3
Superplasticizer Content (C) %	C_1	C_2	C_3
Mound soil content (D) %	D_1	D_2	D_3

Table 5: Control Factors and Levels for Grade 50 concrete

Factors	Levels		
	1	2	3
Cement content (A) kg	645	610	580
Water-cement ratio (B)	0.35	0.33	0.31
Superplasticizer Content (C) %	0.6	0.8	1.0
Mound soil content (D) %	20	15	10

5. Selection of appropriate orthogonal array

The orthogonal array for the factors and levels is selected from standard orthogonal arrays. The L_9 (3^4) orthogonal array is appropriate. The orthogonal array is shown in the Tables 6 and 7 for the standard and for the specific grade 50 concrete.

Table 6: Standard L_9 Orthogonal array

Experiment No	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 7: Orthogonal array for Grade 50 concrete

Experiment No	Cement Content (kg)	Water-cement ratio	SP Content (%)	Mound soil content (% of Cement)
1	645	0.35	0.6	10
2	645	0.33	0.8	15
3	645	0.31	1.0	20
4	610	0.35	0.8	20
5	610	0.33	1.0	10
6	610	0.31	0.6	15
7	580	0.35	1.0	15
8	580	0.33	0.6	20
9	580	0.31	0.8	10

2.2. Validation Protocol

Using the results gotten to predict the optimum combination of materials, using Taguchi model, confirmation experiments were performed and checked to see that the result is consistent with the prediction. Three number of experiments were conducted using the model: $A_3 + B_1 + C_2 + D_2$ for the optimization of compressive strength.

3.0 RESULTS AND DISCUSSION

3.1. Quantitative Results

As presented in Table 8, the highest compressive strength at 7 days for the binary superplasticized concrete was obtained with a water-cement ratio of 0.35, a 20% reduction in cement content, 10% incorporation of mound soil, and 1.0% superplasticizer dosage. These results highlight the critical influence of both the presence and proportion

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of chemical admixtures on the early-age strength development of concrete.

Table 8: 7 Days Compressive Strength Results

Experiment No	Cement Content (kg)	Water-cement ratio	SP Content (%)	Mound soil content (% of Cement)	Average Compressive Strength (N/mm^2)
1	645	0.35	0.6	10	39.26
2	645	0.33	0.8	15	40.34
3	645	0.31	1.0	20	38.34
4	610	0.35	0.8	20	41.61
5	610	0.33	1.0	10	40.21
6	610	0.31	0.6	15	39.57
7	580	0.35	1.0	15	41.97
8	580	0.33	0.6	20	39.73
9	580	0.31	0.8	10	38.40
CONT	645	0.35			32.58

Table 9 shows that maximum compressive strength at 28 days of binary SP concrete was achieved at 0.35 w/c, 20% cement reduction content, mound soil addition of 15% and 1.0% SP resulting in a 21% increase from the control.

Table 9: 28 Days Compressive Strength Results

Experiment No	Cement Content (kg)	Water-cement ratio	SP Content (%)	Mound soil content (% of Cement)	Average Compressive Strength (N/mm^2)
1	645	0.35	0.6	10	52.30
2	645	0.33	0.8	15	47.11
3	645	0.31	1.0	20	44.67
4	610	0.35	0.8	20	46.12
5	610	0.33	1.0	10	51.48
6	610	0.31	0.6	15	51.08
7	580	0.35	1.0	15	54.59
8	580	0.33	0.6	20	51.56
9	580	0.31	0.8	10	50.56
CONT	645	0.35			46.06

Appendix 1 shows that maximum slump value of binary SP concrete was achieved at 0.35 w/c, 20% cement reduction content, mound soil addition of and 20% and 1.0% SP resulting in a huge increase from the control which gave a zero-slump value.

3.1. Qualitative Analysis

The main effects plots for the various factors and levels are shown in Fig. 1, the response means and analysis of variance are shown in Appendices 2-4, indicating the factors that contribute the highest and lowest in the optimization of the compressive strength. The main effect plot gives the mean response values at each level of the design parameters considered ie how each factor affects the response characteristic. It examines the differences between level means for one or more factors.

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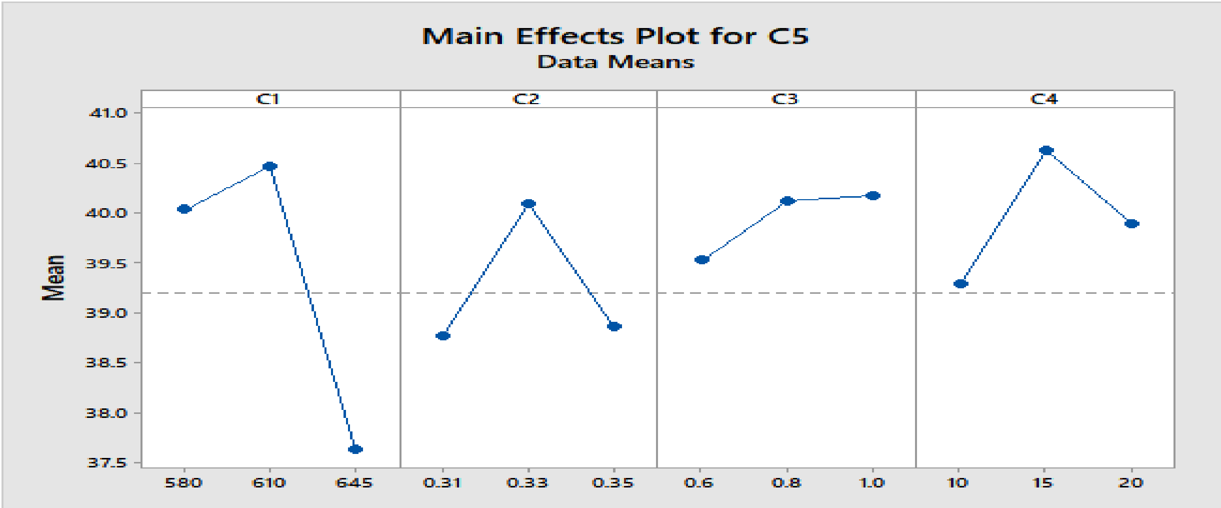

Figure 1: Main Effects Plot for Compressive Strength

The regression equation is shown in Eqn. (8), where A, B, C, D and E represent the cement content, water cement ratio, superplasticizer content, mound content and resulting compressive strength from the combination.

$$C = 39.94 + 0.09667\ A\_580 + 0.5267\ A\_610 - 0.6233\ A\_645 - 1.167\ B\_0.31 + 0.1567\ B\_0.33 + 1.010\ B\_0.35 - 0.4167\ C\_0.6 + 0.1800\ C\_0.8 + 0.2367\ C\_1.0 - 0.6467\ D\_10 + 0.6900\ D\_15 - 0.04333\ D\_20 \quad (4)$$

Key Findings: The model used proposed that the water cement ratio has the highest rank, while the SP content has the lowest rank in the contribution to the early strength (7 days) of high strength concrete.

The reliability of the results obtained also provides room for other properties of high strength concrete to be considered. Areas of consideration using other optimization techniques would bridge the gap in this work.

3.1. Qualitative Analysis

The main effects plots for the various factors and levels are shown in Fig. 1, the response means and analysis of variance are shown in Appendices 2-4, indicating the factors that contribute the highest and lowest in the optimization of the compressive strength. The main effect plot gives the mean response values at each level of the design parameters considered ie how each factor affects the response characteristic. It examines the differences between level means for one or more factors.

4.0 CONCLUSION

This study demonstrated that the Taguchi method offers an effective, structured, and straightforward framework for optimizing mix design parameters in concrete production. Analysis of the experimental data revealed that cement content and superplasticizer dosage had the most substantial influence on compressive strength, while workability was predominantly governed by the superplasticizer content. The optimal parameter combination identified as A3B1C2D2 produced a compressive strength of 54.59 N/mm², even with reduced cement usage. A verification test conducted using the Taguchi-predicted mix yielded a compressive strength of 54.1 N/mm², confirming the reliability of the model. Overall, the use of the Taguchi approach led to a notable 21% improvement in compressive strength, underscoring its value as a robust and efficient tool for process optimization in high-performance concrete formulation.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Authors' Contribution

Daniel Ogheneochuko conceived the research idea, developed the experimental design using the Taguchi approach, and supervised the entire project.

Ogheneale Orie conducted the laboratory experiments, analyzed the data, and contribute

Authors' Declaration

The authors affirm that the content of this manuscript is original, has not been published elsewhere and it is not under any consideration for publication in any other journal. The authors accept full responsibility for the integrity and accuracy of all data and interpretations presented therein.

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Supplementary

Supplementary 1 - Workability for SP Concrete

Experiment No	Cement Content (kg)	Water-cement ratio	SP Content (%)	Mound soil content (% of Cement)	Measured Slump (mm)
1	645	0.35	0.6	10	45
2	645	0.33	0.8	15	30
3	645	0.31	1.0	20	60
4	610	0.35	0.8	20	65
5	610	0.33	1.0	10	55
6	610	0.31	0.6	15	45
7	580	0.35	1.0	15	65
8	580	0.33	0.6	20	50
9	580	0.31	0.8	10	55
CONT	645	0.35			0

Supplementary 2 - Response Table for Means

Level	A	B	C	D
1	40.03	38.77	39.52	39.29
2	40.46	40.09	40.12	40.63
3	39.31	40.95	40.17	39.89
Delta	1.15	2.18	0.65	1.34
Rank	3	1	4	2

Supplementary 3 - Analysis of Variance

Source	DF	Adj SS	Adj MS
A	2	2.0258	1.0129
B	2	7.2173	3.6086
C	2	0.7861	0.3930
D	2	2.6885	1.3442
Error	0	*	*
Total	8	12.7176	

Supplementary 4 - Variance Components

Source	Var	% of Total
A	0.210160	10.55%
B	1.075397	53.98%
C	0.003538	0.18%
D	0.320605	16.09%
Error	0.382420	19.20%
Total	1.992121	

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