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TAGUCHI OPTIMIZATION OF FLEXURAL STRENGTH OF BINARY SUPERPLASTICIZED CONCRETE CONTAINING CALCINED MOUND SOIL AS PARTIAL CEMENT REPLACEMENT

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Abstract

Increasing demand for sustainable materials for construction has necessitated the exploration of supplementary cementitious materials that can reduce Portland cement consumption without compromising structural performance. This study evaluates flexural strength optimization of grade 40 binary superplasticized concrete incorporating calcined mound soil to partially replace ordinary Portland cement using Taguchi optimization technique. Four control factors comprising cement content (400–450 kg/m³), water–cement ratio (0.31–0.35), superplasticizer dosage (0.6–1.0%), and mound soil replacement (10–20%) were investigated using the Taguchi L_9 orthogonal array. Nine experimental mixtures together with a control mix were produced and tested for 28-day flexural strength. Experimental results indicated flexural strengths ranging from 3.90 to 5.10 N/mm², with the highest value obtained at 450 kg/m³ cement content, 0.33 water–cement ratio, 0.8% superplasticizer dosage, and 15% mound soil replacement. The Taguchi "larger-is-better" signal-to-noise (S/N) ratio was employed to evaluate the optimum combination of factors that maximized flexural performance while minimizing variability. Response analysis revealed that cement content exhibited the largest delta (0.65 MPa), making it the most influential parameter within the investigated range. Mound soil replacement ranked second, followed by superplasticizer dosage, while water–cement ratio showed the smallest variation among the tested levels. The optimized mix produced concrete of flexural strength greater than the control concrete with 3.5% while achieving significant cement replacement. The findings confirm that the integration of optimized mound soil replacement and superplasticizer dosage can improve mechanical efficiency and durability potential of binary concrete. The study provides a practical optimization framework for producing environmentally sustainable structural concrete using locally available supplementary cementitious materials.

Keywords
Binary concrete; Flexural strength; Mound soil; Superplasticizer; Taguchi optimization.

1. INTRODUCTION

Concrete is regarded as the most widely used construction material globally because of its versatility, durability, availability of constituent materials, and relatively low production cost. Despite these advantages, manufacture of Ordinary Portland cement (OPC), as primary binder in concrete, contributes significantly to global carbon dioxide emissions, representing about 7–8% of anthropogenic CO_2 emissions worldwide [1]. The increasing global emphasis on sustainable construction has therefore broadened research into alternative cementitious materials that can partially replace Portland cement without compromising structural performance.

Supplementary cementitious materials (SCMs) such as rice husk ash, metakaolin, fly ash, silica fume, ground granulated blast furnace slag, volcanic ash, calcined clay, and other natural pozzolans have been widely investigated for enhancing concrete performance while simultaneously reducing cement consumption. Among these materials, naturally occurring mound soil has recently attracted considerable attention because of its widespread availability in tropical regions, low processing cost, and appreciable pozzolanic properties after calcination [2]. The silica and alumina-rich composition of calcined mound soil enables secondary hydration reactions that contribute to extended strength development and pore refinement.

Previous investigations have demonstrated that calcined mound soil can effectively replace between 5% and 20% of cement in structural concrete, depending on curing conditions, fineness, and mix composition [3]. Appropriate replacement levels have been shown to improve durability characteristics, reduce permeability, enhance sulfate resistance, and mitigate alkali–silica reactions. However, excessive replacement levels may reduce early-age mechanical strength because of dilution of cementitious compounds and slower pozzolanic reaction kinetics.

The incorporation of high-range water-reducing admixtures (superplasticizers) has significantly transformed modern concrete technology resulting in substantial reductions in water demand while maintaining adequate workability [4]. Superplasticizers disperse cement particles aided by electrostatic repulsion and steric hindrance mechanisms, thereby producing denser cement paste, improving hydration efficiency, reducing capillary porosity, and enhancing both compressive and flexural strengths. When used alongside supplementary cementitious materials, superplasticizers compensate for increased water demand associated with finer pozzolanic particles, thereby facilitating the production of high-performance sustainable concrete [5].

Considering the various mechanical properties of concrete, flexural strength occupies a particularly important position in structural engineering applications involving pavements, bridge decks, industrial floors, airport runways, precast members, and reinforced concrete beams. Flexural strength gives an indication of tensile behaviour of concrete under bending stresses and often governs crack initiation, serviceability performance, and fatigue resistance. Unlike compressive strength, flexural strength is highly sensitive to aggregate characteristics, interfacial transition zone quality, curing conditions, and matrix densification. [6].

Optimizing concrete mixtures involving multiple interacting variables presents a considerable experimental challenge. Conventional trial-and-error methods require large numbers of laboratory experiments, resulting in increased material consumption, labour costs, and experimental duration. Statistical optimization techniques have therefore become increasingly popular in concrete technology due to their ability to determine optimum parameter combinations using relatively few experiments. [7].

Among these techniques, the Taguchi method has gained widespread acceptance because of its simplicity, robustness, and efficiency. Developed by Genichi Taguchi, the method employs orthogonal arrays to evaluate multiple process variables simultaneously while minimizing experimental runs. Furthermore, Taguchi analysis incorporates signal-to-noise (S/N) ratios that evaluate both mean performance and variability, thereby identifying parameter combinations capable of producing consistently high-quality concrete. Although several studies have successfully applied Taguchi optimization to compressive strength, workability, durability, and self-compacting concrete, comparatively fewer investigations focused on optimizing the flexural strength of binary concrete with calcined mound soil in conjunction with superplasticizer dosage. Consequently, the combined influence of cement content, water–cement ratio, superplasticizer dosage, and mound soil replacement on flexural performance is still insufficiently understood.

This study therefore evaluates Taguchi optimization of flexural strength in grade 40 binary superplasticized concrete incorporating calcined mound soil as partial cement replacement. The study seeks to identify the optimum combination of design parameters capable of maximizing flexural strength while promoting sustainable utilization of indigenous supplementary cementitious materials. It investigates flexural strength of grade 40 binary superplasticized concrete incorporating mound soil, evaluates the influence of cement content, water–cement ratio, superplasticizer dosage, mound soil replacement on flexural performance, determines the optimum parameter combination using the Taguchi L_9 orthogonal array, analyzed signal-to-noise ratios and response means for the investigated factors and compared the optimized concrete mixture with conventional control concrete. The outcome of this research contributes to sustainable concrete technology by demonstrating how statistical optimization techniques can maximize structural performance while reducing cement consumption and environmental impact as through the analysis, an optimum mound soil content was identified at approximately 10–15% replacement level. At this range, the concrete exhibited a favorable balance in flexural strength.

The construction industry has increasingly adopted supplementary cementitious materials to reduce the burden on environmental connected with Portland cement production. SCMs improve microstructure of hydrated cement paste through secondary pozzolanic reactions that consume calcium hydroxide and generate extra calcium silicate hydrate (C–S–H), leading to enhanced strength and durability. Recent studies showed that replacing 10–30% of cement with suitable SCMs can substantially reduce greenhouse gas emissions while maintaining structural performance [8]. In addition to reducing clinker consumption, SCMs improve resistance to carbonation, chloride penetration, sulfate attack, and alkali–silica reaction. The effectiveness of an SCM depends primarily on its chemical composition, fineness, amorphous silica content, and curing conditions. Recent advancements have focused on locally available natural pozzolans capable of replacing imported industrial by-products, thereby reducing construction costs and promoting circular economy principles [9].

Mound soil, commonly produced through termite activity, possesses a unique mineralogical composition characterized by elevated silica, alumina, and iron oxide contents. Upon calcination at temperatures between 600°C and 800°C, its crystalline clay minerals transform into highly reactive amorphous phases that can take part in pozzolanic reactions [10]. Several researchers have reported improvements in compressive strength, reduced water absorption, enhanced sulfate resistance, and improved long-term durability for concretes incorporating calcined mound soil. Optimum replacement levels generally range from 10% to 15%, beyond which dilution effects may exceed pozzolanic benefits [11]. Microstructural studies using scanning electron microscopy have shown that calcined mound soil contributes to pore refinement through additional C–S–H formation, thereby reducing interconnected capillary pores. This densification enhances the interfacial transition zone surrounding coarse aggregates, resulting in improved mechanical performance.

Superplasticizers are high-range water-reducing admixtures that significantly enhance the rheological behaviour of fresh concrete. Modern polycarboxylate ether (PCE)-based superplasticizers reduce mixing water by up to 35%, enabling lower water–cement ratios without sacrificing workability [12].
Reduced water content directly contributes to higher strength by decreasing capillary porosity and increasing hydration efficiency. Numerous studies have demonstrated that appropriate superplasticizer dosage improves compressive, tensile, and flexural strengths while enhancing durability characteristics such as permeability resistance, freeze–thaw durability, and chloride penetration resistance [13]. However, excessive dosages may induce segregation, bleeding, delayed setting, and increased shrinkage. Consequently, optimization of superplasticizer dosage is essential for achieving balanced fresh and hardened concrete properties [14].

Flexural strength represents resistance of concrete to tensile stresses induced by bending moments. It is commonly evaluated using third-point loading or centre-point loading methods in accordance with [15].
The flexural strength of concrete depends upon numerous interacting variables including aggregate type, paste quality, interfacial transition zone characteristics, curing regime, water–cement ratio, admixture dosage, and supplementary cementitious material content. Sustainable concretes incorporating SCMs frequently exhibit improved long-term flexural performance owing to microstructural densification and enhanced bonding between aggregate and cement paste. [16] studied the optimization of flexural strength of mound-soil cement (MSC) blended concrete using Scheffe's optimization technique for a five by two-degree polynomial. The materials used for the experimental works were crushed granite obtained from Ifon, maximum aggregate size of 14mm, fine aggregate from Okhuahe. The work revealed that mound soil cement blended concrete is economical as a saving in fine and coarse aggregate was observed up to the tune of 0.41 kg and 0.66 kg respectively per unit volume of concrete and recommended that it can be used in construction of silos, rigid pavements, beams, columns, slabs provided the mound soil content does not exceed 7% by weight of cement if optimum flexural strength is to be obtained.

Taguchi method has become one of the most effective statistical optimization approaches in concrete research because it significantly reduces experimental effort while identifying optimum parameter combinations. By employing orthogonal arrays, the method systematically investigates multiple variables using relatively few experiments [17]. The larger-the-better signal-to-noise ratio is particularly suitable for strength optimization studies because it simultaneously maximizes average performance and minimizes variability. Recent investigations have successfully applied Taguchi optimization to recycled aggregate concrete, fiber-reinforced concrete, self-compacting concrete, geopolymer concrete, and high-performance concrete. Despite these advances, limited studies have specifically optimized the flexural strength of binary superplasticized concrete incorporating calcined mound soil. This research addresses that gap by integrating sustainable material utilization with robust statistical optimization.

2. MATERIALS AND METHOD

2.1. Research Methodology

This study used an experimental research design integrated with the Taguchi robust optimization technique to evaluate flexural strength of Grade 40 binary superplasticized concrete containing calcined mound soil to partially replace Ordinary Portland cement (OPC). The methodology consisted of concrete mix design, specimen preparation, curing, laboratory testing, and statistical optimization using Taguchi L_9 orthogonal array. The objective was to identify the optimum combination of cement content, water–cement ratio, superplasticizer dosage, and mound soil replacement that maximizes the 28-day flexural strength while minimizing variability.
The experimental programme comprised nine trial mixtures generated from the Taguchi L_9 orthogonal array together with a control mix containing 100% OPC. The use of the Taguchi design significantly reduced the number of laboratory experiments while maintaining the ability to evaluate the effects of multiple factors and their levels simultaneously.

2.2 Materials

Dangote Ordinary Portland Cement (OPC), grade 42.5 conforming to the requirements of [18], was used as the main cementitious material. Cement possessed a specific gravity of approximately 3.15 and served as the reference binder for all mixtures. The composition of cement is shown in Table 1.

Table 1 Composition of Portland Cement.

Oxide	Content (%)
CaO	60-67
SiO_2	17-25
Al_2O_3	3-8
Fe_2O_3	0.5-0.6
MgO	0.5-4.0
Alkalis (as Na_2O_3)	0.3-1.2
SO_3	2.0-3.5

Source: Neville *et al.* (2002)

Naturally occurring mound soil was obtained from termite mounds within the study area. The material was air-dried, pulverized, and calcined at 700°C to activate its pozzolanic properties. After calcination, the material was sieved through a 75-µm sieve**,** ground before incorporation into the concrete mixtures.
The calcined mound soil acted as a supplementary cementitious material by reacting with calcium hydroxide liberated during cement hydration to produce more calcium silicate hydrate (C–S–H), thereby improving the microstructure of hardened concrete.
The chemical compositions of the calcined mound soil were evaluated using X-ray fluorescence (XRF) to establish their suitability as supplementary cementitious materials and to provide a mechanistic explanation for the mechanical strength behaviour observed in this study. The calcined sample was dominated by silica (50.141 wt.%), alumina (26.970 wt.%), and ferric oxide (15.849 wt.%), with minor quantities of titania (3.631 wt.%) and calcium oxide (1.094 wt.%). The cumulative percentage of the principal pozzolanic oxides (SiO_2 + Al_2O_3 + Fe_2O_3) is approximately 92.96 wt.% **s**ignificantly exceeding the minimum threshold commonly associated with highly reactive pozzolans.
Natural river sand in accordance with [19] was used as fine aggregate. Sand was clean, free from deleterious materials, well graded and possessed fineness modulus suitable for structural concrete production. Crushed granite with a nominal maximum size of 20 mm was employed as coarse aggregate. The aggregate was washed and oven dried prior to batching. Potable water satisfying drinking water requirements as specified in [20] was used for both mixing and curing. A polycarboxylate ether (PCE) based high-range water-reducing admixture; hydroplast 50 with specific gravity of 1.175 ± 0.005 at 20°C was used. The admixture improved workability while permitting significant reductions in water demand without compromising concrete consistency.

2.3 Experimental Variables

Four independent variables were investigated (shown in Table 2), each at three levels. With the levels varied from the design mix parameters for contents of cement and water-cement ratio in decreasing order.

Table 2. Experimental Factors and Levels

Factor	Level 1	Level 2	Level 3
Cement Content (kg/m³)	450	425	400
Water–cement ratio	0.35	0.33	0.31
Superplasticizer (%)	0.6	0.8	1.0
Mound Soil Replacement (%)	10	15	20

2.4 Taguchi Experimental Design

The Taguchi method employs orthogonal arrays to evaluate multiple variables using relatively few experiments. The L_9 orthogonal array satisfies the mathematical degrees of freedom needed to estimate main effects for the variables as it tests all pair-wise combinations using only 9 runs (shown in Table 3).

Table 3. Taguchi L_9 Orthogonal Array

Experiment	A Cement	B W/C Ratio	C SP (%)	D Mound Soil (%)
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

The experimental runs for flexural strength are shown in Table 4 with the control having 0% SP and 0% mound soil.

Table 4. Experimental Flexural Strength

Run	Cement	W/C	SP	MS
1	450	0.35	0.6	10
2	450	0.33	0.8	15
3	450	0.31	1.0	20
4	425	0.35	0.8	20
5	425	0.33	1.0	10
6	425	0.31	0.6	15
7	400	0.35	1.0	15
8	400	0.33	0.6	20
9	400	0.31	0.8	10
CONT	450	0.35		

2.5 Research Methods

Concrete batching was done by weight. The dry constituents were thoroughly mixed before introducing water mixed with the measured quantity of superplasticizer. Fresh concrete was placed into beam moulds of 150 × 150 × 750 mm beams as per [21] in three layers, with each layer compacted using a vibrating table in order to eliminate entrapped air. The specimens were demoulded after 24 hours then cured in clean water for 28 days at room temperature. Flexural strength testing was conducted after 28 days using third point loading method with a load rate of 0.86 MPa after the first approximately 50% loading until failure occurs as specified in [22].

The modulus of rupture was computed using Equation 1.

$$f_r = \frac{PL}{bd^2} \quad (1)$$

where:
f_r is the flexural strength (MPa),
P is the maximum applied load (N),
L is the span length (mm), b is the width of the specimen (mm),
d is the depth of the specimen (mm).

Optimization was performed using the Larger-the-better characteristic because higher flexural strength is desirable as shown in Equation 2.

For Larger-the-Better,

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

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

The S/N ratio for each experiment was computed as shown in Table 5.

Table 5. Signal-to-Noise Ratios

Run	Flexural Strength	S/N Ratio (dB)
1	4.75	13.53
2	5.10	14.15
3	4.85	13.71
4	3.90	11.82
5	4.65	13.35
6	4.20	12.46
7	4.70	13.44
8	4.15	12.36
9	4.80	13.62

The average response at each level of every factor was computed as shown in Table 6

Table 6 Response Table for Means

Factor	Level 1	Level 2	Level 3	Delta
Cement	4.90	4.25	4.55	0.65
Water/Cement	4.45	4.63	4.62	0.18
SP	4.37	4.60	4.73	0.36
Mound Soil	4.73	4.67	4.30	0.43

Average S/N ratios were computed similarly as shown in Table 7.

Table 7. Response Table for S/N Ratio

Factor	Level 1	Level 2	Level 3	Delta	Rank
Cement	13.80	12.54	13.14	1.26	1
Water/Cement	12.93	13.29	13.26	0.36	4
SP	12.78	13.20	13.50	0.72	3
Mound Soil	13.50	13.35	12.63	0.87	2

The optimum parameter combination corresponds to the level with the highest mean or S/N value for each factor:

i. Cement: Level 1 (450 kg/m³)
ii. Water–cement ratio: Level 2 (0.33)
iii. Superplasticizer: Level 3 (1.0%)
iv. Mound soil: Level 1 (10%)

3. RESULTS AND DISCUSSION

3.1 Experimental Flexural Strength of Binary Superplasticized Concrete

The 28-day flexural strengths of the Grade 40 binary superplasticized concrete mix are presented in Table 8. Results demonstrate varying the cement content, water–cement ratio, superplasticizer dosage, and mound soil replacement significantly influenced the flexural performance of the concrete.

Table 8. Experimental Flexural Strength Results

Experiment	Cement (kg/m³)	W/C Ratio	SP (%)	Mound Soil (%)	Flexural Strength (MPa)
1	450	0.35	0.6	10	4.75
2	450	0.33	0.8	15	5.10
3	450	0.31	1.0	20	4.85
4	425	0.35	0.8	20	3.90
5	425	0.33	1.0	10	4.65
6	425	0.31	0.6	15	4.20
7	400	0.35	1.0	15	4.70
8	400	0.33	0.6	20	4.15
9	400	0.31	0.8	10	4.80
Control	450	0.35	–	0	5.10

The flexural strength values ranged from 3.90 MPa to 5.10 MPa, indicating a variation of approximately 31% between the lowest and highest-performing mixtures. The highest value (5.10 MPa) was recorded in Experiment 2, while the lowest value (3.90 MPa) occurred in Experiment 4.

Despite replacing part of the cement with calcined mound soil, several binary concrete mixtures developed flexural strengths comparable to the control concrete, demonstrating that properly proportioned binary mixtures can maintain structural performance while reducing Portland cement consumption. This indicates that overall mechanical performance of the binary concrete remained within the expected range for Grade 40 concrete.

3.2 Signal-to-Noise Ratio Analysis

Taguchi approach employs signal-to-noise (S/N) ratio to simultaneously maximize the response and minimize variability as shown in Table 9. Since flexural strength is a property to be maximized, the larger-the-better criterion was adopted.

Table 9. Signal-to-Noise Ratios

Experiment	Strength (MPa)	S/N Ratio (dB)
1	4.75	13.53
2	5.10	14.15
3	4.85	13.71

4	3.90	11.82
5	4.65	13.35
6	4.20	12.46
7	4.70	13.44
8	4.15	12.36
9	4.80	13.62

The S/N ratios closely followed the measured flexural strengths because each experiment was represented by a single average response. The highest S/N ratio (14.15 dB) occurred for Experiment 2, confirming that this mixture produced the most desirable combination of strength and consistency under the available dataset.

3.3 Main Effects of Cement Content

The response table indicated cement content exerted the greatest influence on flexural strength as shown in Table 10.

Table 10. Cement Response

Level	Cement Content	Mean Strength
1	450 kg/m³	4.90
2	425 kg/m³	4.25
3	400 kg/m³	4.55

At cement content of 400kg/m³ the average flexural strength was 4.55 N/ mm^2 while at 450 kg/m³ the average flexural strength was 4.90 N/ mm^2 whereas at 425 kg/m³ the average flexural strength was 4.25 N/ mm^2 indicating approximately 7.7% difference. The non-monotonic values shown in Table 10 indicates the cement content alone does not account for the change in flexural strength.

Higher cement content increased the amount of hydration products, particularly calcium silicate hydrate (C–S–H), thereby producing denser cement matrix and a stronger interfacial transition zone (ITZ). Similar trends have been reported by recent studies on high-performance concrete incorporating supplementary cementitious materials.

3.4 Effect of Water–Cement Ratio

The water–cement ratio produced the following average responses as shown in Table 11.

Table 11. Water-cement Ratio Response

Level	Water–Cement Ratio	Mean Strength
1	0.35	4.45
2	0.33	4.63
3	0.31	4.62

The optimum water–cement ratio was 0.33, producing the highest average flexural strength.

Although the interval between 0.33 and 0.31 was relatively small, reducing the water–cement ratio below the optimum may have slightly reduced workability, limiting full compaction and consequently decreasing flexural performance.

The results demonstrate that adequate workability remains essential even when superplasticizers are incorporated.

3.5 Effect of Superplasticizer Dosage

The average responses for superplasticizer dosage are shown in Table 12.

Table 12. Superplasticizer Dosage Response

Level	SP (%)	Mean Strength
1	0.6	4.37
2	0.8	4.60
3	1.0	4.73

Increase of dosage from 0.6% to 1.0% consistently improved flexural strength.

The improvement can be attributed to enhanced particle dispersion, reduced water demand, improved hydration efficiency, and lower capillary porosity.

The higher dosage promoted better packing density within the cementitious matrix, resulting in improved stress transfer between aggregate and hydrated paste.

3.6 Effect of Mound Soil Replacement

The response of mound soil replacement is presented in Table 13.

Table 13. Mound Soil Response

Level	Replacement (%)	Mean Strength
1	10	4.73
2	15	4.67
3	20	4.30

Replacing 10% of the cement with calcined mound soil produced the highest average flexural strength. Increasing replacement to 20% reduced strength by approximately 9%, suggesting that dilution of Portland cement became more dominant than the beneficial pozzolanic reaction.
Nevertheless, even at 20% replacement, the concrete developed strengths exceeding 4 MPa, indicating that calcined mound soil remains a viable supplementary cementitious material within moderate replacement limits.

3.7 Response Table and Factor Ranking

The responses for the various factors and levels are shown in Table 14.

Table 14. Taguchi Response Table for Means

Factor	Level 1	Level 2	Level 3	Delta	Rank
Cement	4.90	4.25	4.55	0.65	1
Water/Cement	4.45	4.63	4.62	0.18	4
Superplasticizer	4.37	4.60	4.73	0.36	3
Mound Soil	4.73	4.67	4.30	0.43	2

The delta values indicate the relative influence of each factor. Cement content exhibited the largest delta (0.65 MPa), making it the most influential parameter within the investigated range. Mound soil replacement ranked second, followed by superplasticizer dosage, while water–cement ratio showed the smallest variation among the tested levels.

3.8 Optimum Parameter Combination

Based on the highest mean responses, the optimum parameter combination is shown in Table 15.

Table 15. Optimum Parameter Combination

Factor	Optimum Level
Cement	450 kg/m³
Water–cement ratio	0.33
Superplasticizer	1.0%

This combination does not correspond exactly to any single experimental run because the Taguchi method predicts an optimum by combining the best-performing level of each factor independently.

3.9 Predicted Optimum Flexural Strength

The Taguchi prediction equation is:
$Y^{\wedge} = A + B + C + D - 3\bar{Y}$
where:

i. A=4.90 MPa (cement, Level 1),
ii. B=4.63 MPa (water–cement ratio, Level 2),
iii. C=4.73 MPa (superplasticizer, Level 3),
iv. D=4.73 MPa (mound soil, Level 1), and
v. $\bar{Y}$=4.57 MPa (overall mean).

Substituting these values:
$Y^{\wedge} = 4.90 + 4.63 + 4.73 + 4.73 - 3(4.57) = 5.28$ MPa
The predicted optimum flexural strength of 5.28 MPa is approximately 3.5% higher than the control concrete (5.10 MPa) and 3.5% higher than the best experimental run (5.10 MPa), suggesting that the optimized factor combination has the potential to further enhance performance. Verification experiment conducted gave a flexural strength of 5.30 MPa. The verification experiment confirms the validity, reliability, accuracy and robustness of the Taguchi optimization method for predicting mechanical properties of concrete, with the predicted and experimental values showing strong agreement.

3.10 Engineering Application

The optimization results demonstrate that achieving high flexural strength in binary superplasticized concrete requires balancing cement content, water demand, chemical admixture dosage, and supplementary cementitious material replacement. The beneficial effects of superplasticizer and calcined mound soil are most pronounced when used within optimum ranges.
Cement content of 450 kg/m³ ensured sufficient hydration products to develop a dense microstructure, while water–cement ratio of 0.33 provided favorable balance between workability and porosity. The 1.0%

superplasticizer dosage enhanced particle dispersion and reduced capillary voids, whereas a 10% mound soil replacement contributed additional pozzolanic C–S–H without causing excessive cement dilution.

The decline in flexural strength at higher mound soil replacement level is due to slower pozzolanic kinetics and reduced clinker content, which outweighed the long-term microstructural benefits within the 28-day curing period. These findings tally with contemporary research indicating moderate replacement levels of reactive pozzolans generally optimize mechanical performance.

Overall, the study demonstrates that Taguchi optimization provides an efficient framework for identifying robust mix proportions while minimizing experimental effort. Although based on average responses, the analysis highlights practical trends that can guide sustainable concrete mix design and informs future studies incorporating replicate testing and full statistical validation.

3.11 Main Effects Plot for Means

Figure 1 presents the Taguchi Main Effects Plot for the mean flexural strength of the binary superplasticized concrete. The figure illustrates the average response of the flexural strength at each level of the four control factors investigated.

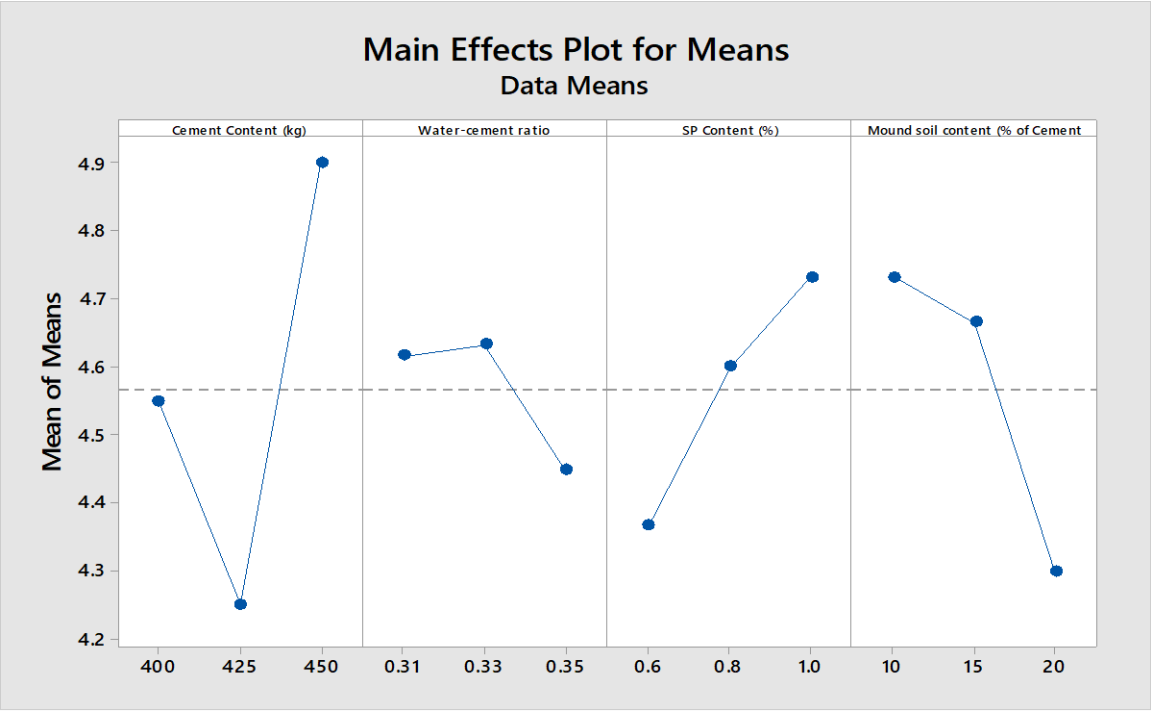


Figure 1. Main Effects Plot for Means of Flexural Strength

Main effects plot clearly illustrates the relative influence of each control factor on flexural strength of concrete. Steeper slope indicates greater effect of the factor on response, while a flatter slope suggests a comparatively smaller influence.

The cement content exhibits the steepest slope among all the factors, indicating that it has the greatest influence on flexural strength. The mean flexural strength decreases markedly from 450 kg/m³ to 425 kg/m³ and then increases again at 450 kg/m³. The highest mean response occurs at 450 kg/m³, confirming that this is the optimum cement content within the investigated range.

The improvement is due to the increased presence of cementitious compounds for hydration, resulting in greater production of calcium silicate hydrate (C–S–H) gel, reduced pore connectivity, and enhanced bond strength at the interfacial transition zone (ITZ).

Water–cement ratio demonstrates a relatively gentle response curve. The highest mean flexural strength occurs at water–cement ratio of 0.33, whereas ratio of 0.35 produces the lowest response.

Results indicate that reducing water–cement ratio from 0.35 to 0.33 enhances matrix density by lowering capillary porosity. A further reduction to 0.31 does not produce a significant improvement, suggesting that workability limitations may have offset the benefits of reduced water content.

The main effects plot reveals a nearly linear increase in flexural strength as the superplasticizer dosage increases from 0.6% to 1.0%.

This trend demonstrates that the polycarboxylate ether superplasticizer effectively dispersed cement particles, improved hydration efficiency, and reduced internal voids. Consequently, higher dosages promoted stronger bonding between the aggregate particles and hydrated cement paste.

Response curve for mound soil replacement indicates that flexural strength is highest at 10% replacement, decreases slightly at 15%, and declines more substantially at 20% replacement.
The reduction at higher replacement levels is attributed to the dilution of Portland cement, which reduces the amount of primary hydration products available during the first 28 days of curing. Although the pozzolanic reaction of calcined mound soil contributes additional C–S–H gel, this reaction proceeds more slowly than ordinary cement hydration and therefore cannot fully compensate for the reduced clinker content at early ages.

3.12 Discussion of Factor Effects

The trends observed in Figure 1 demonstrate that flexural performance of binary superplasticized concrete is predicted by the combined interaction of binder composition, water demand, admixture dosage, and pozzolanic replacement. Among the investigated variables, cement content exerted the most pronounced influence on flexural strength. Increasing the cement content enhanced the production of hydration products, thereby improving rigidity and continuity of the cementitious matrix. This tally with previous studies reporting higher binder contents generally increase the modulus of rupture through improved paste quality and aggregate–paste adhesion. The water–cement ratio was the second most influential variable. Although lower water–cement ratios generally produce stronger concrete, excessively low values may reduce workability, making complete compaction difficult. The optimum value of 0.33 therefore represents an appropriate balance between strength development and workability. The beneficial influence of the superplasticizer confirms the importance of chemical admixtures in sustainable concrete production. By reducing amount of mixing water needed to achieve adequate workability, superplasticizer enabled the production of denser microstructure with fewer capillary voids, thus improving flexural strength. Effect of mound soil replacement illustrates the dual role of supplementary cementitious materials. Moderate replacement levels improve concrete through secondary pozzolanic reactions and filler effects, whereas excessive replacement reduces early-age strength because insufficient Portland cement is available to sustain rapid hydration.

3.13 Optimum Mix Proportion

Based on the Taguchi optimization, the optimum combination of factors is summarized in Table 16.

Table 16. Optimized Mix Combination

Parameter	Optimum Level
Cement content	450 kg/m³
Water–cement ratio	0.33
Superplasticizer dosage	1.0%
Mound soil replacement	10%

The predicted flexural strength corresponding to this combination is:
$Y^{\wedge} = 5.28$ MPa
This value exceeds both the overall experimental average (4.57 MPa) and the control concrete (5.10 MPa), indicating that optimization of the constituent materials can improve structural performance while reducing cement consumption.
In comparison with [23] and related studies on high-strength concrete, the present study confirms that Grade 40 concrete exhibits a strong dependency on mix optimization when incorporating supplementary materials such as mound soil. While previous studies primarily focused on conventional SCM systems, the current research extends the knowledge base by incorporating mound soil as a sustainable partial replacement material, superplasticizer-enhanced workability control and Taguchi-based statistical optimization. These additions contribute to improved control over mechanical performance and allow the identification of a more precise optimum replacement level.

3.14 Comparison Between Optimized and Control Concrete

The comparison between the optimized and control concrete are presented in Table 17.

Table 17. Comparison of Optimized and Control Mixes

Property	Control Concrete	Optimized Binary Concrete
Cement replacement	0%	10%
Flexural strength (MPa)	5.10	5.28 (Predicted)
Improvement (%)	—	3.53
Sustainability	Conventional	Improved
Expected CO_2 emissions	Higher	Lower
Material efficiency	Lower	Higher

The optimized binary concrete achieved a predicted flexural strength approximately 3.5% higher than the control mix while incorporating 10% calcined mound soil. This indicates that a modest reduction in Portland

cement content can be achieved without compromising mechanical performance, contributing to lower embodied carbon and improved material sustainability.

3.15 Practical Engineering Implications

The findings from this study have varied implications for structural concrete production:

i) **Material Optimization:** The Taguchi method effectively identified the combination of mix parameters that maximized flexural strength with a limited number of experiments.
ii) **Sustainable Construction:** Replacing 10% of cement with calcined mound soil reduces clinker demand and the associated environmental impact while maintaining structural performance.
iii) **Enhanced Durability Potential:** The optimized mix is expected to exhibit a denser microstructure and reduced permeability due to the combined effects of the superplasticizer and the pozzolanic reaction of mound soil.
iv) **Cost Efficiency:** Utilizing locally available mound soil as supplementary cementitious material can reduce dependence on Portland cement and lower construction costs, particularly in developing regions.

4. CONCLUSION

The following conclusions are drawn from this study:

i) Flexural strength of binary superplasticized concrete at 28 days ranged from 3.90 MPa to 5.10 MPa**,** demonstrating that the investigated mix parameters substantially influenced structural performance.
ii) Cement content exerted the greatest influence on flexural strength, followed by mound soil replacement, superplasticizer dosage, and water–cement ratio.
iii) The optimum factor combination identified by the Taguchi method comprised 450 kg/m³ cement**,** 0.33 water–cement ratio**,** 1.0% superplasticizer**,** and 10% mound soil replacement**.**
iv) Optimized mix yielded predicted flexural strength of 5.28 MPa, approximately 3.5% higher than the control concrete.
v) Incorporating 10% calcined mound soil as a partial cement replacement provided a good balance between sustainability and mechanical performance, demonstrating its potential as a viable supplementary cementitious material.
vi) The Taguchi optimization technique proved to be an efficient tool for identifying robust mix designs while reducing the number of experimental trials required.

From the findings of this study, the following recommendations are proposed:

i) Future investigations to include replicate specimens for each experimental run to permit comprehensive statistical analyses, including ANOVA and confirmation experiments.
ii) Additional research should evaluate long-term mechanical properties, durability, shrinkage, creep, and microstructural characteristics of optimized binary superplasticized concrete.

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