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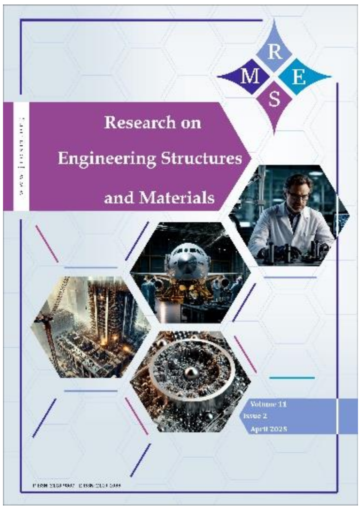

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Research Article

Effect of areca catechu fiber and superplasticizer interaction on the optimization of concrete compressive strength using the Box-Behnken design statistical approach

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Abstract

The use of natural fiber BSKP (Areca Nut Fiber) as a sustainable reinforcement in concrete is promising due to its mechanical properties and biodegradability. However, the hygroscopic nature of BSKP increases the viscosity of the concrete mixture, which affects workability and homogeneity. To overcome this, superplasticizer (SP) is used as a chemical admixture to improve fluidity without altering the water-to-cement ratio, thus supporting cement hydration and strength development. This study investigates the effect of varying BSKP concentrations combined with a fixed SP dosage on compressive strength using Box-Behnken Design within the Response Surface Methodology to optimize the mix. Experiments used BSKP at 2.0, 2.5, and 3.0% by cement weight with a fixed SP dosage of 2.1%. Compressive strength was tested at 7- and 28-days following ASTM C39. The BBD method within Response Surface Methodology (RSM) optimized material proportions. Results showed 2.0% BSKP + 2.1% SP achieved optimal performance with 26.445 MPa at 28 days and a desirability score of 0.542. Increasing BSKP to 3.0% reduced strength to 22.379 MPa due to impaired cement hydration. Statistical analysis confirmed SP's significant effect (coefficient = 6.4884, $p < 0.01$). Model validation indicated high predictive reliability (Adjusted $R^2 = 0.8953$, Predicted $R^2 = 0.8665$). In conclusion, the combination of 2.0% BSKP and 2.1% SP effectively enhances compressive strength while maintaining workability. The Box-Behnken Design within the RSM framework proved useful in optimizing material proportions. These findings support the development of durable, eco-friendly natural fiber-reinforced concrete and offer practical guidance for sustainable concrete formulation.

1. Introduction

Concrete is the primary material in the construction industry, continuously evolving to enhance its mechanical performance, sustainability, and efficiency [1-3]. As the demand for High-Performance Concrete (HPC) increases, various approaches have been developed to improve its mechanical strength and durability against environmental factors [4-6]. One of the most promising innovations in sustainable concrete development is the incorporation of natural fibers as supplementary materials, which has been shown to enhance toughness, reduce plastic shrinkage, and improve resistance to microcracking [7-12].

Natural fibers like coconut, bamboo, and ramie fibers, have also been studied in concrete as they can increase the tensile strength, cohesion between materials, and limit the formation of

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microcracks [13-17]. Areca catechu (areca nut) fiber, is one of the natural fibers with high tensile strength, is affordable and more sustainable than synthetic fibers that have potential to run four times strong constructional practice in concrete [2,18,19]. Nonetheless, the high-water absorption tendency of areca nut fiber is a significant challenge because it increases viscosity and reduces the workability of concrete [20-24].

Findings by [25,26] have shown that addition of natural fibers reduces workability, making it difficult to mix and cast the mixtures, and that can influence homogeneity of the mixture and thus strength of concrete. Superplasticizers, chemical admixtures that improve the plasticity and flowability of the cement paste while maintaining hydration levels [27-30], have thus been widely used to mitigate this issue. Superplasticizers aid in a wetting of the cement particles, allowing for a more homogenous material, with greater compressive strengths achieved without losing workability [31-34]. There have been limited studies on the interaction between areca nut fiber and superplasticizers and their effect on enhancing concrete performance [35-39].

Several studies have been conducted on fiber-reinforced concrete, but very few relate to the interaction between areca nut fiber and superplasticizers and their influence on the mechanical properties of concrete. The studies mentioned so far were prior research on natural fibers added to concrete, detailed in Table below, which did not investigate workability and compressive strength simultaneously when superplasticizers were mixed with natural fibers [22,40-42]. Furthermore, the previous research on natural fibers in concrete is more qualitative with a great degree of trial-and-error optimization of the fiber and admixture dosage, which is inefficient [43-46].

Thus, there is a need for a more systematic approach to optimize natural fiber-reinforced concrete mixtures and improve the efficiency of research in this field. A possible approach is the Box-Behnken Design (BBD), a micro-vox of Response Surface Methodology (RSM). The advantage of BBD is that it allows you to explore relationships between numerous variables with fewer experimental trials than would be required in standard experimentations, which results in a more efficient way of identifying which combinations of materials work best [1,2,21,47]. It is commonly used for combinatorial optimization problem research in the case of concrete specimens, where the goal is to test the best performance of concrete with various combinations of supplementary materials, natural fibers, and superplasticizers [32,48-51]. However, till date the research on optimizing the areca nut fiber-based concrete using BBD is mostly unexplored [51].

At the laboratory scale, the study uses main materials involving Type I Portland cement, fine aggregate (uniformly graded sand), and coarse aggregate (graded gravel) that are well mixed and uniformly distributed in the concrete matrix [52,53]. In order not to contaminate the cement hydration reaction, the water injected into the concrete mixture is in accordance with [54] standards [19]. The effect of its inclusion on properties of concrete is studied by adding it in different percentages of 2.0, 2.5 and 3.0% v/s cement weight, while maintaining a fixed dosage of superplasticizer (2.1% of cement wt) to improve workability without compromising compressive strength [28]. Compressive strength tests are also carried out at 7 and 28 days for strength variation over time [21,48].

The present study was conducted to investigate the effect of interaction between areca nut fiber and superplasticizers on the compressive strength of concrete and to optimize their proportions through BBD approach. The study also aims to conduct a comparative study between areca nut fiber-reinforced concrete and plain concrete to highlight the performance of this material as an authentic component for structural applications [41,55,56]. This research novelty focuses on the systematic exploration of the behavior of the areca nut fiber on the superplasticizers, which has been rarely reported in existing literature [6,40,57].

It is assumed that the findings would contribute to filling research gaps in the field and would help in opening up new avenues for natural fiber-reinforced concrete technology, particularly as applying areca nut fiber in structural applications has yet to be fully explored. These discoveries not only provide scientific basis for further studies, but also may act as natural solutions for the construction industry to design more effective, longer lasting, and eco-friendlier concrete building materials [5,8,26,58].

2. Materials and Methods

2.1 Materials

The materials that were used in this study are cement, fine aggregate, coarse aggregate, water, Areca catechu fiber, and superplasticizer. The materials were chosen according to well-known quality indicators so as to obtain homogeneity and uniformity in the concrete mixture.

2.1.1 Cement

Commercially available Type I Portland Cement, in accordance with [59], was used in this study. The versatile nature and good early and final strength load ensured the use of this type of cement. Cement is the main binder in the concrete mixture and takes part in hydration reactions that lead to the generation of compressive strength.

Fig. 1. Type I Portland Cement used in the concrete mixture

2.1.2 Fine and Coarse Aggregates

Fine aggregate: it comprises natural sand having a uniform gradation that satisfies [60] requirements to promote even particle distribution and facilitate convenient workability. The function of sand is to fill the voids in between the coarse aggregates to promote the high-density matrix as much as possible. It is used to develop the bond or link between the cement paste and the aggregate particles. Two types of sands used included fine sand and coarse sand. The former is characterized by smaller-sized particles and improves the cohesion of the major four constituents. Cohesion would help to prevent segregation and promote uniformity across the newly constructed matrix, ensuring the proper function. The latter has bigger and enhances the stability of the combination. Shrinkage is minimized to avoid excessiveness across the construction. Appropriate particle size distribution and grading are employed to optimize the workability of the concrete mix, while controlling bleeding to maintain mixture stability and achieve an ideal proportioning of constituents.

Fig. 2. Fine sand (left) and coarse sand (right) used in the concrete mix

The coarse aggregate used is crushed gravel with a uniform size distribution that also meets [60] specifications. Fine aggregate is provided by a park sand plant, while a gravel pit supplies coarse aggregate, which is becoming increasingly important in providing structural strength, lowering shrinkage and enhancing the mechanical performance of the mix. No new ideas just fancy wording in this phrasing of the degree of angularity of the selected gravel resulting in increased interlocking and bond strength in the concrete matrix. Properly graded aggregate of small enough size provides a compact mass with minimal voids for efficient load transfer, in turn increasing the overall durability of the concrete structure. This study used an upper limit of 20 mm for the maximum aggregate size following the guidelines prescribed for structural concrete [60].

Fig. 3. Coarse aggregate (gravel) used in the concrete mixture

2.1.3 Water

Comply with the [54] standard for mixing water, free from harmful substances such as chloride or sulfate, which could interfere with cement hydration. Good quality mixing water is crucial for preserving the bond between cement and aggregates and to obtain the best mechanical properties of hardened concrete.

2.1.4 Areca Catechu Fiber

Fiber was obtained from dried areca nut husks (Areca catechu) and was mechanically processed for separating the natural fibers. The pre-treatment process for the fibers before mixing them with the concrete includes washing to remove uncleanness and drying to reduce moisture content. The length of fiber used in this study was 30–50 mm depending on what has been recommended in the prior literature regarding the application of natural fibers in concrete [20], [23]. The fiber percentage was taken as 2.0, 2.5, and 3.0% of weight of cement. These variations were chosen because previous studies showed that natural fibers could help increase the crack resistance of concrete but excessive fiber will have a negative effect on mixture homogeneity, hindering the cement hydration process [7], [9].

Fig. 4. Areca catechu fiber after processing, cut into lengths of 30–50 mm before being used in the concrete mixture

2.1.5 Superplasticizer

The superplasticizer employed in this research is a polycarboxylate-based admixture with a constant dosage of 2.1% by weight of cement. Superplasticizers are used to enhance the workability of the concrete, allowing a decrease of viscosity at the same time as no increase of water is added to the mixture. The application of its most significant alkaloids aims to reduce the adverse effects of Areca catechu fiber in increasing water consumption as well as in decreasing the flowability of the mixture [28], [31].

Fig. 5. Superplasticizer admixture used to improve the workability of fiber-reinforced concrete

2.2 Experimental Design

This research utilized statistical Box-Behnken Design (BBD) under Response Surface Methodology (RSM); for the interaction study of Areca fiber and Superplasticizer for Concrete Compressive strength [1]. Here, corresponds to experimental design for three main factors affecting compressive strength: areca fiber percentage (A), superplasticizer percentage (B) and curing age (C). To evaluate the effect of the fiber dosage on mechanical properties of the concrete, the A variable (fiber content), was set to the values 2%, 2.5% and 3% according to the mass of cement (see Table 3). The B variable reflects the amount of superplasticizer, which was defined as 2.1% of the cement mass, according to previous studies indicating the usefulness of admixtures in workability improvement and compressive strength [3]. As for the curing age C variable, it was based on 7 and 28 days, just to see how compressive strength evolves through time due to cement hydration. The Box-Behnken Design (BBD) method was used to evaluate these three variables, which can explore interaction (interdependent) effects with fewer trials than traditional methods [1].

2.3 Concrete Preparation and Testing

2.3.1 Mixing and Casting of Concrete

The dry mixing method of preparing the concrete was used, with the fine aggregate, coarse aggregate, and cement mixed first until a complete homogeneous mix was obtained. After that, water and superplasticizer were added according to the designed proportions, and then areca fiber. To ensure the uniform distribution of the optical fibers in the concrete matrix [3], the mixing was performed for 5 min by use of a laboratory concrete mixer.

Fig. 6. Concrete mixing process incorporating Areca catechu fiber before casting in cylindrical molds

The concrete specimens were cast in cylindrical molds with dimensions of 150 mm diameter and 300 mm height, in accordance with [61] standards for compressive strength testing. The casting process followed the procedures specified in [61], including proper compaction using a mechanical vibrator to ensure uniform density and minimize entrapped air voids. These procedures align with the requirements outlined in Tables 1 and 2 of [61], which standardize specimen preparation to ensure reliable and reproducible compressive strength results.

2.3.2 Curing of Concrete

Concrete specimens were kept in the Ambient environment for demolding for 24 h and then placed inside the water-curing tank until the test age. Hydration continues under controlled moisture conditions, so this curing method enables the concrete to achieve ultimate strength [4].

Fig. 7. Curing of concrete specimens in a water tank to maintain hydration and ensure optimal strength development

2.3.3 Compressive Strength Test

Compressive strength test was carried out using Universal Testing Machine (UTM) as per [62] standard. The concrete specimens were prepared and cured in accordance with [61] standards prior to compressive strength testing, which was conducted using a Universal Testing Machine (UTM) as per [62]. Each mix variation was tested for three specimens to give a representative average value for the two tests performed at 7 and 28 days respectively.

Fig. 8. Compressive strength testing of concrete cylinders using a Universal Testing Machine (UTM) as per [62] standards

The objectives of this study are to acknowledge the effects of Areca catechu fiber on the properties of concrete, specifically regarding the effect superplasticizer may have on the composition of the mixture through the Box-Behnken Design (BBD). It is anticipated that the conclusion of this research will help for the creation of energy-efficient, fiber-reinforced sustainable concrete bases.

3. Results and Discussion

3.1 Experimental Results

3.1.1 Effect of Areca Catechu Fiber and Superplasticizer on Concrete Compressive Strength

Compressive strength testing was conducted at 7 and 28 days to evaluate the effect of Areca Catechu Fiber (BSKP) and superplasticizer (SP) on concrete strength. Various BSKP contents and SP dosages were used to determine their impact on the mechanical performance of the concrete. The results of the compressive strength tests from different mixtures are presented in Table 1.

Table 1. Compressive strength test results

Specimen Name	Testing Age	Specimen Weight	Cylinder Area	Cylinder Volume	Load (P)		fc= P/A	Average
	(days)	(kg)	(mm²)	(mm³)	kN	N	(Mpa)	(Mpa)
BN. I	7	12.14	17671.46	5301437.60	243.164	243164	13.7603	14.084
BN. II		12.12	17671.46	5301437.60	248.980	248980	14.0894	
BN. III		11.98	17671.46	5301437.60	254.488	254488	14.4011	
BSKP 2% + SP 2,1%. I	7	11.52	17671.46	5301437.60	343.336	343336	19.4288	19.729
BSKP 2% + SP 2,1%. II		11.60	17671.46	5301437.60	350.276	350276	19.8216	
BSKP 2% + SP 2,1%. III		11.70	17671.46	5301437.60	352.308	352308	19.9366	
BSKP 2,5% + SP 2,1%. I	7	11.36	17671.46	5301437.60	340.916	340916	19.2919	19.341
BSKP 2,5% + SP 2,1%. II		11.37	17671.46	5301437.60	341.196	341196	19.3077	
BSKP 2,5% + SP 2,1%. III		11.38	17671.46	5301437.60	343.224	343224	19.4225	
BSKP 3% + SP2,1%. I	7	11.52	17671.46	5301437.60	325.224	325224	18.4039	18.384
BSKP 3% + SP2,1%. II		11.48	17671.46	5301437.60	320.180	320180	18.1185	
BSKP 3% + SP2,1%. III		11.66	17671.46	5301437.60	329.236	329236	18.6309	
BSP 2,1%. I	7	12.08	17671.46	5301437.60	424.256	424256	24.0080	24.106
BSP 2,1%. II		12.04	17671.46	5301437.60	427.564	427564	24.1952	
BSP 2,1%. III		12.14	17671.46	5301437.60	426.152	426152	24.1153	
BN. I	28	11,77	17671.46	5301437.60	354.492	354492	20.0601	20.500
BN. II		11,78	17671.46	5301437.60	364.356	364356	20.6183	
BN. III		11,74	17671.46	5301437.60	367.960	367960	20.8223	
BSKP 2% + SP 2,1%. I	28	11,26	17671.46	5301437.60	446.240	446240	25.2520	25.242
BSKP 2% + SP 2,1%. II		11,27	17671.46	5301437.60	448.984	448984	25.4073	
BSKP 2% + SP 2,1%. III		11,44	17671.46	5301437.60	442.976	442976	25.0673	
BSKP 2,5% + SP 2,1%. I	28	11,52	17671.46	5301437.60	406.508	406508	23.0036	22.960
BSKP 2,5% + SP 2,1%. II		11,56	17671.46	5301437.60	401.236	401236	22.7053	
BSKP 2,5% + SP 2,1%. III		11,58	17671.46	5301437.60	409.448	409448	23.1700	
BSKP 3% + SP2,1%. I	28	11,25	17671.46	5301437.60	398.836	398836	22.5695	22.379
BSKP 3% + SP2,1%. II		11,24	17671.46	5301437.60	396.960	396960	22.4633	

Specimen Name	Testing Age	Specimen Weight	Cylinder Area	Cylinder Volume	Load (P)		fc= P/A	Average
	(days)	(kg)	(mm^2)	(mm^3)	kN	N	(Mpa)	(Mpa)
BSKP 3% + SP2,1%. III		11,28	17671.46	5301437.60	390.620	390620	22.1046	
BSP 2,1%. I		11,94	17671.46	5301437.60	653.952	653952	37.0061	
BSP 2,1%. II	28	12,04	17671.46	5301437.60	656.764	656764	37.1652	37.003
BSP 2,1%. III		11,74	17671.46	5301437.60	650.992	650992	36.8386	

It was noticed that the compressive strength has increased remarkably at 7 and 28 days for all specimens. At 7 days, the average compressive strength of normal concrete (BN) was 14.084 MPa, that increased to 20.500 MPa at 28 days, which corresponds to an increase of 45% due to continuous hydration of cement. The use of added materials improved the compression strength. [9] As a comparison, BSKP 2% + SP 2.1% concrete reached a 7-day average compressive strength of 19.729 MPa and a compressive strength of 25.242 MPa at 28 days-an obvious indicator of how effective their admixture was at improving strength development. Increasing BSKP dosage to 3% decreased the strength as compared to 2% dosage with average compressive strength of 18.384 MPa at 7 days and 22.379 MPa at 28 days. This indicates that there is an optimal level of BSKP dosage, beyond which too much may be detrimental to strength gains. The average compressive strength of concrete containing BSP 2.1% was the best at 24.106 MPa at 7 days and 28 days was 37.003 MPa. The obtained values are greater than normal concrete and all BSKP variations, indicating that BSP is more effective than BSKP in enhancing compressive strength. These results highlight the need for a further investigation for selecting the dose and material of supplementary material to ensure the best performance of concrete. When it came to the best at improving compressive strength was the dosage application of BSP 2.1% while the dosages of BSKP must be optimized further to avoid strength deterioration due to overdoses.

3.1.2 Analysis of the Effect of Areca Fiber Concrete (BSKP) and Superplasticizer on Concrete Mechanical Performance: Comparison with Additional Literature

This study concludes that the addition of Areca Fiber Concrete (BSKP) and superplasticizer (SP) to the concrete greatly impacts the strength of concrete compressive strength, but the results will depend largely on the amount of these materials used. Experimental Results show BSKP 2% + SP 2.1% give the most strength improvement, while compressive strength drops when increasing BSKP to 3% as viscosity increases and workability decreases. Also, excess amounts hinder cement hydration, causing non-homogeneous distribution within the concrete.

Table 2. Comparison of experimental results and literature

Aspect	Experimental Findings	Findings from Additional Literature
Effect of BSKP on Compressive Strength	BSKP 2% + SP 2.1% increased compressive strength by 39.9% (7 days) and 23.5% (28 days).	Areca fiber enhances internal cohesion and crack resistance [7], [9].
Optimal BSKP Dosage	BSKP 3% led to a reduction in compressive strength (18.384 MPa - 7 days, 22.379 MPa - 28 days).	Excessive fiber content increases viscosity and reduces workability [20], [23].
Role of SP in Workability	SP improves cement dispersion, resulting in better workability and compressive strength.	Superplasticizer reduces water demand and prevents segregation [28], [31].
Interaction of BSKP & SP	BSKP 2% + SP 2.1% was found to be the optimal combination.	Studies on the interaction of areca fiber and SP remain limited [35], [38].
Comparison with Conventional Concrete	BSP 2.1% achieved the highest compressive strength (37.003 MPa - 28 days, +80.6% vs. normal concrete).	Optimized fiber-admixture combinations significantly enhance HPC performance [32], [34].

The kind and amount of fiber can determine whether the fiber is effective since it induces a substantial increase in bonding strength [7], [9], similarly as found in this work and supported by others where natural fibers were shown to reduce the volume of microcracks, enhancing material cohesion, ultimately improve its compressive strength, [42] confirming their positive effect on BSKP concrete at a dosage of 2%. Nevertheless, the addition of BSKP at 3% would reduce the compressive strength due to higher viscosity and lower homogeneity, as supported by the previous findings of the adverse impact of a large amount of high water-absorbing fibers on cement hydration. Superplasticizer (SP) based materials promote enhanced workability, optimal cement dispersion, and segregation control, leading to the formation of concrete with improved compressive strength. The confirmed optimum combination was BSKP 2% + SP 2.1% that showed a 39.9% increase in strength at 7 days and 23.5% increase in strength at 28 days in comparison with control concrete. On the other hand, BSKP was shown to increase only 71.45%, while BSP 2.1% was 80.60% compared to normal concrete at 28 days, indicating that BSP proves to be more efficient than BSKP in improving structural concrete performance.

This study applies the Box-Behnken Design (BBD) response surface methodology (RSM) to systematically optimize the proportions of Areca fiber and superplasticizer for enhancing concrete compressive strength. The BBD approach, widely utilized in concrete research, offers an efficient experimental framework to explore multifactor interactions and reduce the number of required trials, as supported by previous studies [1,2,21,32,48-50]. Integrating BBD in this research strengthens the reliability and robustness of the optimization process, thereby enriching the contribution to sustainable HPC development. Moreover, while the compressive strength values obtained may appear moderate relative to traditional HPC benchmarks, it is critical to recognize that HPC performance encompasses multifaceted criteria beyond compressive strength alone, including durability, toughness, crack resistance, and workability. The synergistic effect of natural fibers and superplasticizers in this study aligns with this comprehensive HPC paradigm. Consequently, the findings are consistent with the evolving understanding of HPC as a multifunctional material system, emphasizing sustainability and practical workability alongside mechanical strength. This holistic perspective, reinforced by systematic optimization using BBD, validates the applicability of optimized fiber-admixture combinations in producing eco-friendly, high-performance concrete.

3.2 Statistical Analysis

3.2.1 Analysis of the Interaction between Areca Fiber and Superplasticizer

This study analyzes three main factors affecting concrete compressive strength. Factor 1 (Areca Fiber Concrete, BSKP) refers to the percentage of areca fiber (0%, 2.0%, 2.5%, 3.0%), which enhances crack resistance but may reduce cement homogeneity at higher doses. Factor 2 (Superplasticizer, SP) represents the superplasticizer content (0% and 2.1%), which reduces the water-cement ratio and optimizes hydration. Factor 3 (Concrete Age) is the testing period (7 and 28 days) to evaluate strength development due to the hydration process.

Table 3. Design (actual)

Std	Run	Factor 1	Factor 2	Factor 3	Response 1
		A: Areca Nut Fiber Variation with Superplasticizer	B: Superplasticizer	C: Testing Age	Compressive Strength
		%	%	day	MPa
16	2	0	2.1	7	24.008
20	3	0	0	7	13.7603
21	5	0	0	7	14.4011
9	8	0	2.1	7	24.1952
22	9	0	0	28	20.0601
7	13	0	0	7	14.0894
23	14	0	0	28	20.6183
18	19	0	2.1	7	24.1153

Std	Run	Factor 1	Factor 2	Factor 3	Response 1
		A: Areca Nut Fiber Variation with Superplasticizer	B: Superplasticizer	C: Testing Age	Compressive Strength
		%	%	day	MPa
17	21	0	2.1	28	37.1652
25	23	0	2.1	28	36.8386
29	25	0	0	28	20.8223
15	29	0	2.1	28	37.0061
24	1	2	2.1	7	19.9366
26	4	2	2.1	28	25.252
28	6	2	2.1	28	25.4073
1	7	2	2.1	28	25.0673
3	17	2	2.1	7	19.4288
5	22	2	2.1	7	19.8216
13	11	2.5	2.1	28	23.0036
30	12	2.5	2.1	7	19.2919
10	15	2.5	2.1	7	19.3077
19	16	2.5	2.1	28	22.7053
11	18	2.5	2.1	28	23.17
14	20	2.5	2.1	7	19.4225
4	10	3	2.1	7	18.6309
8	24	3	2.1	28	22.1046
27	26	3	2.1	28	22.5695
6	27	3	2.1	7	18.4039
12	28	3	2.1	28	22.4633
2	30	3	2.1	7	18.1185

3.2.2 Fit Summary

Statistical analysis shows that the linear model has a p-value of 1.75×10^{-13}, an Adjusted R^2 of 0.895, and a Predicted R^2 of 0.866, making it the recommended choice. The 2FI model has an Adjusted R^2 of 0.985 and a Predicted R^2 of 0.983 but suffers from aliasing. While the 2FI model fits better statistically, the linear model is simpler and free from aliasing, making it more reliable for predicting compressive strength.

Table 4. Response 1: compressive strength

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	< 0.0001	0.8953	0.8665	Suggested
2FI	< 0.0001	< 0.0001	0.9854	0.9830	Aliased

Table 5. Results of the Sequential Model Sum of Squares [Type I]

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	15016.33	1	15016.33			
Linear vs Mean	898.00	3	299.33	83.69	< 0.0001	Suggested
2FI vs Linear	81.01	2	40.51	81.16	< 0.0001	Aliased
Residual	11.98	24	0.4991			
Total	16007.31	30	533.58			

The linear model shows a sum of squares of 897.997, an F-value of 83.69, and a p-value of 1.75×10^{-13}, indicating high statistical significance. The 2FI model has a p-value of 2.09×10^{-11} but suffers from aliasing, which may hinder interpretation. Therefore, the linear model is recommended due to its stability and aliasing-free nature, making it more reliable for compressive strength analysis.

Table 6. Results of the lack of conformity test

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Linear	91.83	6	15.31	264.11	< 0.0001	Suggested
2FI	10.82	4	2.70	46.67	< 0.0001	Aliased
Pure Error	1.16	20	0.0580			

The linear model demonstrates high significance but has a lack-of-fit that should be considered. The 2FI model has a lower lack-of-fit but suffers from aliasing. Therefore, the linear model remains recommended, with caution in result interpretation. The 2FI model has a higher Adjusted R^2 (0.985) and Predicted R^2 (0.983) compared to the linear model (Adjusted R^2 0.895, Predicted R^2 0.866), along with a lower standard deviation. However, the 2FI model suffers from aliasing, which may affect parameter interpretation. The 2FI model is statistically superior, but aliasing effects should be carefully considered.

Table 7. Model summary statistics

Model	Std. Dev.	Adjusted R^2	Predicted R^2	Press	Information
Linear	1.891	0.895	0.866	132.323	Recommended, but less than optimal
2FI	0.706	0.985	0.983	16.858	Aliased, better performance but needs attention

3.2.3. ANOVA Analysis for Linear Model on Compressive Strength

Analysis of variance (ANOVA) was performed to evaluate the effect of Areca Nut fiber variation, superplasticizer usage, and curing age on compressive strength. The results indicate that the model is statistically significant ($F = 83.69$, $p = 1.748 \times 10^{-13}$), with all three factors significantly influencing the response. However, the Lack of Fit is also significant ($F = 264.11$, $p = 5.837 \times 10^{-18}$), suggesting a discrepancy between the model and the actual data. The Areca Nut fiber variation, superplasticizer usage, and curing age significantly influence the compressive strength. The significant Lack of Fit indicates that the model may not fully align with the observed data.

Table 8. ANOVA for linear model

Source of Variation	SS	df	MS	F-value	p-value	Interpretation
Model	897.9965	3	299.3322	83.6933	1.748×10^{-13}	Significant
A - Areca Nut Fiber Variation with Superplasticizer	388.6576	1	388.6576	108.669	8.859×10^{-11}	
B - Superplasticizer	524.1400	1	524.1400	146.550	3.450×10^{-12}	
C - Curing Age	315.7199	1	315.7199	88.2753	7.641×10^{-10}	
Residual	92.9900	26	3.5765			
Lack of Fit	91.8309	6	15.3052	264.106	5.837×10^{-18}	Significant
Pure Error	1.1590	20	0.05795			
Total Correlation	990.9865	29				

3.2.4. Model Fit Statistics.

The model fit evaluation indicates good predictive performance. The coefficient of determination (R^2) = 0.9062 shows that 90.62% of the response variability is explained by the model. The Adjusted R^2 = 0.8953 and Predicted R^2 = 0.8665 differ by less than 0.2, indicating strong predictive capability. The Adequate Precision = 28.187, well above the minimum threshold of 4, confirms a strong signal for reliable predictions. The high R^2 values and Adequate Precision suggest that the model is reliable and effective for exploring and optimizing the design space.

Table 9. Model fit statistics

Statistic	Value	Interpretation
Standard Deviation	1.8912	Measures model error
Mean	22.3728	Average response value
Coefficient of Variation (C.V. %)	8.4530	Relative measure of data dispersion
R^2 (Coefficient of Determination)	0.9062	Model explains 90.62% of response variability
Adjusted R^2	0.8953	Adjusted for predictor count
Predicted R^2	0.8665	Close agreement with Adjusted R^2, indicating good predictive accuracy
Adequate Precision	28.1870	Signal-to-noise ratio, confirming model suitability for prediction

3.2.5. Model Comparison Statistics.

The model comparison evaluation indicates that PRESS = 132.323 represents the model's prediction error. -2 Log Likelihood = 119.075 assesses model fit, where lower values indicate a better-fitting model. BIC = 132.680 and AICc = 128.675 balance model fit and complexity, with lower values suggesting a more optimal model. These values assist in selecting the best model by balancing goodness of fit and complexity.

Table 10. Model comparison statistics

Statistic	Value	Interpretation
PRESS	132.323	Prediction error; lower is better
-2 Log Likelihood	119.075	Model fit; lower is better
BIC	132.680	Balances model fit and complexity; lower is better
AICc	128.675	Corrected Akaike Information Criterion for small sample sizes

3.2.6. Coefficients in Terms of Coded Factors.

Regression analysis shows that Superplasticizer (B) has the highest positive impact on the response (coefficient = 6.4884), while Areca Nut Fiber Variation with Superplasticizer (A) has a negative effect (-1.7668). Testing Age (C) also contributes positively (3.2441). The Variance Inflation Factor (VIF) ≤ 1.542 indicates no significant multicollinearity issues among factors. These results indicate that Superplasticizer has the most significant positive effect on the response, while Areca Nut Fiber Variation with Superplasticizer negatively affects it.

Table 11. Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	14.9461	1	0.6832	13.5417	16.3505	-
A - Areca Nut Fiber Variation with Superplasticizer	-1.7668	1	0.1695	-2.1152	-1.4185	1.542
B - Superplasticizer	6.4884	1	0.5360	5.3867	7.5901	1.542
C - Testing Age	3.2441	1	0.3453	2.5343	3.9538	1.000

3.2.7. Final Equation in Terms of Actual Factors.

The final equation is used to predict compressive strength based on factor values in their original units:

$$Compressive\ Strength = 11.8851 - 3.5337(A) + 6.1794(B) + 0.3089(C) \tag{1}$$

Where, A = Areca Nut Fiber Variation with Superplasticizer; B = Superplasticizer; C = Testing Age

Superplasticizer has the highest positive contribution to compressive strength, while Areca Nut Fiber Variation with Superplasticizer has a negative impact. Testing Age has a small but positive effect. This equation is for prediction purposes only and should not be used to determine the relative impact of each factor.

3.2.8. Data Analysis Results

The analysis indicates that some data points have high residuals, suggesting potential outliers or significant influence on the model. Run 2, 8, 21, 23, and 29 have notable Cook's Distance and DFFITS values, meaning these data points may strongly affect the model's performance. Further evaluation is needed to determine whether the model should be adjusted or if these points require special handling. These results indicate that some data points have a strong influence on the model, requiring further investigation.

Table 12. Data Analysis Results

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	DFFITS	Standard Order
1	19.94	19.96	-0.02	0.076	-0.011	-0.011	0.000003	-0.0032	24
2	24.01	27.02	-3.02	0.188	-1.770	-1.851	0.1813	-0.8905	16
3	13.76	14.05	-0.29	0.200	-0.170	-0.167	0.0018	-0.0834	20
4	25.25	26.45	-1.19	0.076	-0.656	-0.649	0.0088	-0.1855	26
5	14.40	14.05	0.35	0.200	0.209	0.205	0.0027	0.1025	21
6	25.41	26.45	-1.04	0.076	-0.571	-0.563	0.0067	-0.1610	28
7	25.07	26.45	-1.38	0.076	-0.758	-0.752	0.0117	-0.2148	1
8	24.20	27.02	-2.83	0.188	-1.660	-1.722	0.1595	-0.8284	9
9	20.06	20.54	-0.48	0.200	-0.281	-0.276	0.0049	-0.1381	22
10	18.63	16.42	2.21	0.116	1.241	1.255	0.0504	0.4538	4
11	23.00	24.68	-1.67	0.088	-0.927	-0.925	0.0206	-0.2864	13
12	19.29	18.19	1.10	0.088	0.610	0.602	0.0089	0.1865	30
13	14.09	14.05	0.04	0.200	0.025	0.024	0.00004	0.0120	7
14	20.62	20.54	0.08	0.200	0.049	0.048	0.0001	0.0239	23
15	19.31	18.19	1.12	0.088	0.618	0.611	0.0092	0.1893	10
16	22.71	24.68	-1.97	0.088	-1.092	-1.097	0.0286	-0.3397	19
17	19.43	19.96	-0.53	0.076	-0.291	-0.285	0.0017	-0.0816	3
18	23.17	24.68	-1.51	0.088	-0.835	-0.830	0.0167	-0.2571	11
19	24.12	27.02	-2.91	0.188	-1.707	-1.777	0.1686	-0.8547	18
20	19.42	18.19	1.23	0.088	0.682	0.675	0.0112	0.2090	14
21	37.17	33.51	3.65	0.188	2.143	2.316	0.2658	1.1143	17
22	19.82	19.96	-0.14	0.076	-0.075	-0.073	0.0001	-0.0209	5
23	36.84	33.51	3.33	0.188	1.952	2.071	0.2204	0.9965	25
24	22.10	22.91	-0.81	0.116	-0.454	-0.447	0.0067	-0.1616	8
25	20.82	20.54	0.29	0.200	0.169	0.166	0.0018	0.0830	29
26	22.57	22.91	-0.34	0.116	-0.192	-0.189	0.0012	-0.0683	27
27	18.40	16.42	1.98	0.116	1.114	1.119	0.0405	0.4046	6
28	22.46	22.91	-0.45	0.116	-0.252	-0.248	0.0021	-0.0895	12
29	37.01	33.51	3.49	0.188	2.050	2.195	0.2431	1.0561	15
30	18.12	16.42	1.69	0.116	0.953	0.951	0.0297	0.3440	2

The normal plot of residuals is used to assess the normality assumption of the regression model residuals. In this plot, the residual data points closely follow the diagonal reference line, indicating that the residuals approximate a normal distribution. This is an important assumption for the validity of linear regression models. Meeting this assumption implies that the regression model is appropriate and the statistical analysis results can be reliably interpreted.

The Residuals vs. Predicted plot is used to assess the homoscedasticity (constant variance) assumption of the regression model. In this plot, the residuals are randomly scattered around zero without any discernible pattern, indicating that the residual variance is consistent across all predicted values. This suggests that the model fits the data well and that the homoscedasticity assumption is satisfied, supporting the reliability of the regression analysis.

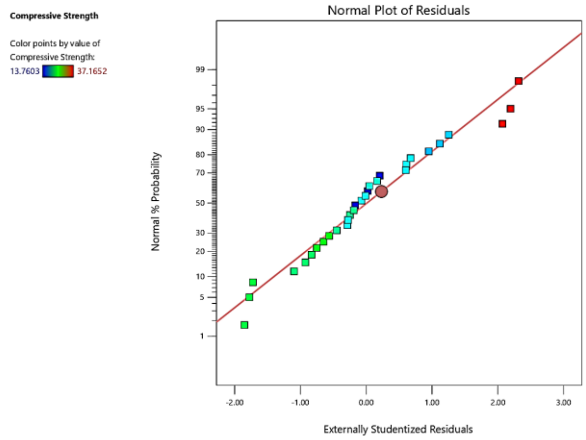

Fig. 9. Normal Plot of Residuals

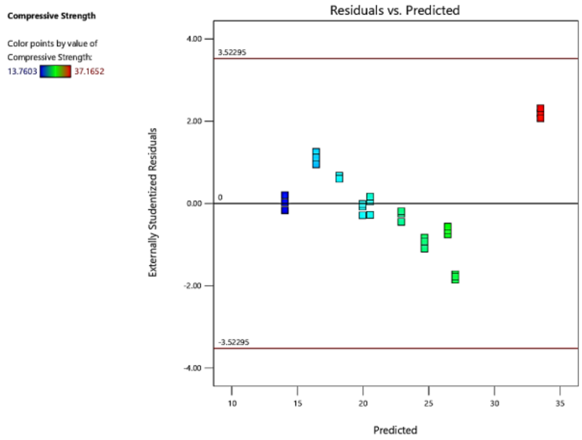

Fig. 10. Residuals vs. Predicted

The Residuals vs. Run plot is used to examine the pattern of residuals across the sequence of experimental runs. A random scatter of residuals without any systematic pattern indicates that there is no autocorrelation or run order effect influencing the data. This confirms the independence of residuals and supports the validity and stability of the regression model throughout the experimental runs.

The Cook's Distance plot is used to identify data points with a disproportionately large influence on the regression model. Data points with high Cook's Distance values indicate a significant impact on parameter estimates and overall model fit. In this plot, points approaching or exceeding the threshold are flagged for further examination to ensure the stability and reliability of the regression analysis. The absence of extreme Cook's Distance values suggests no outliers unduly dominate the model results.

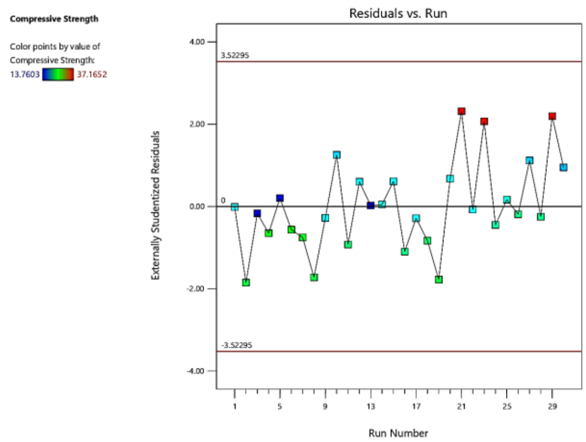

Fig. 11. Residuals vs. Run

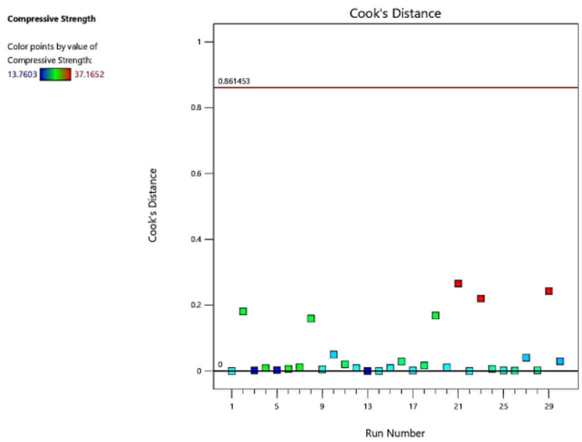

Fig. 12. Cook's Distance

The Box-Cox plot is utilized to identify the optimal power transformation that stabilizes variance and improves the normality of residuals in the regression model. This transformation aids in satisfying the assumptions of homoscedasticity and normality, which are essential for valid statistical inference. The plot displays the range of lambda (λ) values within the confidence interval, indicating acceptable transformation values. A lambda value close to 1 suggests no transformation is necessary, whereas values differing from 1 indicate that data transformation is required to enhance model validity.

The Predicted vs. Actual plot is used to evaluate the accuracy of the regression model in predicting concrete compressive strength based on experimental data. Data points closely clustered around the diagonal line indicate a strong agreement between predicted and actual measured values, demonstrating the model's robust predictive capability. Minor deviations from the diagonal represent minimal prediction errors, confirming the model's reliability in estimating concrete performance across different variable combinations. This plot reinforces the validity and robustness of the statistical model employed in this study.

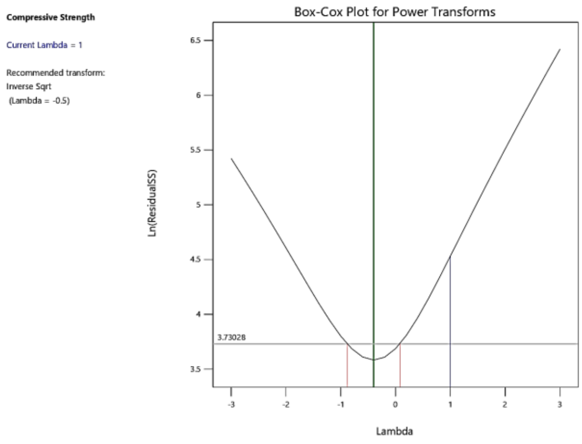

Fig. 13. Box-Cox Plot for Power Transforms

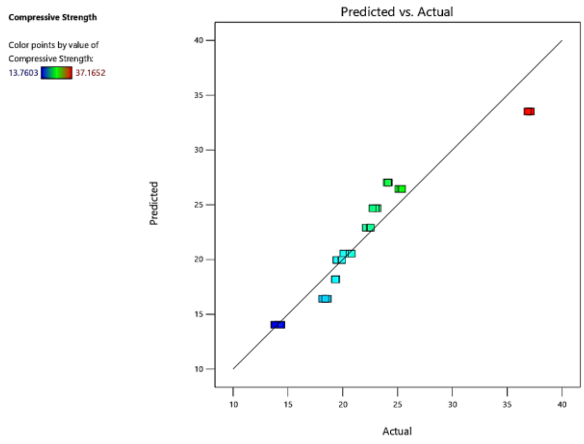

Fig. 14. Predicted vs. Actual

This plot illustrates the residuals from the regression model against variations in Areca Nut Fiber dosage combined with a fixed percentage of superplasticizer. The random scatter of residuals without any clear pattern indicates that the model consistently explains the variability of the data across the tested fiber dosage range. The absence of systematic trends confirms that the assumptions of linearity and homoscedasticity are met for this factor, supporting the validity of the regression analysis in predicting concrete compressive strength with varying fiber content.

The Leverage vs. Run plot is used to identify data points that have a significant influence on the regression model. High leverage values indicate observations that are outliers in terms of predictor variables and have a strong impact on the estimation of model parameters. In this plot, no data points exhibit extremely high leverage, suggesting that there are no observations disproportionately influencing the model. This supports the stability and reliability of the regression analysis results.

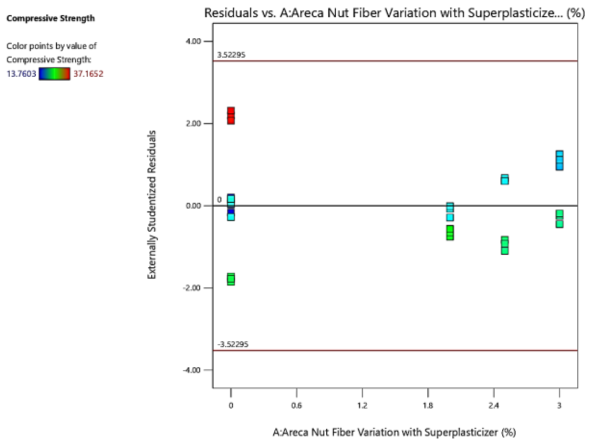

Fig. 15. Residuals vs. A: Areca Nut Fiber Variation with Superplasticizer (%)

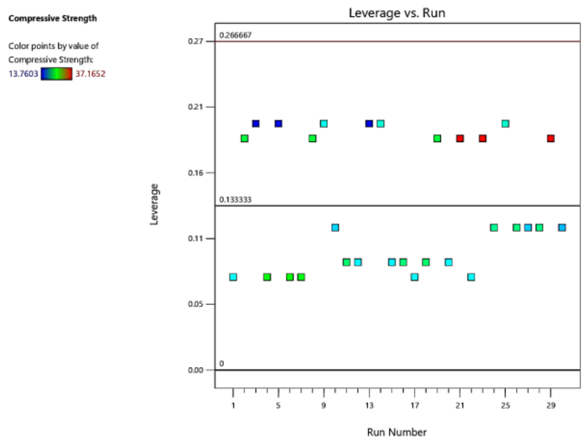

Fig. 16. Leverage vs. Run

The DFFITS vs. Run plot is used to detect observations that have a significant influence on the regression model's predictions. DFFITS measures the impact of removing each data point on the fitted model values. Data points with large absolute DFFITS values exceeding a critical threshold are considered influential and may disproportionately affect the model estimates. In this plot, no data points exceed this threshold, indicating that no individual observation unduly influences the model, thereby reinforcing the robustness and reliability of the regression analysis.

The DFBETAS for Intercept vs. Run plot assesses the influence of individual data points on the estimated intercept of the regression model. DFBETAS measures the change in the intercept coefficient when each data point is excluded. Points with large absolute DFBETAS values indicate observations that have a strong impact on the intercept estimation. In this plot, no points exceed the typical threshold, suggesting that no single observation unduly affects the intercept, supporting the stability and robustness of the regression model.

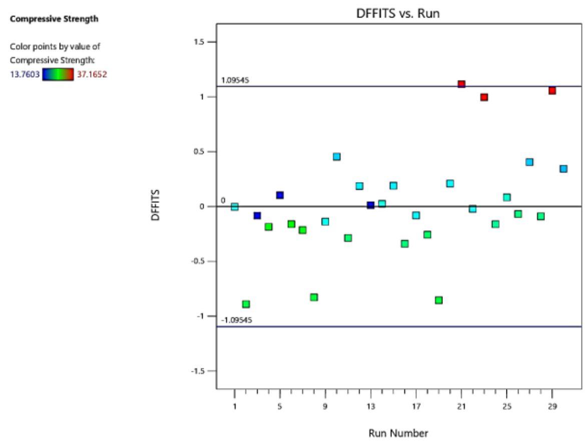

Fig. 17. DFFITS vs. Run

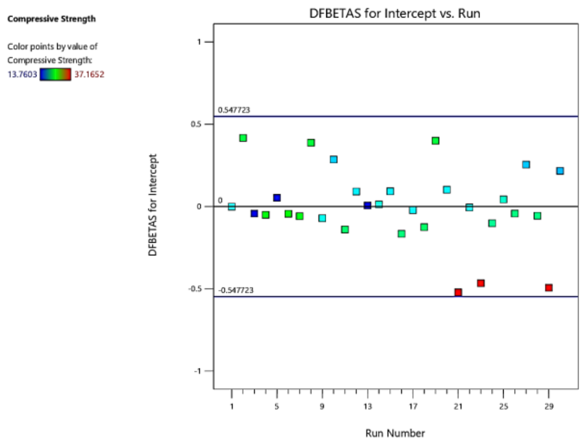

Fig. 18. DFBETAS for Intercept vs. Run

The perturbation plot illustrates the sensitivity of the response variable—in this case, compressive strength—to small changes in each factor while holding other factors constant at a reference point. Steeper slopes on the plot indicate greater sensitivity, highlighting which variables have the most significant effect on the response. This information guides the optimization of mixture proportions by identifying key influential factors.

The one factor plot illustrates the individual effect of each variable on the response, compressive strength, by varying one factor at a time while holding other factors constant. This plot helps in understanding the direct influence of each factor independently, revealing trends such as linearity or non-linearity in the response. It is a useful tool for identifying the optimal range and levels of factors to enhance compressive strength.

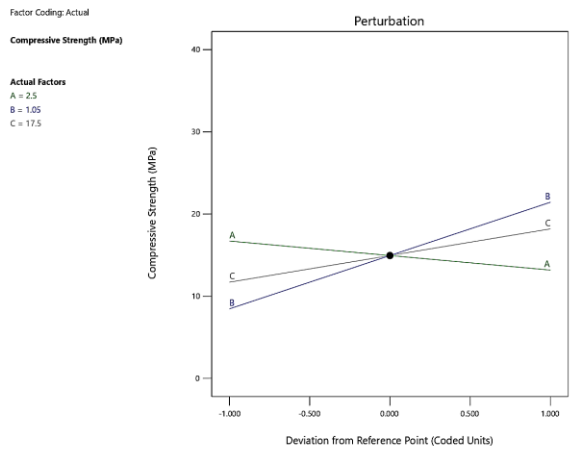

Fig. 19. Perturbation

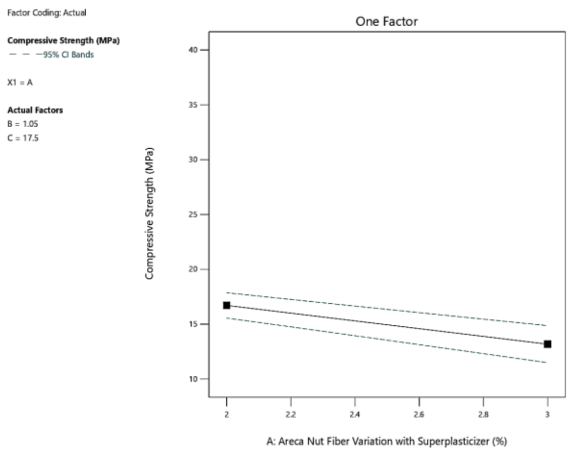

Fig. 20. One Factor

The analysis examines the effects of Factors A, B, and C on Compressive Strength (MPa: 13.7603 to 37.1652), validated by 95% Confidence Intervals (CI). Factor A (0% to 2.5%) shows a negative correlation, reducing compressive strength. Factor B (0.8% to 1.2%) and Factor C (7 to 28 days) exhibit positive correlations, increasing strength. All factors significantly impact compressive strength, with B and C enhancing strength and A reducing it. The 95% CI bands confirm statistical reliability.

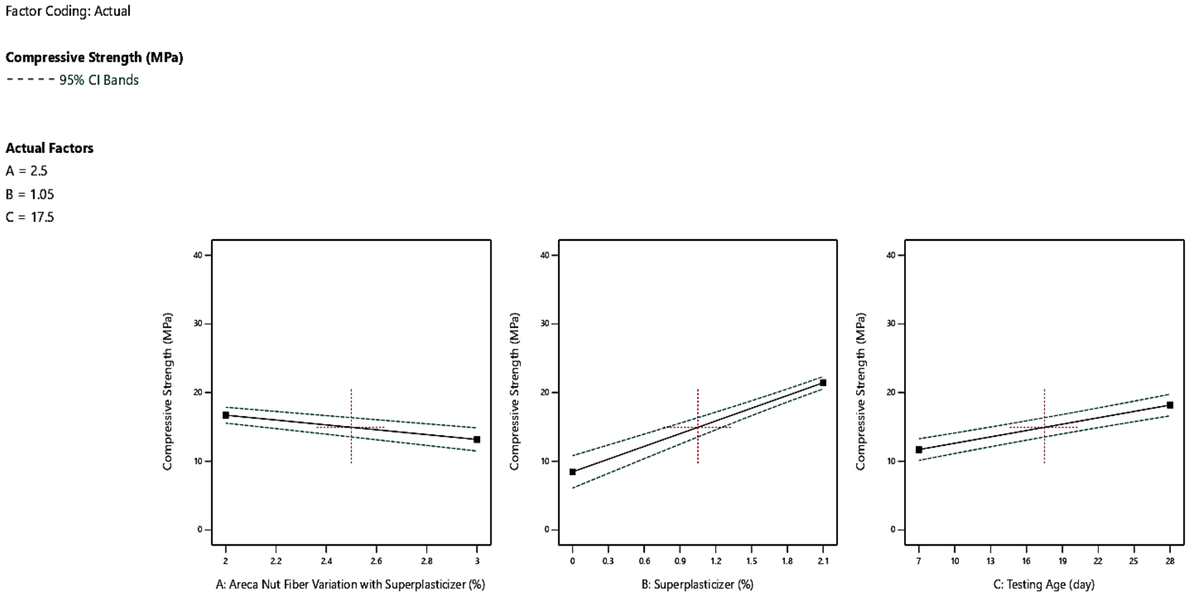

Fig. 21. All Factor

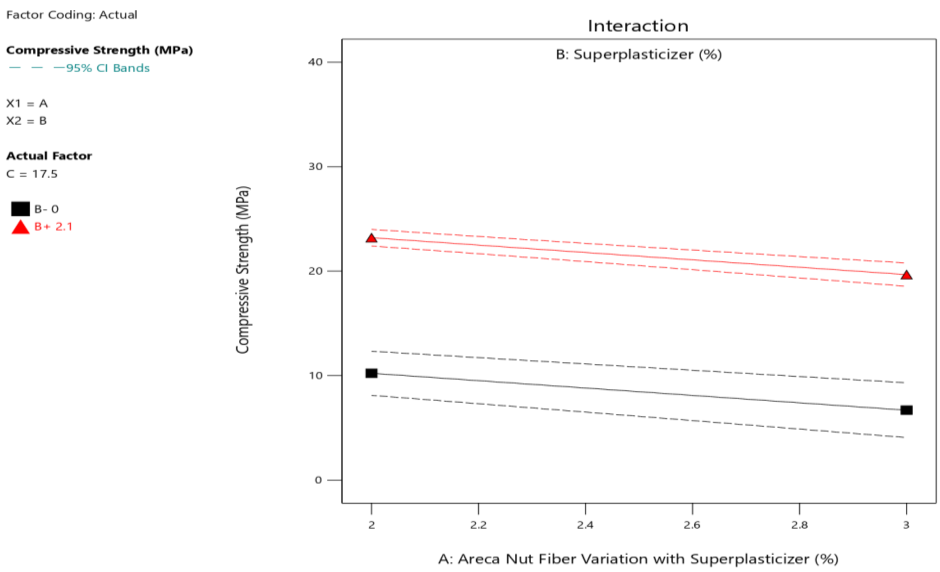

Fig. 22. Interaction

The Interaction Plot examines the effect of Factor A (Areca Nut Fiber Variation: 2.0% to 3.0%) and Factor B (Superplasticizer: 0.0 and 2.1%) on Compressive Strength (MPa: 13.7603 to 37.1652), with Factor C (Testing Age) fixed at 17.5. When B = 0.0, compressive strength decreases as A increases. At B = 2.1, compressive strength remains higher at increased A levels. The 95% Confidence Interval (CI) overlap suggests an interaction effect, with A's influence stronger at B = 2.1.

The 3D Surface Plot illustrates the relationship between Areca Nut Fiber Variation (A: 2.0% to 3.0%), Superplasticizer (B: 0.0% to 2.1%), and Compressive Strength (MPa: 10 to 20), with Testing Age (C) fixed at 17.5. The plot shows a positive correlation, where increasing A and B leads to higher compressive strength, as indicated by the upward slope and color gradient (blue to green).

In the experiment, 94 solutions were analyzed based on Desirability values, which assess factor suitability for maximizing compressive strength. The optimal solution (Desirability = 0.542) achieved 26.445 MPa with a standard error of 0.520, using 2.0% Areca Nut Fiber, 2.1% Superplasticizer, and 28-day Testing Age.

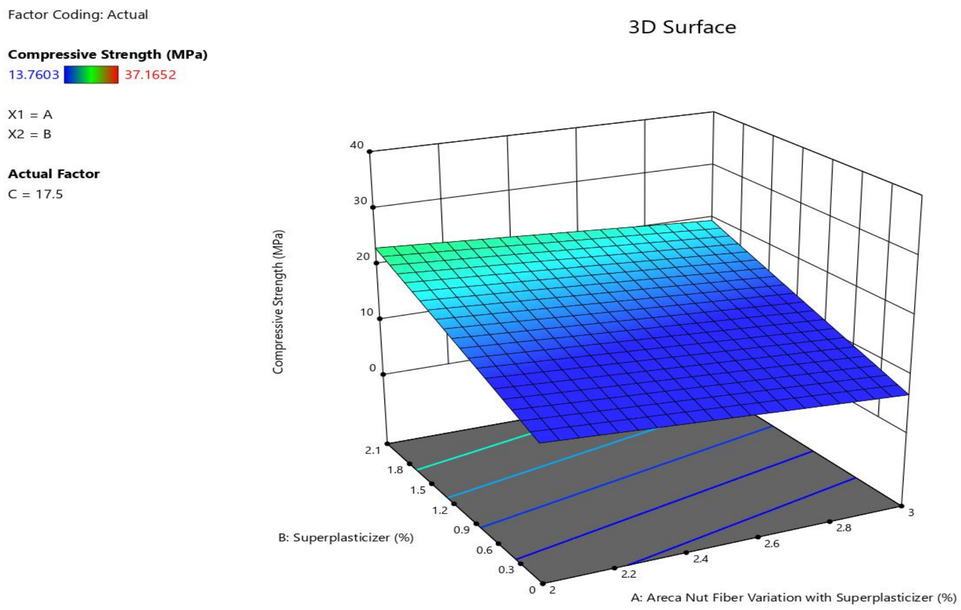

Fig. 23. 3D Surface Plot illustrates

Table 13. Experimental results for the 94 solutions tested, showing the Desirability values and factors used

Number	Areca Nut Fiber Variation with Superplasticizer	Superplasticizer	Testing Age	Compressive Strength (MPa)	StdErr (Compressive Strength)	Desirability	Remarks
1	2.000	2.100	28	26.445	0.520	0.542	Optimal solution, highest Desirability
2	2.007	2.100	28	26.415	0.520	0.541	
3	2.016	2.100	28	26.389	0.520	0.540	
4	2.022	2.100	28	26.367	0.520	0.539	
5	2.031	2.100	28	26.326	0.520	0.537	
6	2.026	2.092	28	26.304	0.520	0.536	
7	2.037	2.100	28	26.295	0.520	0.536	
8	2.031	2.091	28	26.281	0.520	0.535	
9	2.057	2.100	28	26.242	0.522	0.533	
10	2.045	2.085	28	26.196	0.520	0.531	
11	2.076	2.100	28	26.139	0.520	0.529	
12	2.055	2.081	28	26.132	0.520	0.529	
13	2.088	2.100	28	26.089	0.520	0.527	
14	2.101	2.100	28	26.035	0.520	0.524	
15	2.073	2.071	28	26.012	0.520	0.523	
16	2.078	2.068	28	25.970	0.520	0.522	
17	2.119	2.100	28	25.955	0.520	0.521	
18	2.099	2.070	28	25.911	0.521	0.519	
19	2.088	2.061	28	25.896	0.520	0.518	
20	2.092	2.058	28	25.863	0.520	0.517	
21	2.166	2.100	28	25.857	0.527	0.517	
22	2.186	2.100	28	25.788	0.529	0.514	
23	2.150	2.076	28	25.765	0.524	0.513	
24	2.165	2.098	28	25.746	0.520	0.512	
25	2.171	2.100	28	25.726	0.520	0.511	
26	2.175	2.100	28	25.708	0.520	0.510	
27	2.236	2.100	28	25.612	0.532	0.506	
28	2.242	2.100	28	25.592	0.533	0.506	
29	2.127	2.020	28	25.503	0.520	0.502	
30	2.272	2.100	28	25.450	0.536	0.499	
31	2.292	2.100	28	25.415	0.537	0.498	
32	2.135	1.988	28	25.400	0.520	0.497	
33	2.305	2.100	28	25.368	0.538	0.496	
34	2.315	2.100	28	25.331	0.539	0.494	
35	2.320	2.100	28	25.314	0.539	0.493	
36	2.326	2.100	28	25.292	0.540	0.493	

Number	Areca Nut Fiber Variation with Superplasticizer	Superplasticizer	Testing Age	Compressive Strength (MPa)	StdErr (Compressive Strength)	Desirability	Remarks
37	2.296	2.075	28	25.243	0.536	0.491	
38	2.147	1.987	28	25.220	0.520	0.490	
39	2.358	2.100	28	25.166	0.543	0.487	
40	2.388	2.100	28	25.074	0.546	0.483	
41	2.376	2.100	28	25.042	0.540	0.482	
42	2.404	2.100	28	25.020	0.548	0.481	
43	2.159	1.959	28	25.009	0.520	0.481	
44	2.466	2.100	28	24.800	0.555	0.472	
45	2.481	2.100	28	24.747	0.557	0.469	
46	2.428	2.100	28	24.445	0.520	0.456	
47	2.134	1.849	28	24.423	0.520	0.456	
48	2.433	2.100	28	24.413	0.520	0.455	
49	2.440	2.100	28	24.377	0.520	0.454	
50	2.432	2.084	28	24.328	0.520	0.451	

The optimal solution, achieving the highest Desirability value (0.542), is found in Solution Number 1. This combination-Areca Nut Fiber Variation (2%), Superplasticizer (2.1%), and Testing Age (28 days)-yields the highest compressive strength (26.445 MPa). These results suggest that this specific factor combination optimally enhances material performance.

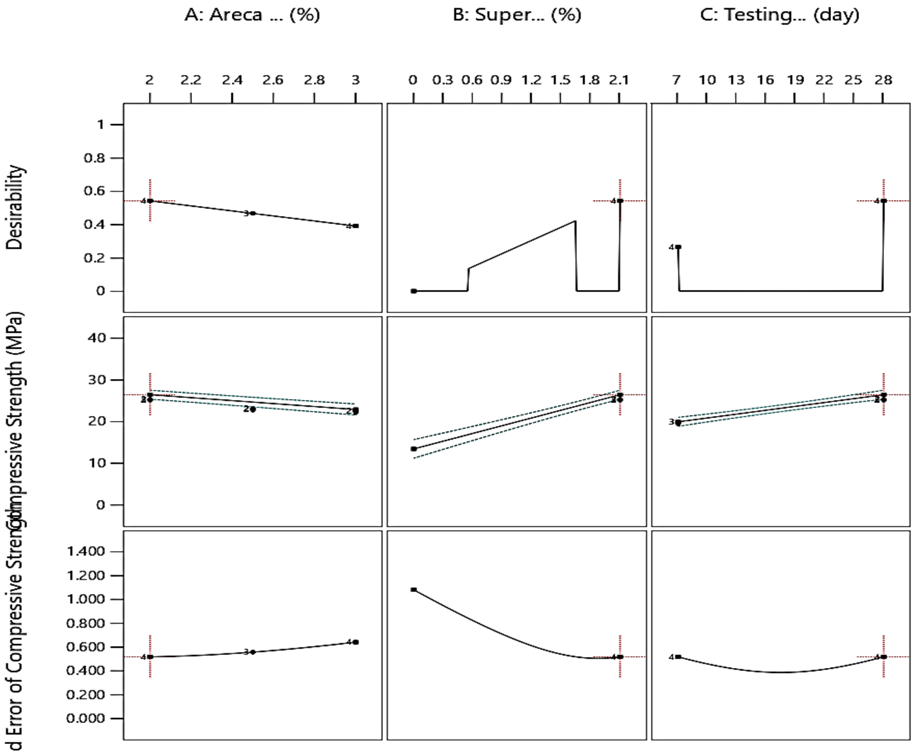

Fig. 24. Graph all factor

The graph examines the effect of Areca Nut Fiber (0%–2.5%), Superplasticizer (0.8%–2.1%), and Testing Age (7–28 days) on Desirability and Compressive Strength Error (0.1–1.5 MPa). Desirability increases with Areca and Superplasticizer, though inconsistently. Compressive Strength declines initially, then stabilizes. Error fluctuations suggest measurement uncertainty, requiring further analysis to improve reliability.

The 3D Surface Plot visualizes desirability for optimizing Compressive Strength, based on Areca Nut Fiber Variation (A: 2%–3%) and Superplasticizer (B: 0%–2.1%), with Testing Age (C) fixed at 28 days. The Z-axis represents Desirability (0 to 1), transitioning from blue (low) to green (high). Green regions indicate optimal factor combinations, while blue regions reflect suboptimal conditions. Red design points mark experimental settings. This plot helps identify the best A and B combinations for improved material performance.

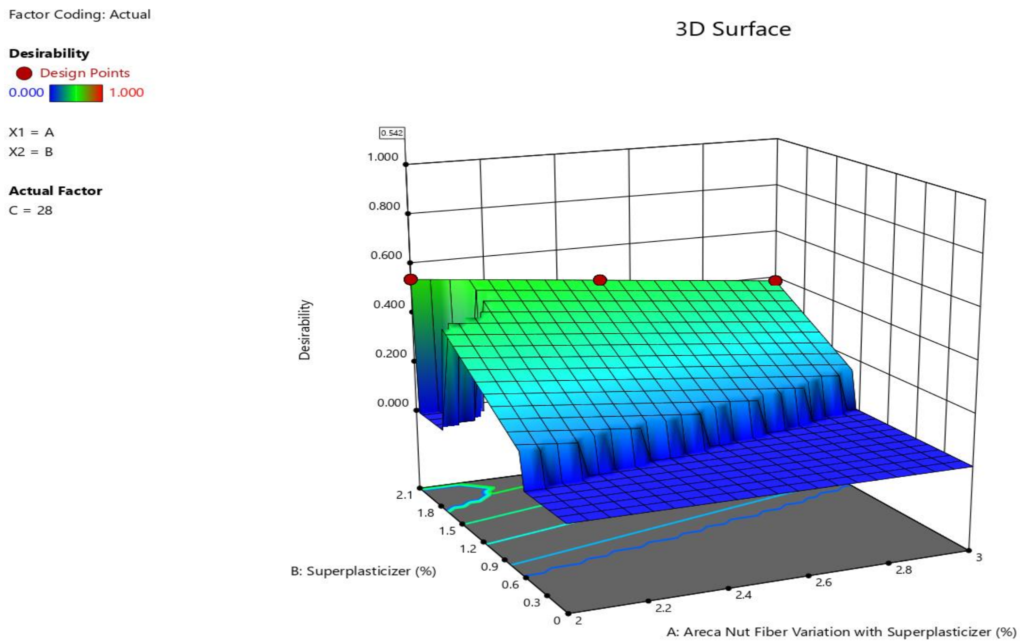

Fig. 25. 3D Surface Plot visualizes desirability

4. Conclusions

This study demonstrates that the incorporation of Superplasticizer (SP) and Areca Nut Fiber (BSKP) significantly improves the compressive strength of concrete. The optimal mixture, consisting of 2.0% BSKP and 2.1% SP, achieved a compressive strength of 26.445 MPa at 28 days. Increasing BSKP content to 3.0% resulted in a strength reduction to 22.379 MPa, attributed to increased mixture viscosity adversely affecting cement hydration and homogeneity. Meanwhile, BSP at 2.1% exhibited the highest compressive strength of 37.003 MPa, representing an 80.6% improvement over conventional concrete. Optimization via the Box-Behnken Design (BBD) identified effective dosage ranges for BSKP and SP at 1.8%–2.2% and 1.9%–2.3%, respectively, producing desirability values ≥ 0.55 and compressive strengths between 27.5 and 28.0 MPa.

The findings hold significant implications for sustainable development and innovation in construction materials. Utilizing renewable Areca catechu fiber as a reinforcing agent not only enhances mechanical performance but also reduces reliance on synthetic fibers, thereby mitigating environmental impacts. This approach valorizes agricultural waste into value-added construction materials, supporting resource efficiency and circular economy principles. The observed improvements in compressive strength and workability enable broader application across structural elements, potentially extending service life and lowering maintenance costs. Accordingly, this technology aligns with sustainable development goals by reducing the ecological footprint of construction and fostering local economic empowerment through sustainable material sourcing.

Nonetheless, several limitations should be acknowledged. Comprehensive durability assessments, including water absorption, permeability, and chemical resistance tests, were not conducted, restricting evaluation of long-term material performance. The fixed superplasticizer dosage (2.1%) limited exploration of dose-response relationships and formulation optimization. While the employed linear statistical model provided stability and interpretability, it may inadequately capture complex nonlinear interactions among factors. Additionally, the experimental scope was confined to laboratory-scale investigations, necessitating field-scale validation and long-term performance monitoring to confirm practical applicability and durability under real-world conditions. Therefore, future research should prioritize comprehensive durability testing to assess long-term resilience against environmental and chemical degradation. Expanding the range of superplasticizer dosages will facilitate a deeper understanding of dose effects and interactions with natural fibers. The development and application of advanced statistical models, including nonlinear and interaction-based approaches, will improve predictive accuracy and mechanistic insight. Moreover, field trials incorporating extended performance monitoring are critical to validate laboratory findings and establish reliability for sustainable natural fiber-reinforced concrete in construction practice.

In summary, this study contributes substantially to the advancement of eco-friendly, high-performance concrete materials reinforced with natural fibers, while charting a clear path for ongoing research and innovation to support efficient and sustainable construction in the future.

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