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Original Research Article

Central Composite Design for Enhancing the Compressive Strength of a Natural Lignocellulosic Fiber -Reinforced Concrete

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Abstract

This study evaluates the compressive strength performance of Nipa Palm Fibre Reinforced Concrete (NPFRC) as a sustainable alternative for low- to medium-strength construction. Using Central Composite Design, the research examined how varying fibre content and length influence compressive strength. NPFRC compressive strength ranged from 9.17 to 21.96 MPa, compared to 26.12 MPa for conventional concrete. Higher fibre content and length generally reduced strength due to poor workability, compaction, and increased porosity. Fibre dosage had a more significant impact than fibre length. Interaction plots revealed that fibre content and length had interdependent, not additive, effects on strength. Response Surface Methodology (RSM) optimized the mix design, identifying 0.5% fibre content and 34.25 mm fibre length as ideal, yielding a predicted strength of 20.98 MPa with 92.30% desirability. A confirmatory test recorded 19.87 MPa, a 5.58% deviation from the prediction, within acceptable limits. Although the optimized compressive strength does not meet structural-grade standards (ASTM and EN 206), the results demonstrate NPFRC's potential for non-load-bearing and light structural applications. The study highlights the importance of fibre treatment, optimal proportioning, and quality control, reinforcing NPFRC's viability in eco-friendly construction where moderate strength and sustainability are prioritized.

Keywords: Central composite design, Nipa Palm fiber (NPF), Compressive Strength, Fiber-reinforced concrete.

1. INTRODUCTION

The integration of natural lignocellulosic fibers into concrete has gained increasing interest due to the dual benefits of sustainability and mechanical enhancement. Among various bio-based fibers, Nipa palm (Nypa fruticans) fiber, commonly found in coastal and swampy regions of Southeast Asia and West Africa, emerges as a promising reinforcement material. Nipa palm fibers are rich in cellulose and hemicellulose, contributing to their tensile strength and affinity for bonding in cementitious matrices (Lisa Oksri-Nelfia *et al*., 2025). Chemical analyses reveal that the cellulose content in Nipa palm fibers ranges from 28.9% to 45.6%, while hemicellulose content varies between 21.6% and 26.4%, both of which are integral to improving tensile strength and flexibility (Chong *et al*., 2022). Furthermore, the lignin content, which ranges from 19.4% to 33.8%, enhances rigidity and microbial resistance, making the fibers more durable in concrete environments (Mekonnen *et al*., 2023).

However, the hydrophilic nature of natural fibers such as Nipa palm can hinder their bonding with cementitious matrices. To overcome this challenge, alkali treatments such as sodium hydroxide application are used to remove amorphous components and increase surface roughness, resulting in better mechanical interlock and bonding within concrete (Azwa *et al*., 2022). Such surface modifications significantly improve the strength, durability, and water resistance of bio-fiber-reinforced composites.

In addition to mechanical benefits, the environmental sustainability of Nypa palm fibers adds to their appeal. Their renewable nature, local availability in tropical regions, and biodegradability make them a low-carbon alternative to synthetic fibers like polypropylene or glass fibers (Rajak *et al*., 2023). Their use in concrete thus contributes to green construction practices and supports global sustainability goals.

Central Composite Design (CCD), a prominent component of Response Surface Methodology (RSM), is

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a widely accepted design of experiments (DOE) tool used for the modeling and optimization of multifactorial systems. CCD enables the investigation of both linear and quadratic effects, along with interaction terms, to predict and optimize response variables such as compressive strength (Garg & Jain, 2017). It incorporates factorial points, axial points, and center points to efficiently explore the design space, making it particularly useful for understanding complex relationships among factors.

In the field of fiber-reinforced concrete research, CCD has proven especially effective in optimizing mix parameters such as fiber content, fiber length, curing time, and water-cement ratio, all of which significantly influence the mechanical behavior and durability of concrete composites (Singh *et al.*, 2022). By allowing researchers to model nonlinear behavior and interaction effects, CCD facilitates the development of robust predictive models for mechanical properties like compressive strength, flexural strength, and toughness (Kumar & Sharma, 2023).

Moreover, CCD aids in reducing the number of experimental runs compared to full factorial designs, thereby saving time and resources while maintaining statistical rigor (Patel *et al.*, 2021). This efficiency has led to its widespread adoption in optimizing not only fiber-reinforced concretes but also other cementitious materials such as geopolymer concretes and concrete with supplementary cementitious materials (Kumar *et al.*, 2020).

Recent studies demonstrate the use of CCD coupled with advanced optimization algorithms to further refine the performance characteristics of fiber-reinforced composites. For example, integration with genetic algorithms or desirability functions enhances multi-objective optimization, balancing factors like strength, workability, and durability (Rathore & Yadav, 2023). Moreover, Islam *et al.* (2022) reported that optimal dosages of natural cellulosic fibers, similar in structure to Nipa palm, enhanced compressive strength by up to 20.2% compared to conventional concrete.

The incorporation of Nipa palm fiber into concrete, guided by CCD-based optimization, not only improves compressive strength but also contributes to the broader goals of sustainable construction and waste valorization. This synergy of local material utilization and advanced statistical modeling underscores a paradigm shift toward green infrastructure solutions. Overall, CCD remains an indispensable tool in contemporary concrete materials research, supporting data-driven optimization that aligns with sustainability and performance goals.

2. MATERIALS AND METHODS

2.1 Materials

The primary material used in this research is Nipa palm fiber (NPF), complemented by conventional concrete constituents including river sand, crushed granite rock, Portland cement, and water.

1. Nipa Palm Fiber (NPF)

The Nipa palm fibers were mechanically extracted from the fronds of dead, partially dried nipa palms collected from the estuarine mangrove forest of Akaradi Town, Andoni Local Government Area, Rivers State, Nigeria. At the time of harvesting, the fleshy and sticky parts of the fronds had naturally decomposed, leaving only the fibrous content intact. Following extraction, the fibers underwent a drying process where they were sun-dried for three days. Subsequently, they were stored in well-ventilated bags for one year before being incorporated into the concrete mixes. Figure 1 illustrates the extraction process of the NPF, while Table 1 summarizes NPF's physiochemical properties. The physiochemical analysis reveals that the NPF has a density of 1.794 g/ml, slightly higher than that of water (1 g/ml). The fiber's composition is characterized by a high cellulose content (45.19%), the primary structural component responsible for tensile strength, compared to lignin content (24.20%), which is known to reduce fiber strength.

Figure 1: Extraction of NPF from palm fronds

Table 1: Physiochemical Properties of Nipa Palm Fibre

S/N	Sample	Plant Fibre
1	Moisture Content (%)	19.53
2	Density (g/ml)	1.794
3	pH	6.74
4	Porosity	90.3
5	Total Organic Compound (TOC) (%)	13.86
6	Cellulose (%)	45.19
7	Hemicellulose (%)	21.76
8	Lignin (%)	24.20
9	Zn (mg/kg)	10.68541
10	Cu (mg/kg)	12.90874
11	Fe(mg/kg)	15.01321
12	Mg(mg/kg)	7.39496
13	Na(mg/kg)	4.02734
14	K(mg/kg)	51.30813

2. Crushed Granite Rock

The coarse aggregate utilized in this study was crushed granite rock with a maximum particle size of 20 mm and a bulk density of 1700 kg/m³. This aggregate was sourced from the Aluu granite chipping sales depot in Rivers State, Nigeria. Prior to mixing, the granite was thoroughly washed with clean water to remove dust and impurities, spread out in the laboratory, and air-dried for three days to ensure moisture content was minimized.

3. River Sand

The fine aggregate comprised river sharp sand, classified as Zone II, with a bulk density of 1777 kg/m³. It was dredged from the Rumuokparali stretch of the New Calabar River and obtained from the Rumuokparali sand depot in Rivers State. The careful selection and preparation of both coarse and fine aggregates ensured consistent quality, which is critical for reliable and accurate experimental results.

4. Cement

Grade 42.5 Portland cement was used, conforming to the Nigerian Cement Standard NIS 444-1 and classified as CEM II. This class of cement consists of clinker blended with limestone and gypsum and meets the specifications outlined in BS EN 197-1 (2000). The cement was procured from the Aluu cement depot in Rivers State, Nigeria.

2.2 Methods

2.2.1 Pre-Design Mix

In this study, the concrete mix proportions for a target compressive strength of 25 MPa (C25) were established based on the guidelines provided in the Council for the Regulation of Engineering in Nigeria (COREN) Concrete Mix Design Manual (reference COREN/2017/016/RC). The mix consists of 470 kg of cement, 593.25 kg of fine aggregate, 1101.75 kg of coarse aggregate, and 235 kg of water per cubic meter of concrete. Expressed as ratios relative to cement, the proportions are 1 part cement to 1.26 parts fine aggregate, 2.34 parts coarse aggregate, and 0.5 parts water.

2.2.2 Central Composite Design Mix Formulation

The variables selected for the concrete mix design of nipa palm fiber-reinforced concrete (NPFRC) were fiber content and fiber length. To establish the experimental framework, the study utilized the Face-Centered Central Composite Design (FCCCD) within the Response Surface Methodology (RSM). Drawing from existing research, fiber length was varied from 10 mm to 60 mm, while fiber content was adjusted between 0.5% and 5% by weight of the concrete mix. All other mix ingredients, including crushed granite, river sand, cement, and water, were kept constant throughout the experiments. The FCCCD model was generated using Minitab software, which employed these variable ranges to create 13 randomized experimental runs. Each run was replicated, resulting in a total of 26 experimental runs, as shown in Table 2.

Table 2: FCCCD for NPFRC

S/N	Cement	Sand	Granite	Water	Fibre %	Fibre Length
1	1	1.26	2.34	0.5	2.75	35
2	1	1.26	2.34	0.5	2.75	35
3	1	1.26	2.34	0.5	0.5	35
4	1	1.26	2.34	0.5	2.75	35
5	1	1.26	2.34	0.5	2.75	35
6	1	1.26	2.34	0.5	5	10
7	1	1.26	2.34	0.5	2.75	60
8	1	1.26	2.34	0.5	0.5	35

9	1	1.26	2.34	0.5	2.75	35
10	1	1.26	2.34	0.5	2.75	60
11	1	1.26	2.34	0.5	5	60
12	1	1.26	2.34	0.5	2.75	10
13	1	1.26	2.34	0.5	2.75	35
14	1	1.26	2.34	0.5	2.75	35
15	1	1.26	2.34	0.5	0.5	10
16	1	1.26	2.34	0.5	2.75	35
17	1	1.26	2.34	0.5	0.5	10
18	1	1.26	2.34	0.5	2.75	10
19	1	1.26	2.34	0.5	5	60
20	1	1.26	2.34	0.5	5	10
21	1	1.26	2.34	0.5	2.75	35
22	1	1.26	2.34	0.5	2.75	35
23	1	1.26	2.34	0.5	5	35
24	1	1.26	2.34	0.5	0.5	60
25	1	1.26	2.34	0.5	0.5	60
26	1	1.26	2.34	0.5	5	35

2.2.3 NPFRC Samples Production

Concrete cubes measuring 150 mm by 150 mm by 150 mm were produced using corresponding molds. Prior to mixing, the nipa palm fibers (NPF) were cut to various lengths as specified by the developed FCCCD. Assuming a concrete density of 2400 kg/m³, the required amounts of cement, sand, granite, water, and fiber were calculated according to the FCCCD parameters. The concrete specimens were prepared by first mixing the cement, sand, and NPF, then adding the granite, and finally incorporating the water. This is shown in Figure 2.

a) Mixing of fibre with cement and aggregates **b) Placement of concrete mix in mould**

c) concrete cube **d) 24 hours concrete cube specimen after Demolding**

Figure 2: Preparation of NPFRC

2.2.4 Compressive Strength Test of NPFRC

The compressive strength test of Nipa palm fiber-reinforced concrete cubes was conducted after 28 days of curing through complete immersion of concrete cubes in water. Test was carryout according to BS 1881: Part 116:1983. Each cube was first weighed, then crushed using a compressive strength testing machine. The mass and crushing load were recorded accordingly. Figure 3 illustrates the compressive strength test of NPFRC. The compressive strength of NPRC cube was calculated using Equation (1).

$$\mathbf{C} = \frac{\mathbf{P}}{\mathbf{b^2}} \qquad (1)$$

C is cube compressive strength, P is failure load in Newton, b is cube width.

Figure 3: Compressive Strength Testing of NPFRC Sample

2.2.5 Response Surface Method for Optimizing of the Compressive Strength of NPFRC

The compressive strength of NPFRC was optimized using the Response Surface Method with the assistance of Minitab software. Following the completion of laboratory experiments, the observed compressive strength values were entered into Minitab. For analysis, the steps followed were: Stat > DOE > Response Surface > Analyze Response Surface Design, with compressive strength designated as the response variable. The resulting optimization plot and summary tables were examined to interpret the outcomes, identifying the predicted optimal fiber length and content for achieving maximum compressive strength.

2.2.6 Evaluating the Optimization Process through Confirmatory Test

To evaluate the accuracy of the optimization process, confirmatory tests were performed using the optimal mix design parameters aimed at achieving the predicted maximum compressive strength. The experimental results obtained were then compared with the targeted compressive strength, and the percentage deviation was calculated.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength of NPFRC

The compressive strength results of Nipa Palm Fibre Reinforced Concrete (NPFRC), as shown in Figure 4, ranged from 9.17 MPa to 21.96 MPa. In contrast, the average compressive strength of the conventional control concrete without fibres was 26.12 MPa (Table 3). This indicates that while NPFRC exhibited lower compressive strength than conventional concrete, it still achieved strengths within acceptable limits for light structural or non-load-bearing applications, depending on the mix configuration and fiber dosage.

According to ASTM C39/C39M-20, which outlines the standard test method for compressive strength of cylindrical concrete specimens, a minimum compressive strength of 17 MPa is often regarded as acceptable for general concrete construction (ASTM, 2020). Furthermore, the British Standard BS EN 206:2013+A2:2021 stipulates that structural concrete should generally achieve a characteristic compressive strength of at least 20–25 MPa depending on the exposure class and structural requirements (BSI, 2021).

The lower compressive strength values observed in some NPFRC samples, particularly those below 17 MPa, suggest that the inclusion of natural fibers like NPF may interfere with compaction and uniform hydration if not properly optimized. This performance drop may be due to poor fiber dispersion or inadequate matrix bonding, both of which are common challenges in natural fiber-reinforced composites (Ali *et al*., 2021). However, the upper range of the NPFRC compressive strengths (up to 21.96 MPa) demonstrates the potential of optimized NPF usage in achieving strengths comparable to medium-strength concrete classes.

These findings highlight the importance of fiber treatment, optimal dosage, and mix proportioning, factors that can significantly influence the mechanical performance of bio-based fiber concrete composites (Kabir *et al*., 2022). As such, NPFRC has prospects for use in sustainable construction, especially where compressive strength demands are moderate, and environmental sustainability is prioritized.

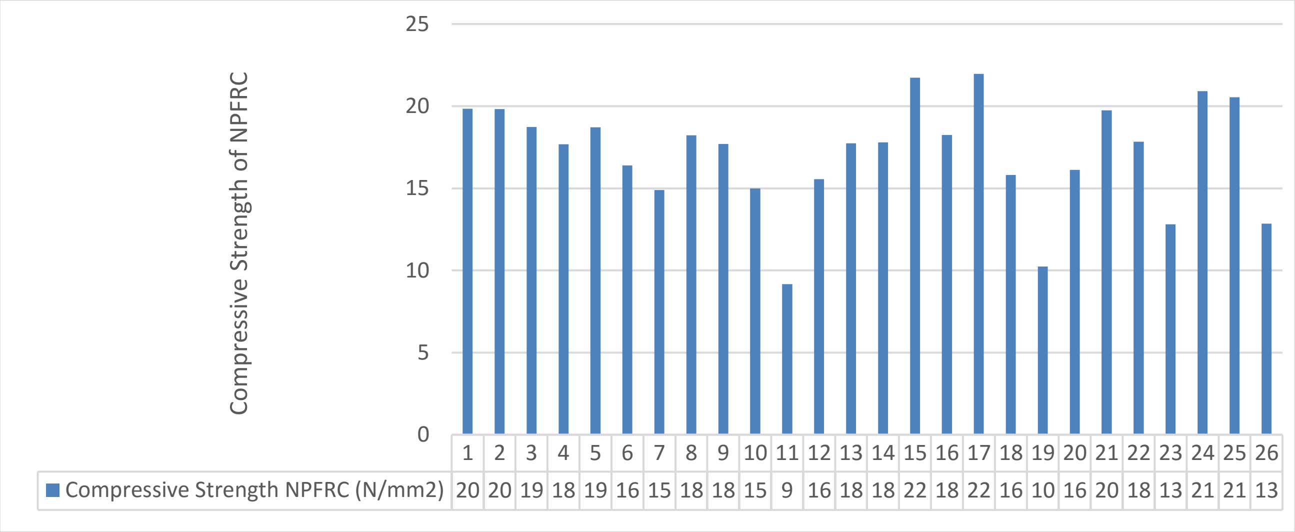

Figure 4: Compressive Strength of NPFRC

Table 3: Compressive Strength Test Results for Conventional Concrete

S/N	Fibre %	Fibre Length(mm)	Crushing load P(kN)	Compressive Strength (N/mm^2)
Cube Without Fibre				
1	0	0	486.6	21.63
2	0	0	577.5	25.67
3	0	0	699.2	31.08

3.2 Effects of Design Parameters on Compressive Strength of NPFRC

Figure 5 illustrates the influence of varying Nipa Palm Fibre (NPF) content and fibre length on the average compressive strength of NPFRC. A general trend is evident: as both NPF content and fibre length increase, the compressive strength of the concrete tends to decrease. This decline is particularly sharp when NPF content increases, indicating a stronger sensitivity of compressive strength to fibre dosage than to length.

This observation aligns with previous research on other natural fibre-reinforced concretes. For instance, Ali *et al*. (2020) examined the use of coconut fibres in high-strength concrete and reported a notable reduction in compressive strength with increasing fibre length and content beyond optimal thresholds. Their findings indicated that longer fibres and excessive content levels reduced the workability of the mix, thereby impeding compaction and increasing internal voids, which collectively weakened the compressive performance of the concrete.

Similarly, Kabir *et al*. (2022) conducted a study on date palm sheath fibre-reinforced cementitious composites and found that the optimal compressive strength was achieved at 1 wt.% fibre loading with a length of 20 mm. Beyond this threshold, increases in fibre length and dosage led to fibre clumping, reduced matrix-fibre bonding, and higher porosity—factors contributing to the overall strength reduction.

Kriker *et al*. (2005) also emphasized that while the inclusion of natural fibres like date palm enhances ductility and tensile characteristics, it often compromises compressive strength when not properly optimized. These findings are crucial, especially when considering the standard strength benchmarks outlined in ASTM C39/C39M-20 and BS EN 206:2013+A2:2021, which stress the importance of maintaining uniformity and density in concrete to achieve compressive strength specifications required for structural applications (ASTM International, 2020; BSI, 2021).

Therefore, the reduction in compressive strength observed in the NPFRC samples at higher NPF content and lengths is consistent with broader literature. These results underscore the importance of precise mix optimization, especially when incorporating plant-based fibres, to balance enhancements in toughness or ductility with the preservation of adequate compressive capacity for load-bearing applications.

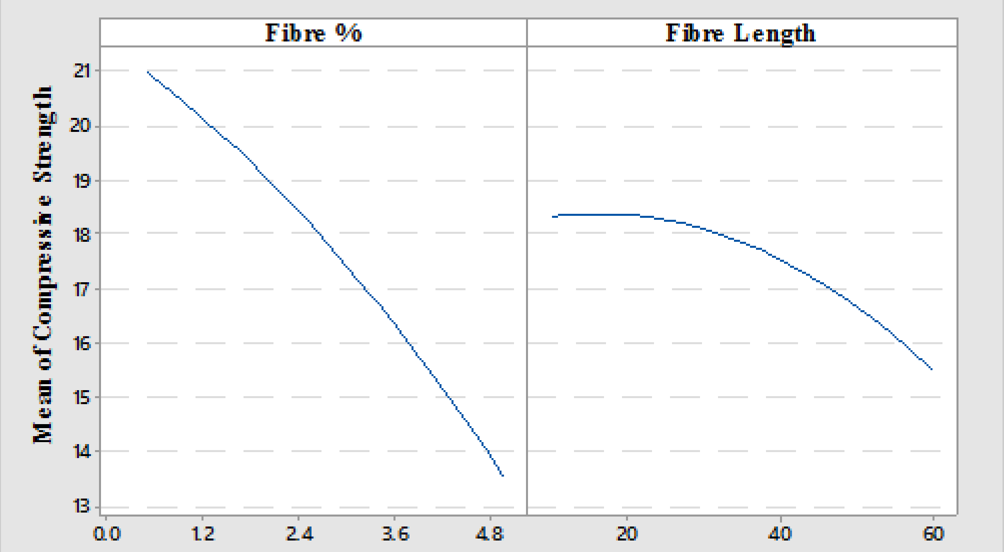

Figure 5: Relationship Between Mean Compressive Strength Vs Design Parameters (Fibre % and Fibre Length)

3.3 Design Parameter Interactions on Compressive Strength of NPFRC

Figure 6 illustrates the interaction plot between Nipa Palm Fibre (NPF) content (%) and fibre length, highlighting their combined influence on the mean compressive strength of NPF Reinforced Concrete (NPFRC). The non-parallel orientation of the curves indicates a statistically significant interaction between these two variables. This suggests that simultaneous variation in both fibre content and length does not simply yield additive effects but rather interdependent impacts on the compressive strength of the composite.

This interactive behaviour is consistent with patterns observed in other natural fibre-reinforced concretes. For example, Rajak *et al*. (2020) reported that increasing the fibre volume fraction of coir fibre-reinforced concrete beyond optimal levels (above 5.2% at 12 mm length) resulted in a decline in compressive strength. This reduction was attributed to increased water demand and fibre clumping, which compromised the integrity of the concrete matrix. Similarly, Islam *et al.* (2020) demonstrated that for jute fibre-reinforced concrete, optimal performance was achieved at fibre lengths of 10–20 mm and fibre contents between 0.3%–0.45%. Beyond these thresholds, compressive strength declined significantly due to poor workability and fibre entanglement leading to voids within the concrete.

These observations underscore the importance of carefully selecting both the content and length of natural fibres in concrete mix designs. A higher fibre dosage or excessive length, while potentially beneficial for tensile resistance, can reduce compressive performance due to the formation of weak zones, poor compaction, and increased porosity. Therefore, optimizing these parameters is crucial for maximizing the mechanical performance of NPFRC.

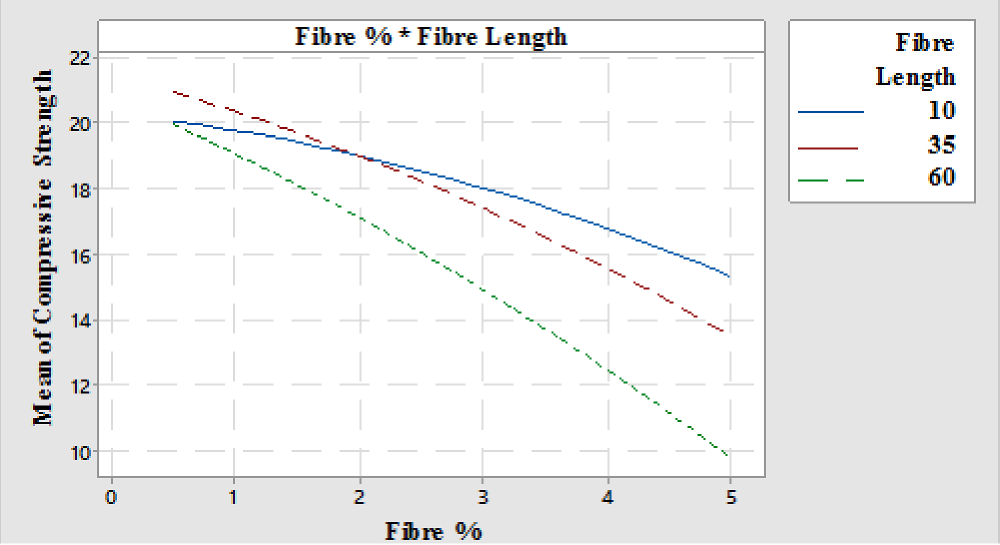

Figure 6: Interactive Plot of Mean Compressive Strength Vs Design Parameters

3.4 Optimization of Design Parameters for Maximum Compressive Strength

Figure 7 presents the response surface optimization results for Nipa Palm Fibre Reinforced Concrete (NPFRC), indicating that the optimal compressive strength achieved is 20.9792 MPa. This peak strength corresponds to a fibre content of 0.5% and a fibre length of 34.2525 mm, with a desirability value of 0.9230 (92.30%). The desirability metric, ranging from 0 to 1, reflects the closeness of the response to the target value, with values closer to 1 indicating more favourable outcomes.

The optimization process employed Response Surface Methodology (RSM), a statistical technique that explores the relationships between several explanatory variables and one or more response variables. RSM utilizes a sequence of designed experiments to obtain an optimal response, often using a second-degree polynomial model for approximation (Alani *et al.*, 2024). In this context, RSM facilitated the identification of the optimal combination of fibre content and length to maximize compressive strength.

The achieved compressive strength of 20.9792 MPa, while optimized for the given parameters, falls below the standard requirements for structural concrete. According to ASTM C39/C39M-20, the standard test method for compressive strength of cylindrical concrete specimens, concrete used in structural applications typically requires a minimum compressive strength of 25 MPa (ASTM International, 2020). Similarly, the European standard EN 206:2013+A2:2021 specifies performance criteria for concrete, emphasizing the importance of meeting specified strength classes for structural integrity (British Standards Institution, 2021).

Therefore, while the optimization process effectively identified the most favourable combination of fibre content and length for NPFRC, the resulting compressive strength suggests that further modifications to the mix design or additional treatments may be necessary to meet standard structural requirements.

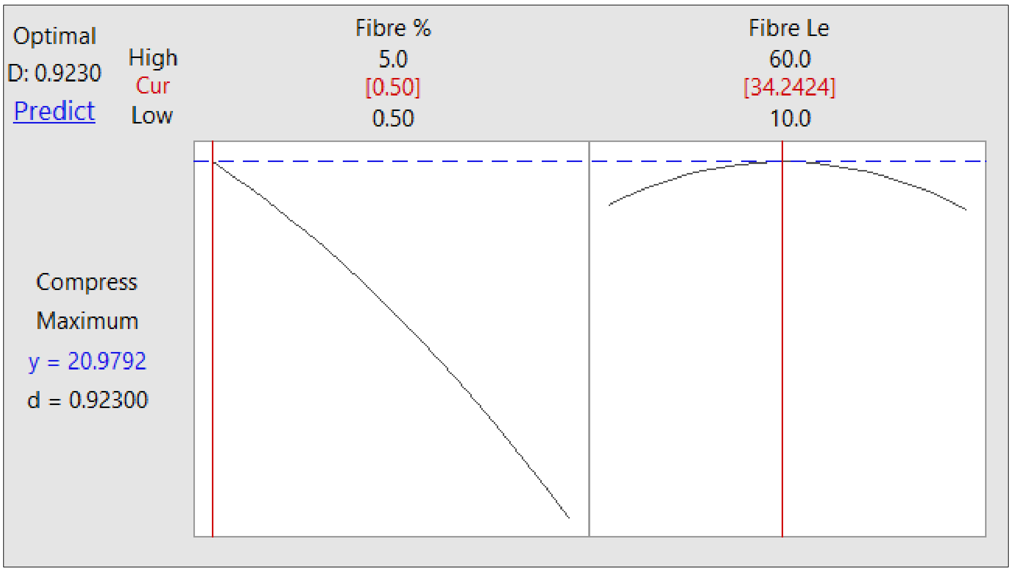

Figure 7: Optimization of compressive strength of NPFRC

3.5 Confirmatory Experimental Results to Validate Optimization Process

Figure 8 presents the results of the confirmatory test conducted to validate the compressive strength outcomes derived from the optimization process for Nipa Palm Fibre Reinforced Concrete (NPFRC). Utilizing an optimized fibre content of 0.5% and a fibre length of 34 mm, the experimental compressive strength achieved was 19.87 MPa, compared to the predicted value of 20.9792 MPa. This discrepancy corresponds to a percentage deviation of approximately 5.58%.

Such deviations between predicted and actual compressive strength values are not uncommon and can be attributed to various factors inherent in concrete production and testing processes. According to the National Ready Mixed Concrete Association (NRMCA), deviations from standard procedures in making, curing, and testing concrete specimens often result in lower measured strengths. They note that the coefficient of variation between companion cylinders tested at the same age should be about 2 to 3%, and differences exceeding 8% may indicate issues with testing procedures (NRMCA, 2021).

Furthermore, ASTM C39/C39M, the standard test method for compressive strength of cylindrical concrete specimens, emphasizes the importance of strict adherence to standardized procedures to ensure accurate and reliable results. Variations in specimen preparation, curing conditions, and testing methods can significantly influence the measured compressive strength (ASTM International, 2020).

The observed 5.58% deviation in this study falls within acceptable limits as per industry standards, suggesting that the optimization process provides a reliable prediction of compressive strength for NPFRC. However, it also underscores the necessity for meticulous control over the entire process of specimen preparation and testing to minimize variability and enhance the accuracy of the optimization process.

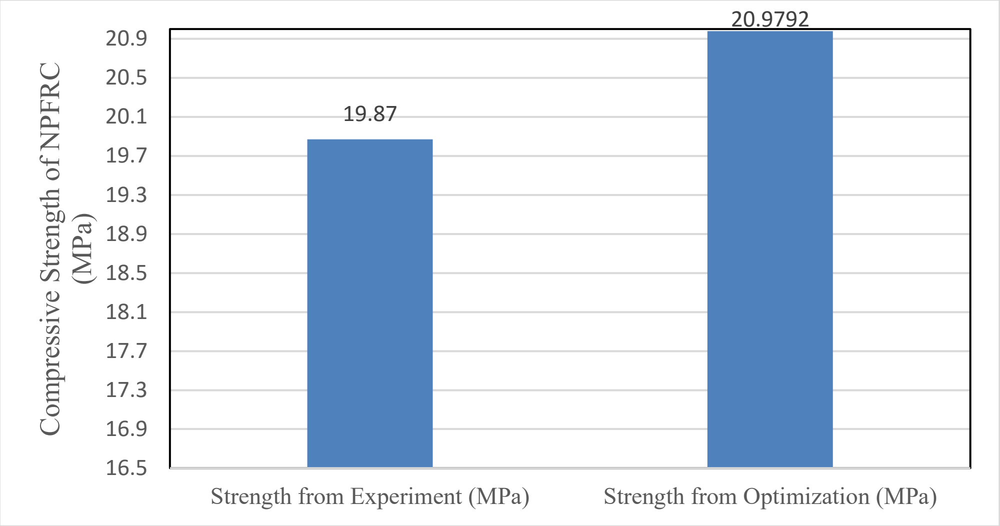

Figure 8: Validation of Optimization Results with Experiment

4. CONCLUSIONS

These conclusions are hereby put forward as deduced from the results and discussion of this study;

i. Nipa Palm Fibre Reinforced Concrete (NPFRC) showed compressive strengths ranging from 9.17 to 21.96 MPa, lower than the 26.12 MPa of conventional concrete. With proper optimization, NPFRC presents a sustainable alternative for moderate-strength, eco-friendly construction.
ii. Increasing Nipa Palm Fibre (NPF) content and length generally reduced the compressive strength of NPFRC. The strength drop was more pronounced with higher fibre content due to poor compaction and increased porosity.
iii. The interaction between NPF content and fibre length significantly affects NPFRC compressive strength. Non-parallel trends reveal interdependent, not additive, effects on strength reduction at suboptimal combinations.
iv. The optimization process using RSM identified 0.5% fibre content and 34.25 mm length as optimal for NPFRC. This yielded a compressive strength of 20.98 MPa with high desirability (92.30%). Despite optimization, the result falls short of structural standards like ASTM and EN 206
v. The confirmatory test achieved a compressive strength of 19.87 MPa, compared to the predicted 20.98 MPa. This reflects a 5.58% deviation, which is within acceptable limits based on NRMCA guidelines. Such variation may arise from inconsistencies in mixing, curing, or testing procedures.

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