International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Optimization of Nano Cellulose in Fly Ash Blended M35 Concrete for Enhanced Mechanical Performance

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Abstract - The present study investigates the effect of nanocellulose as a nano-modifier on the performance of ready-mix concrete incorporating fly ash. An M35 grade mix was used as the base, and nanocellulose was added in varying percentages from 0% to 0.8% by weight of cementitious materials. The experimental program included slump test for workability and compressive strength evaluation at 7 and 28 days. The results showed a non-linear trend, with compressive strength increasing up to an optimum dosage of approximately 0.4% and decreasing at higher contents. The improvement is attributed to pore refinement and enhanced bonding within the cement matrix, while the reduction at higher dosages is due to particle agglomeration. Statistical and regression analyses validated the findings and confirmed the optimum range. Although the initial cost is slightly higher, enhanced strength and durability make nanocellulose-modified concrete particularly suitable for road construction, where improved service life and reduced maintenance are critical. Overall, the study highlights the potential of nanocellulose for developing high-performance and sustainable concrete.

***Keywords*: Nanocellulose, Nano-modified concrete, Compressive strength, Fly ash, Workability, Sustainable concrete, Road construction, Durability, Optimization, Ready-mix concrete**

1. INTRODUCTION

Concrete remains the backbone of modern construction due to its adaptability, strength, and widespread availability. However, conventional concrete often faces limitations such as microcracking, permeability, and long-term durability issues, especially under repetitive loading and varying environmental conditions. These challenges become more critical in infrastructure applications like road construction, where materials are continuously subjected to mechanical stress and environmental exposure. Therefore, improving the internal structure and performance of concrete has become an important area of research.

In recent years, the use of supplementary cementitious materials such as fly ash has contributed significantly toward enhancing durability and reducing environmental impact. Fly ash not only improves long-term strength through pozzolanic reactions but also promotes sustainable construction by reducing cement consumption. However, its slower early-age strength development creates a need for additional modification to achieve balanced performance.

To address this limitation, nano-scale materials have gained attention due to their ability to alter the microstructure of cementitious systems. Among these, nanocellulose has emerged as a promising material owing to its high surface area, strong bonding capability, and eco-friendly nature. When added in small quantities, it can enhance the density of the matrix, improve interfacial bonding, and reduce internal defects. However, its effectiveness depends largely on proper dosage and uniform dispersion, as excessive content may lead to particle clustering and reduced efficiency.

In this study, an attempt has been made to investigate the combined effect of nanocellulose and fly ash in M35 grade ready-mix concrete. The focus is placed on evaluating workability and compressive strength, along with identifying the optimum dosage of nanocellulose. The study also explores its potential application in road construction, where improved durability and reduced maintenance are essential for long-term performance.

2. LITERATURE REVIEW

The development of high-performance and sustainable concrete has attracted significant attention in recent years. Researchers have explored various supplementary and nano-scale materials to enhance the mechanical and durability properties of concrete. In this context, fly ash and nanocellulose have emerged as important materials due to their individual as well as combined benefits.

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2.1. Fly Ash (FA)

Fly ash is a widely used supplementary cementitious material obtained as a by-product from thermal power plants. Due to its pozzolanic nature, it reacts with calcium hydroxide in the presence of water to form additional cementitious compounds, which contribute to strength development at later ages. The incorporation of fly ash generally improves workability because of its fine particle size and spherical shape, which enhances the flow characteristics of concrete.

From previous studies, it is understood that fly ash contributes significantly to improving durability by reducing permeability and refining the pore structure. However, one of the commonly observed limitations is the reduction in early-age strength due to its slower reaction rate. Researchers have suggested that an optimum replacement level exists, beyond which the strength starts decreasing due to dilution of cement content. Therefore, while fly ash enhances long-term performance and sustainability, it requires modification to improve early strength characteristics.

2.2 Nanocellulose (NC)

Nanocellulose is a bio-based nano material derived from natural sources such as plant fibers. It possesses unique properties such as high surface area, excellent tensile strength, and strong bonding capability, making it suitable for use in cementitious composites. When incorporated in small amounts, nanocellulose helps in refining the microstructure by filling micro and nano-scale voids within the matrix.

Based on existing research, it can be observed that nanocellulose improves both strength and durability characteristics of concrete. It enhances bonding within the cement matrix and reduces porosity, resulting in a denser and more compact structure. However, its performance is highly sensitive to dosage. Beyond an optimum range, nanocellulose particles tend to agglomerate, leading to non-uniform distribution and reduction in strength. Hence, careful control of mixing and dosage is necessary to achieve maximum effectiveness.

2.3 Combined Effect of Fly Ash and Nanocellulose

Recent studies indicate that combining fly ash with nanocellulose can produce a synergistic effect in concrete. While fly ash contributes to long-term strength and sustainability, nanocellulose improves early-age strength and enhances the microstructure. This combination helps in overcoming the individual limitations of both materials.

The addition of nanocellulose has been found to accelerate microstructural development and improve bonding, thereby compensating for the slower strength gain associated with fly ash. It also contributes to better particle packing and reduced pore connectivity, which results in improved strength and durability. However, similar to individual applications, the combined system also requires optimization of nanocellulose dosage to avoid clustering and ensure uniform performance.

Despite promising results, there is still limited research focused on practical applications such as ready-mix concrete and road construction. Therefore, further investigation is required to evaluate performance under real conditions and to establish cost-effective solutions for large-scale implementation.

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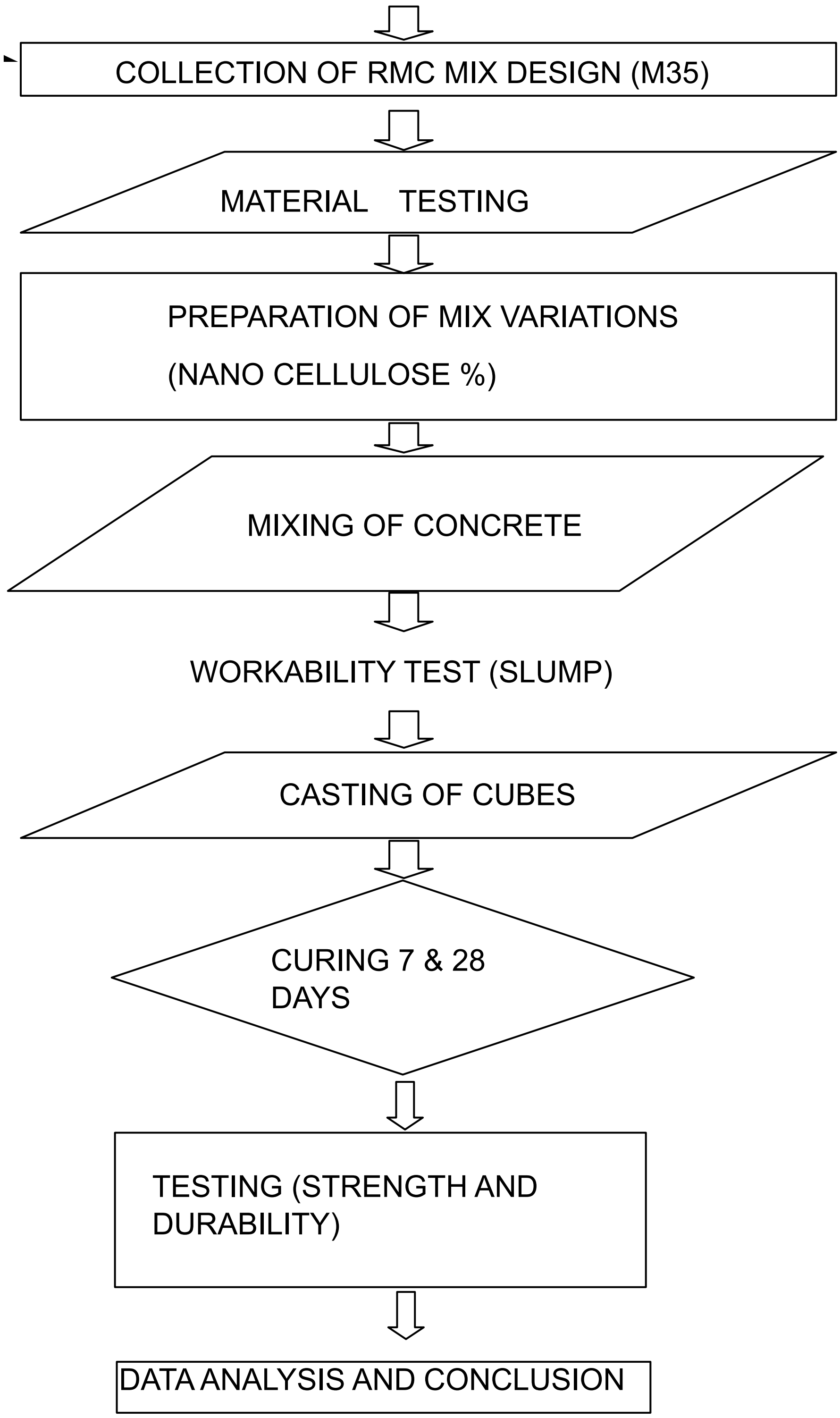
.METHODOLOGY



In the present investigation, M35 grade concrete was selected to study the influence of nanocellulose in combination with fly ash on its performance. The base mix was obtained from a ready-mix concrete plant, and modifications were introduced by incorporating fly ash and varying percentages of nanocellulose. Fly ash was used as a partial replacement for cement at a constant proportion, while nanocellulose was added in small dosages to evaluate its effect on both fresh and hardened properties.

The experimental program was designed by varying the nanocellulose content as 0%, 0.2%, 0.4%, 0.6%, and 0.8% by weight of cementitious material, while keeping all other parameters constant. These dosage levels were selected based on previous

International Journal of Engineering Research & Technology (IJERT)
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research indicating that nano materials are effective only within a limited range. The mix design was prepared in accordance with standard guidelines to achieve the desired strength and workability.

To ensure proper dispersion, nanocellulose was initially mixed with water before being added to the concrete mix. This step was necessary to avoid particle clustering and to achieve uniform distribution within the matrix. All materials were proportioned accurately and mixed thoroughly to obtain a consistent mix.

Cube specimens of size 150 mm × 150 mm × 150 mm were cast for each mix variation. Three specimens were prepared for each case to ensure reliability of results. Proper compaction was carried out to eliminate air voids, and the specimens were left undisturbed for 24 hours before demolding. After demolding, the specimens were cured in water under controlled conditions until the specified testing ages.

Compressive strength tests were conducted at 7 days and 28 days, and the average of three specimens was considered for analysis. In addition, the workability of fresh concrete was evaluated using the slump test. The overall methodology was aimed at identifying the optimum percentage of nanocellulose that enhances performance without adversely affecting workability.

1. COMPRESSIVE STRENGTH TEST DATA

The compressive strength results obtained from experimental testing at 7-day and 28-day curing periods are presented in the following section. The mix without nanocellulose was considered as the control specimen for comparison. It was observed that all mixes exhibited an increase in strength with curing time; however, the variation in nanocellulose content significantly influenced the strength values, indicating the presence of an optimum dosage for improved performance.

Figures & Tables

Table no. 5.1: **M35 Mix Design (Per m³ of Concrete)**.

Sr. No.	Materials as per (RMC Plant)	Quantity (kg/m³)
1.	Cement	370
2.	Fly Ash	60
3.	Crushed sand	759
4.	10 mm Aggregate	456
5.	20 mm Aggregate	689
6.	Water	167
7.	Admixture	4.73
8.	Density	2506 kg/m3

Table no. 5.2: M35 Mix Design (Per Bag – 50 kg Cement)

Sr. No.	Materials as per (RMC Plant)	Quantity per bag (50 kg)
1.	Cement	50 kg
2.	Fly Ash	8 kg
3.	Crushed sand	103 kg
4.	10 mm Aggregate	62 kg
5.	20 mm Aggregate	93 kg
6.	Water	23 litre
7.	Admixture	0.639 kg

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Table no. 5.3: Fly Ash & Nanocellulose content

Mix no.	Fly Ash (%)	Nanocellulose (%)
1	14%	0.2%
2	14%	0.4%
3	14%	0.6%
4	14%	0.8%

Table no. 5.4: Compression strength when cement replaced with Fly ash & Nanocellulose for 7 days.

Mix no.	Nanocellulose (%)	Cube 1 (MPa)	Cube 2 (MPa)	Cube 3 (MPa)	Average (MPa)
1	0%	26.92	27.36	27.28	27.18
2	0.2%	29.36	29.84	29.57	29.59
3	0.4%	30.86	31.62	31.28	31.25
4	0.6%	29.46	30.52	30.91	30.29
5	0.8%	27.43	28.58	28.36	28.12

The graph shows the relationship between nanocellulose content and compressive strength of concrete at 7 days of curing.

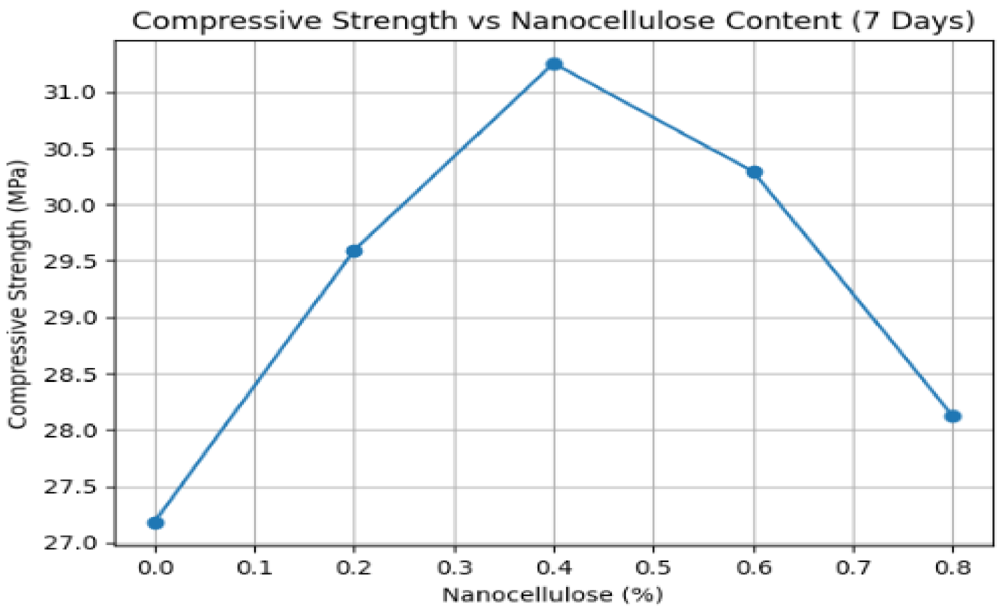

Table no. 5.5: Compression strength when cement replaced with Fly ash & Nanocellulose for 28 days.

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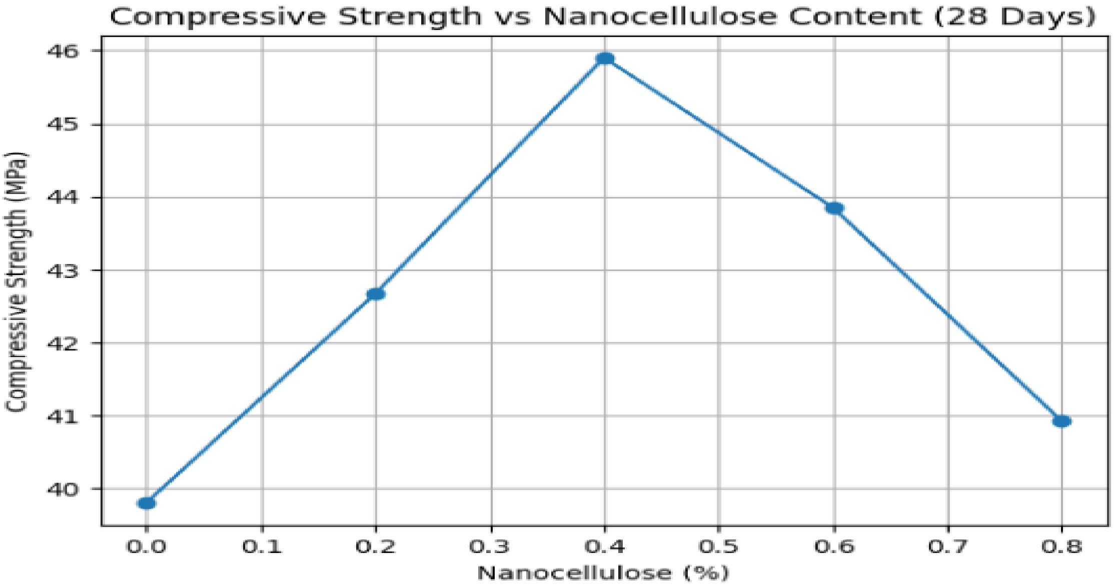
Mix no.	Nanocellulose (%)	Cube 1 (MPa)	Cube 2 (MPa)	Cube 3 (MPa)	Average (MPa)
1	0%	39.56	40.12	39.76	39.81
2	0.2%	42.44	43.63	41.96	42.67
3	0.4%	45.23	46.32	46.16	45.90
4	0.6%	43.65	44.21	43.69	43.85
5	0.8%	40.28	41.30	40.93	40.93

The graph shows the relationship between Nanocellulose content and compressive strength of concrete at 28 days of curing.



The results indicate that the compressive strength increases significantly with curing time for all mixes. The maximum strength is observed at 0.4% nanocellulose, beyond which the strength decreases slightly due to possible agglomeration of nanocellulose particles.

2. COST ANALYSIS OF CONCRETE PAVEMENT

In addition to evaluating the mechanical properties of concrete, an economic analysis was carried out to assess the feasibility of using nanocellulose in concrete pavements. Although nanocellulose improves the strength and durability of concrete, it is relatively expensive compared to conventional materials. Therefore, a comparative cost analysis was performed between conventional concrete and nanocellulose-modified concrete by considering both initial construction cost and long-term maintenance cost.

Assumptions for Cost Analysis

For the purpose of analysis, a standard single-lane rigid pavement was considered with the following dimensions:

- Length of road = 1000 m

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- Width of road = 3.75 m
- Thickness of concrete slab = 0.20 m

Volume of Concrete Required

The total volume of concrete required for the pavement was calculated as:

$$\text{Volume} = Length \times Width \times Thickness$$

$$= 1000 \times 3.75 \times 0.20 = 750\ m^3$$

Initial Cost of Concrete

Conventional Concrete

The cost of conventional concrete was calculated as ₹5950 per m^3 based on material estimation.

$$\text{Total Cost} = 750 \times 5950 = ₹44{,}62{,}500$$

Nanocellulose Modified Concrete (0.4% Dosage)

The cost of nanocellulose-modified concrete was calculated as ₹7430 per m^3.

$$\text{Total Cost} = 750 \times 7430 = ₹55{,}72{,}500$$

Initial Cost Comparison

Type of Concrete	Cost per m³ (₹)	Total Cost (₹)
Conventional Concrete	5950	44,62,500
Nanocellulose Concrete	7430	55,72,500

Table no. 6.1 Initial cost comparison between conventional concrete & Nanocellulose concrete

Maintenance Cost Analysis

The maintenance cost plays a significant role in determining the overall economy of concrete pavements.

Conventional Concrete

Conventional concrete is susceptible to cracking, shrinkage, and permeability, leading to frequent repairs. It was assumed that maintenance is required every 5 years.

- Maintenance cost per cycle = 20% of initial cost

$$= 0.20 \times 44{,}62{,}500 = ₹8{,}92{,}500$$

- Total maintenance over 20 years (4 cycles):

$$= 8{,}92{,}500 \times 4 = ₹35{,}70{,}000$$

Nanocellulose Concrete

- Maintenance is assumed only once in 20 years
- Maintenance cost = 10% of initial cost

$$= 0.10 \times 55{,}72{,}500 = ₹5{,}57{,}250$$

Nanocellulose improves microstructure, reduces cracks, and enhances durability. Therefore, maintenance frequency is significantly reduced.

Life Cycle Cost Analysis:

Type of Concrete	**Initial Cost (₹)**	**Maintenance Cost (₹)**	**Total Cost (₹)**
Conventional Concrete	44,62,500	35,70,000	**80,32,500**
Nanocellulose Concrete	55,72,500	5,57,250	**61,29,750**

Table no. 6.2 Life cycle cost analysis of conventional concrete Nanocellulose concrete

3. ENVIRONMENTAL IMPACT

The incorporation of fly ash and nanocellulose in concrete contributes significantly toward sustainable construction practices. Fly ash, being an industrial by-product from thermal power plants, is often disposed of as waste, leading to environmental concerns. Its utilization in concrete not only reduces waste disposal problems but also decreases the demand for cement, thereby lowering carbon emissions associated with cement production.Nanocellulose, derived from natural and renewable resources, offers an eco-friendly alternative to synthetic additives. Its biodegradable nature and ability to enhance material performance make it suitable for sustainable construction applications. When used in concrete, nanocellulose improves the internal structure by reducing micro-level defects and enhancing bonding, which ultimately increases durability. Improved durability results in longer service life of structures, thereby reducing the frequency of repairs and maintenance. This leads to conservation of materials, energy, and resources over the lifespan of the structure. In applications such as road construction, where maintenance activities are frequent and resource-intensive, the use of durable materials can significantly reduce environmental impact. Overall, the combined use of fly ash and nanocellulose promotes sustainability by reducing waste, minimizing emissions, and improving the longevity of concrete structures. This approach supports the development of environmentally responsible construction practices.

4. CONCLUSION

The present investigation focused on assessing the influence of nanocellulose on fly ash-based concrete and its overall performance characteristics. The findings indicate that the incorporation of nanocellulose plays a significant role in modifying both fresh and hardened properties of concrete. A gradual reduction in workability was observed with increasing nanocellulose content, which can be linked to its extremely fine particle size and higher affinity for water, resulting in reduced free water within the mix. Despite this reduction, the mixes remained workable and suitable for practical applications. In terms of strength behaviour, the results clearly demonstrate that the addition of nanocellulose enhances compressive strength up to a certain limit, beyond which the benefits begin to decline. The optimum performance was achieved at 0.4% dosage, where a noticeable improvement in strength was recorded. This enhancement can be associated with the ability of nanocellulose to refine the internal structure, improve particle packing, and strengthen the bond between cement paste and aggregates. However, higher dosages led to a slight drop in strength, which may be due to particle clustering and uneven distribution within the matrix. The durability characteristics also showed positive trends, as the modified concrete exhibited a denser structure with reduced permeability, suggesting improved resistance to moisture ingress and long-term degradation. From a cost perspective, although the initial investment for nanocellulose-modified concrete is comparatively higher, the improved durability and reduced maintenance requirements make it a more efficient option over the lifecycle of the structure. Overall, the outcomes of this study align well with existing research trends and confirm that nanocellulose can be effectively utilized as a nano-level additive to enhance the performance and sustainability of concrete.

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