ENHANCING THE FLEXURAL STRENGTH OF CONCRETE BEAMS USING NYLON FIBERS AS SUSTAINABLE REINFORCEMENT

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Abstract- In today's world, one of the problems that persists over time in civil engineering is the formation of concrete cracks because of shrinkage, temperature changes, and load stressors. With traditional polishing methods, few to no efforts are placed in stopping the resistance of micro-cracks. This particular study is meant to assess the degree of effectiveness that adding nylon fiber to concrete as a reinforcing material has in increasing durability, cracking, and tensile strength. The study analyzes the works of others over the last ten years when nylon fiber was added to concrete in varying percentages. This research investigates the flexural behavior of Plain Cement Concrete (PCC) reinforced with locally available nylon fibers (known as BAAN). A mix design incorporating 3% nylon fibers by volume was tested for fresh and hardened properties. Also, several construction projects in the recent past measure compressive strength, tensile strength, and crack resistance. Results showed that the incorporation of nylon fibers improved the flexural strength significantly compared to expected values for plain concrete. Nylon fiber reinforced concrete presents a very promising solution in terms of improving the performance of reinforced concrete beams, particularly under seismic applications. Nylon fibers make concrete more sustainable by reducing the amount of traditional steel reinforcement that can be used in concrete and, therefore also reducing long-term maintenance costs.

Keywords- Concrete, Durability, Flexural Cracks, NFRC, Nylon Fibers

1 Introduction

Over the years, engineers alongside researchers have worked relentlessly to find solutions using other materials to improve the performance of concrete structures around the world. Reinforcing concrete with fibers, such as nylon, considering them as potential additives for the last century [1]. Concrete is a fundamental material in civil engineering. Everyone knows about its great compressive strength and how versatile it is. Originally developed during the 1930s, nylon fibers are classified as synthetic polyamides. They are known for fortifying tendons along with flexibility and high resistance to abrasion and chemicals durability [2]. Nylon, while flexible and resistant to chemicals, may absorb water, which can slightly affect its performance; however, it is generally known for good tensile strength. Concrete is prone to cracking over time due to thermal expansion, shrinkage, and loading conditions. To address these challenges, researchers have explored the incorporation of fibers into concrete, resulting in what is known as fiber-reinforced concrete (FRC) [3]. Among various fibers, nylon, a synthetic polymer, has gained attention due to its high tensile strength, elasticity, and resistance to environmental factors [4]. Nylon fibers can enhance the ductility and crack resistance of concrete, making them a promising additive for improving concrete performance in structural applications. This improved crack resistance makes nylon fiber reinforced concrete a strong candidate for enhancing structural performance [5].

To Concrete is strong under compression but weak in tension. It can also crack over time due to thermal expansion and shrinkage. Steel reinforcement helps with large cracking, but does not alleviate micro marks and early cracking that could affect long term durability [6]. Despite the advantages of traditional concrete, its propensity for cracking remains a significant concern, leading to reduced durability and increased maintenance costs. Previous studies have indicated that incorporating fibers can improve the tensile properties of concrete, however identifying the most effective fiber type and dosage for specific applications continues to be an area of active research [7]. Nylon fibers, in particular, offer potential benefits, but comprehensive studies on their impact on concrete's mechanical properties are limited. This research aims to investigate the effects of varying nylon fiber content on the flexural strength of concrete, thereby addressing the gap in knowledge and providing insights into optimizing concrete mixtures for enhanced performance. Nylon fibers help reduce micro-cracking by bridging cracks as they form and by distributing tensile stresses more evenly throughout the concrete matrix [8].

The fibers are added while mixing so that they become uniformly dispersed throughout the concrete, creating an additional reinforcement skeleton. It has also been demonstrated that nylon reinforced concrete is better at flexural impacting post crack load bearing capability, as well as dynamic impact and loading [9]. Compared to steel, polypropylene, or glass fibers, nylon offers a practical balance of mechanical performance, durability, and ease of use during mixing and placement [10]. Standardized procedures were followed for mixing, casting, and curing the specimens. After letting them cure for 28 days, we ran flexural strength tests using a universal testing machine, sticking to ASTM C78/C78M standards [11]. They recorded how the load-deflection behavior changed to see how the nylon fiber content affected the concrete's flexural performance. Statistical analyses were performed to evaluate the significance of the results and determine the optimal fiber content for maximum flexural strength enhancement [12].

In this study, previously mentioned properties of nylon still remain, especially the tendency to absorb water, despite nylon's tendency to absorb moisture, its beneficial properties have led to increased use in slabs, pavements, shotcrete, and concrete overlays. Concrete is strong in compression, but weak in tension and it cracks. Nylon fibers are known for their strength in tension as well they are flexible therefore control micro cracks and impart ductility. Specimens were prepared and tested after 28 days using ASTM C78 standards. Results showed improved load-bearing and crack resistance, confirming nylon fibers as an effective additive for enhancing concrete performance. Overall, nylon fibers could be a great way to enhance the flexural performance of concrete in various structural applications.

2 Research Methodology

2.1 Raw Material

For this study, monofilament nylon fibers used that were 72.2 mm long and 0.5 mm in diameter. The experimental setup involved preparing concrete mixes that included 3% nylon fibers by volume. Standardized procedures were followed for mixing, casting, and curing the specimens. After letting them cure for 28 days, we ran flexural strength tests using a universal testing machine. In this research work following standards were followed ASTM C78/C78M [16]. We recorded how the load-deflection behavior changed to see how the nylon fiber content affected the concrete's flexural performance. Statistical analyses were performed to evaluate the significance of the results and determine the optimal fiber content for maximum flexural strength enhancement. The concrete mix was produced by layering and mixing dry ingredients as four separate, sequential operations (the first batch was cement, followed by sand, coarse aggregates, and finally the nylon fiber). The dry ingredients were thoroughly mixed, and then water was added slowly. The four stages mixing process was important to have a consistency of mixing the nylon fiber throughout the concrete mix.

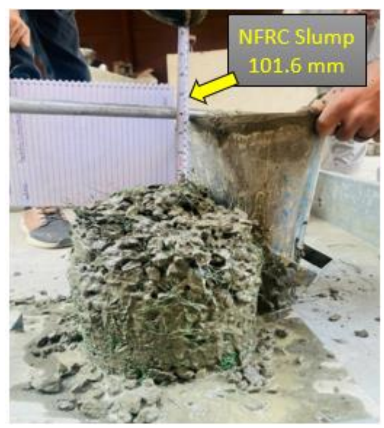
2.2 Mix Design

The manufacturing and fresh properties of Plain Concrete (PC) and Fiber Reinforced Concrete (FRC). Manufactured for testing in CUST CE Lab for 4 cylinders and 3 beamlets. To produce plain concrete (PC), Ordinary Portland Cement (Type-1) was used in both the PC and Nylon Fiber Reinforced Concrete (NFRC) mixtures. The concrete had a density of 1440 kg/m³ and a specific gravity of 3.15. Each mix contained 6.5 kg of cement. Coarse aggregate with a maximum size of 20 mm, uniformly graded, was used in both mixes. The weight of the coarse aggregate was 26 kg for PC and 13 kg for NFRC. Fine aggregate (sand) with a particle size smaller than 2 mm was also used in both mixes. For PC, 13 kg of sand was used, while NFRC contained 26 kg Nylon fiber was added at a dosage rate of 3 volumetric % in the mix and for preparation of PC, mix design ratio of 1:2:4 (cement: sand: aggregate) is used and water to cement ratio (W/C) of 0.5. The four stages mixing process produced an even infiltration of fiber, a key factor in enhancing the performance of the concrete mix mechanical properties that were expected, particularly flexural strength, and fracture resistance.

Table 1: Mix design of Plain Cement Concrete (PCC) (1:2:4) because of most commonly used mix design ratio.

Mix Design	**Quantity**
(PCC) & (NFRC) ratio	= (1:2:4)
Total wet volume of PCC	= 0.731cft
Total dry volume of PCC	= 1.1254 cft
Dry volume of cement	= 6.5kg
Fine aggregate natural sand	= 13kg
Coarse aggregate crushed stone (20 mm max size)	= 26kg
Water-cement ratio	= 0.5
Nylon Fibers	= 3%
Fiber Type	= Nylon Fiber (Locally known as BAAN)
Fiber Density	= 1140 (kg/m3)
Fiber Length	= 72.2mm
Fiber Diameter	= 0.5 mm
Fiber Aspect Ratio	= 72.2/0.5= 144.4

(a)

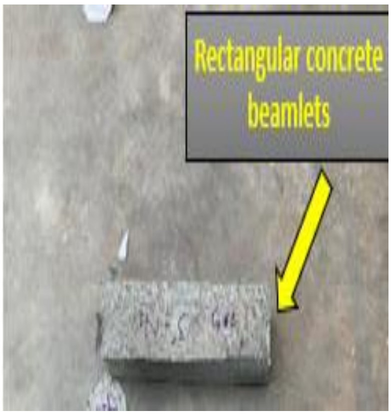


(b)

Figure 1: (a) show the PCC Slump is 125mm and (b) show the Nylon Fiber Reinforced Concrete (NFRC) mix showed a slump of 101.6 mm, but the result may not be fully accurate due to improper handling of the slump cone, causing concrete leakage. Despite this, the mix displayed moderate workability, which is expected with a 3% fiber volume that tends to reduce flow. The proper mixing in multiple turns ensured even fiber distribution.

2.3 Testing and Parameters

To assess the flexural strength of the concrete, plain cement concrete beamlets were fabricated and tested at the Civil Engineering Laboratory at CUST. The dimensions of the beamlets were 4 inches × 4 inches × 18 inches resulting in a total volume of about 0.166 cubic feet per beamlet. A total of three beamlets were prepared which resulted in a combined volume of 0.499 cubic feet. The testing of the flexural strength was carried out according to ASTM C78 / C78M, the standard test method for the flexural strength of concrete using a third-point loading scheme. The specimens were prismatic beams and the testing was completed using a Universal Testing Machine (UTM) fitted with a flexure frame. The support span that was typically used was 400 mm as the exact span was based on the lab equipment available. The loading was applied at two points equal distance from the supports following the third-point method. The load was applied at a rate of approximately 0.05 MPa per second or as directed by ASTM. The testing was set up to allow for the flexural representation of the concrete specimens to be obtained in a controlled standardized situation.



(a)

(b)

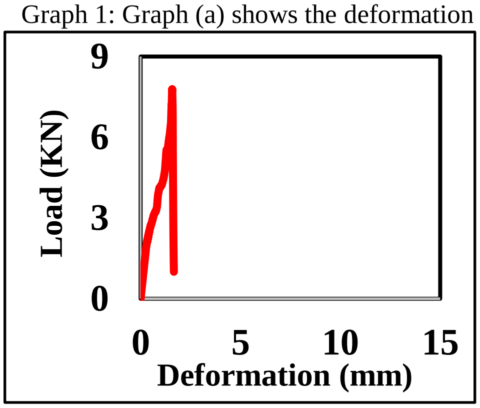
Figure 2: As the load increased, flexural cracks developed at the tension face of the beam, progressing vertically toward the neutral axis.

The reinforcing material was nylon fibers dosage of 3% volume, with an aspect ratio of 144.4. The load was applied gradually until failure, allowing for proper visualization of both crack initiation and propagation as shown in figure 2. The most common mode of failure seen in the specimens were cracking followed by failure in the tension zone of the beamlets, which was expected flexural loading behavior. In terms of flexural strength, the measured values of the tested beams ranged from 1.442 MPa to 3.071 MPa, with a reported average of 2.426 MPa. The slump of the mix was slightly low due to a testing error, with some leakage from the slump cone. However, the results of the testing are indicative of the mechanical performance of nylon fiber reinforced concrete under flexural loading.

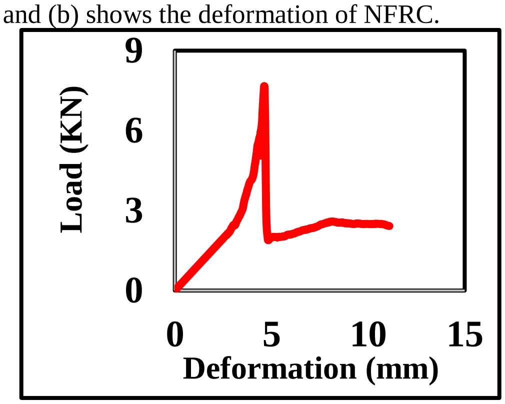
3 Results

Addition of nylon fiber clearly enhanced the flexural behavior compared to plain concrete. Strength results being not consistent, controlled mixing and uniform fiber distribution together with quality assurance during production are required. This may take place in applications of nylon fiber reinforced concrete where crack control, toughness, and durability are critical (e.g., industrial floors, overlays, precast panels).

Graph 1: Graph (a) shows the deformation of PCC and (b) shows the deformation of NFRC.



(a)



(b)

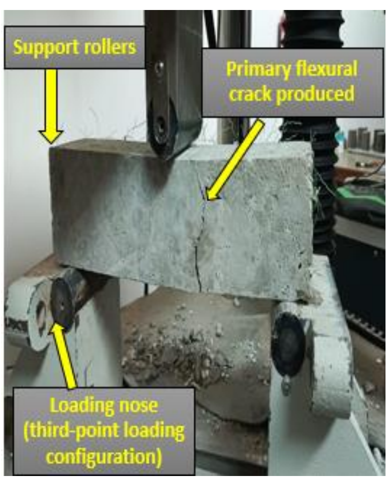
The graphs (a) show the load-deformation behavior of Plain Cement Concrete (PCC) and (b) show the Nylon Fiber Reinforced Concrete (NFRC). Nylon Fiber is significantly better than PCC. Fibers increase load-carrying capacity and stiffness. NFRC showed higher flexural toughness energy graph (b) shows a sharp peak with sudden failure, meaning it absorbed more energy because of a brittle break, not ductility. PCC graph (a) showed gradual increase to failure, better for controlled cracking even though numerical energy is lower. In table 2 the coefficient *c* is defined as the ratio of the initial elastic modulus to the tangent modulus in the ascending branch of the stress–strain curve, prior to the peak stress. It focuses on the ascending branch (before the peak), where the tangent modulus is well-defined. It avoids the undefined or misleading situation at the peak NFRC is better for strength, stiffness, and controlled failure which is the goal of Fiber reinforcement.

Table 2: The flexural strength test was carried out in accordance with ASTM C78 (or equivalent local standards), using third-point loading.

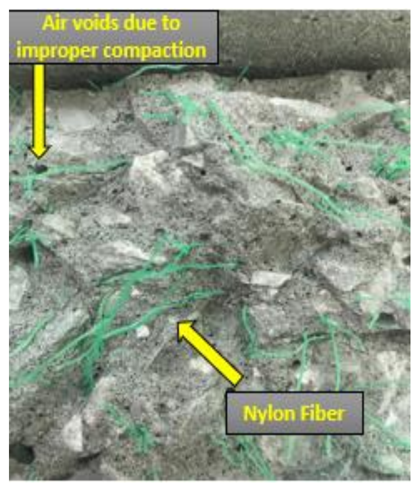
Specimens	Peak Load (KN)	MOR (MPa)	E1 (GPa)	E2 (GPa)	FTI (Mpa)	Failure mode
PC	5.52 ±1.22	4.1 ±1.15	1.5 ±0.7	6.3 ±0.12	4.3 ±1.20	Flexural
NFRC	3.32 ±0.30	2.5 ±0.25	0.1 ±0.04	2.4 ±0.70	2.91 ±0.30	

MOR=Modulus of Rupture; E1 = Flexural Pre-Cracking energy absorption; E2 = Flexural Post-Cracking energy absorption; FT1 =Flexural toughness index

In terms of pre-crack energy absorption (E1), plain concrete (PC) showed higher initial stiffness compared to nylon fiber reinforced concrete (NFRC), likely because nylon fibers are more flexible. However, NFRC demonstrated better plastic deformation and handled loads more effectively, with a 34% higher Modulus of Rupture (MOR) than PC, as shown in Table 3. This improved performance is due to the ductile nature of nylon fibers, which can absorb more energy during deformation. For post-crack energy absorption (E2), PC had a higher value, indicating it resisted deformation better after cracking. Even in later stages of bending, PC maintained more resistance. However, nylon fibers may provide post-crack ductility that isn't fully reflected in E2. Regarding flexural toughness, PC showed a higher cracking load capacity. The first crack strength was lower in NFRC, but the nylon fibers likely helped slow crack growth, improving energy absorption and ductility even if they didn't raise the initial cracking strength. The results are summarized in Table 2.



(c)



(d)

Figure 3: (c) and (d) captures the final stage of the test, where a visible crack has formed and propagated, indicating the ultimate flexural strength of the sample.

For PC sample shown in figure 3, post cracking behavior (upwards) shows ductile behavior as compare for NRFC sample presented in figure 3. Crack patterns provide valuable insight into the ductility and fiber-bridging effect in NFRC specimens. This enhanced performance is attributed to the effective bridging mechanism of nylon fibers (NF), which significantly improves load distribution and delays crack propagation. The strong interfacial bond between nylon fibers and the concrete matrix enables superior stress transfer, allowing the composite to sustain higher flexural loads before failure (Figure 3).

3.1 Flexural Behavior

Flexural strength results of Nylon Fiber reinforced concrete appear to be much better than that of regular concrete. Basically, this is because the Nylon Fiber help hold the concrete together when it begins to crack. As the concrete bends under load, these fiber span across small cracks, stopping them from growing quickly. This not only helps reduce the size and number of cracks but also makes the concrete more flexible and less likely to fail suddenly. Instead of breaking all at once like plain concrete, NFRC tends to fail more gradually, giving some warning before it actually gives out. During flexural tests, NFRC was better at spreading out the load and absorbing energy thanks to the fiber ability to stretch and adjust to the stress. Even after the concrete starts to crack, the fiber keeps it from completely falling apart, allowing it to carry some load. In lab tests, adding 3% nylon fiber by volume increased the flexural strength of concrete to an average of about 3.071 MPa, with results ranging from 1.442 to 3.071 MPa. This gain is mostly because the fiber helps the concrete handle tension better, especially in the lower part of the beam where it usually cracks first. Another big advantage is the way NFRC fails. While normal concrete tends to crack in one place and break quickly, NFRC shows more fine cracks before it fails. This change makes the concrete behave in a more ductile or flexible way, which is especially useful in structures that face vibration, impact, or sudden loads. However, one thing to watch out for is workability. Adding nylon fiber can make the mix a little harder to handle, especially at higher percentages. In some tests, a lower slump was noticed, partly due to a leak in the slump cone. So, it's important to mix the concrete properly and make sure the fiber is evenly spread out to get the full benefits.

3.2 Flexural Properties

Nylon Fiber reinforced concrete (NFRC) proves to be much superior than plain cement concrete (PCC) in terms of its flexural properties such as strength, toughness, and crack resistance. While PCC has a limited ability to resist bending and usually breaks suddenly, NFRC can handle more stress and typically shows a 10-25% increase in flexural strength. This is because the Nylon Fiber help hold the concrete together by bridging small cracks that form under bending. PCC usually fails all at once with one large crack, but NFRC cracks more gradually, giving it a more controlled and safer failure pattern. After cracking, NFRC continues to carry load thanks to the fiber, which prevent the concrete from falling apart right away. It also absorbs more energy during loading, which means it's tougher and better suited for conditions where stress changes or impacts are involved. NFRC also does a better job at controlling cracks while cracks in PCC tend to grow quickly and become wide, the fiber in NFRC slow them down and keep them smaller. This helps protect the concrete over time. In terms of flexibility, PCC doesn't stretch or bend much before breaking, but NFRC allows a bit more movement, which can be important for safety. When you look at the stress-strain behavior, PCC shows a quick peak and then drops sharply after cracking, meaning it loses strength fast. NFRC, on the other hand, shows a gentler drop after the peak because the fiber keeps working even after cracks form, allowing the concrete to hold some load and last longer.

4 Practical Application of NFRC in Concrete Beams

Nylon fiber reinforced concrete presents a very promising solution in terms of improving the performance of reinforced concrete beams, particularly under seismic applications. It is well evident that the inclusion of nylon fibers improves crack resistance, ductility, and post-cracking behavior- all important parameters for structural elements expected to resist dynamic and impact loads. In its application on beams, nylon fibers act as secondary reinforcement control shrinkage and microcracking plus energy absorption during seismic events. This greatly improves strength-to-cost ratio and structural integrity; hence NFRC could be recommended as an appropriate material for beams in seismic regions It's also useful in shotcrete applications, like tunnel linings and slope stabilization, where the fiber improve material cohesion and reduce the amount of rebound during spraying. In bridge decks and highway overlays, nylon fiber help prevent cracks caused by temperature changes and repeated vehicle loads, which extends the lifespan of the structure. In residential and commercial slabs, nylon fiber provides excellent crack control, often removing the need for traditional steel mesh. This not only cuts down on material costs but also speeds up construction and reduces labour. NFRC is also being used in precast concrete elements, footpaths, driveways, and parking structures, where early-age cracking and shrinkage are common issues. Because nylon fiber help keep these cracks in check, the final product is more durable and requires less maintenance. Additionally, NFRC is a good option for repair works, such as patching damaged concrete, since the fiber help improve bonding and reduce future cracking. It's also being explored for use in marine structures and water-retaining structures, where durability and crack resistance are critical due to exposure to moisture and chemical attack. Using nylon fibers in large construction projects comes with challenges such as limited supply, higher costs, and difficulty in achieving even distribution in concrete mixes. Standard batching plants may need upgrades, and contractor familiarity is often low. The lack of specific construction codes and environmental concerns due to nylon's synthetic nature also limit widespread use.

5 Conclusion

The addition of nylon fibers to concrete introduces a very promising new composite within construction materials with additional improved mechanical properties, improved crack resistance behavior, and sustainability. The improvements noticed in flexural strength and durability further cement NFRC's potential for both structural and non-structural applications where high performance and longevity are required.

- Nylon Fibers help improve concrete's strength and crack resistance, especially in terms of flexural performance. Adding 3% nylon fibers with a high aspect ratio (144.4) significantly increased the concrete's ability to resist bending and delayed crack formation, with an average flexural strength of about 3.759 MPa higher than that of standard concrete.

- While higher fiber content can reduce workability and cause issues in slump testing, these challenges can be managed through proper mix design and the use of admixtures. Despite a slight drop in workability, the fresh concrete mix still maintained a density close to 2400 kg/m³, making it suitable for structural use.

- Nylon fibers make concrete more sustainable by reducing the amount of traditional steel reinforcement that can be used in concrete and, therefore also reducing long-term maintenance costs.

Overall, nylon fiber reinforced concrete performed better than plain concrete in terms of strength, durability, and crack control. It shows great potential for use in both structural and non-structural applications.

6 Recommendation for Future Research

More research is needed on standardizing its use and exploring recycled nylon fibers to improve sustainability in construction. Challenges that come with reduced workability should be tackled by careful mix design aided by admixtures. Further exploration in terms of standardization and use of recycled nylon fibers will be essential to unlock the environmental benefits as well as the structural contributions of nylon fiber reinforced concrete as the construction industry begins moving toward more sustainable practices.

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