ISSN 2717-4638

# Experimental Study on Flexural Performance of Sun-Dried Bamboo (Nigalo) Reinforced Concrete Beams

Subigya Dhungana[1], Sandeep Adhikari[2], Prakash Ayer[1], Roshan Ghimire[1], Sandesh Aryal[1], Sanjaya Paudel[1], Saugat Tiwari[1], Sanjay Baral[1]*
[1]School of Engineering, Faculty of Science and Technology, Pokhara University, Nepal
[2]University of Waikato, Hamilton, New Zealand
* Corresponding author email: sanjaybaral@pu.edu.np

## Abstract

Arundinaria falcata is a fast-growing, renewable bamboo species locally called Nigalo in Nepal, offers a sustainable option for reinforcement material. This study investigates the structural performance of concrete beams reinforced with Nigalo, known for its high flexural performance and local availability. The goal is to explore untreated Nigalo as a sustainable alternative to steel reinforcement in concrete structures. The research focuses on understanding the compatibility of Nigalo with concrete and evaluating its mechanical behavior, particularly in terms of flexural strength. An experimental analysis was carried out using sun-dried Nigalo as reinforcement in concrete beams. Tests included flexural strength measurements, as well as assessments of moisture absorption. The interaction between the Nigalo and the cement matrix was also studied to understand long-term performance and environmental resistance. The results showed that Nigalo reinforced beams performed better than plain concrete beams, with strength increases of 19.30%, 64.30%, and 83.72% at reinforcement levels of 1%, 2.55%, and 3.88%, respectively. However, challenges remain due to Nigalo's vulnerability to moisture and biodegradation within the concrete. These findings suggest that while Nigalo has potential as a cost-effective and eco-friendly reinforcement material, further research is needed on protective treatments to improve its durability. This study contributes to the growing interest in sustainable building materials and highlights Nigalo's potential use is abundant. It supports the broader goal of reducing reliance on non-renewable construction materials through the use of locally available renewable alternatives.

***Keywords:*** *Construction, Nigalo, Reinforcement, Structural Performance, Sustainable*

## Introduction

Concrete is the most commonly used building material worldwide due to its excellent compressive strength, durability, and versatility (Li et al., 2022; Naik, 2020; Sandanayake et al., 2020; Shuvo et al., 2022). The composite material consists primarily of cement, water, and aggregates such as sand, gravel, or crushed stone (Wang et al., 2025). Upon mixing with water, cement undergoes a chemical reaction called hydration (Mačiulaitis et al., 2009), forming a rigid and cohesive solid that provides the structural integrity necessary for building construction (Surahyo et al., 2019). Because of its ability to bear heavy compressive loads (Wang et al., 2021; Wang et al., 2025), concrete serves as the foundation of modern infrastructure, including buildings, bridges, dams, and roads.

Concrete performance depends on its mix proportions and material quality. Portland cement binds aggregates through hydration, with the water cement ratio controlling strength and workability (Alawode & Idowu, 2011; Ayanlere et al., 2023; Cheng et al., 2023; Falade, 1994; Yiğiter et al., 2007). Aggregate properties affect durability (Aïssoun et al., 2016; Dixon et al., 1991; Kaplan, 1958). Proper mixing and curing ensure high compressive strength and resistance to weathering (ACI., 2010). Concrete is strong in compression but weak in tension (Eyre & Nasreddin, 2013). Reinforced with steel bars enhances its tensile strength, forming reinforced concrete a durable, versatile material (Ahmed et al., 2016; Lee et al., 2017; Zheng & Campbell, 2021). Concrete's low cost, availability, and fire resistance make it a cornerstone of construction (Shuvo et al., 2022). However, producing steel and cement consumes large amounts of energy and generates significant CO2 emission, crating sustainability challenges (Sikora et al., 2016; Singh et al., 2017). The global use of reinforced concrete revolutionized construction, still steel reinforcement is energy intensive, costly, and corrodes easily, demanding maintenance. This has driven many research into sustainable, locally sourced, low energy alternatives, including ecofriendly reinforcements (Geremew et al., 2021b; Geremew et al., 2021a; Kumar & Ashish, 2015).

Bamboo is increasingly recognized as a sustainable and low cost alternative to steel for concrete reinforcement due to its high tensile and compressive strength, rapid growth, and renewability, making it especially suitable for reducing environmental impact and construction costs (Adom-Asamoah et al., 2017; Fahim et al., 2022; Jayanetti & Follett, 2008; Manandhar et al., 2019; Narayanan, 2013). According to Das (1988), bamboos are classified into two categories: "Bans" and "Nigalo" (Das, 1988). The term "Bans" refers to bamboos with a larger diameter, where as "Nigalo" denotes those with a smaller diameter. Among various species, Arundinaria falcata, is a common species of Himalayan Bamboo locally called Nigalo in Nepal (Liese & Kohl, 2015; Nepal et al., 2018). Chemically, Nigalo consists mainly of cellulose, hemicellulose, and lignin which together give it strength, flexibility, and rigidity (Ma et al., 2020). Extractives like resins and tannins enhance its resistance to pests and decay (Liese & Kohl, 2015). Nigalo also aids carbon sequestration, prevents soil erosion, and supports rural livelihoods in Asia, making it a sustainable choice for construction (Tamang et al., 2013).

Although bamboo has been explored globally as a potential alternative reinforcement in concrete, the use of Nigalo specifically as a reinforcing material in concrete beams remains largely unstudied globally and as well in Nepal. Most existing research has focused on other bamboo species like Bambusa Vulgaris Vittata, Bambusa Heterostachya and Schizostachyum Brachycladum Yellow, with promising results on tensile strength and bonding performance in tropical environments (Al-Fasih et al., 2022; Sakaray et al., 2012). Many researchers had highlighted the structural potential of bamboo in general (Adom-Asamoah et al., 2017; Al-Fasih et al., 2022; Fahim et al., 2022; Kumar & Ashish, 2015; Manandhar et al., 2019; Shuvo et al., 2022), but specific data on Nigalo's mechanical behavior under flexural loading, particularly in sun-dried conditions, is absent. Bamboo has been studied as an eco-friendly material for reinforcing concrete. Umeonyiagu (2019) found that using bamboo splints in concrete beams improved both their flexural and tensile strength (Umeonyiagu, 2019). This research advances on the study by employing Nigalo bamboo, a small diameter Himalayan species that is indigenous to Nepal (Das & Thapa, 2011). Unlike the larger tropical bamboos often studied, Nigalo bamboo has thinner stems, a special structure suited to high-altitude growth, and is readily available in Nepal. This make it potentially stronger and more suitable for local construction. Additionally, research in Nepal has yet to address the compatibility of Nigalo with concrete and its flexural performance when used as reinforcement. This experimental study presents a significant gap, emphasizing the need to evaluate the flexural strength of sun-dried Nigalo reinforced concrete (NRC) beams.

Sun drying reduces bamboo’s moisture and sugars, improving its stability and bonding in concrete, making Nigalo bamboo ideal for rural, low cost construction (Ikponmwosa et al., 2014). The integration of Nigalo bamboo as a reinforcement material in concrete offers a promising shift toward sustainable construction by reducing reliance on steel and lowering carbon emissions. It provides cost-effective, resource-efficient alternatives, especially beneficial for developing countries, while enhancing structural durability with renewable materials. Additionally, it supports local economies through the sustainable use of indigenous resources and promotes innovation in green building, aligning with global sustainability goals. This study aims to evaluate the flexural strength and ductility of concrete beams reinforced with Nigalo under different reinforcement conditions. It assumes that Nigalo bamboo used is healthy and 2–3 years old. The size and quality of untreated Nigalo reinforcement could not be fully standardized. All materials like cement and aggregates were taken from one source for consistency and the long-term performance and degradation of Nigalo-reinforced concrete was not covered in this study.

## Material and Methodology

### *Material*

Widely used hydraulic binder in construction, OPC of grade 43 was used for making concrete (Gill et al., 2023). Local sand passing through 4.75 mm sieve and retaining on 200-micron sieve was used as fine aggregate. Determination of fineness modulus of fine aggregate was performed according to ASTM C136 (ASTM, 2006). Fine aggregate was in surface saturated dry condition. Crushed stone was used as coarse aggregate in sample beam preparation. Coarse aggregate of size range of 20 mm to 4.75mm was used in concrete mix. Coarse aggregates were free from organic substances and dirt coating and in surface dried condition. Flaky and elongated particles were filtered out as far as possible. Water used to prepare different samples of concrete had been clean and free from impurities and dirt. No such foreign matter was presented in water, i.e., oil, salts, alkalis, and sugar. The water used is portable water. We ensured that the Nigalo culms were at least two - three years old, as this maturity is crucial for their strength. We selected the longest and largest diameter culms for their superior strength. By adhering to these rigorous selections and seasoning criteria, the Nigalo culms used in concrete mix.

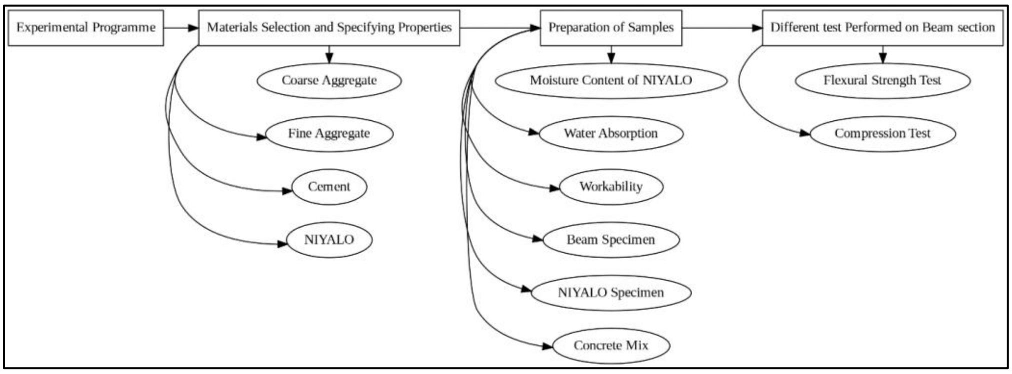



*Figure 1: Experimental methodology for NRC*

***Sample preparation***

Experimental methodology used for NRC beam is shown in figure 1. The concrete mix (Plain cement concrete (PCC), Reinforced Cement Concrete (RCC)) was designed as per the Indian Standard (IS) method, targeting an M20 grade with a characteristic compressive strength (fck) of 20 MPa. The design considered a slump range of 50–100 mm and a standard concrete density of 2400 kg/m³, suitable for moderate exposure conditions. The mix was proportioned using OPC Type 1 (also referred to as Type C), sand as the fine aggregate, and crushed stone chips with a maximum size of 20 mm as the coarse aggregate. A volumetric mix ratio of 1:1.5:3 and a water-cement ratio of 0.50 were adopted, aiming to achieve the desired 28-day strength. To ensure accurate mix proportioning, material properties were determined through laboratory tests, including pycnometer tests for specific gravity. The test results showed that the specific gravity of water was 1.00, cement was 3.15, fine aggregate (sand) was 2.49, and coarse aggregate (gravel) was 2.87. A standard deviation of 4 MPa and a Himsworth constant (k) of 1.65 were used to account for variability in strength as per IS 456-2000 and IS 10262-2009 (Standards, 2000, 2009). These carefully selected parameters contributed to the effective preparation and performance of the concrete mix used in beam specimens.

Nigalo was selected from Arghaun Archale, Pokhara, Nepal (figure 2 (c)). After being cut, Nigalo were given three weeks to dry and season. Nigalo should be kept away from direct sun and sudden moisture changes to prevent cracking. It must be stored off the ground in a ventilated space to protect against insects and fungi. To prepare for the reinforcement, Nigalo culms, were cut into length of 48cm. The outer diameter of each Nigalo culm was measured using a micrometer and inner diameter was measured using vernier caliper and minimum 12mm in diameter Nigalo was taken for the analysis. A drum-type mixer was utilized for the mixing process in this experiment. The procedure began with the addition of half the coarse aggregate into the mixer, followed by half of the fine aggregate and the full amount of cement. Subsequently, the remaining portions of fine and coarse aggregates were added. Water was introduced gradually during the process, and mixing was continued for an additional two minutes after all materials had been placed in the drum to ensure a uniform and consistent mix (figure 2 (a), (b)). A mould measuring 500 mm in length, 100 mm in breadth, and 100 mm in depth was used for casting the beam specimens. Prior to casting, each mould was thoroughly cleaned and its inner surfaces were coated with a lubricant. As the specimens were unreinforced, concrete mortar was poured into the moulds and compacted properly in three layers. A total of six specimens were prepared, three designated for testing on the 7th day and the remaining three for testing on the 28th day after casting.


*Figure 2 (a), (b): Preparation of cement concrete mix for experiment and (c): Sun-dried Nigalo after cutting from Arghaun Archale, Pokhara, Nepal*

***Steel RCC***

A total of 12 beam specimens were cast using moulds, with two different reinforcement ratios (Figure 3). The first type was a singly reinforced beam (SRB) containing 1% steel reinforcement, and the second was a doubly reinforced beam (DRB) with 2.01% reinforcement (Table 1). The steel bars were properly tied to maintain correct spacing, ensuring a clear cover of 10 mm on all sides. The concrete was placed in three layers, with each layer compacted by applying 25 tamping strokes.

*Figure 3: Cutting of steel Reinforcement for the Beam, preparation of the Beam and Compaction of the Beam Using a Vibrator*

*Table 1: Specimen reinforcement details*

| S.N. | Concrete Beam | Reinforcement (%) | Beam Marking | Remarks |
|---|---|---|---|---|
| 1 | PCC | 0 | 1-6 | - |
| 2 | RCC | 1% | 7-12 | SRB |
| | | 2.01% | 13-18 | DRB |
| 3 | NRC | 1% | 19-24 | SRB |
| | | 2.55% | 24-30 | DRB |
| | | 3.8% | 31-36 | DRB |

### *Nigalo Reinforced Beam Specimen*

18 beams with dimensions of 500mm × 100mm × 100mm were casted for flexural test. The beam specimens were casted in three layers, but with 25 tamping strokes at each layer. Nigalo reinforcement was placed carefully with 10 mm clear cover on each side (Figure 4). Careful attention was given to the finishing of the upper surface to ensure an even surface and prevent void. The details of all types of beams used in the concrete mix are presented in table 1.

*Figure 4: Nigalo reinforcement preparation and casting of NRC Beam*

### *Curing*

Following the completion of specimen casting, initial curing was carried out for 24 hours by covering the upper surface with clean, damp clothes in a controlled way. After this initial period, all specimens were demolded and placed inside a water curing tank, where they remained until the day before testing and were taken out 24 hours before testing.

A fixed water-cement ratio (0.5) was maintained across all mixes to ensure uniform workability and strength development. All specimens were prepared and cured under normal room conditions within the civil engineering laboratory. While temperature and humidity were not specifically measured, the environment remained stable throughout the testing period, as all specimens were cast, stored, and cured in the same space under identical conditions. Therefore, any variation in strength results can be attributed to differences in material composition and mix properties rather than environmental effects. This consistency in laboratory handling and curing environment ensures that the comparative analysis remains valid and reliable.

### *Laboratory Test*

The slump test was done to check the workability of the concrete. According to IS 1199 (Part 5): 2018, only a true slump is allowed, where the concrete holds its shape without collapsing, using a water-cement ratio of 0.5. The Los Angeles Abrasion test was performed in the laboratory to determine the resistance of aggregate to abrasion. The abrasive action was produced using standard steel balls when mixed with aggregates and rotated in drum for specific number of revolutions. The percentage wear of aggregates due to rubbing with steel balls was determined, which is known as Los Angeles Abrasion Value. Water absorption had been determined through the water absorption test on concrete cubes according to IS 1124(1974). The average water absorption values of three concrete cubes immersed in water was calculated (Equation 1).

$$\text{Water absorption} = \frac{W_1 - W_2}{W_2} * 100\% \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$W_1$= Initial weight taken after 28 days, $W_2$= Final weight taken after 24 hrs. oven dry

The initial weights (sun-dried weight) of six Nigalo sample sticks were noted. Then they were oven-dried to get the final weights. The difference between the initial (sun-dried) weight and the final (oven-dried) weight gives the moisture content of each Nigalo sample. Finally, the average moisture content of Nigalo was calculated (Equation 1). Compressive strength had been measured through the compression test on concrete cubes using compression testing machine according to IS No.14858:2000. The cubes were removed from curing tank and weighted before the cubes had been placed for compressive strength test. The specimens were then loaded to failure in a compression testing machine. The load was set with constant rate of loading to prevent sudden failure and to obtain the maximum concrete compressive load. The maximum load sustained was recorded and compressive strength of the concrete was determined.

Flexural strength of beam was determined by Universal Testing Machine (UTM). Flexural test is also known as tensile strength test which the load was applied to concrete beam after 7th and 28th days of curing. This test was done to test the ability of concrete to withstand failure in bending. The load was applied at the rate of 0.1 MPa/min - 0.2 MPa/min for the flexural stress until the maximum load was applied. The beam was designed according to IS 1199 (Part 5) with size of specimen was cast for 100x100x500 mm dimension. The test machine was cleaned, and the specimen was properly aligned with the machine. Flexural strength (or Modulus of Rupture) for mid-point loading is given by:

Flexural strength = $1.5 * \frac{P*L}{b*d^2}$ , ……………………………………. (2)

where, P = Load at failure, L= Length between two supports, b = Breadth of beam, d = Depth of beam

## Results and Discussion

The specific gravity of fine aggregate (2.49) and coarse aggregate (2.87) was determined using the pycnometer method. Based on the gradation results (figure 5), the sand used was classified as Zone I as per IS: 383-1970. Zone I sand is coarse sand, suitable for concrete requiring high strength. The gradation of coarse aggregate used in the research is shown in figure 5. Based on the gradation results, the coarse aggregate meets the requirements of IS: 383-1970 (Standards, 1970).

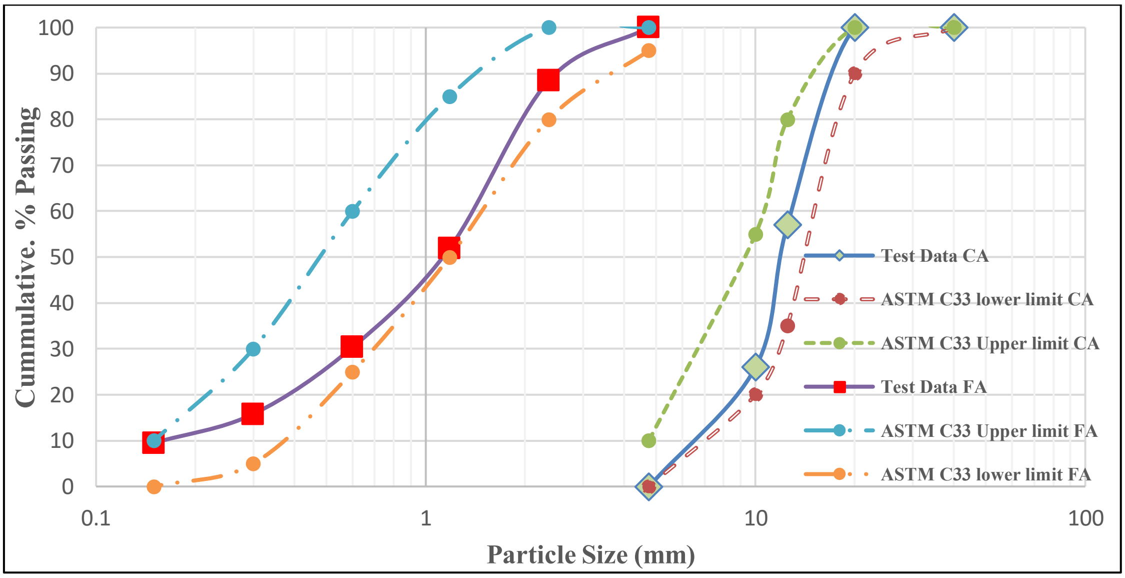



*Figure 5: Grading curve of fine and coarse aggregate*

### *Workability*

The slump test had been done as per IS 456:2000 and the slump should be within range 25mm - 100mm for lightly reinforced beam (Standards, 2000). The slump test results (Table 2 and figure 6) shows that the slump has met the design requirement for normal concrete design grade 20.

*Table 2: Specifying of slump test*

| Batch Number | Slump Test Value (mm) |
|---|---|
| 1 | 56 |
| 2 | 60 |
| 3 | 57.5 |

| | |
|---|---|
| 4 | 68 |
| 5 | 59 |
| 6 | 63 |
| Average | 60.58 |

*Figure 6: Sample Cast for Slump Test*

***Water absorption***

Test on cubes of 7cm * 7cm * 7cm was performed after drying the cubes for 24 hrs. in 100 ±5ºC temperature in oven. The average water absorption of cube was obtained as 5.061 percentage. A 15cm sized long Nigalo was oven dried for 24 hours at 105±5ºC and moisture content of Nigalo was obtained as 17.325 percentages. According to Ahmad et al (Ahmad et al., 2020) the mechanical strength and durability of bamboo are influenced by its moisture content and hence it is essential to maintain the moisture level below 20%.

***Compression Test***

Average compressive strength was found to be 23.59 MPa after testing on 15cm cubes (Table 3). This result is suitable for general RCC works in residential buildings, as it exceeds the required characteristic strength of 20 MPa at 28 days, meeting IS 456 acceptance criteria (Standards, 2000).

*Table 0: Compression test results of cube*

| S.N. | Weight (KG) | Maximum Load (kN) | Compressive Strength (MPa) |
|---|---|---|---|
| 1 | 8.941 | 543 | 24.1 |
| 2 | 8.614 | 508 | 22.57 |
| 3 | 8.855 | 543 | 24.1 |
| Average | 8.803 | 531.33 | 23.59 |

***Los Angeles Test***

After conducting Los Angeles Test of coarse aggregate, 25% abrasion value was obtained which is within acceptable limit as per IS 383: 2016. These aggregates are considered standard and typically exhibit minimal abrasion effects.

***Flexural Strength***

The results (Table 4) show that PCC beams gained strength over time. At 7 days, the beams carried an average load of 6.2 kN, had a flexural strength of 3.72 MPa, and showed 5.93 mm of deflection. By 28 days, their performance improved, the average load increased to 8.6 kN, flexural strength rose to 5.16 MPa, and deflection dropped to 5.37 mm. The PCC beam exhibits completely plastic behavior (Figure 9). Figure 9 indicates that beam immediately collapses after it reaches the maximum load.

During testing of the PCC beam, a hairline crack appeared even under a low load (Figure 10). As the load increased to its maximum, the beam suddenly broke into two pieces and failed due to its brittle nature (Figure 10). This result highlights the problem of brittleness in concrete and the need for better material design and reinforcement to improve strength and durability.

*Table 4: Maximum load and deflection of PCC beam*

| Material | Days | Weight (KG) | Maximum Load (kN) | Maximum Deflection (mm) | Flexural Strength (MPa) |
|---|---|---|---|---|---|
| PCC | 7 | 13 | 5.9 | 6.2 | 3.54 |
| | | 13.12 | 5.2 | 5.9 | 3.12 |
| | | 12.83 | 7.5 | 5.7 | 4.5 |
| Average | | 12.9833 | 6.2 | 5.93 | 3.72 |
| PCC | 28 | 12.829 | 10.8 | 5.5 | 6.48 |
| | | 12.72 | 6 | 4.9 | 3.6 |
| | | 12.866 | 9 | 5.7 | 5.4 |
| Average | | 12.805 | 8.6 | 5.37 | 5.16 |

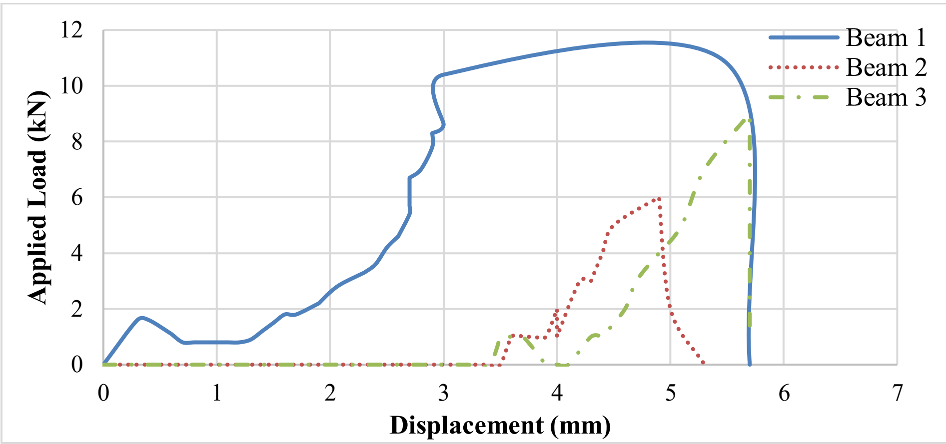



*Figure 9: 28 Day Compressive Strength of PCC Beam*

*Figure 10: PCC beam showing crack formation during testing (left) and collapsed beam after failure (right)*

The test results (Table 5) show that RCC beams with both 1% and 2.01% reinforcement improved significantly from 7 to 28 days of curing, following the typical behavior of reinforced concrete. For 1% reinforcement, load capacity and flexural strength increased by 41.9%, with a notable 67.1% reduction in deflection, indicating a major gain in stiffness. In comparison, 2.01% reinforcement beams showed a slightly higher increase in load capacity and flexural strength (44.5%) but a smaller deflection reduction of 15%. This suggests that while both reinforcement levels enhanced strength with curing, the 1% beams showed a more significant improvement in stiffness, whereas the 2.01% beams offered slightly better strength gains over time. This clearly shows that as the concrete cures longer, it becomes stronger and stiffer, making it better at handling loads without bending too much (Anwar et al., 2022; Rath et al., 2018). These results follow the normal behavior expected from reinforced concrete.

*Table 5: Maximum load and deflection of 1% and 2.01 % RCC beam*

| Reinforcement Percentage Of RCC | Days | Weight (Kg) | Maximum Load (kN) | Maximum Deflection (mm) | Flexural Strength (MPa) |
|---|---|---|---|---|---|
| SRB 1% | 7 | 13.69 | 27.4 | 25.5 | 16.44 |
| | | 12.7 | 23.1 | 11.4 | 13.86 |
| | | 13.148 | 28.6 | 17.9 | 17.16 |
| Average | | 13.179 | 26.36 | 18.26 | 15.816 |
| SRB 1% | 28 | 13.552 | 35.9 | 5.6 | 21.54 |
| | | 13.168 | 38.6 | 4.1 | 23.16 |
| | | 13.078 | 37.7 | 8.3 | 22.62 |
| Average | | 13.266 | 37.4 | 6 | 22.44 |
| DRB 2.01% | 7 | 13.335 | 22.1 | 6.3 | 13.26 |
| | | 13.53 | 29.7 | 6.9 | 17.82 |
| | | 13.351 | 25 | 6.8 | 15 |
| Average | | 13.4 | 25.6 | 6.67 | 15.36 |
| DRB 2.01% | 28 | 13.904 | 38.4 | 4.0 | 23.04 |
| | | 13.914 | 35.4 | 5.1 | 21.24 |
| | | 13.935 | 37.2 | 7.9 | 22.32 |
| Average | | 13.917 | 37 | 5.67 | 22.2 |

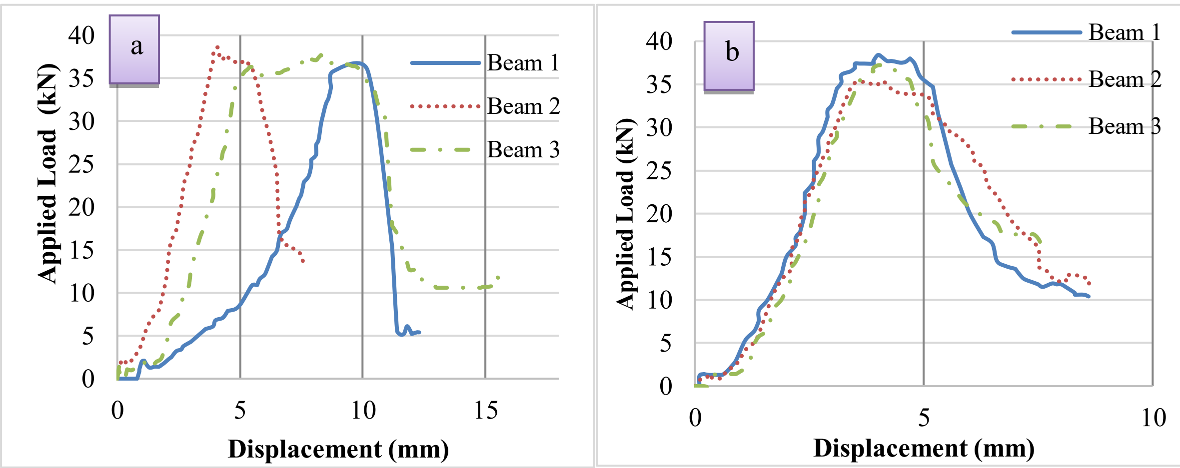



*Figure 11: 28-day strength of RCC beam with (a) 1% reinforcement SRB and (b) 2.01% reinforcement DRB*

The Steel RCC beam shows that beam does not collapse immediately after peak load is achieved. Even after the peak load DRB can withstand the more load than SRB before the complete failure (**Error! Reference source not found.**11, 12). The test result of the 2.01% steel RCC DRB is shown in figure 11. During the flexural testing of steel reinforced beam, the beam undergoes shear failure starting from the support of the beam and gradually increasing toward the center of the compression region (Figure 12) (Al-Nasra & Asha, 2013; Słowik, 2014).

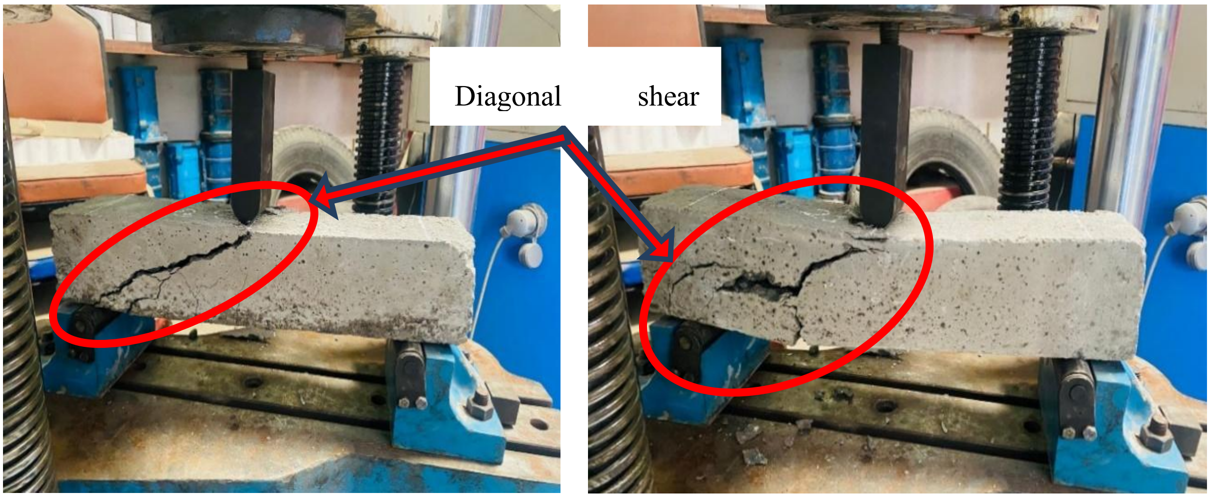



*Figure 12: Flexural testing of RCC Beam using UTM*

### *Untreated Nigalo Reinforced Concrete (NRC) Beam*

The test results (Table 6) show that beams with higher percentages of untreated Nigalo reinforcement carried more load but had varied deflection and strength over time. At 7 days, beams with 3.8% reinforcement showed the highest load capacity (21.86 kN) and flexural strength (13.116 MPa), while beams with 1% reinforcement had lower load (15.88 kN) and strength (9.528 MPa). However, after 28 days, all beams showed a drop in both load and flexural strength, with 3.8% reinforced beams still performing best (15.8 kN load and 9.48 MPa strength), but the deflection remained higher (18.5 mm) compared to others. Beams with 1% reinforcement showed the biggest drop in strength and deflection improvement over time. This means higher reinforcement increased initial strength but showed less improvement with curing, while lower reinforcement beams gained more stiffness over time. Overall, more reinforcement led to higher initial strength, but curing benefited lower reinforcement beams more in terms of stiffness and crack control.

*Table 6: Maximum load and deflection of 1%, 2.55 % and 3.8% NRC beam*

| **Days** | **Reinforcement Percentage** | **Weight Kg** | **Maximum Load (kN)** | **Maximum Deflection (mm)** | **Flexural Strength (MPa)** |
|---|---|---|---|---|---|
| 7 | 1% | 14.028 | 13 | 7.3 | 7.8 |
| | | 13.18 | 17.3 | 20.5 | 10.38 |
| | | 13.19 | 17.35 | 22.2 | 10.41 |
| Average | | 13.46 | 15.88 | 16.67 | 9.528 |
| 28 | 1% | 12.962 | 9.7 | 4.6 | 5.82 |
| | | 13.275 | 11 | 5.8 | 6.6 |
| | | 13.005 | 10.1 | 4 | 6.06 |
| Average | | 13.08 | 10.26 | 4.8 | 6.156 |
| 7 | 2.55% | 12.84 | 17.55 | 22.9 | 10.53 |
| | | 13.28 | 21.75 | 21.4 | 13.05 |
| | | 12.48 | 21.8 | 24.5 | 13.08 |
| Average | | 12.86 | 20.36 | 22.93 | 12.216 |
| 28 | | 12.992 | 16.7 | 14.8 | 10.06 |

| | | | | | |
|---|---|---|---|---|---|
| | 2.55% | 13.108 | 12.8 | 13.5 | 7.68 |
| | | 13.009 | 12.9 | 17.3 | 7.74 |
| Average | | 13.036 | 14.13 | 15.2 | 8.478 |
| | | 12.8 | 24.4 | 23.8 | 14.64 |
| 7 | 3.80% | 13.54 | 18.2 | 21.8 | 10.92 |
| | | 13.24 | 23 | 21.5 | 13.8 |
| Average | | 13.19 | 21.86 | 22.36 | 13.116 |
| | | 13.692 | 16.4 | 20.3 | 9.84 |
| 28 | 3.80% | 13.715 | 18 | 27.9 | 10.8 |
| | | 14.028 | 13 | 7.3 | 7.8 |
| Average | | 13.81 | 15.8 | 18.5 | 9.48 |

The test results and load-deflection curves (Figures 13) show that NRC beams can continue to carry load even after cracking, as they do not fail immediately upon reaching maximum load. Instead, they sustain load for some time after major cracks appear. This post-crack load-carrying ability of NRB improves with higher percentages of reinforcement, with the 3.8% reinforced beams showing the best performance. Although higher reinforcement increases initial strength, it shows less improvement over time with curing, while lower reinforcement beams benefit more in stiffness and crack control. Overall, increased reinforcement enhances the beam's capacity to resist failure after cracking, with 3.8% reinforced beams proving most effective.

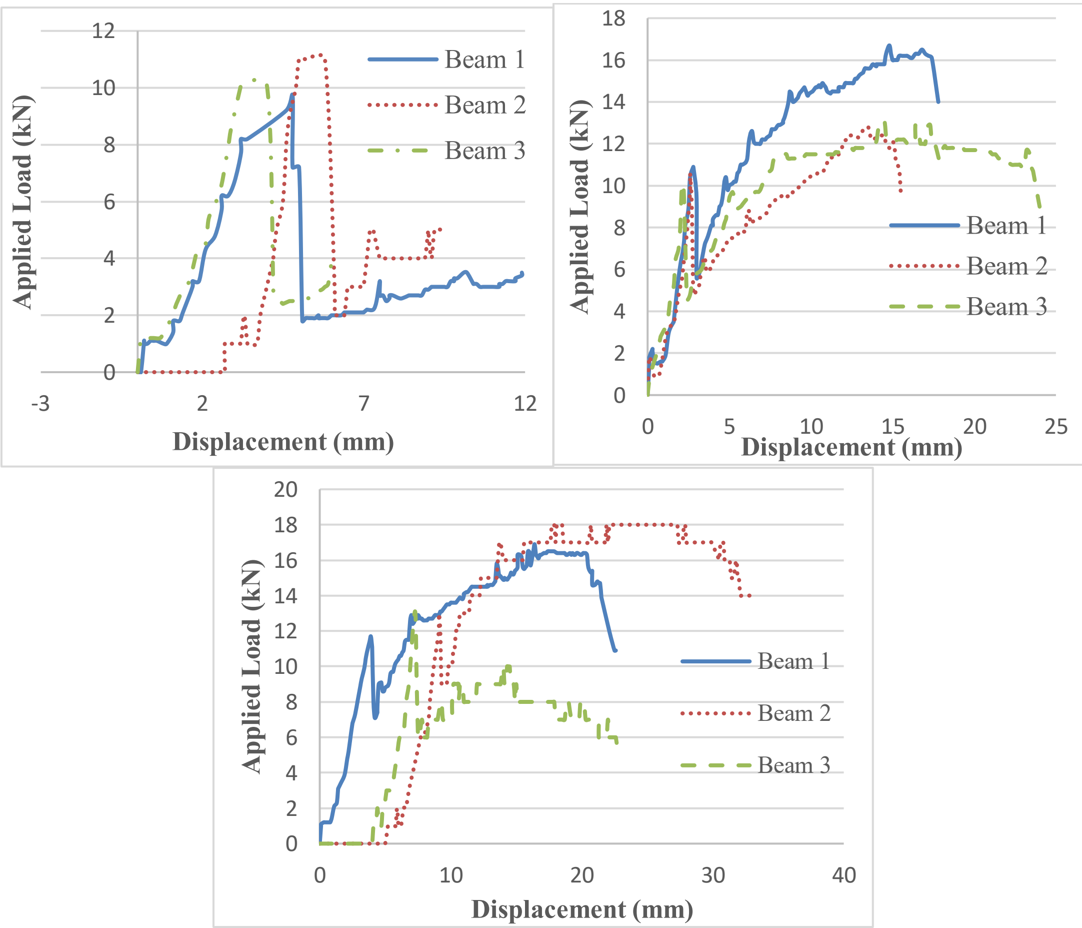



*Figure 13: 1%, 2.55% and 3.8% NRC beam 28th day strength*

During the flexural testing of the NRC beam, it was observed that the beam did not collapse suddenly after reaching its peak load but continued to carry load for some time, as shown in Figure 14. Individual Nigalo reinforcements may fail, but they do not fail all at once, highlighting Nigalo's potential as a reinforcement material. However, Nigalo is vulnerable to environmental effects, as seen in Figure 15, where signs of fungal attack and discoloration are visible. Additionally, when cracks appeared in the Nigalo, moisture absorbed during curing and casting was seen, indicating its susceptibility to biological degradation.

The decreased in flexural strength of NRC beams after 28 days is attributed to the detrimental effects of moisture on the Nigalo reinforcement and the Nigalo concrete bond (Archila et al., 2018; Pacheco-Torgal & Jalali, 2011). The Nigalo is hygroscopic and undergoes swelling and shrinkage cycles due to moisture variations within the concrete, which damages the interfacial bond and leads to micro and macro-cracking (Archila et al., 2018). Hosoda (1942) found that bamboo loses a significant portion of its strength when exposed to moisture and high alkali conditions over time about 50% after one year and only 30% after three years, which explain the reduction in flexural strength of NRC beams as the Nigalo swells, degrades, or its bond with concrete deteriorates (Hosoda, 1942). The combined effect of bond deterioration from swelling and moisture-induced degradation leads to a reduction in the composite action and consequently, the flexural strength of the beams over time.

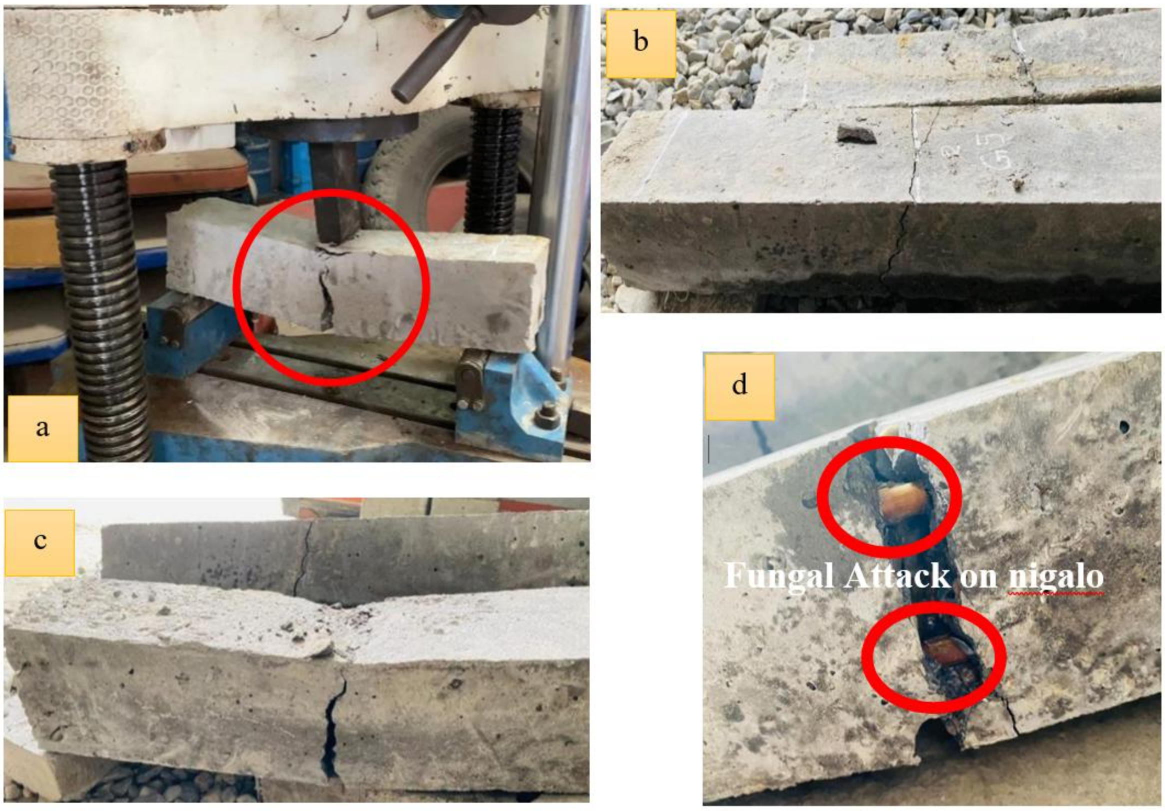



*Figure 14: (a) Flexural testing of NRC Beam using UTM (b), (c) NRC Beam after testing (d) Degraded untreated Nigalo after 28 days of casting*

***Comparison of Flexural Strength***

On the 7th day strength test, PCC exhibited the lowest flexural strength of 3.72 MPa, which is expected due to the lack of reinforcement that significantly enhances the structural capacity of concrete beams (figure 15). In contrast, both RCC and NRC demonstrated substantially higher flexural strengths due to their reinforcement materials. In RCC beams, 1% reinforcement resulted in a flexural strength of 15.816 MPa but increasing the reinforcement to 2.01% slightly decreased the flexural strength to 15.36 MPa due to shear failure during the test. NRC beams showed a different trend, with increasing percentages of Nigalo reinforcement leading to progressively higher flexural strengths: 9.528 MPa at 1%, 12.216 MPa at 2.55%, and 13.116 MPa at 3.88%, suggesting that enhancing the proportion of Nigalo reinforcement effectively boosts the flexural strength of NRC beams.

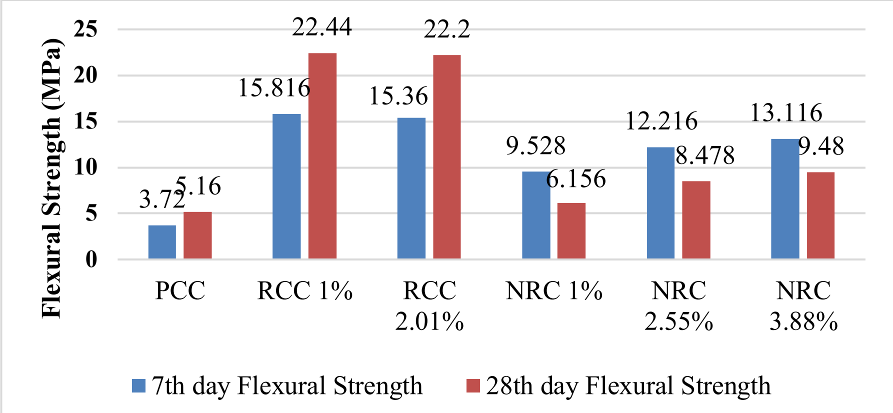
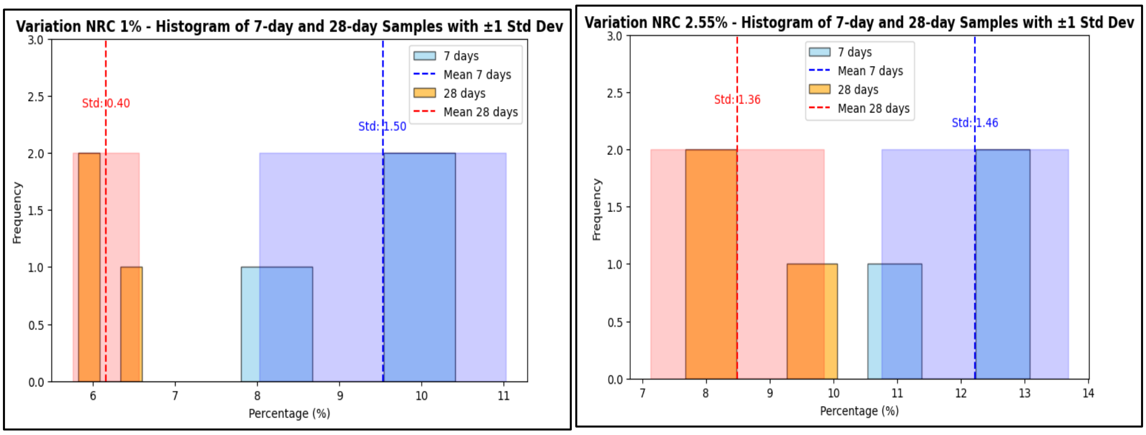



*Figure 15: Flexural strength comparison of PCC, RCC and NRC*

PCC exhibits the lowest flexural strength of 5.16 MPa, as it lacks reinforcement, while both RCC and NRC show significantly higher flexural strengths due to the presence of reinforcement. For RCC, 1% reinforcement results in a flexural strength of 22.44 MPa, slightly decreasing to 22.2 MPa at 2.01% reinforcement, as RCC beams experienced shear failure. In NRC, flexural strength increases with higher Nigalo reinforcement: 6.156 MPa at 1%, 8.478 MPa at 2.55%, and 9.48 MPa at 3.88%, though still lower compared to RCC. Comparatively, RCC beams consistently exhibit higher flexural strengths than NRC beams at similar reinforcement levels. For instance, RCC with 1% reinforcement has 22.44 MPa, whereas NRC with 1% has 6.156 MPa. Even with increasing reinforcement percentages, NRC beams, such as the 3.88% NRC achieving 9.48 MPa, remain below the 22.2 MPa of RCC with 2.01%.

***Statistical Evaluation of Strength Variability and Data Consistency***

The statistical evaluation of strength variability and data consistency is shown in figure 16. Each graph compares the 7-day and 28-day strength results, showing the mean values and ±1 standard deviation ranges. The bars demonstrate a consistent pattern, where the 28-day strengths generally increase with NRC variation, reflecting the expected improvement in material performance over time. The narrow spread of data within one standard deviation in all three cases indicates low variability and good repeatability among the specimens, even though only three samples were tested per condition. The close alignment between 7-day and 28-day mean values also suggests stable curing behavior and minimal random error. Overall, the results confirm that despite the limited sample size, the experimental data exhibit acceptable statistical consistency and reliability for comparative analysis.



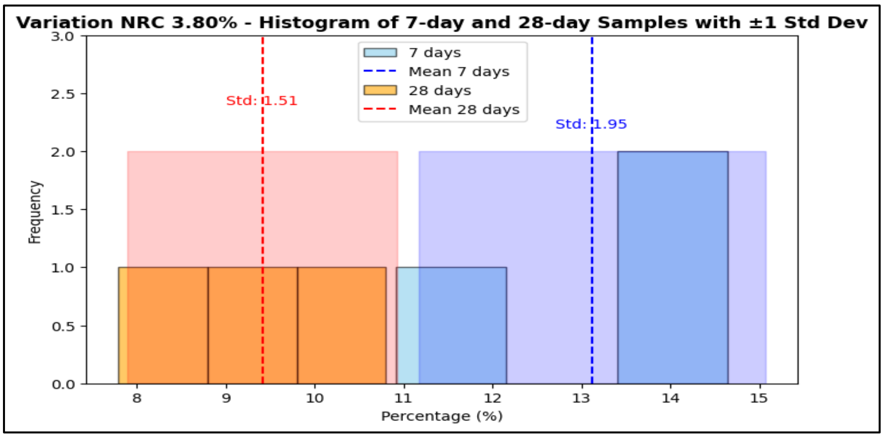



*Figure 16: Histograms for NRC variations of 1%, 2.55%, and 3.8%*

### *Economic analysis*

The Nigalo beam demonstrates significant cost-effectiveness compared to the conventional concrete beam, making it an attractive alternative for budget conscious construction projects. While both beams use the same volume of concrete (0.005 cu.m) and identical formwork, the Nigalo beam dramatically reduces reinforcement costs. Instead of steel rebar, it uses Nigalo materials for reinforcement, which totals only Rs. 68 compared to Rs. 263.39 for traditional steel (rebar and stirrups combined) (Table 7). This reduction leads to a substantial drop in the overall cost per meter, with the Nigalo beam costing just Rs. 366.50 per meter versus Rs. 757.28 for the standard beam, cutting the cost nearly in half. This clearly showcases Nigalo's efficiency in maintaining structural elements at a much lower expense, offering an effective solution without compromising the basic construction integrity for certain types of low-load applications.

*Table 7: Comparison of cost of NRC beam and RCC beam (Source Kaski district rate 2025)*

| SN | Description | Nos | Length (m) | Breadth (m) | Height (m) | Quantity | unit | Rate | Amount (Rs.) |
|---|---|---|---|---|---|---|---|---|---|
| A | Concrete Beam | | | | | | | | |
| 1 | Concrete | 1 | 0.5 | 0.1 | 0.1 | 0.005 | cu.m | 14500 | 72.5 |
| 2 | Rebar | | | | | | | | |
| | 12mm | 4 | 0.5 | @ | 0.89 | 1.78 | Kg | 113.00 | 200.89 |
| | Stirrups | 4 | 0.35 | @ | 0.40 | 0.55 | Kg | 113.00 | 62.50 |
| 3 | Form Work | 1 | 0.5 | 0.1 | | 0.05 | | | |
| | | 2 | 0.5 | | 0.10 | 0.10 | | | |
| | | | | | | 0.15 | Sq.m | 285.00 | 42.75 |
| Rate of Cost per meter | | | | | 757.28 | | | | 378.64 |
| B | Nigalo Beam | | | | | | | | |
| 1 | Concrete | 1 | 0.5 | 0.1 | 0.1 | 0.005 | cu.m | 14500 | 72.5 |
| 2 | Nigalo | | | | | | | | |
| | 12mm | 4 | 0.5 | | | 2.00 | | | |
| | Stirrups | 4 | 0.35 | | | 1.40 | | | |
| | | | | | | 3.40 | M | 20.00 | 68 |
| 3 | Form Work | 1 | 0.5 | 0.1 | | 0.05 | | | |
| | | 2 | 0.5 | | 0.10 | 0.10 | | | |
| | | | | | | 0.15 | Sq.m | 285.00 | 42.75 |
| | | Rate of Cost per meter | | | 366.50 | | | | 183.25 |

## Conclusion

This study looked at how sun-dried untreated Nigalo can be used as a reinforcement material in concrete beams. The experiments showed that Nigalo has good natural strength, which helps improve the bending strength of concrete when used as reinforcement. Beams reinforced with sun-dried Nigalo performed better in bending tests compared to plain concrete beams, meaning they could carry more load before breaking.

Although RCC beams had higher strength overall, the tests showed that increasing the amount of Nigalo significantly improved the strength of NRC beams. The results suggest that Nigalo contributes to better bending performance in concrete and, with improved application methods, could serve as a promising alternative reinforcement. The flexural strength gains were clear that 1% reinforcement improved strength by 19.30%, 2.55% gave a 64.30% increase, and 3.88% showed the highest gain at 83.72%. These findings confirm that using the right amount of Nigalo can effectively enhance the strength of concrete. The Nigalo beam offers a highly cost-effective alternative to traditional concrete beams, reducing per-meter costs by over 50% primarily through cheaper reinforcement materials. This makes it an ideal choice for projects requiring budget efficiency without significantly compromising structural function. However, the study also found a challenge. Since Nigalo is a natural material, it can degrade over time when exposed to moisture, temperature changes, or pests. This weakens the reinforcement effect in the long run. Because of this, it's important to find ways to protect Nigalo and make it last longer in concrete. Despite this, the findings are encouraging. Nigalo shows real promise as a low-cost, locally available, and eco-friendly reinforcement option. With more research and better protection methods, Nigalo could reduce the use of traditional steel in some cases, making construction more sustainable and affordable. Further work on improving its durability could make Nigalo a valuable material for future building projects.

### *Recommendations*

Based on the findings of this study, the future study can be conducted with the proper treatment of the Nigalo, so it can resist fungal attacks. The flexural strength of the beam can also be studied for a long term, as to know about the weather-resisting capacity of the Nigalo.

## References

ACI Committee 211. (1997). *Standard practice for selecting proportions for normal, heavyweight, and mass concrete (ACI 211.1-91)*. American Concrete Institute.

ACI Committee 363. (2010). *Report on high-strength concrete (ACI 363R-10)*. American Concrete Institute.

Adom-Asamoah, M., Osei Banahene, J., Obeng, J., & Antwi Boasiako, E. (2017). Bamboo-reinforced self-compacting concrete beams for sustainable construction in rural areas. *Structural Concrete, 18*(6), 1000–1010. https://doi.org/10.1002/suco.201600150

Ahmad, S. I., Alam, M. S., & Alam, M. J. (2020). Structural and life-cycle economic feasibility of rooftop low-height bamboo telecom tower: A case study from Bangladesh. *Practice Periodical on Structural Design and Construction, 25*(3), 05020007. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000485

Ahmed, M., Mallick, J., & Hasan, M. A. (2016). A study of factors affecting the flexural tensile strength of concrete. *Journal of King Saud University – Engineering Sciences, 28*(2), 147–156. https://doi.org/10.1016/j.jksues.2014.11.001

Aïssoun, B. M., Hwang, S.-D., & Khayat, K. H. (2016). Influence of aggregate characteristics on workability of superworkable concrete. *Materials and Structures, 49*, 597–609. https://doi.org/10.1617/s11527-015-0523-7

Al-Fasih, M., Hamzah, S., Ahmad, Y., Ibrahim, I., & Mohd Ariffin, M. (2022). Tensile properties of bamboo strips and flexural behaviour of bamboo reinforced concrete beams. *European Journal of Environmental and Civil Engineering, 26*(13), 6444–6460. https://doi.org/10.1080/19648189.2021.1875476

Al-Nasra, M. M., & Asha, N. (2013). Shear failure investigation of reinforced concrete beams with swimmer bars. *Journal of Civil Engineering and Construction Technology, 4*(2), 56–74.

Alawode, O., & Idowu, O. (2011). Effects of water–cement ratios on the compressive strength and workability of concrete and lateritic concrete mixes. *Pacific Journal of Science and Technology, 12*(2), 99–105.

Anwar, A., Tariq, H., Adil, A., & Iftikhar, M. A. (2022). Effect of curing techniques on compressive strength of concrete. *World Journal of Advanced Research and Reviews, 16*(3), 694–710. https://doi.org/10.30574/wjarr.2022.16.3.1341

Archila, H., Kaminski, S., Trujillo, D., Zea Escamilla, E., & Harries, K. A. (2018). Bamboo reinforced concrete: A critical review. *Materials and Structures, 51*(4), Article 102. https://doi.org/10.1617/s11527-018-1217-1

ASTM International. (2006). *Standard test method for sieve analysis of fine and coarse aggregates (ASTM C136/C136M)*. ASTM International.

Ayanlere, S., Ajamu, S., Odeyemi, S., Ajayi, O., & Kareem, M. (2023). Effects of water–cement ratio on bond strength of concrete. *Materials Today: Proceedings, 86*, 134–139. https://doi.org/10.1016/j.matpr.2023.01.222

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications, 14*(1), Article 8213. https://doi.org/10.1038/s41467-023-43706-x

Das, A. (1988). Bamboo research in Nepal. In *Proceedings of the International Bamboo Workshop*. INBAR.

Das, A., & Thapa, H. (2011). Distribution and utilization of bamboos in the midwestern and far-western regions of Nepal. *Banko Janakari, 21*(1), 13–14.

Dixon, D. E., Prestrera, J. R., Burg, G. R., Abdun-Nur, E. A., Barton, S. G., Bell, L. W., Blas, S. J., Carraquillo, R. L., & Carraquillo, P. M. (1991). *Standard practice for selecting proportions for normal, heavyweight, and mass concrete*. American Concrete Institute.

Eyre, J. R., & Nasreddin, H. S. (2013). Tension strain failure criterion for concrete. *Magazine of Concrete Research, 65*(21), 1303–1314. https://doi.org/10.1680/macr.13.00143

Fahim, M., Haris, M., Khan, W., & Zaman, S. (2022). Bamboo as a construction material: Prospects and challenges. *Advances in Science and Technology Research Journal, 16*(3), 1–10.

Falade, F. (1994). Influence of water/cement ratios and mix proportions on workability and characteristic strength of concrete containing laterite fine aggregate. *Building and Environment, 29*(2), 237–240. https://doi.org/10.1016/0360-1323(94)90026-4

Geremew, A., De Winne, P., Adugna, T., & De Backer, H. (2021b). An overview of the characterization of natural cellulosic fibers. *Key Engineering Materials, 881*, 107–116.

Geremew, A., De Winne, P., Demissie, T. A., & De Backer, H. (2021a). Treatment of natural fiber for application in concrete pavement. *Advances in Civil Engineering, 2021*, Article 6667965. https://doi.org/10.1155/2021/6667965

Gill, P., Jangra, P., Roychand, R., Saberian, M., & Li, J. (2023). Effects of various additives on crumb rubber integrated geopolymer concrete. *Cleaner Materials, 8*, Article 100181. https://doi.org/10.1016/j.clema.2023.100181

Hosoda, K. (1942). *Bamboo reinforced concrete*. Syukyosya Syoin.

Ikponmwosa, E., Falade, F., Fapohunda, C., & Aransiola, J. (2014). Flexural performance of bamboo-reinforced foamed aerated concrete beams. *Journal of Engineering Research*.

Jayanetti, D., & Follett, P. (2008). Bamboo in construction. In *Modern bamboo structures* (pp. 35–44). CRC Press.

Kaplan, M. (1958). The effects of the properties of coarse aggregates on the workability of concrete. *Magazine of Concrete Research, 10*(29), 63–74.

Kumar, G., & Ashish, D. K. (2015). Review on feasibility of bamboo in modern construction. *SSRG International Journal of Civil Engineering, 2*, 66–70.

Lee, J.-H., Cho, B., & Choi, E. (2017). Flexural capacity of fiber-reinforced concrete with consideration of concrete strength and fiber content. *Construction and Building Materials, 138*, 222–231.

Li, Z., Zhou, X., Ma, H., & Hou, D. (2022). *Advanced concrete technology*. John Wiley & Sons.

Liese, W., & Kohl, M. (2015). *Bamboo: The plant and its uses*. Springer.

Ma, Y., Tan, W., Wang, J., Xu, J., Wang, K., & Jiang, J. (2020). Liquefaction of bamboo biomass and production of aromatic compounds. *Journal of Bioresources and Bioproducts, 5*(2), 114–123.

Mačiulaitis, R., Vaičiene, M., & Žurauskiene, R. (2009). Effect of concrete composition and aggregate properties on performance. *Journal of Civil Engineering and Management, 15*(3), 317–324.

Manandhar, R., Kim, J.-H., & Kim, J.-T. (2019). Environmental, social, and economic sustainability of bamboo-based construction materials. *Journal of Asian Architecture and Building Engineering, 18*(2), 49–59.

Naik, T. R. (2020). Sustainability of the cement and concrete industries. In *Sustainable construction materials and technologies* (pp. 19–25). CRC Press.

Narayanan, S. (2013). *Introduction to reinforced concrete*. Oxford University Press.

Pacheco-Torgal, F., & Jalali, S. (2011). Cementitious materials reinforced with vegetable fibres: A review. *Construction and Building Materials, 25*(2), 575–581.

Rath, B., Deo, S., & Ramtekkar, G. (2018). Curing: The easiest method to improve concrete durability. *Facta Universitatis – Architecture and Civil Engineering, 16*(3), 475–487.

Sakaray, H., Togati, N., & Reddy, I. R. (2012). Investigation on properties of bamboo as reinforcing material. *International Journal of Engineering Research and Applications, 2*(1), 77–83.

Sandanayake, M., Bouras, Y., Haigh, R., & Vrcelj, Z. (2020). Sustainable trends in waste materials in concrete. *Sustainability, 12*(22), 9622.

Shuvo, R., Tahmid, A., Chowdhury, S., Ahsan, K., & Sarkar, R. (2022). Bamboo as a reinforcing material in concrete: A review. In *Proceedings of the 6th International Conference on Advances in Civil Engineering (ICACE 2022)*.

Sikora, P., Horszczaruk, E., Cendrowski, K., & Mijowska, E. (2016). Influence of nano-$Fe_3O_4$ on cementitious composites. *Nanoscale Research Letters, 11*, Article 193.

Singh, N., Kalra, M., & Saxena, S. (2017). Nanoscience of cement and concrete. *Materials Today: Proceedings, 4*(4), 5478–5487.

Słowik, M. (2014). Shear failure mechanism in concrete beams. *Procedia Materials Science, 3*, 1977–1982.

Standards Bureau of India. (1970). *IS 383: Coarse and fine aggregate from natural sources for concrete*. BIS.

Standards Bureau of India. (2000). *IS 456: Plain and reinforced concrete—Code of practice*. BIS.

Standards Bureau of India. (2009). *IS 10262: Concrete mix proportioning—Guidelines*. BIS.

Surahyo, A., Surahyo, L., & Luby. (2019). *Concrete construction*. Springer.

Tamang, D. K., Dhakal, D., Gurung, S., Sharma, N., & Shrestha, D. (2013). Bamboo diversity and uses in Sikkim Himalaya. *International Journal of Scientific and Research Publications, 3*(2), 1–6.

Umeonyiagu, I. E. (2019). Effect of bamboo reinforcement on flexural and tensile strength. *NIPES Journal of Science and Technology Research, 1*(3).

Wang, J., Sun, H., Yu, L., Liu, S., Geng, D., Yuan, L., Zhou, Z., Cheng, X., & Du, P. (2021). Improving self-healing ability of concrete. *Construction and Building Materials, 309*, Article 124959.

Wang, X., Lou, G., & Wang, Y. (2025). Relationship between water consumption and sand–aggregate ratio. *Construction and Building Materials, 458*, Article 139664.

Yiğiter, H., Yazıcı, H., & Aydın, S. (2007). Effects of cement type and water–cement ratio on seawater resistance. *Building and Environment, 42*(4), 1770–1776.

Zheng, H., & Campbell, J. W. (2021). Early reinforced concrete in Shanghai. *Construction History, 36*(2), 81–122.