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Experimental Study of Natural Fibre Reinforced Concrete (NFRC) Pavements

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Abstract
The construction industry is rapidly shifting towards sustainable practices, with Natural Fiber Reinforced Concrete (NFRC) emerging as a promising eco-friendly alternative to conventional concrete. While NFRC offers enhanced mechanical and thermal properties, its use in pavements remains largely unexplored due to limited research on its performance and load transfer behavior. This study investigates the potential of using Natural Flax Fibre to enhance mechanical properties of concrete pavements. This study is part of an overall effort to investigate non-corrosive ecofriendly Glass Fibre Reinforced Polymer (GFRP) Bars to improve joints in NFRC pavements. In this first phase of this research study, flax fibres were introduced into concrete as a partial replacement of cement by weight (FRC-A mixes), and fine aggregates by volume (FRC-R mixes), at 0.5% and 1%. The benchmark concrete achieved a compressive strength of 6224.8 psi. Cement replacement with flax fibres resulted in slight compressive strength reductions of 5.77% and 11.31%, while fine aggregate replacement led to a significant drop of compressive strength, especially at 1% replacement. flexural strength improved with cement replacement, with FRC-A1 and FRC-A2 increasing the modulus of rupture by 4.4% and 8.66%, respectively.

Keyword
Carbon Fibre Reinforcement Polymer (CFRP), Natural Fibre Reinforced Concrete (NFRC), Jointed Plain Concrete Pavement (JPCP), Compressive Strength, Flexural Strength.

1. Introduction
Concrete is one of the most widely used construction materials due to its availability, high compressive strength, and durability. However, it has notable drawbacks, including its contribution to 8–10% of all anthropogenic CO_2 emissions and its inherent weakness in tension. To address these limitations and promote more sustainable construction practices, Natural Fiber Reinforced Concrete (NFRC) is gaining increasing attention. NFRC utilizes renewable fibers such as coir, sisal, bamboo, flax, hemp, and palm to enhance the tensile strength, toughness, and durability of concrete. Among these, flax fibers are particularly promising due to their favorable mechanical properties and environmental benefits.

Flax fibers have emerged as promising natural reinforcement material in concrete pavements due to their high tensile strength, low density, and renewable nature. When incorporated into pavement concrete, flax fibers help improve tensile and flexural performance, enhance crack resistance, and mitigate shrinkage effects. These improvements are particularly valuable in concrete pavements, where controlling micro-cracking and enhancing toughness can extend service life under heavy traffic and variable environmental conditions. Beyond pavements, flax fibers are also applied in a range of construction products, including fiber-reinforced concrete panels, insulation boards, and lightweight composites. Their sustainable and biodegradable characteristics make them attractive for green construction practices, as they reduce reliance on synthetic fibers and contribute to lowering the overall carbon footprint of construction materials. However, flax fibers are sensitive to moisture and long-term durability issues, which has led researchers to investigate surface treatments, chemical modifications, and hybridization with synthetic fibers or polymers to improve performance and longevity in demanding civil engineering applications [1,2].

JPCP is a commonly used pavement system for urban roadways and airport runways, where joints are strategically placed to manage cracks from temperature and moisture variations. These joints, however, are vulnerable to high stress and deflections, often resulting in distresses such as faulting, pumping, and corner breaks. To maintain load transfer and slab alignment, dowels are typically used across joints. Steel dowels, while effective, suffer from corrosion over time, which leads to internal stresses, joint locking, cracking, and eventual pavement deterioration. As a more durable alternative, Glass Fiber Reinforced Polymer (GFRP) dowels offer significant advantages, including corrosion resistance, lower modulus of elasticity, and lightweight characteristics [3].

This research focuses on optimizing flax fiber content in Jointed Plain Concrete Pavement (JPCP) by partially replacing fine aggregates by volume and cement by weight, aiming to improve pavement performance while reducing environmental impact. Additionally, this ongoing study investigates the use of GFRP dowels in flax fiber-reinforced NFRC pavements, aiming to enhance joint performance, extend pavement lifespan, and reduce long-term maintenance requirements. This paper presents partial findings regarding the use of natural flax fiber to enhance the mechanical properties of concrete pavements.

2. Objectives

The primary objectives of the overall study are to optimize the use of flax fibres as a partial replacement for fine aggregate and cement to enhance the mechanical properties of concrete, and to evaluate the load transfer efficiency and bond strength between dowels (steel or GFRP) and concrete in both conventional and natural fibre-reinforced concrete (NFRC) pavements. This paper presents the findings from Phase I of the overall study, which focuses on optimizing flax fibre incorporation for improved mechanical performance.

3. Materials and Research Methodology

Various materials were utilized in this research study. Portland Cement (Type I/II), along with coarse and fine aggregates, were sourced from a local supplier in Pocatello, Idaho. Flax fibres were imported from a company based in Egypt. To enhance the workability of the concrete mix, MasterPolyheed 997 admixture was incorporated. A 4% concentration of sodium hydroxide (NaOH) was used for the surface treatment of the flax fibres. The following research protocol was established to guide the study:

[1] Preparation of design mix.
[2] Preparation of concrete specimens with flax fibres.
[3] Compressive and Flexural Strength Test.
[4] Optimization of fibre content in concrete.

3.1 Concrete Mix Design

The concrete mix was designed based on the absolute volume method as defined by Mamlouk and Zaniewski [1]. Flax fibre was introduced as partial replacement of fine aggregate (0.5% and 1% by volume) and cement (0.5% and 1% by weight). Table 1. shows the mix design per cubic foot of concrete. Table 2. summarizes the various concrete specimen tested in the project.

Table 1. Mix design (per cubic foot).

Materials	Weight (lb)
Cement	24.94
Coarse Aggregate	65.14
Fine Aggregate	44.13
Water	11.23
Superplasticizer	1.75 ml/lb

Table 2. Concrete Specimen.

Sample ID	Flax fibre content	Flax fibre content (lb/yd3)	Partial replacement
CC	0%	0	-
FRC-A1	0.5%	3.24	By weight of cement
FRC-A2	1%	6.48	By weight of cement
FRC-R1	0.5%	8.18	By volume of fine aggregate
FRC-R2	1%	16.36	By volume of fine aggregate

In this study, two concrete mixes were evaluated: one conventional concrete mix (CC Mix) and one natural fibre-reinforced concrete mix (NFRC Mix) incorporating flax fibre. These concrete mixes were evaluated based on their mechanical properties.

3.2 Flax Fibre and Concrete Specimen Preparation

Flax fibres were prepared through a series of steps to ensure optimal performance and uniform distribution in the concrete mix. They were manually cut down to ≤¾ in., matching the maximum coarse aggregate size, to reduce clumping and improve dispersion. Fibers were then separated to prevent entanglement. A 24-hour alkali treatment in 4% NaOH removed surface impurities and improved bonding with the cement matrix. Afterward, fibres were rinsed and air-dried for 24 hours at room temperature. Before mixing, they were soaked in water (equal to their weight) for at least 4 hours to prevent absorption of mix water. Finally, the saturated fibres were separated again before incorporation into the concrete. Fig. 1. shows the series of steps for flax fibre preparation before adding to the concrete mixes.

Fig. 1. Preparation of fibres: a) Cutting of fibres, b) Soaking in NaOH, c) Rinsing and Drying of fibres, d) Separating of fibres before mixing.

Cylindrical and beam concrete specimens were prepared in accordance with ASTM C192 [4] using a 3.5 cu. ft. mixer. Concrete was mixed for 3 minutes, rested for 3 minutes, and mixed again for 2 minutes. Flax fibres, pre-soaked in water equal to their weight due to their high absorption capacity, for at least 4 hours, were separated and gradually added to the mix, followed by 30 seconds of additional mixing for uniform distribution. The liquid admixture was added with the mixing water. Concrete was placed in layers, consolidated by rodding, and cast in steel (cylindrical) and wooden (beam) molds. Specimens were covered with impervious plastic wraps and left undisturbed for 24 hours, then demolded and cured in water bath up to 28 days at room temperature. After curing, compressive and flexural strength tests were conducted on 50 cylindrical and 15 prismatic beam specimens, respectively at both 7 and 28 days of curing.

3.3 Compressive and Flexural Strength Test

Cylindrical specimens (4 in. × 8 in.) were tested for compressive strength at 7 and 28 days using a UTC-4722 FPR machine, following ASTM C39 [5]. Dimensions were measured with a vernier calliper, and load was applied at 35 psi/sec until failure occurred with a clear fracture pattern.

Beam specimens of size 6 inches x 6 inches x 21 inches were tested in 28 days with three-point testing machine, following ASTM C293 [6]. After the breaking point, the width and depth were measured at the fractured faces, and the modulus of rupture was calculated using Eq. 1.

$$R = \frac{3PL}{2bd^2} \tag{1}$$

Where, R = Modulus of rupture, MPa [psi], P = Maximum applied load, N [lbf], L= Span length, mm [in.], b = Average width of specimen at the fracture, mm [in.], d= Average depth of specimen at the fracture, mm [in.]. Fig. 2. shows the flexural strength test setup as per ASTM C293.

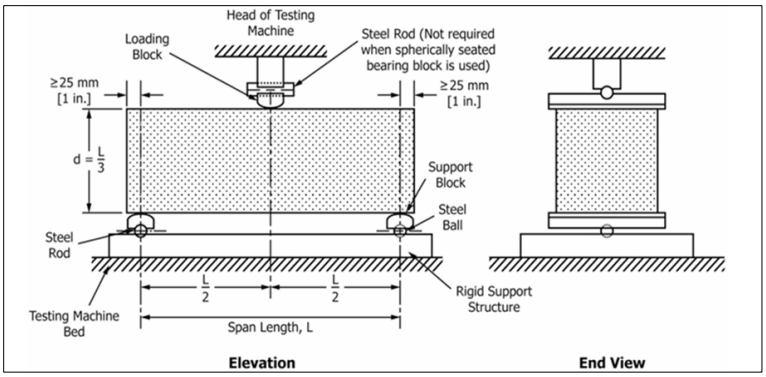
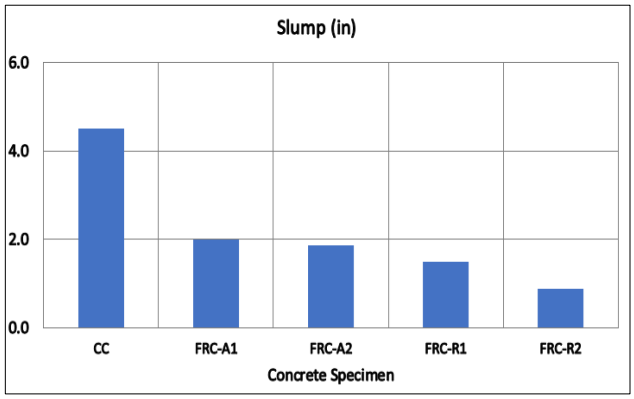


Fig. 2. Flexural strength test setup as per ASTM C293 [6].

4. Results and Discussions

4.1 Slump Test Results

The slump test was performed according to ASTM C143 [6]. Due to their high-water absorption, natural fibre reduces concrete workability. As shown in Fig. 3., increasing flax content led to a decrease in slump, indicating lower workability. Fibre length and balling also significantly affect slump. Previous studies reported slump reductions of 12%, 40%, and 60% for fibre lengths of 12, 24, and 36 mm, respectively [8], and a drop from slump of 1.5 in (38 mm) to 0 in with 0.5% flax content [9].



(a)

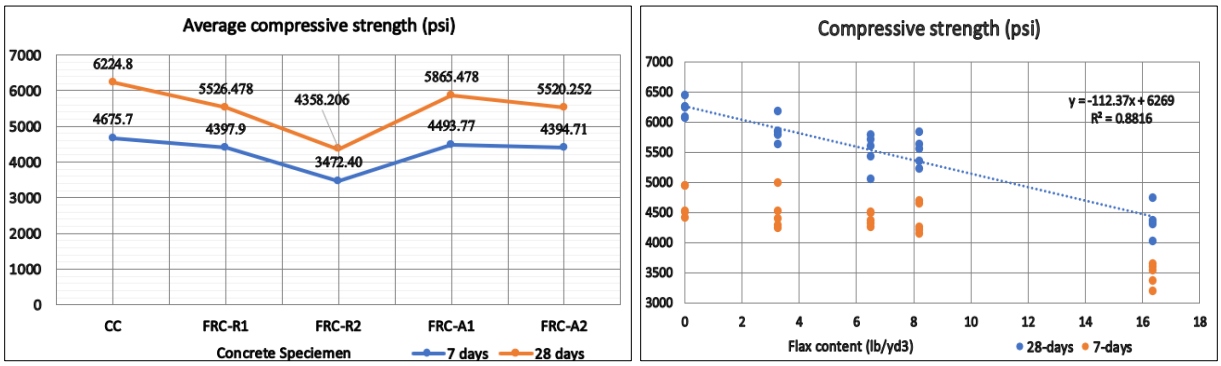
(b)

Fig. 3. (a) Slump test results, (b) Slump measurements.

4.2 Concrete Flexural and Compressive Strength Test Results

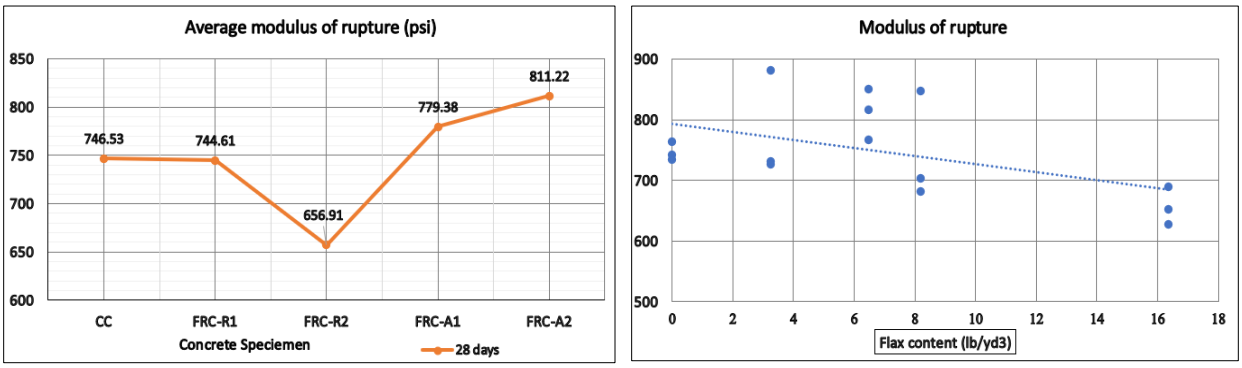
Five cylindrical samples were tested at 7 and 28 days to determine compressive strength, with average values shown in Fig. 4(a). The benchmark concrete reached 6224.8 psi. Partial cement replacement with 0.5% and 1% flax fibres yielded 5865.47 psi and 5520.25 psi, reflecting strength reductions of 5.77% and 11.31%, respectively. Replacing fine aggregate with flax fibres showed a greater decline—about 30% at 1% replacement—while 0.5% replacement maintained comparable strength at 5526.48 psi. As shown in Fig. 4(b), strength decreased with increased flax content. Similar trends were reported in previous studies [8,9], showing compressive strength reductions of 1.44%, 10.86%, and 17.48% for 0.1%, 0.2%, and 0.3% flax fibre additions, respectively. Some studies noted slight strength gains at very low fibre contents, but overall strength declined with higher doses [10]. Other factors—such as natural fiber length, type, and surface treatment—also have a direct impact on the mechanical properties of NFRC, as discussed in recent studies [2,11].At 28 days, concrete beam samples underwent center-point loading to determine modulus of rupture, with average values of modulus of rupture shown in Fig. 5(a) and the modulus of rupture values versus flax content shown in Fig. 5(b). Control concrete mix (CC) had a flexural strength of 746.53 psi. Cement replacements with flax fibres (FRC-A1 and FRC-A2) showed increases to 779.38 psi (4.4%) and 811.22 psi (8.66%), respectively. In contrast, sand replacements (FRC-R1 and FRC-R2) yielded 744.61 psi and 656.91 psi, with the 1% replacement

reducing strength by 12%. These results align with previous studies reporting improved flexural strength at lower fibre contents, despite reduced compressive strength. For example, 0.3% flax fibre increased flexural strength by 21.15% [9], and 1.5% content raised tensile strength by 18% [10]. Similar trends were noted by Vigneshkannan et al. (2020), with peak flexural strength at 1% fibre content, followed by a decline [3].



(a) (b)

Fig. 1. (a) Average compressive strength, and (b) Compressive strength vs. Flax content.



(a) (b)

Fig. 2. (a) Average modulus of rupture, and (b) Modulus of rupture vs. Flax content.

5. Conclusions

In Phase I of the study, flax fibres were used to partially replace cement and fine aggregate at 0.5% and 1%. Natural fibre-reinforced concrete was tested for slump, compressive strength, and flexural strength, with results compared to conventional concrete. Based on study findings, it can be concluded that, the mechanical performance of concrete with flax fibre reinforcement was significantly influenced by both fibre content, replacement procedure and surface treatment. While higher fibre content reduced compressive strength, it improved flexural strength and crack resistance. Among all samples, FRC-A1 showed the best overall performance with a compressive strength of 5865.48 psi and a 4.4% increase in flexural strength, making FRC-A1 and FRC-A2 suitable candidates for the next research phase. NFRC demonstrated strong potential as a sustainable alternative to synthetic or steel reinforcements by incorporating renewable materials. However, challenges remain, including inconsistent fibre lengths due to manual chopping, reduced workability despite surface treatment with sodium hydroxide and the use of superplasticizer, and fibre tangling leading to balling, which required manual separation. Future research should aim to optimize fibre content and enhance treatment methods to improve compressive strength and workability.

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