

ECO-FRIENDLY ALTERNATIVES TO SYNTHETIC FIBERS: DURABILITY PROPERTIES OF NATURAL FIBER-REINFORCED CONCRETE

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Graphical abstract



Abstract

Concrete, though strong in compression, remains weak in tension and vulnerable to various durability challenges such as shrinkage, permeability, and chemical attacks. Incorporating natural fibers, such as jute, bamboo, coconut, banana, sisal, and kenaf has shown significant potential in enhancing these properties. This study investigates the durability properties of natural fiber-reinforced concrete (NFRC) through an extensive review of existing research. Findings reveal that the inclusion of natural fibers effectively reduces drying shrinkage, controls crack propagation, and enhances resistance against freeze and thaw cycles, acid and sulfate attacks, and chloride penetration. Jute and coconut fibers improve toughness and chemical durability, while bamboo and banana fibers enhance long-term performance when treated or combined with supplementary cementitious materials like fly ash. Although fiber addition slightly decreases workability, it increases ductility, reduces permeability, and prolongs the service life of concrete. Overall, natural fibers present a sustainable and eco-friendly alternative to synthetic reinforcements, contributing to the development of durable, cost-effective, and environmentally responsible construction materials.

Keywords: natural fiber-reinforced concrete (NFRC), eco-friendly, sustainable, durability, and natural fiber.

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1.0 INTRODUCTION

Concrete is a popular composite building material comprised of cement, water, fine and coarse particles in different ratios (Mehta and Monteiro, 2014). Portland cement concrete has a tendency to fracture and is weak in tension but reasonably robust in compression. Using traditional steel reinforcing bars and, to a lesser extent, adding an appropriate amount of certain fibers can help to overcome the weakness in tension (Bentur and Mindess, 2007). The addition of fibers also makes

the fiber-matrix composite tougher, which alters how it behaves after cracking.

Fiber is a small, distinct reinforcing material. Fiber-Reinforced Concrete (FRC) is a composite material made by adding small, uniformly distributed fibers. Fibers used in concrete can generally be classified into synthetic and natural types, based on their origin and composition (Assan and Saeed, 2024).

Whereas, synthetic fibers are steel fiber, carbon fiber, nylon fiber, glass fiber, rayon fiber, and natural fibers are jute fiber, bamboo fiber, coconut fiber, banana fiber, sisal fiber,

kenaf fiber, flax (Iqbal et. al., 2024 & Roy et. al., 2024). Due to some advantageous effects of natural fiber-reinforced concrete over synthetic fiber-reinforced concrete, natural fiber-reinforced concretes are more repayable.

The advantageous effects of FRC are shown in Figure 1.



Figure 1 Advantagous effects of FRC.

In order to prevent cracking in concrete brought on by drying shrinkage and plastic shrinkage, fibers are typically employed. Fiber makes concrete components more ductile. Moreover, it decreases the permeability of concrete, which in turn lessens water leakage. Greater abrasion and shatter resistance are produced by certain fiber kinds in concrete. It increases the impact load's resistance. The material offers a mechanism for both toughness and fracture resistance while it is under stress. Fiber-reinforced concrete may sustain substantial loads even at deflections far greater than the fracture deflection of plain concrete, whereas plain concrete fractures quickly when the deflection equivalent to the ultimate flexural strength is exceeded (Usman et. al., 2024 & Ferreira et. al., 2023). Figure 2 shows the Stress-Strain relationship between Plain concrete and FRC, and Figure 3 illustrates the Crack and fracture resistance between Plain concrete and FRC that are discussed in this article.

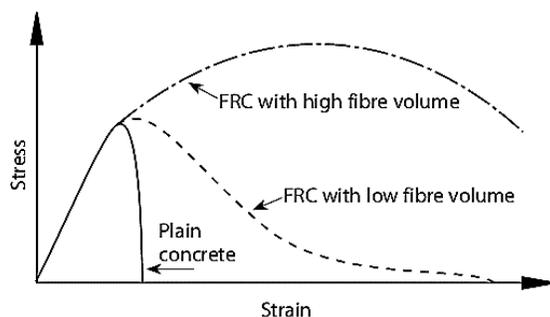


Figure 2 Stress-Strain relationship between Plain concrete and FRC (Hossain, 2012).

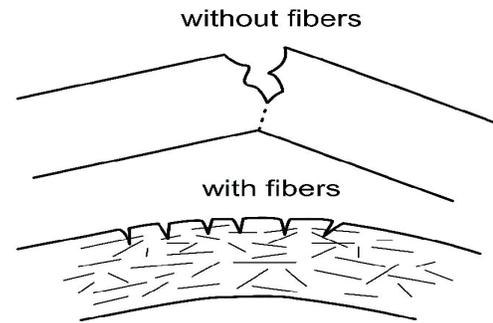


Figure 3 Crack and fracture resistance between Plain concrete and FRC (Rocha et. al., 2022).

The aim of the study is to:

- Investigate the durability properties of natural fiber-reinforced concrete according to various researchers.
- Observe different types of natural fiber reinforced concrete.
- Investigate the different durability parameters for different types of natural fibers that are incorporated in concrete.

2.0 BACKGROUND ON NATURAL FIBERS IN CONSTRUCTION

In the past, a lot of work has gone toward improving concrete structure behavior. Several researchers have investigated concretes using steel-glass fibers and other elements to enhance the behavior of concrete, focusing on tensile, compressive, flexural, shear strength, and other qualities. It has long been known that introducing fibers can enhance the behavior of brittle materials (Ali et. al., 2024).

Fibers are now made from steel, glass, carbon, synthetic, and natural substances. Each of these fibers has unique advantages. Yet, the most typical one is steel fiber. According to reports, the first experimental test to enhance the properties of concrete using discontinuous steel reinforcing components, such as nail segments, was conducted in 1910 (American Concrete Institute [ACI], 2003).

Since time immemorial, man has used natural fibers in constructions. In ancient Mesopotamia (c. 3000 BCE), adobe bricks were made by mixing mud and straw, which enhanced tensile strength and minimized cracking during drying. Nile mud bricks were made more ductile and long-lasting in pharaonic buildings by the addition of straw, reeds, and animal hair in ancient Egypt (Lucas and Harris, 1962). These methods became common throughout the world: sisal and coconut coir were used to reinforce earthen walls in Mesoamerica, bamboo was used to reinforce rammed earth in China, and hemp or flax was used in lime mortars in medieval Europe.

The 20th century moved to steel, glass and synthetic fibers due to their mechanical excellence, however, problems such as corrosion, high embodied carbon and non-biodegradability led to the reversion to natural fibers in the 1990s. The development of alkali resistance treatments and hybridization has rendered sisal, jute, coir, and flax applicable to modern concrete, enhancing tensile, flexural, and impact strength and enhancing sustainability (Ali et al., 2024).

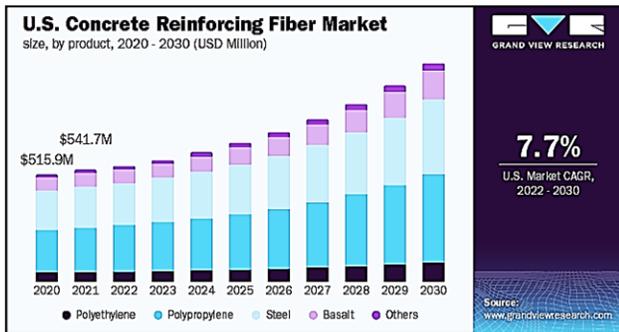


Figure 4 U.S. concrete reinforcing fiber market (Grand View Research, 2023).

Concrete reinforcing fibers were valued at USD 2.19 billion in 2021, and the market is expected to increase at a compound annual growth rate (CAGR) of 6.8% from 2022 to 2030. A greater emphasis on employing environmentally friendly building materials and more public investment in infrastructure construction are expected to support the company's growth. It may be concluded from Figure 4 that the use of fiber-reinforced concrete increases day by day. By 2023, it may be almost double.

3.0 OVERALL DURABILITY ISSUES ON CONCRETE

Concrete durability refers to its ability to resist weathering, chemical attacks, and surface wear while maintaining its essential mechanical properties. The required level of durability varies based on the environmental conditions to which the concrete is exposed and the performance characteristics desired for its specific application.

All concrete durability issues are caused by water. For the issues to arise, water must be present or be involved in the reactions. As a result, the water-tightness, or permeability, of concrete is inextricably linked to its durability. Some factors that affect the durability of concrete are (The Constructor, 2023):

- i. Water Quality.
- ii. Aggregate Quality.
- iii. Cement Content.
- iv. Permeability.
- v. Mix proportions.
- vi. Curing Period.
- vii. Concrete Compaction.
- viii. Moisture

Water to be used in concrete production should be potable, clear, and devoid of substances such as salts, sugar, oils, acids, and alkalis. These contaminants can cause concrete to deteriorate or steel to corrode as a result of various chemical reactions. If the water contains a high amount of salt, then the concrete may suffer from Sulfate Attacks, chloride attacks.

The durability of hardened concrete will undoubtedly be enhanced with the use of high-quality aggregates in the concrete mix. The aggregate particles should have a smooth, rounded form. The workability of fresh concrete is affected by particles that are flaky and elongated. Rough-textured angular

aggregates are suggested for improved bond formation between components, although they require more cement. Before utilizing, aggregates should have their moisture content checked. A very workable mix might result from an aggregate with too much moisture (Reddy, 2024).

The water-cement ratio will decrease, and the workability will also decrease if the cement content utilized is less than what is needed. If too much cement is used, issues like drying shrinkage and the alkali-silica reaction may develop, which ultimately affects how durable the concrete is.

Concrete that is water-permeable expands in volume, develops fractures, and eventually disintegrates. Since it regulates water flow and the pace at which moisture, which may contain a toxic chemical, enters concrete, concrete permeability affects how long concrete will last.

Improper mixing and compaction may increase the porosity of concrete, which may lead to a reduction in the durability of concrete.

Some durability issues that arise within the concrete are:

- i. Shrinkage
- ii. Creep
- iii. Alkali Aggregate Reaction
- iv. Frost Resistance
- v. Corrosion of Embedded Rebar
- vi. Sulfate Attack
- vii. Acid Attack
- viii. Resistance to Heat and Fire



Figure 5 Concrete affected by Freezing and Thawing (DRPC Inc., 2023).

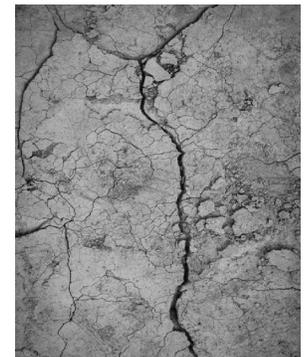


Figure 6 Concrete damage due to drying shrinkage (Zhang et. al., 2024).



Figure 7 Concrete damage due to creep (CivilConcept., 2023).



Figure 8 Carbonated Concrete (Rooflock., 2019).



Figure 9 Spalling of Concrete due to Sulfate Attack (Mirvalad, 2023).



Figure 10 Concrete damage due to Alkali-Aggregate Reaction (Wikipedia., 2021).



Figure 11 Concrete damage due to Acid Attack (The Constructor., 2023).

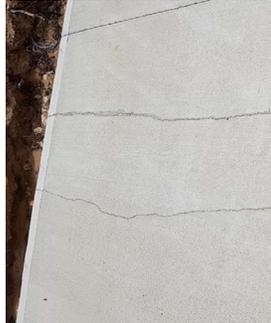


Figure 12 Concrete damage due to High Temperature (EP & Consulting., 2023).

Figures 5 to 12 illustrate the different durability issues that arise within the concrete.

Concrete that is completely saturated is harmed by the freezing and softening of the water within it when it is repeatedly frozen and thawed. When concrete is continuously frozen and thawed, the water inside of it softens and freezes, which damages the entirely saturated concrete. Concrete may spill due to the coarse aggregate included in the concrete being affected by freeze-thaw cycles.

Drying shrinkage is a crucial factor influencing the durability of cement-based composites. It occurs when hardened concrete loses capillary water, leading to volume reduction and the formation of cracks that compromise the material's long-term performance (Zhang et. al., 2024)

Concrete's pH is lowered when wet concrete is exposed to the environment due to a reaction with atmospheric carbon dioxide. Concrete reinforcement begins to corrode when the pH of the concrete falls below 10. Concrete degradation results from the corrosion of reinforcement.

Concrete disintegration occurs when sulfates like sodium sulfate, magnesium sulfate, and others damage concrete buildings. Chemical reactions between hydrated cement products and sulfate solutions are to blame for this response. Sulfate attack often occurs because of unclean aggregates, excessive sulfate content in the water used to mix the concrete, sulfate-containing soil around the concrete building.

Alkali-aggregate reaction, also known as an alkali-silica reaction, occurs when the cement's alkali concentration reacts with the aggregates' silica content. This reaction affects how long concrete will last. This reaction causes the concrete to expand, which ultimately results in significant cracking and concrete degradation.

Concrete durability suffers significantly when exposed to organic acids such as acetic acid, lactic acid, butyric acid. Concrete can corrode if formic acid is applied to its surface.

4.0 DURABILITY PROPERTIES OF DIFFERENT TYPES OF NATURAL FIBER-REINFORCED CONCRETE

Different types of fibers are available that can use in concrete to improve different compressive and tensile strength of concrete. Natural fibers are jute fiber, bamboo fiber, coconut fiber, banana fiber, sisal fiber, kenaf fiber, flax, etc. Different types of Natural fibers used in concrete are shown in Figure 13.



Figure 13 Different types of Natural Fiber used in concrete (Nidhi, 2018).

Table 1 shows the summary of different durability issues in the

case of natural fiber-reinforced concrete according to various researchers.

Table 1 Case study on different durability issues.

Researcher's Name	Sample Descriptions	Identifications
(Zhang, 2019)	9±2 mm, 16±2 mm, and 25±2 mm length jute fibers were used in this research. These fibers are immersed in the alkaline solution at a bath ratio of 1:40 for two hours.	The study found that treating jute fibers with an alkaline solution effectively removes hemicellulose, creating deeper surface grooves that enhance friction and bonding with the cement matrix. The proper incorporation of jute fibers can fill microcracks, decrease porosity, and delay or prevent crack initiation and propagation. Consequently, jute fiber reinforcement improves the toughness, crack resistance, and overall durability of concrete.
(Affan, 2022)	In order to test under freeze-thaw conditions, 50 mm length and 10 to 50 μm diameter jute fibers are used to prepare the specimens.	In the conclusion, each property is compared in relation to the corresponding PC specimens and the corresponding number of freeze-thaw cycles. Seasonal temperature variations can lead to concrete degradation and deterioration. Concrete's physical and mechanical qualities changed as a result of degradation. In this investigation, fissures on the specimen surfaces and mass loss are seen as a result of freeze-thaw cycles. Dynamic and mechanical characteristics change as a result of the decrease in specimen mass. Figure 14 displays a comparison of mechanical characteristics. There is no discernible difference in the strength qualities between JFRC (with 5% inclusion, by cement mass, which is just 0.8%, by concrete volume) and PC (i.e., only up to 16%). Even after freeze-thaw cycles, the toughness index for JFRC has improved significantly (up to 89%). Given the increase in concrete's strength, fibers have drawn a lot of interest. Moreover, an increase in hardness can aid in limiting the start, spread, or coalescence of cracks. Similarly, to this, by considering such positive outcomes, additional natural fibers may also be investigated. The investigation of the behavior of jute fibers in concrete under freeze-thaw conditions is only the first phase.

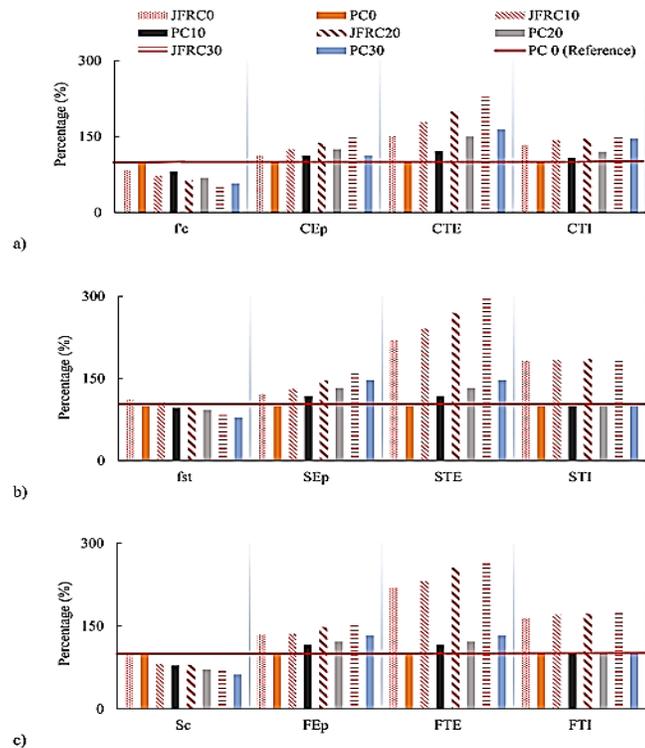


Figure 14 JFRC and PC characteristics after 0, 10, 20, and 30 cycles of freezing and thawing are compared. Compressive, split tensile, and flexural characteristics are listed in order from a to c.

(Ahmad et. al. 2022) Review over a different percentage of jute fibers with different lengths of jute fibers from 10 to 25 mm.

The WA of concrete reinforced with nylon and JTF combination is shown in Figure 16 after 28 days. At a 2% combination of nylon and JTF, the water absorption (WA) of concrete was measured at 3.07%, whereas the mix containing 0% nylon and JTF by volume exhibited a lower WA value of 2.40%.

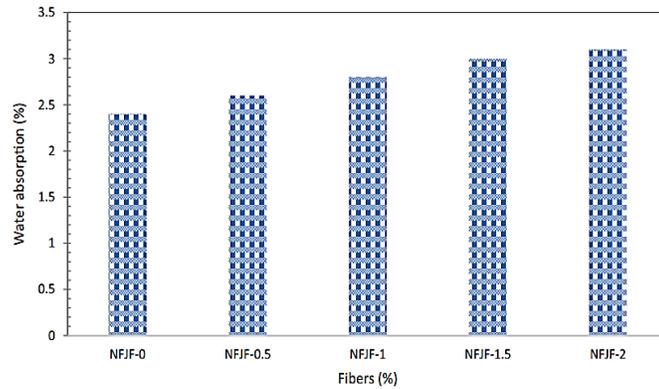


Figure 15 Water absorption of concrete

From Figure 15, it was concluded that water absorption increases with the percentage of fiber increase.

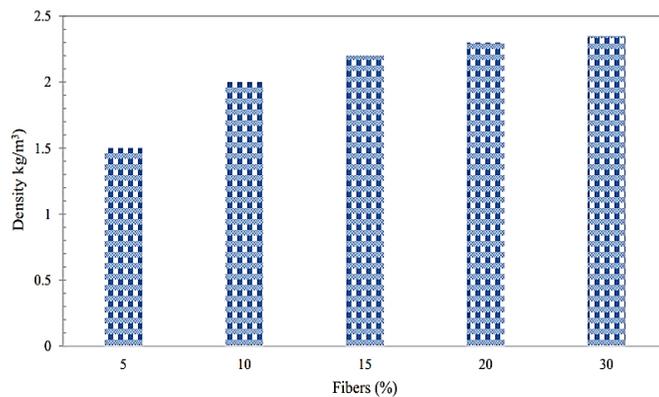


Figure 16 Density of concrete

From Figure 16, it was summarized that density increases with the percentage of fiber increase.

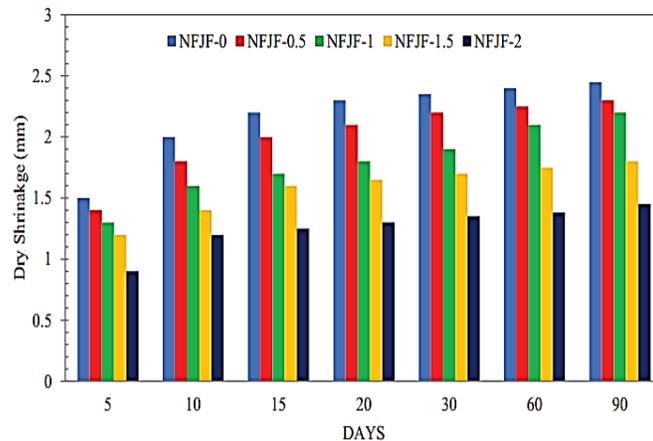


Figure 17 Dry shrinkage of concrete

According to Figure 17, incorporating a combination of nylon and JTF fibers after each curing period effectively reduces the drying shrinkage (DS) of concrete. A significant decrease in DS was observed in concrete reinforced with varying volume fractions of nylon and JTF, with the reduction becoming more pronounced as the fiber content increased. Following exposure to an acid attack, the compressive strength (CS) of concrete decreased notably. Between 30 and 90 days after the acid exposure, the CS dropped by approximately 40.63%. When JTF was added at 1% and 2%, the reductions in CS were 35.77% and 39.39%, respectively. Figure 18(a) and (b) present the compressive strength results before and after the acid attack.

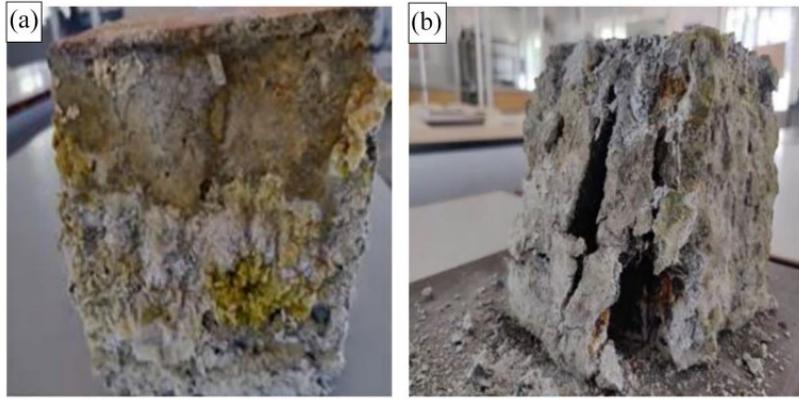


Figure 18 Acid attack (a) before and (b) after compression.

(Gao et. al., 2022)

Bamboo fiber with 10 to 50 mm length was used to prepare the specimen.

From Figure 19, it was concluded that the degradation of bamboo fibers caused by immersion in an alkaline pore solution poses the greatest risk to the long-term durability of bamboo fiber-reinforced cement composites. However, optimizing the cementitious materials to lower pore solution alkalinity, boiling the bamboo fibers in distilled water, and applying NaOH treatment can significantly enhance the performance of bamboo fiber-reinforced cement mortar.

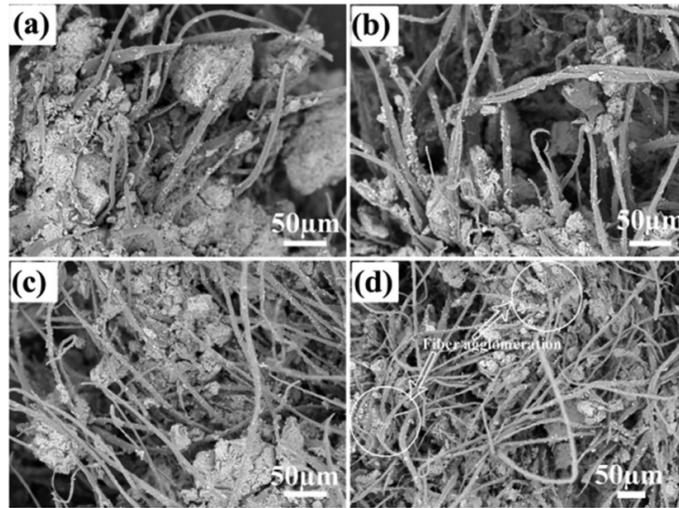


Figure 19 SEM images of the fracture surface of the specimens with different BF contents: (a) 4 wt% BF, (b) 8 wt% BF, (c) 12 wt% BF, and (d) 16 wt% BF

(Thanushan et. al., 2019)

Blocks of size 100 x 100 x 60 mm³ were made for the control, and 0.4% of coconut fiber-reinforced earth cement blocks were for durability testing.

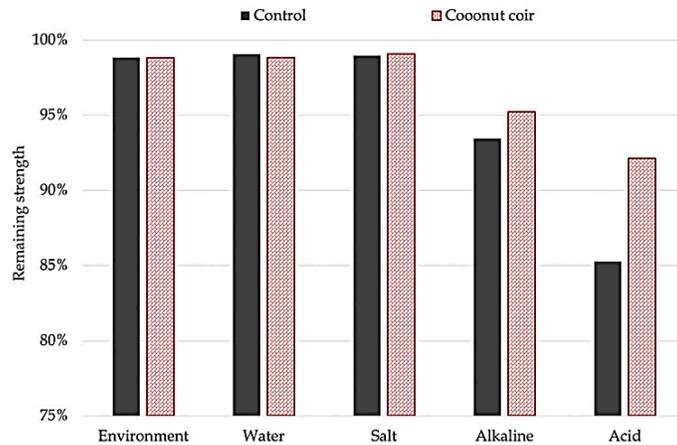


Figure 20 Remaining strength after a chemical attack

From Figure 20, it was concluded that coconut fiber saves concrete from different types of chemical attacks.

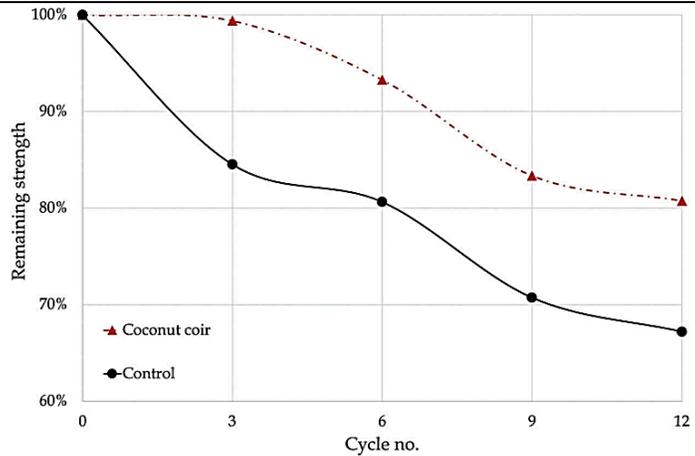


Figure 21 Remaining strength after freeze and thaw cycles.

According to Figure 21, coconut fiber reinforced concrete shows better results than conventional concrete.

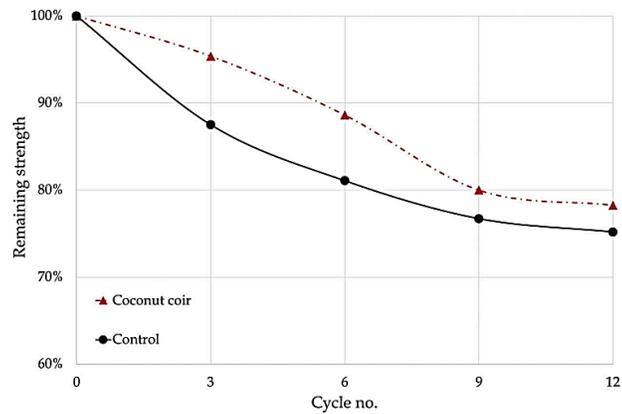


Figure 22 Remaining strength after wet and dry cycles.

According to Figure 22, coconut fiber reinforced concrete shows better results than conventional concrete.

(Kandasamy Sekar, 2019) and The durability characteristics of coconut fiber utilized in coconut shell concrete (CSC) have been researched. According to the literature, this study took into account the effects of three alternative curing conditions: complete water immersion W1, site curing condition W2, (the technique used in the field-covering the specimen with wet gunny bags), and no curing W3 (air-dry).

The water absorption of CC, CCF, CSC, and CSCF mixes under W1, W2, and W3 curing conditions is depicted in Figure 23.

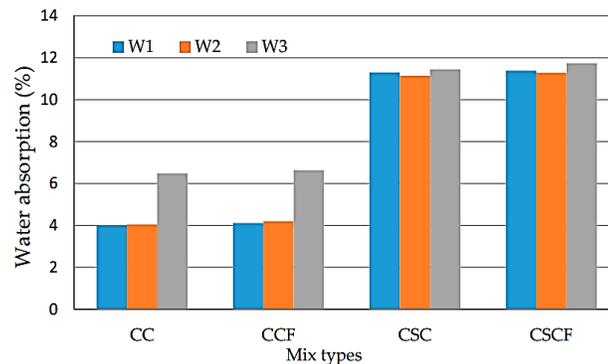


Figure 23 Results of a test for water absorption.

Figure 24 displays the Volume of Permeable Voids (VPV) test results for the CC, CCF, CSC, and CSCF mixes for the W1, W2, and W3 curing conditions at 28 days.

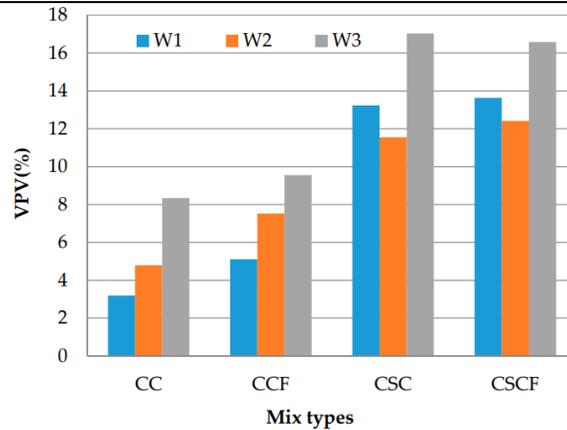


Figure 24 Volume of Permeable Voids (VPV) test results.

Figure 25 displays the results of the Rapid Chloride Penetration Test (RCPT) tests on the CC, CCF, CSC, and CSCF mixes for the W1, W2, and W3 curing conditions at 28 days.

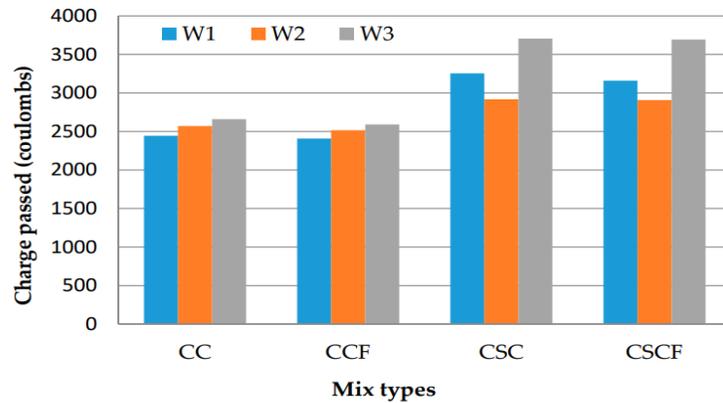


Figure 25 Results of the Rapid Chloride Penetration Test (RCPT)

Information on the pore structure of concrete in Figure 26 will be revealed by a sorptivity test on a concrete specimen.

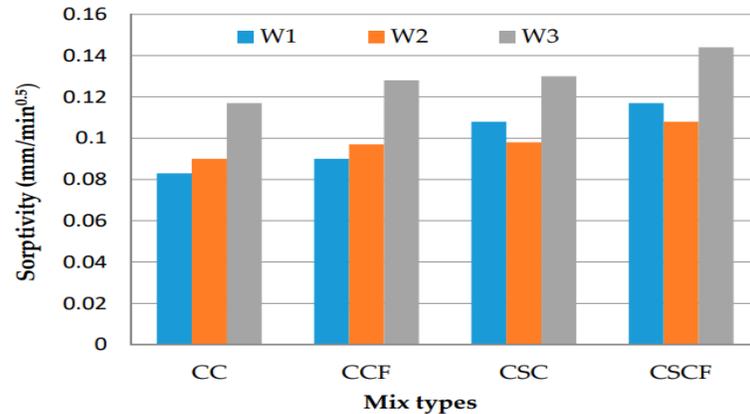


Figure 26 Test results for sorptivity.

Compared to site curing and air-dry curing, full water immersion yields better results regarding water absorption and the number of permeable pores in standard concrete mixes, both with and without coconut fibers. However, for coconut shell concrete mixes, with or without coconut fibers, site curing outperforms both full immersion and air-dry curing. All mixtures of conventional concrete as well as coconut shell concrete, with or without fibers, are classified as having moderate chloride-ion penetrability. Under both full immersion and site curing conditions, sorptivity test results for standard concrete mixes, with or without coconut fibers, remain below 0.1 mm/min^{0.5}. Similarly, coconut shell concrete without fibers under site curing also shows reduced sorptivity. This indicates that the quality of these concretes is superior to other mixtures. Both conventional and coconut shell concrete

mixtures, regardless of fiber inclusion, demonstrate sufficient resistance to temperature variations for two hours, making them suitable for construction purposes. Overall, the findings confirm that, despite being derived from wood, coconut fibers and shells can be effectively used in concrete production and applied practically, thanks to their favorable durability characteristics.

(Anowai and Job, 2017) Cement was substituted with fly ash at mass ratios of 0, 10, 20, 30, and 40%. For all mixtures, banana fibers with a length of 30 mm and a volume percentage of 0.5%, which were the best results for grade 25 concrete reinforced with banana fiber, were employed.

Fly ash reduces the acid attack shown in Figure 27. And Fly ash reduces the sulfate attack shown in Figure 28.

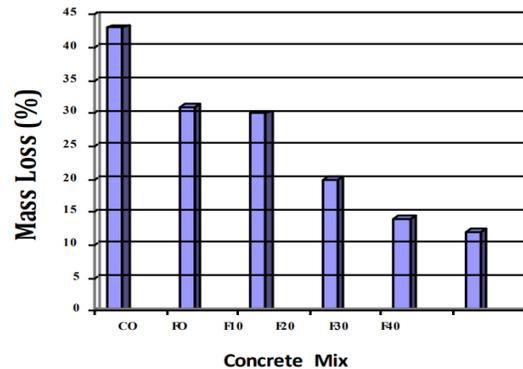


Figure 27 After being exposed to sulphuric acid, banana fiber-reinforced fly ash concrete lost mass.

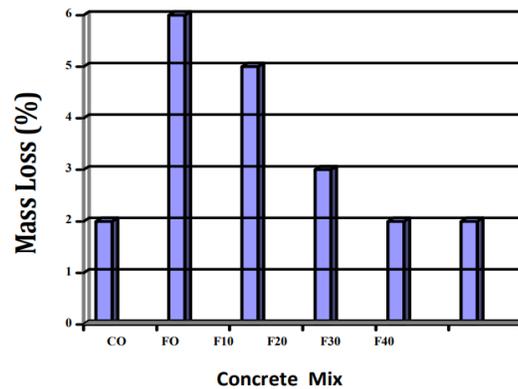


Figure 28 After being exposed to magnesium sulfate, banana fiber-reinforced fly ash concrete lost mass.

By minimizing weight loss and compressive strength loss, partial cement substitution with fly ash increased the resilience of banana fiber-reinforced fly ash concrete. The best outcome was obtained with a specimen that replaced 10% of the cement with fly ash. The 20% fly ash substitution, however, is also beneficial. According to the findings, concrete specimens made with fly ash and banana fiber reinforcement saw a reduced mass loss as a result of acid exposure. The resistance of concrete reinforced with banana fiber to chloride attack was increased by partially substituting cement with 10% and 20% fly ash. The fire resistance of concrete with banana fiber reinforcement was increased by partially substituting fly ash for cement.

(Balasubramanian, 2016) Sisal fibers were used in concrete in varying percentages and lengths.

Plain and fiber-resistant special concrete, as well as conformist concrete, were evaluated for their durability using the rapid chloride penetration test (RCPT), impact testing, water absorption, and saturated water absorption. Through the learning process, it is clear that special concrete has superior durability qualities to normal concrete of an equivalent grade, and that the inclusion of fibers improves those qualities.

(Awang, 2015) 19 mm length kenaf fibers were used to prepare concrete specimens.

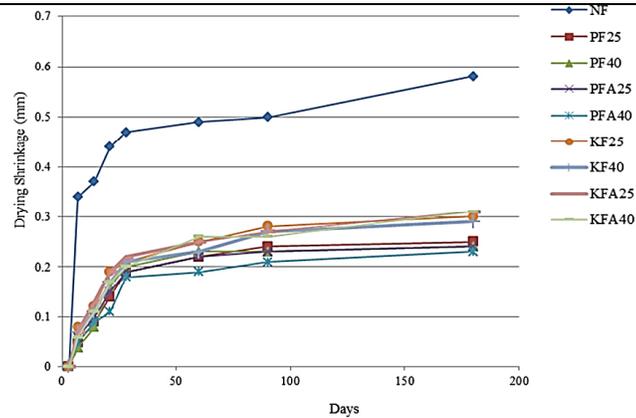


Figure 29 Drying Shrinkage of Kenaf by Days of Test.

Compared to conventional concrete, Kenaf fiber-reinforced concrete reduces the drying shrinkages of concrete. From Figure 29, it can be concluded that due to the reduction of drying shrinkage, the durability of kenaf fiber-reinforced concrete increases at a certain percentage.

Having learned the case study in Table 1, there were some issues that were raised regarding treated and untreated Natural fibers. The natural fibers are not treated and are therefore likely to degrade in the alkaline cement matrix leading to poor fiber-matrix bonding, high porosity, and low durability. Chemically treated fibers, especially those treated with alkaline solutions, on the other hand, exhibit better bonding, reduced water absorption, better crack control and

increased long-term durability, which underscores the significance of chemical treatment in natural fiber-reinforced concrete. Table 2 showed the Treatment Methods of improving Durability of Natural Fibers in Concrete.

Table 2 Treatment Methods for Enhancing Durability of Natural Fibers in Concrete

Fiber Type	Treatment Methods
Jute Fiber	Alkaline (NaOH) treatment to remove hemicellulose and lignin, reduce water absorption, and improve fiber-matrix bonding.
Bamboo Fiber	Alkaline treatment (NaOH) or surface coating (epoxy/latex) to enhance alkali resistance and durability.
Coconut Fiber	Alkaline (NaOH) treatment or silane treatment to improve interfacial bonding and durability.
Banana Fiber	Alkaline (NaOH) treatment or steam/thermal treatment to increase fiber stability and bonding.
Sisal Fiber	Alkaline (NaOH) treatment followed by water washing to improve alkali resistance and tensile performance.
Kenaf Fiber	Alkaline (NaOH) treatment or acetylation to reduce moisture sensitivity and enhance durability.

5.0 DISCUSSION AND CONCLUSION

It may be concluded from various researchers:

- Natural fibers reduce the tensile cracks, which enhance the durability of natural fiber-reinforced concrete.
- Drying shrinkage may be reduced by using natural fiber in concrete.
- Although the size of the cracks is less in FRC, the crack density is higher. Any form of fiber addition to plain concrete makes it less workable.
- Natural fiber may reduce Rapid Chloride Penetration which increases the durability of natural fiber-reinforcement concrete.
- Concrete's ductility and capacity to support loads after breaking are both improved by fiber inclusion.
- Untreated natural fibers degrade in the alkaline cement matrix, leading to poor bonding and reduced durability, whereas chemically treated fibers show improved bonding and long-term durability, making

- fiber treatment essential for durable natural fiber reinforced concrete.

From the overall observations of various researchers, Table 3 may be recommended.

Table 3 Different Types of Fiber and their Key Findings on Durability

Fiber Type	Key Findings on Durability
Jute Fiber	Reduces porosity, delays cracking, improves toughness; resistant to freeze-thaw cycles.
Bamboo Fiber	Needs alkaline treatment to prevent degradation; excessive fiber increases porosity.
Coconut Fiber	Improves chemical and thermal resistance; reduces permeability; performs well under freeze-thaw and wet-dry cycles.
Banana Fiber	Enhanced when combined with fly ash—reduces mass loss under acid/sulfate attacks, improves fire resistance.
Sisal Fiber	Improves impact and chloride resistance; strengthens concrete under harsh exposure.
Kenaf Fiber	Reduces drying shrinkage, leading to better long-term durability.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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