Fiber Reinforced Polymer Composite as a Strengthening of Concrete Structures: A Review

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Abstract. For centuries, concrete is the main material most widely used in a building. The strength and durability of this material will decrease over time due to several factors that influence the mechanism of its structural characteristics. Although the compression strength is excellent, it is weak in tensile. Fiber reinforced polymer (FRP) composites are widely used as an alternative material to replace metal-based engineering materials. This material has properties such as lightweight products, low production costs, easy to form, high tensile and flexural strength, and elastic. The purpose of this review paper is to provide information about the application of FRP composites as reinforcement of concrete structures either as repairs or new structures. Initially, FRP composite materials were used as reinforcement structures for reinforced concrete column-beam joints. The resulting structure has increased the flexural ability due to the load given. The addition of natural fiber (jute) to concrete also increases in the hardness of concrete. Other investigations regarding the application of FRP composites in concrete to improve strength performance are discussed in this paper. Finally, the technique of wrapping FRP composites in concrete in an effort to improve the performance of the resulting structure is also discussed in the paper.

1. Introduction

In this paper, the reinforcement of damaged concrete structures using the application of fiber-reinforced polymer composite materials will be reviewed and reported. The importance of using FRC materials to strengthen concrete structures will be discussed briefly and the technologies used to wrap damaged concrete from FRP materials will be studied. Initially, an introductory study of current composite materials will be discussed. The application of natural, synthetic and hybrid fibers reinforced composite materials for concrete wrappers will also be studied. Finally, the strength of the new concrete structure reinforced by them will be summarized to obtain the best potential of each fibers material.
In general, FRP materials consisting of high strength fibers embedded in a polymer matrix. These materials were developed primarily using fibers such as natural fibers (jute, kenaf, cellulose, etc.), synthetic fibers (glass, carbon, aramid, Kevlar, etc), and hybrid fibers (sisal/glass, jute/glass, etc.) [1]. The fibers in this material have the ability to carry good loads, are rigid and strong, resistant to environmental conditions and possible damage [2]. In addition, they have a long fatigue life and good adaptability in a structure [3]. Moreover, these materials have corrosion resistant, wear resistant, good appearance, high temperature resistance, environmental stability, heat and electricity resistant, so it is widely applied as an advanced material in the fields of aircraft, automotive, sports equipment, etc. [4].

In the late 1990s, concrete beam-column joints in industrial buildings used reinforcement from FRP composites as an alternative material [5]. These applications include RCs on beams, floor slabs, beam joints, pipes, etc. RC geometry that is used varies, including: rectangular, square, circular, etc., with reinforcement of E-glass-epoxy or carbon-epoxy jacket. The work is shown in Figure 1.

In general, the application of FRP composite materials in a concrete structure is the method of wrapping part or all of its surface [6–9]. Therefore, methods of wrapping concrete using FRP composite materials are discussed and reviewed. Initially, the FRP wrapping concept used the steel jacket application technology [10]. This technique uses FRP wrapping on concrete surfaces and steel reinforcement structures on the outside. Next, other wrapping concepts developed, such as the hand lay-up method [11] and carbon anchor [6].

![Figure 1](image-url) Repair on building RC column with FRP composites: (a) damaged concrete, (b) wrapping process, and (c) RC column has been repaired [5].

2. Composite Materials
For decades, composite materials have been widely used as an alternative material to substitute metal-based engineering materials. This is due to the light weight of the product, low cost of production and easy to form [12]. In addition, there are several other characteristics of this material which will be discussed further. At present, this material is found in various forms of products that are closely related to human needs, such as components of household appliances, automotive, buildings, aircraft, etc. In this study, this material will be used to strengthen the beam/column concrete structure as either a repair or a new structure. The investigation was carried out using jute, glass, and hybrid fibers as the reinforcement to obtain the mechanical behavior of the structure produced due to tensile, compressive, and flexural loads.

Composite material is a combination of two or more materials with different phases chemically forming a new material structure with new mechanical properties which are still dominated by the constituent materials independently [13]. This material consists of two main components, including: fiber as a reinforcement and a continuous phase material as a matrix. In general, in polymer composite materials, fibers are solid and rigid, and as a source of reinforcing the material formed. While the matrix is generally in the form of liquid covering the fiber so that the load is given not directly to it, but will be continued in all directions.
2.1. Classification of Composite Materials

Based on the reinforcement, composite materials can be divided into: particle reinforced, fiber reinforced and structure reinforced composites [12] (see Figure 1). In sketch, the forms of reinforcing the composite material are shown in Figure 2 [14].

The application of fiber in composite materials is due to its basic properties of being light, stiff, and strong. In the manufacturing process, fiber has stronger properties than the basic material. This is due to the preferential orientation of the molecules in the fiber and the small number of defects compared to the base material. Based on its length, the fibers are divided into: short, long, and continuous fibers. Based on its strength: low (LM), medium (MM), high (HM), ultrahigh (UHM) modulus. Based on its chemical composition: organic and inorganic [15] (See Figure 3).

The matrix has the main function to hold the fibers together and transferring the load through the interface to the reinforcing fiber and to the composite from an external source [16]. In general, Matrix is distinguished into three major types: polymer, metal and ceramic matrix composites [17] (See Figure 4).

![Figure 2. The classification of composite reinforcements [12]](image1)

![Figure 3. Geometries of composite materials reinforcement: (a) particulate composites, (b) fiber composites, and (c) laminar composites [14]](image2)

The matrix of polymer matrix composites (PMCs) is a polymer that can be either a thermoset or a thermoplastic. The thermoset matrix is formed by the process of irreversible chemical transformation of the resin system to form the composition of the cross-linked polymer matrix, such as: polyester resin, epoxy resin, vinyl ester resin, etc. On the other hand, in the hardening process, the thermoplastic polymer does not undergo any chemical transformation [18].
The ability to withstand high temperatures, humidity, radiation, zero gas release in a vacuum, and good thermal and electrical conductivity are the advantages of metal matrix composite matrices (MMCs) [19]. In a ceramic matrix composite (CMC), the matrix and fibers can be composed of ceramic materials. [20]. For example: carbon fiber and carbon can also be considered as ceramic materials. The materials most commonly used as raw materials for CMC include: Carbon fiber (C), silicon carbide (SiC), alumina (Al2O3) and mullite (Al2O3 - SiO2) [21].

2.2. Natural Fibers
Natural fiber reinforced composite materials (NFRC) are a new class of engineering materials. The focus in this area is increasing rapidly, especially in terms of industrial applications and fundamental research. This is because they are renewable, inexpensive, recyclable and biodegradable. [22]. There are various types of natural fibers that are being studied by previous researches such as wood [23], roselle [24], pineapple [25], jute [26], ramie [27], hemp [28], kenaf [29], sisal [1], palm [30], and banana [31].

Some previous researchers have divided NFRC into several types. Based on the source, NFRC is divided into three major classifications: plant fibers, animal fibers and mineral fibers [32], [33]. Furthermore, plant fibers are further divided into two sub categories: primary plant fiber and secondary plant fiber. Animal fiber comes from animal body parts, such as wool, silk, feathers, etc. Primary plant fiber is produced by plants such as: jute, kenaf, hemp, flax, ramie, etc. Secondary plant fiber is obtained as a waste product from plants, such as wood pulp, roots, etc. [32]. Mineral fibers are
made from mineral materials that have been further modified, such as: glass fibers, asbestos, aluminum oxide, silicon carbide, etc. [33].

The mechanical properties of NFRC are a response due to the external load applied. These properties are used to characterize and distinguish composite materials [34]. The mechanical properties of natural fiber reinforced composites are shown in table 1.

| No | Name of fiber | Tensile strength (MPa) | Young’s modulus (GPa) | Flexural strength (MPa) |
|----|---------------|------------------------|-----------------------|------------------------|
| 1  | Abaca         | 400-980                | 6.2-20                | -                      |
| 2  | Alfa          | 35                     | 22                    | -                      |
| 3  | Bamboo        | 140-800                | 11.32                 | 32                     |
| 4  | Banana        | 600                    | 17.85                 | 76.53                  |
| 5  | Coconut       | 500                    | 2.5                   | 58                     |
| 6  | Coir          | 175                    | 4-6                   | 6                      |
| 7  | Cotton        | 400                    | 12                    | 43.3                   |
| 8  | Curaua        | 87-1150                | 11.8-96               | -                      |
| 9  | Flax          | 800-1500               | 60-80                 | 165                    |
| 10 | Fique         | 200                    | 8-12                  | -                      |
| 11 | Hemp          | 550-900                | 70                    | -                      |
| 12 | Henequen      | 430-570                | 10.1-16.3             | 95                     |
| 13 | Harakeke      | 778                    | 32.09                 | 225                    |
| 14 | Jute          | 320-800                | 8-78                  | 45                     |
| 15 | Kenaf         | 930                    | 53                    | 74                     |
| 16 | Palf          | 170                    | -                     | -                      |
| 17 | Palm          | 377                    | 2.75                  | 24.4                   |
| 18 | Piassava      | 134-143                | 1.07-4.59             | -                      |
| 19 | Pineapple     | 413-1627               | 34.5-84.5             | -                      |
| 20 | Ramie         | 500                    | 44                    | -                      |
| 21 | Sisal         | 600-700                | 38                    | 288.6                  |
| 22 | Vakka         | 549                    | 15.85                 | -                      |
| 23 | Wool          | 120-174                | 2.3-3.4               | -                      |

| 2.3. Synthetic Fibers |

Synthetic fibers are man-made because it undergoes various processes before becoming a so-called fiber which is extruding fibers building materials through spinnerets into air and water, developing a thread [35]. Aircraft components, automotive, building panels, etc. high performance products are manufactured using this material. The most popular synthetic fibers that are generally used widely in industry include glass, carbon, and aramid [18], [36].

Synthetic fibers are divided into two types: organic and inorganic fibers [37]. Organic fibers come from living things such as plants and animals, while inorganic fibers come from inanimate objects such as minerals, rocks, etc. Aramid (kevlar), polyethylene, and aromatic polyester are organic synthetic fibers. Glass, carbon, boron, silicarbonate are inorganic synthetic fibers. Mechanic properties of glass and aramid fibers are shown in Table 2.
Table 2. Physical and mechanical properties of synthetic fibers [38]

| Fibers | Density (g/cm³) | Elongation (%) | Tensile strength (MPa) | Young modulus (GPa) |
|--------|-----------------|----------------|------------------------|---------------------|
| E-glass| 2.5             | 2.5            | 2000-3500              | 70                  |
| S-glass| 2.5             | 2.8            | 4570                   | 86                  |
| Aramide| 1.4             | 3.3-3.7        | 3000-3150              | 63.0-67.0           |

2.4. Hybrid Fibers

Hybrid composites are a type of composite material that consists of reinforcing two or more fibers in a matrix in order to obtain the desired properties [18]. The mechanical behaviour of this material is the sum of the properties of each fiber component so that it provides an advantage over other types of composite materials. [39]. Hybrid composites are developed using reinforcement materials of different types, sizes and shapes. The use of two or more different types of fibers can improve the weakness of the mechanical properties of other types of fibers [18].

2.5. FRP Applications

FRP are widely used for various applications. Some of these applications include: increasing in the flexural strength of RC beams using corrugated glass fiber reinforced polymer (GFRP) laminates [9], the utilization of FRP wraps on corrosion activity and concrete cracking in chloride-contaminated concrete cylinders [40], carbon-fiber-reinforced polymer (CFRP) laminates are used as external bonds to extend the service life of corroded RC beams [41], and FRP jacketing system to repair fire-damaged RC columns [10]. The findings of each researcher differ in terms of application and methods, but the goal is to obtain the highest strength thus reducing the complexities and expenditure.

3. Composite in Concrete

3.1. Introduction to Concrete

For centuries, concrete is the main material most widely used in a building. The use of this material is found in buildings, offices, highways, bridges, dams, houses, etc. This material is a mixture of at least three main materials: cement, sand and gravel [42]. The presence of water in this mixture serves to accelerate the hardening process into concrete. The combination of the materials enhances its characteristics in terms of strength and durability. However, the strength and durability of this material will decrease over time due to several factors that affect the mechanism of its structural characteristics [43].

In most structures of major buildings, concrete is recognized as the main character in the whole process of construction [44], [45]. The researches and his co-workers also said that conventional concrete consists of cement, aggregates, water and with or without the admixture of each of these ingredients is considered as a composite compound. In addition, although the compression strength is very good, it is weak in tension. Only with one vital constraint, even of good quality of conventional concrete can wield the presence of micro-cracks, capillaries, and micro-capillaries [45].

3.2. FRP in Concrete

As an alternative technique, FRP composite materials were introduced to RC beam-column joint structures for repair and rehabilitation operations [5]. To increase the flexural strength of RC floors and bridge decks, the FRP composites are bonded using steel plates. This method has been accepted by the construction industry [46]. The method is to laminate the top and bottom of the floor plate or bridge deck with a composite material so as to increase the capacity for negative and positive moments.
Repairs to the concrete bridge column due to the earthquake using a combination of quickly installed epoxy mortars and four layers of unidirectional carbon/epoxy composite jackets have been developed and applied to damage specimens [47]. The results obtained are the effectiveness of repair schemes that can be used to provide quick emergency repair of bridge columns, thereby reducing the impact of traffic due to bridge closure.

The addition of jute fiber to fresh and hardened concrete has been investigated and evaluated [48]. In this study, jute fiber was added to concrete columns and beams. The results of this study are the addition of 0.50% jute fiber had an adverse impact on the fresh properties of concrete. A smaller dosage (0.25%) of jute fiber showed a positive influence on the hardened properties of concrete.

Other investigations have been carried out to improve the reinforcement performance of concrete using jute fibers [14]. Reinforced concrete is divided into two types, including: jute fiber reinforced concrete (JFRNSC) and jute fiber reinforced high fluidity concrete (JFRHFC). The specimens were tested under conditions of axial compression loads, bending and split tensile strength. The results showed that the slump value in JFRHFC concrete decreased significantly with the increase in fiber content. This indicates that the presence of jute fiber must be limited to maintain HFC characteristics.

3.3. Wrapping of Concrete Damaged
Concrete jacketing is a typical concrete-strengthening method through increasing the sectional area to improve the ultimate strength of RC columns [10]. FRP wrapper has advantages in handling ease, light weight, anti-corrosion and high strength / stiffness to weight ratio compared to steel jacket or steel enlargement.

Mohammed A.A. et al [8] use a FRP prefabricated jacket of e-glass fiber embedded in vinyl ester resin to repair concrete structures damaged by bending loads. The result is that FRP jackets are more effective in repairing bending parts with damage located at the top than at the bottom.

Luca A.D. et al [49] have investigated the strength of FRP laminated fiberglass and basalt glass externally subjected to pure axial loads on full-scale square and rectangular RC columns. This investigation aims to determine the effect of external confinement on peak axial strength and deformation in prismatic RC columns. The results of these investigations indicate that FRP confinement can increase the axial strength of the concrete, especially increasing the tensile capacity of the concrete.

3.4. Strength of Concrete
In General, concrete material has excellent strength at compressive loads. Conversely, it does not have good tensile strength because it is not designed to be capable of this type of load [50]. Nowadays, engineers and researchers combine concrete with FRP to improve the mechanical properties of concrete.

Kim et al. [14] have conducted an investigation and analysis of the mechanical properties of concrete reinforced with jute fibers. The test was carried out in three ways: slump, compressive and splitting tensile test. Study results are shown in Figure 5. The addition of jute fibers results in a more dramatic decrease in slump for high fluidity concrete when compared to normal strength concrete. The addition of jute fiber in a large amount in the concrete mixture caused a significant increase in compressive strength of about 55% when compared to those without fiber. The addition of jute fibers in normal strength concrete and high fluidity concrete increases tensile strength by about 6% and 30% when compared to plain concrete, respectively.

Pesic et al. [51] have investigated the mechanical properties of concrete reinforced with recycled HDPE plastic fibers. The results confirm that the presence of HDPE fibers has no clear influence on the elastic modulus and compressive strength of concrete. The compressive strength and modulus of elasticity of concrete are not improved by the addition of HDPE fibers. The marginal increases of 3-14% to the peak tensile strength over the plain concrete and 6% to the air content in the fresh concrete mix need to be confirmed by further experimental evidence. The data of the test results are shown in table 3.
Labib et al. [52] has investigated the strength of punching shear in concrete slab columns using steel-polypropylene hybrid fibers. The material mix is based on the type and volume of fiber. Single-fiber concrete mixtures with a volume of 0.5% steel fibers and a volume of 0.2% polypropylene fibers are coded SFC. Hybrid fiber reinforced concrete mixtures with a steel fiber volume of 1.5%, and a volume of 0.2% polypropylene fibers are coded HFC2. The experimental method used a round specimen with a diameter of 600 mm and a thickness of 75 mm. The punching shear strength was significantly increased in HFC2 compared to SFC. The results of testing the slab load variations are shown in the table 4.

Figure 6. Jute fiber reinforced concrete composite test results: (a) slumb test; (b) compressive test; and (c) splitting tensile test [14]
Table 3. Mechanical properties of concrete reinforced with recycled HDPE plastic fibers [1]

| Concrete Properties       | Units | Age (days) | Plain C1 | C2 | C3 | C4 | C5 | C6 | C7 |
|---------------------------|-------|------------|----------|----|----|----|----|----|----|
| Elastic modulus Ec        | GPa   | 28         | 24.2     | 24.5 | 24.9 | 25.2 | 24.2 | 25.9 | 25.5 |
| Compression strengths     |       |            |          | C2 | C3 | C4 | C5 | C6 | C7 |
| $f_{ck}(cube)$            | MPa   | 28         | 33.2     | 34.3 | 31.1 | 32.3 | 31  | 31  | 30.5 |
| $f_{ck}(cube)$            | MPa   | 90         | 38.1     | 40.1 | 38.4 | 37.7 | 37.2 | 37.7 | 38.7 |
| $f_{ck}(cyl)$             | MPa   | 28         | 23.3     | 26.2 | 24.1 | 23.4 | 24.1 | 26.6 | 23.5 |
| Tensile strengths         |       |            |          | C2 | C3 | C4 | C5 | C6 | C7 |
| $f_{ct}(cyl)$             | MPa   | 28         | 2.79     | 3.08 | 2.95 | 2.96 | 3.03 | 2.93 | 2.88 |
| $f_{ct}(cyl)$             | MPa   | 90         | 3.32     | 3.47 | 3.49 | 3.43 | 3.4  | 3.47 | 3.53 |
| $f_{ctn}$                 | MPa   | 28         | 3.84     | 4.35 | 4.14 | 4.37 | 4.01 | 4.05 | 3.96 |

Table 4. Test results of ultimate slab load [52]

| Slab   | Ultimate Load (kN) |
|--------|---------------------|
| PC     | 38                  |
| SFC    | 42                  |
| HFC1   | 47.5                |
| HFC2   | 51                  |

4. Summary

The application of FRP composites to strengthen concrete structures began in the late 1990s. At that time, FRP composite was used to strengthen RC in the column-beam linkage section. The FRP structure is wrapped using a steel jacket. This technique uses FRP composite on concrete surfaces and steel reinforcement structures on the outside.

FRP composite materials are an alternative material that has been introduced to the construction industry as reinforcement for the repair and rehabilitation of RC beam-column joint structures. The position of the composite laminate installation is at the top and bottom of the floor plate or bridge deck. This aims to increase the capacity for negative and positive moments. Repairs to the concrete bridge column due to the earthquake using FRP composite have the effectiveness of repair schemes that can be used to provide quick emergency repair. The addition of natural fiber (jute) to concrete showed a positive influence on the hardened properties of concrete.

FRP wrapper has advantages in handling ease, light weight, anti-corrosion and high strength / stiffness to weight ratio compared to steel jacket or steel enlargement. The FRP prefabricated jacket of e-glass fiber embedded in vinyl ester resin to repair concrete structures damaged were more effective in repairing bending parts with damage located at the top than at the bottom. In this study, RC columns were confined externally with FRP laminated fiberglass and basalt glass and subjected to pure axial loads. The results show that FRP confinement can increase the axial strength of concrete and the tensile capacity of concrete.

Investigation and analysis of the mechanical properties of jute fiber reinforced concrete shows that the addition of these fibers will result in a dramatic reduction in slump value with high fluidity in concrete when compared to normal concrete. In addition, the compressive strength of the concrete will increase by 55% with the addition of a large amount of jute fibers to the concrete mixture. Investigation of the punching shear strength on concrete floor slab columns using polypropylene hybrid fibers showed a significant increase in the shear capacity of the hybrid fiber concrete mix when compared to the single fiber concrete mix.
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