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Review of the mechanical and durability properties of natural fibre laminate-strengthened reinforced concrete beams

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Abstract. The brittle nature of concrete has always necessitated the need for various forms of reinforcement that will absorb the tensile stress that is responsible for cracking. Conventionally, steel rebar embedded in concrete, giving rise to reinforced concrete structures has turned out to be a composite material that has been most used for infrastructural development around the world. The ductility imparted on concrete by steel rebar has been very efficient, though reinforced concrete structures are prone to durability challenges when exposed to adverse environmental conditions. Most times, repairing deficient concrete structures is more economical and sustainable than total replacement. Various approaches have been successfully implemented around the world in strengthening weakened reinforced concrete structures, nevertheless, bonding of fiber reinforced polymer (FRP) composites to the soffit of weak beams is turning out to be a viable option. Of particular interest is the adoption of naturally occurring fibers for laminates used for beam strengthening. In this era of Sustainable Development Goals (SDGs), in which the world is striving to reduce the effects industrial productions on the environment, advances in adopting renewable materials is highly welcomed. This research reviews the past works on the use of natural fibre-based composites in strengthening deficient reinforced concrete beams. The outcome of this research will go a long way in contributing towards the achievement of the SDGs.

Keywords: Natural fibre, FRP, Strengthening, Reinforced concrete beam, SDGs

1. Introduction

Fibres have been utilized by mankind for various purposes since the dawn of time. They have been used to make clothing, to make tools and household implements, and even medicines. Natural fibres however, are greatly preferred over other types of fibre due to their abundance in nature, low cost and sustainability. Natural fibres have already made quite a significant impact on the infrastructural and commercial products market with examples such as jute, flax, kenaf, and hemp [1]. While these fibres are renewable and ecologically meritorious, they have some disadvantages like lower durability and smaller strength. Fortunately, recent research has led to the development of several treatment procedures to enhance the durability of natural fibres [2]. The use of natural fibres in the form of a laminate to strengthen reinforced concrete members is a relatively recent and more sustainable method of retrofitting and upgradation which has been made necessary by numerous factors that ultimately lead to the gradual degradation of reinforced concrete structures. It is only one of numerous techniques utilized some of which include; Polymer injection, Steel plate bonding, Concrete jacketing and use of advanced composite materials like Fibre Reinforced Polymers and Ferro cement [3]. The properties of



natural fibre reinforced polymer laminates rely heavily on the properties of the particular fibre acting as the reinforcement therefore it is vital to understand the behaviors, strengths and weaknesses of these fibres in order to produce a laminate that will effectively serve its purpose of strengthening a concrete beam.

2. Strengthening and repairing concrete

Concrete is one of the most common building materials utilized by man due to its various favorable characteristics and properties that make it an ideal option for construction purposes. It is a composite material that possesses many qualities like strength, versatility, durability and economy, along with the extremely useful ability to be molded into almost any shape or form [4]. Despite its advantages, concrete is notoriously weak in tension, brittle and prone to cracking. Thus, these concrete structures gradually deteriorate over time for various reasons such as; inadequate design and construction, increase in service loads, poor quality of building materials, environmental or external factors, corrosion of steel reinforcement used in the concrete structure, natural disasters like earthquakes, tsunamis, tornados etc. [5]. This necessitates the implementation of retrofitting techniques such as NFRP laminate strengthening.

2.1. Concrete strengthening methods

Concrete members can be strengthened in numerous ways with different materials and varying degrees of success. One of the oldest and most common ways to strengthen or repair concrete structures is by employing sprayed concrete or shotcrete. Sprayed concrete is characterized into wet and dry spraying methods and it is usually implemented when large areas of concrete or mortar have been damaged corrosion or fire, access to damaged area is difficult, and when utilization of formwork is unrealistic [6]. Steel plate bonding is another very popular concrete strengthening procedure. It usually involves the adhesion of steel plates to the tension face of a concrete beam. It effectively increases both the shear and flexural strength capacities of the beam and is a well acknowledged technique because it is readily available, high ductility, low cost, and high fatigue strength. However, it suffers the same disadvantages associated with all forms of plate bonding techniques which is premature debonding [7].

Polymer grouting or polymer injection is yet another technique which is usually employed in underground conditions with the presence of water due to the good reaction time and plugging effect of the polymers [8]. Polymers such as epoxy, vinyl ester, polyester, polyurethane and acrylic resins are used. The commonest polymer used for injection is epoxy. Polyurethane and acrylic resin-based polymers are usually utilized to treat water retaining structures, underground structures and also limit water seepage [9].

The procedure of jacketing has been proven to improve the bending strength, ductility, stiffness, shear capacity and axial load carrying capacity of concrete members. The technique entails wrapping concrete structural elements with jackets which can be fabricated using concrete, steel and even fibre reinforced polymer composites [10].

The use of ferro cement which is an advanced composite is another technique for strengthening concrete. Ferro cement is a kind of thin wall reinforced concrete usually made using hydraulic cement mortar, with minimally spaced layers of continuous and relatively small size wire mesh as reinforcement [11]. Ferro cement is an excellent choice for the strengthening of concrete structures due to its high strength-to-weight ratio, raw materials availability, malleability and its superior cracking behaviour to regular cement [12].

Another commonly used advanced composite is the Fibre reinforced polymer (FRP) composite. This is a composite compound between a polymer and a fibrous material. The most common synthetic fibres utilized in FRP composites are glass, carbon, acrylic and aramid. Even paper and wood have been used on rare occasions with varying degrees of success. These synthetic fibres are products of well-informed research and development of materials in the textile and petrochemical industries to meet precise needs and standards required to create the most effective composite materials. These fibres provide high

tensile strength to support the tensile and bending moment stiffness of the composite structures they are used to construct. However, they have some significant disadvantages which deters engineers from using them in structural construction. The advanced composites created with synthetic materials are relatively expensive to be mass produced for domestic materials and therefore are mostly used for small, unique job descriptions. Also, these composites are non-biodegradable and thus unsustainable. This presents a problem in this recent green age. Some of the composites fabricated with these synthetic fibres have been proven to be detrimental to the health of humans. They have caused adverse reactions on the skin and also in the human respiratory system [13]. These challenges have led to researchers looking to other types of fibres to strengthen concrete. These fibres would have to undoubtedly improve the structural integrity of the concrete, control the effects of cracking, be sustainable and environmentally friendly. The obvious solution was to turn to natural fibres.

2.2. The Natural fibre approaches

Natural fibres can be grouped into Organic and Inorganic fibres. Organic fibres are then further categorized into plant fibres and animal fibres while inorganic fibres consist of mineral fibres. Plant fibres can be procured from leaves, bark, stem, husk, seeds and grass. However, Animal fibres are obtained from the skin and coats of different animals [14].

It has been established that these natural fibres have certain characteristics and properties that give them the ability to counteract different problems experienced by concrete during construction. These unique properties determine the areas of applicability for each fibre and therefore makes them one of the first factors to consider when choosing a particular fibre for a job. These fibres can be used to strengthen concrete in different ways. They can be directly integrated into the concrete mix itself as short discontinuous fibres and they can also be used to make polymer laminates which will then be externally bonded to a concrete member. The advantages of utilizing natural fibres to strengthen concrete are numerous and significant enough to make them a well sought-after commodity in the construction industry. The fibres are readily available and abundant in nature, their extraction from nature requires low energy consumption, they are cost-effective, they are durable have good workability and decent strength. However, they have poor resistance to fire, they are highly susceptible to water and humidity damage, their strength is easily compromised, there is no direct or specific local design code for them and they have poor resistance to most forms of chemical attack. Table 1 shows the properties of some natural fibres.

Table 1. Properties of some natural fibres [15]

Fibre	Fibre type	Density (g/cm ³)	Elongation at break (%)	Tensile strength (MPa)	Elastic Modulus (GPa)
Jute	Bast	1.3	1.5 – 1.8	393 - 773	26.5
Flax	Bast	1.5	2.7 – 3.2	500 – 1500	27.6
Hemp	Bast	1.47	2 – 4	690	70
Kenaf	Bast	1.45	2.7 – 6.9	295 – 930	53
Ramie	Bast	1.44	4 – 4	400 – 938	61.4 – 128
Sisal	Leaf	1.5	2.0 – 2.5	511 – 635	9.4 – 22
Pineapple	Leaf	1.5	1 – 3	170 – 1627	34.5 – 82.5

Banana	Leaf	1.35	3 – 10	529 – 914	8 – 32
Cotton	Seed	1.5 – 1.6	7.0 – 8.0	400	5.5 – 12.6
Coir	Fruit	1.2	30.0	593	4.0 – 6.0
Wheat	Stalk	0.6 – 0.8	2.7	10 – 200	1 – 12
Rice	Stalk	1.65	2.2	449	1.21 – 1.25
Bamboo	Cane	0.6 – 1.1	4.0 – 7.0	140 – 230	11 – 17
Spider silk	Silk		17 – 18	875 – 972	11 – 13

2.3 Some types of natural fibre

2.3.1 Coconut fibre. Identified as the most durable and most resistant of all commercial natural fibres, coconut fibre or coir as it is popularly called is the short fibre extracted from the outer shell of coconuts otherwise called husks [16]. The fibre is obtained from the tissue surrounding the seed of the palm (*Cocos nucifera*) Coconut fibres procured from the tissues of the outer shell, belongs to the palm fibres family. They are agricultural waste products gotten from process of coconut oil. They are available in vast amounts in the tropical areas like in Africa, Asia and southern America. They are found in commercial amounts in the southern parts of Ghana [17]. The lengths of natural coir ranges from 60 to 230mm. Its diameter is about 0.17 to 0.24mm. The color of the fibre varies from pale yellow to dark brown. The chemical components of coconut fibre are similar to the composition of other vegetable fibres. Its main components are cellulose, hemi-cellulose, pectin and lignin. paragraph text follows on from the subsection heading but should not be in italic [3].

2.3.2 Sugarcane fibre

Sugar cane fibre also known as “bagasse” is the fibrous leftover material that is gotten after the juices of the sugar cane plant has been extracted. Sugarcane (*Saccharum officinarum*), is a species of tall perennial true grass and belongs to the grass family known as Poaceae. The sugar cane plant is mainly grown for its sweet tasting juice and is primarily used as an additive in different foods, drinks and other products. The cultivation of sugarcane fibres is an ancient practice as the Chinese and the Indians grew them as far back as 2,500 years ago [18]. There are two main types of sugarcane fibre. The Factory Bagasse which is obtained by industrial processes through repeated steps of extraction and the Farm Bagasse or cane stalks which are procured from small farms or factories. Its quality and quantity are significantly lower than that of the factory bagasse [21]. Bagasse is a lignocellulosic material and so is mostly constituted by cellulose, hemicellulose and lignin. These three constituents contribute more than 90% by dry weight of the fibre [20].

2.3.3 Kenaf fibre.

Kenaf fibre is obtained from the kenaf plant (*Hibiscus Cannabinus L*) which is a warm season annual crop significantly similar to jute and cotton. Recently, there has been a lot of commotion surrounding the use of kenaf fibres especially for composite reinforcement. This is due to the fact that kenaf possesses good mechanical properties and they grow quickly. They can rise to a height of 4-5 m in about 4-5 months of the growing season with the kenaf’s stalk diameter reaching about 25-35 mm [21]. It is native to Africa where it has been cultivated for use in making ropes and animal feed [22]. Kenaf has a single unbranched stem which consists of two main types of fibre; the outer bast fibre which

makes about 35% of the dry stem's weight and is considered the stronger and the more important fibre and the inner core fibre which amounts to about 65% of the stem's dry weight [23].

2.3.4 Banana fibre.

Banana fibre is a ligno-cellulosic fibre that is gotten from the pseudo-stem of the popular banana plant (*Musa Sepientum*) Its scientific name is *Musa acuminata*. It is a naturally occurring bast fibre that is commonly used in the production of hand-crafted works like mats, bags, hats, ropes and twine [24]. It should be noted that the main constituent of the fibre is cellulose which is then followed by hemi-cellulose. The cellulose is also the reinforcement for most of the other constituents present in the fibre. A high cellulose content and low microfibrillar angle are well sought-after properties for bast fibres and therefore make the banana fibre an ideal candidate [25]. Figure 1 shows various fibers recently adopted for improving concrete strengths. They are *Momordica angustisepala* fibers [26], Kenaf fibers [15] and Bamboo fibers [27].

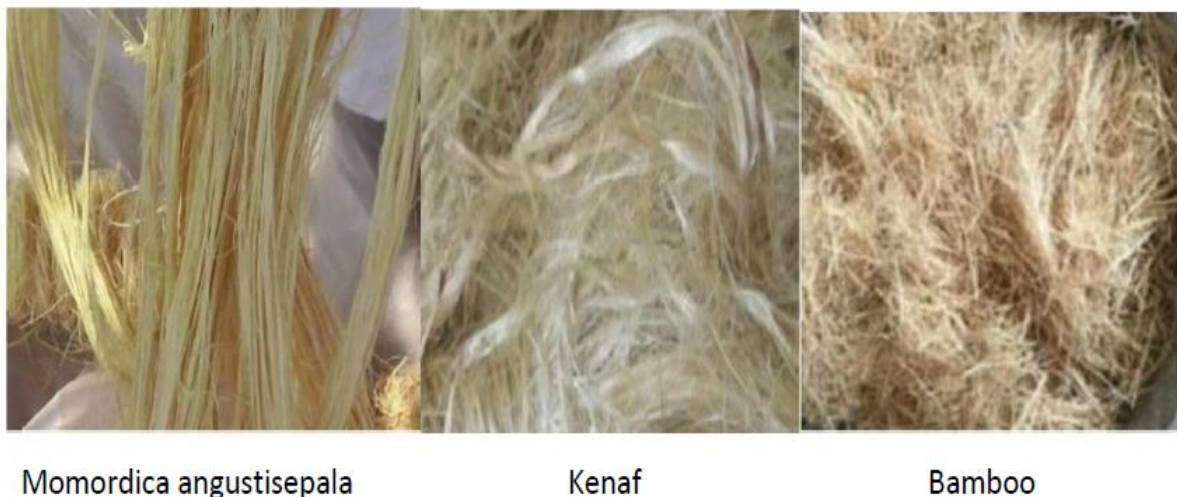


Figure 1. Different types of natural fibres [26, 15, 27]

3. Synthetic and natural FRP flexural strengthening systems

FRPs can be utilised internally as reinforcement for concrete building elements like beams, slabs, girders foundations and walls and also externally to upgrade or repair an existing structure made of concrete, steel or masonry [29]. There have been numerous research works undertaken on the strengthening and repair of reinforced concrete structural elements, bridge components and existing reinforced concrete structures using both synthetic and natural FRPs and some of their various strengthening systems will be discussed in this section. Stiffness enhancement of FRP-strengthened reinforced concrete beams via dynamic-based non-destructive tests were shown in the works [29] for static loads and in [30] for cyclic loads. In these two researches, it was proven that FRP composites are very essential in the restoration of damaged structures to functional state.

Nayak *et al.* [31] investigated the effect of externally strengthening reinforced concrete beams with glass fibre reinforced polymer (GFRP) fabrics on the flexural strength of the beams. They prepared nine beams wrapped externally in different number of layers and different lay-up patterns then one unwrapped control beam. All the beams were subjected to two-point loading. The first four beams were wrapped with the GFRP fabric fully at the bottom and on the sides at a height of 25mm from the bottom. The next four were wrapped at the bottom and 75mm from the bottom in the sides. The remaining one was wrapped completely at the bottom and on the two sides. It was observed that all ten beams showed

similar behaviours initially. It was then concluded that the flexural strength of the concrete beams increased with an increase in the number of layers of GFRP fabric bonded to it in different laying patterns. The increase in layers was all observed to accompany a gradual change in the failure mode from ductile to brittle behaviour. It was also discovered that of the three cases of GFRP wrapping, the model in which the bottom portion and half of the two sided were wrapped exhibited the best performance in strength and ductility when compared to the beam without GFRP sheets. Using multiple layers of synthetic FRP reinforcement has evidently been proven to enhance the mechanical properties of concrete elements as also discovered by Karzad *et al.* (2019) [32]. They found that the strengthening of reinforced concrete beams with shear deficiency using one layer of CFRP resulted in average of 65% improvement of shear capacity which can be further enhanced by adding another layer of CFRP to gain an additional 30% increase in shear capacity.

Despite the effectiveness of synthetic FRP systems, they are less preferred than natural FRPs due to their cost of manufacturing and their non-biodegradability. Natural FRPs have been observed to be cost effective, biodegradable and can achieve better strengthening performance in terms of cost and effect [33]. Chen *et al.* [33] conducted a study to explore the feasibility of replacing synthetic FRPs with natural FRPs in structural strengthening works and highlighted the advantages they had over synthetic FRP. Six beams prepared differently were subjected four-point bending loads. A typical beam was 150mm wide, 250mm in depth and 2400mm in length. Four-point bending was applied thereby equally dividing the shear and pure bending spans into 700mm. One of the beams was unstrengthened (control), four beams were strengthened using jute or flax FRP laminates and one was strengthened with carbon fibre reinforced polymer (CFRP) laminate. The NFRP laminates were formed using the wet lay-up method and left to cure for seven days at the least. They were found to provide better strengthening than the CFRP did when the NFRP laminates were used in large amounts. A cost analysis was further conducted and it exposed the fact that the NFRP laminates were 20% and 40% cheaper in flax and jute respectively than the CFRP laminates for a unit increase of load-carrying capacity. Di Luccio *et al.* [34] performed an experimental study to explore the cyclic response of reinforced concrete walls strengthened externally using carbon and Flax FRP strips in a bid to compare their overall performances. One RC wall was to serve as a reference so it was not strengthened, two walls were strengthened with strong bidirectional strips of CFRP utilising the wet lay-up system. The last three walls were retrofitted with unidirectional flax fibre reinforced polymer (FFRP) strips. One of these three walls however, was additionally strengthened with a bi-directional glass fabric. The test results showed an increase in resistance of about 100% in the FFRP strengthened walls. Also, the RC walls upgraded with the CFRP strips failed at displacement levels lower than those of the control or reference beam, while there was a significant 30% increase of displacement identified in the FFRP strengthened walls. The CFRP strips failed due to concrete peeling or pulling of the external anchorage.

The most common form of FRP reinforcement for concrete and masonry structures is the external bonding reinforcement (EBR) method therefore it is used in most research works and studies. However, there is another relatively recent strengthening method called the near surface mounting method (NSM) which involves cutting out a hole or groove in a concrete element, applying the proper bonding adhesive and placing FRP rods, bars or strips into the hole. The NSM technique has some advantages over the EBR method such as better strain distribution leading to higher utilisation of potential strain and its higher resistance to environmental factors by virtue of its embedment in the concrete cover [35]. In a critical review performed by Parvin and Shah [35], it was deduced that not only does using the NSM technique eliminate the notorious issue of debonding experienced in the EBR method, it also possesses higher fire resistance properties than the EBR method thereby reducing insulation length and thickness required to hinder the adhesive from reaching its glass transition temperature. They additionally observed that prestressing of NSM-FRP greatly improves the structural performance of reinforced concrete structures.

4. Conclusion

Natural fibres present a more sustainable and ecofriendly substitute to synthetic fibres as reinforcement in polymer composites. While the natural fibres have to be used in more quantities to provide as much strength as synthetic fibres would, they are a far cheaper and reasonable option. Concrete members strengthened with NFRP laminates were found to offer up significantly more resistance when subjected to cyclic loading and they also failed at higher displacement levels than CFRP laminates. The adoption of the near surface mounting method (NSM) has eliminated the greatest opposition to the external bonding method (EBR) thereby offering a promising future for the concept of NFRP laminate strengthening of concrete.

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