Exploring Concepts and Aplication of Natural Fibers on Cement-Based Composites

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Abstract: High-performance Cement-Based Composites (CBCs) have emerged as an effective strategy for constructing sustainable civil engineering structures. While cement exhibits commendable compressive strength, its tensile strength falls short in composite applications. A promising solution to address this limitation lies in incorporating natural fibers. This paper presents a comprehensive review of natural fiber utilization in cement-based products. The introduction of cellulose from natural fibers has demonstrated the potential to significantly enhance compressive and flexural strength, with improvements of up to 16% and 22%, respectively. The recommended fiber dosage ranges from 1% to 2% of the cement weight. Cellulose-based particles adeptly occupy even the tiniest voids within the cement paste, while the fibers serve as effective crack-bridging agents. Furthermore, fibers can delay or impede crack propagation, with fiber size emerging as a pivotal factor in the crack-bridging mechanism. Findings from the literature highlight the immense promise of natural fibers as reinforcement materials in CBCs. The integration of natural fibers into CBCs represents a compelling approach to advancing the development of sustainable civil engineering structures.

Keywords: cellulose; cement; composite; fiber; mechanical strength

1 Introduction

Synthetic fibers have gained widespread popularity as reinforcement materials in concrete applications. The appeal of synthetic fibers lies in their ease of incorporation, as they can be directly blended into concrete without the need for a separate synthesis process. However, the production of synthetic fibers involves high-temperature heating processes, raising environmental concerns due to their non-environmentally friendly nature. In contrast, while necessitating pre-treatment before cement mixing, natural fibers offer a compelling alternative. These fibers are readily available and cost-effective, boasting mechanical properties rivaling their synthetic counterparts. Consequently, there is a growing significance in researching and exploring the potential of natural fibers in concrete applications.

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The incorporation of rice husk and bamboo cellulose fibers, ranging from 2% to 16% concentration, yielded a notable increase in flexural strength (24.3%) and in the bulk density (12.4% - 37.3%) [1]. The introduction of cellulose from wood resulted in a substantial boost in concrete's mechanical properties, with a remarkable achievement of 90 MPa at a mere 0.15% cellulose content and a flexural strength of 25 MPa [2]. However, some challenges are associated with utilizing natural fibers within concrete matrices, such as lignin, hemicellulose, pectin, and glucose degradation, which can compromise the durability of concrete. Consequently, it is imperative to judiciously select natural fibers with robust mechanical strength. Cement-based composites (CBC) incorporating blends of natural fibers have garnered considerable popularity within the construction industry due to their cost-effectiveness, ready availability, and excellent malleability. In recent years, bio-composite processing utilizing natural fibers as reinforcement in cement has been the subject of extensive research [3][4]. The inclusion of natural fibers, renowned for their commendable mechanical attributes [5] [6] has widespread application within civil engineering. To further bolster fiber strength, various methods have been employed, including the conversion of fibers into cellulose fibrils through acid hydrolysis [7] [8] [9]. .

To serve as effective reinforcement in Cement-Based Composites (CBC), the hemicellulose and lignin in plant fibers should be removed. This requirement arises from fibers' inherent high water absorption characteristics, which can disrupt the water demand equilibrium within CBC. Therefore, this study aimed to investigate prior research endeavors involving the utilization of natural fibers in cement-based products. By examining these studies, this research endeavors to shed light on the feasibility of harnessing natural fibers to enhance the mechanical strength of CBCs.

2 Lignocellulosic and Mechanical Strength

2.1 Lignocellulosic Fibers

The term "lignocellulosic fiber" is a scientific designation encompassing natural fibers, as all plant-based fibers comprise cellulose, hemicellulose, and lignin constituent elements. Predominantly, plant fibers consist of cellulose, accounting for 50-70% of their composition. Table 1 provides a comprehensive overview of the chemical composition of the fibers employed in Cement-Based Composites (CBC).

Table 1. Chemical Compositions of Various Natural Fibers

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Typha sp.	60.9	7.0	5.7	[10]
oil palm trunk	51.75	-	13.19	[11]
Artisdita hystrix leaf	59.54	11.35	8.42	[12]
Rice straw	59.1	18.4	5.3	[13]
corn cob	39.32	41.52	7. 59	[14]
bark of *albizia amara*	64.54	14.32	15.61	[15]
soy hulls	94.0 ± 1.53	3.5 ± 0.8	2.5 ± 0.4	[16]
Agave angustifolia	97.31 ± 0.02	3.14 ± 0.35	0.23 ± 0.04	[17]
rice husk	96	-	-	[18]

Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
sugarcane bagasse	96.14 ± 1.34	0.23 ± 0.04	0.51 ± 0.12	[19]
pineapple leaf	85.53 ± 2.3	0.3 ± 0.9	0.4 ± 0.3	[20]
Garlic	86	-	-	[21]
walnut shell	87.12 ± 1.42	0.14 ± 0.06	1.21 ± 0.13	[19]
Pandanus tectorius	81.6±0.6	15.9±0.6	0.8±0.1	[22]

Agave angustifolia and sugarcane bagasse are natural fibers distinguished by their elevated cellulose content. Cellulose molecules create a sturdy network, culminating in a dense and compact structure. Cellulose is organized into extended, uniform microfibrils within plant cell walls, ultimately forming fibers. Meanwhile, hemicellulose molecules contribute to the composition of cellulose fibers, while lignin occupies the interstitial spaces between the polysaccharides.

2.2 Structure of Fiber

The arrangement of macromolecular components in plant cell walls is complex, arranged in layers. Figure 1 shows an example of a natural fiber cell wall structure.

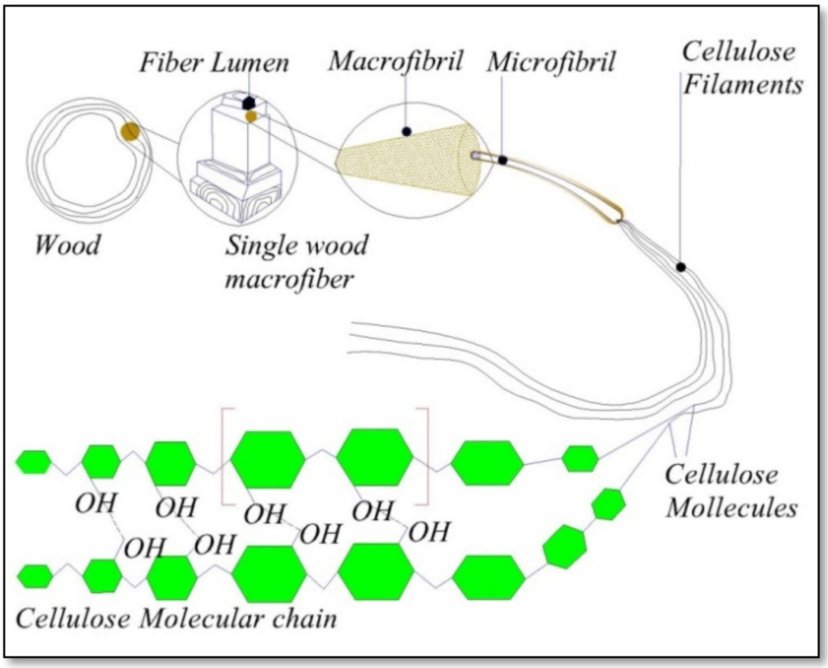

Figure 1. Cell Wall Structure [23]

The characteristics of fibers are contingent upon factors, such as their structure, cell dimensions, and the relative content of cellulose, hemicellulose, and lignin. Consequently, variations in these attributes result in distinctive properties among different lignocellulosic fibers [19], [24], [25].

2.3 The Role of Fiber in Mechanical Improvement

The use of natural fibers as reinforcement in CBC production has four main effects: (1) improving bond strength, modulus of elasticity (MOE), and modulus of rupture (MOR); (2) improving hardening, especially after seven days; (3) reducing fiber pull out and shrinkage during hardening and (4) reducing thermal expansion and porosity. The mechanism of fiber reinforcement in CBC occurs by the following means [26].

a. Protecting the fiber lumen from mineralization
b. Increasing the enlargement (hardening kinetics) on the surface of fibers and other composites
c. Decreasing shrinkage
d. Improving the interaction between fiber and matrix
e. Bridging microcracks

Modifying fibers through nanomaterial conversion significantly alters their specific surface area, increasing it from 50 to 500 m^2/g) [27]. Natural fibers transformed into nanocellulose exhibit heightened hydrogen bonding capabilities attributable to the abundant hydroxyl groups and specialized, reactive surfaces, setting them apart from untreated fibers. These nanocellulose forms of natural fibers are pivotal in facilitating matrix-fiber interactions [10], [28].

In Cement-Based Composites (CBCs), introducing nanocellulose expedites the formation of calcium silicate hydrate (CSH) gel during hydration, thereby improving the physical bond between the fiber and matrix, consequently enhancing mechanical properties. Numerous researchers have substantiated the influence of nano- and microcellulose on cement hydration. For instance, Shuzhen et al. [91] observed that bacterial cellulose (BC) accelerates CSH production during cement hardening. Additionally, Hoyos et al. [90] investigated the cement hydration reaction through thermogravimetric analysis, demonstrating that the incorporation of Microcrystalline Cellulose (MCC) at a 3% weight ratio leads to an augmented hydration rate during accelerated curing of cement paste.

2.4 Application of Cellulose Fiber Reinforced Cement-Based Composite

Multiple researchers have documented the pivotal role of cellulose in augmenting the mechanical properties of materials [23]. Cellulose fibers, with a length range of 100-2,000 μm and diameters from 30-400 nm, have exhibited the capacity to enhance the compressive strength of cement paste by 16% and increase flexural strength by 22% when employed at concentrations from 0.05% to 0.30% relative to the mass of the binder. In a study conducted by Dai et al. in 2015 [29], cellulose with dimensions measuring 600-1700 nm in length and 20-100 nm in diameter yielded substantial improvements, elevating compressive strength by 20% and flexural strength by 15%. Nano-sized natural fibers are poised to occupy the interface zone within Cement-Based Composites (CBCs), thereby enhancing their mechanical properties and serving as effective reinforcement. Figure 2 illustrates an additional investigation utilizing chemically treated typha fibers for evaluating compressive and flexural strength.

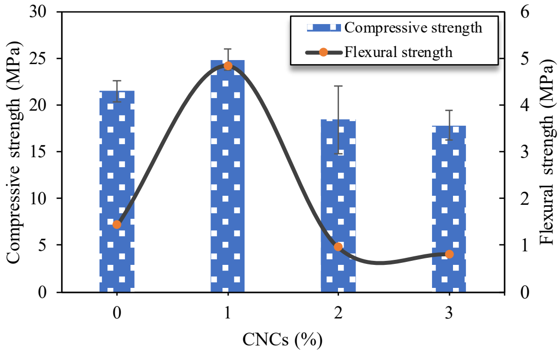

Figure 2. Compressive Strength and Flexural Strength of Typha Fiber-Based Cement [30]

The findings reveal that incorporating 1% fiber by weight of fly ash led to a notable increase in mechanical strength, reaching 24.85 MPa. However, an increase in fiber content by up to 3% resulted in a decline in compressive strength, reducing it by 16.93%. A similar trend was observed in flexural strength, exhibiting a threefold increase compared to specimens without fiber. Figure 2 highlights the capacity of natural fibers to improve the mechanical strength of Cement-Based Composites (CBCs). Furthermore, Figure 3 illustrates the compressive strength outcomes associated with utilizing Oil Palm Trunk (OPT) fiber in CBC.

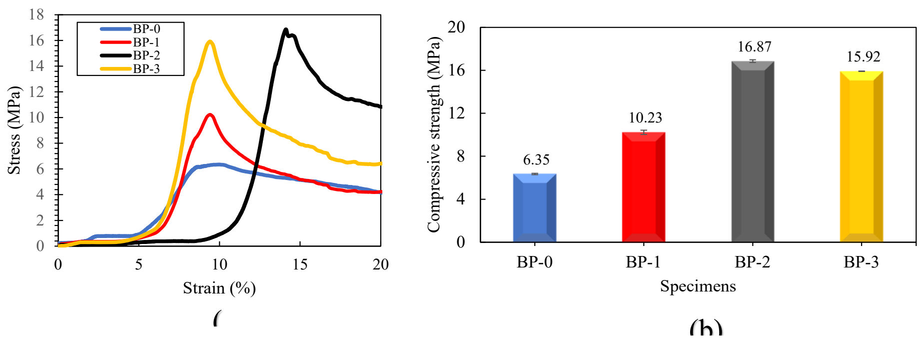

Figure 3. Compressive Strength OPT Fibers [31]

Incorporating 2% Oil Palm Trunk (OPT) fiber resulted in a 2.5-fold increase in compressive strength, whereas the introduction of 3% OPT fiber led to a decrease in compressive strength. Figure 3 demonstrates the potential applicability of OPT fiber in Cement-Based Composites (CBC). The utilization of natural fibers and their impact on compressive and flexural strength outcomes are presented in Table 2.

Table 2 Research Related to Mechanical Strength Utilizing Various Fibers

Natural Fiber	Fiber Concentration (wt%)	Compressive Strength (MPa)	Flexural Strength (MPa)	Reference
Sweet Sorghum	2	22.9	5	[32]
Cotton	1	28.42	5.85	[33]
Sisal	1	25.16	5.90	[33]
Raffia	1	13.66	3.05	[33]
Coconut Coir	1	31.36	5.25	[33]

3 Conclusion

In certain studies, it has been observed that a higher quantity of fibers yields more favorable composite characteristics. Nevertheless, an increased fiber content also corresponds to higher water absorption, which in turn can reduce mechanical strength. However, each type of natural fiber exhibits an optimal threshold for Cement-Based Composites (CBCs) use. An excessive number of fibers within the composite material may result in uneven dispersion and agglomeration. In existing literature, lignocellulosic fibers are typically employed in cementitious materials within 1% to 2% relative to the cement content. Enhanced crystallinity in natural fibers bolsters their mechanical properties and their efficacy as reinforcement. The observed increase in compressive strength (up to 31.36 MPa), and flexural strength (up to 5.90 MPa) underscores the potential of natural fibers to enhance mechanical strength in cement-based products. In summary, it can be concluded that lignocellulosic fibers are promising to apply in cement. This literature reviewed contributes to the comprehensive assessment of fiber potential in cement-based products.

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