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Enhancing Concrete Properties with Plant Fibers: A Comprehensive Analysis of Mechanical and Durability Improvements

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Abstract: Concrete is the world's most widely used building material, its main advantage is excellent compressive strength, but there is also brittleness, low tensile strength, poor cracking resistance, and other shortcomings. To solve these problems, researchers have put forward a variety of methods for the modification of concrete materials, among which increasing the toughness and crack resistance of concrete by adding plant fiber has become an important research direction. As a natural, renewable, and environmentally friendly material, plant fiber has a high specific strength, specific stiffness, and good cohesion, which can greatly improve the mechanical properties and durability of concrete.

Keywords: Plant Fiber Reinforced Concrete, Sisal Fiber, Sustainability in Construction Materials, Fiber Durability, Crack Resistance

1. Introduction

As one of the building materials that is used the most in the world, concrete has been essential to the development of modern infrastructure. Despite its widespread application, traditional concrete exhibits several limitations, including brittleness, susceptibility to cracking, and environmental concerns associated with its production. In the field of sustainable construction materials, the focus of addressing these problems has grown to be the main focus. The use of plant fibers, such as hemp, bamboo, and sisal, has drawn a lot of attention in the last few years because they are useful reinforcements for concrete. These natural fibers offer numerous advantages, including cost-effectiveness, lightweight properties, and environmental sustainability. Unlike synthetic fibers, plant fibers are renewable, biodegradable, and readily available, making them an attractive alternative for promoting sustainable development in the construction industry.

The incorporation of plant fibers into concrete has demonstrated notable improvements in its mechanical properties, including enhanced tensile strength, toughness, and crack resistance.

Additionally, plant fibers have shown promise in increasing the durability and long-term performance of concrete under various environmental conditions. However, challenges remain, such as optimizing fiber distribution, ensuring compatibility with cement matrices, and addressing potential durability concerns, particularly in high-moisture environments.

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This paper aims to provide a comprehensive evaluation of the mechanical and durability properties of plant fiber-reinforced concrete (PFRC). By examining the effects of fibers such as sisal and bamboo on key concrete characteristics, this study contributes to the growing body of knowledge on sustainable construction materials. Furthermore, it highlights the potential of PFRC to address both performance and environmental concerns in modern construction practices.

2. The influence of sisal fiber on high-performance concrete

High-performance concrete (HPC) is a relatively new building material that has been developing quickl in international civil engineering in recent years. It has extraordinary mechanical properties and durability, mainly used in construction, landscape, bridge construction, municipal pipeline, road, railway industry, special environments, and other fields. HPC has features such as water-to-binder ratio (w/b), large amount of cementing material, small aggregate size, and steel fiber incorporation. The accompanying problems are considerable auto shrinkage, easy peeling at high temperatures, and high cost, which limits the application of HPC.

Sisal fiber (Agave fiber) is a natural fiber extracted from the leaves of sisal plants, which are very good in terms of processability and high strength. Its unique structure can effectively enhance the volume stability, self-healing ability, and high-temperature performance of HPC. The influence of sisal fiber on HPC is mainly reflected in the improvement of its compressive strength, tensile strength and bending strength. The effect of sisal fiber in high-strength concrete (HPC), especially after undergoing dry and wet cycles.

2.1. Appearance Aspects

Through the experimental results, it can be known that after 40 dry and wet cycles, the surface of the HPC sample remains relatively intact and there is no obvious damage. For the hybrid reinforced samples of steel and sisal fiber, although rust spots appeared on the surface of steel fiber, sisal fiber did not show significant degradation. This shows that under certain conditions, sisal fiber can effectively enhance the appearance and stability of concrete, and its durability is good [1].

2.2. Mechanical strength

In terms of the change of compressive strength after dry and wet cycling, there was no significant change in the compressive strength of the samples reinforced with steel and sisal fiber, and the samples reinforced with sisal fiber alone, and the change range was within ±5%. This indicates that sisal fiber has little long-term influence on the compressive strength of HPC, and the influence on the compressive strength is stable. In their study, Ziane et al. found that concrete added with 0.5% hemp fiber reduced its compressive strength by about 16% after a 60-day dry-wet cycle, which was brought on by the degradation of hemp fiber[2]. In contrast, sisal fiber maintained better compressive strength under the wet and dry cycle. For the bending properties, the HPC reinforced by the hybrid of steel and sisal fiber showed flexural hardening, while the sample mixed with sisal fiber alone did not brittle fracture and still showed flexural softening after reaching the ultimate load, which indicated that the fiber and the matrix still maintained good adhesion. This phenomenon shows that the HPC reinforced by sisal fiber has good toughness and can effectively prevent brittle failure. In terms of bending strength and toughness, when 1.0% sisal fiber (SI1.0) was added alone, the bending strength of HPC was 4.6% lower than that of ordinary non-fiber samples. Compared with the sample reinforced with 1.0% steel fiber alone, the combined reinforced sample with 1.0% steel fiber and 1.0% sisal fiber showed an 11.0% increase in bending strength. After 40 dry and wet cycles, the HPC bending strength and toughness of sisal fiber were decreased by 8.1% and 10.0%, respectively. The HPC bending strength and toughness of steel and sisal fiber were decreased by 3.6% and 8.8%, respectively. These

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data indicate that sisal fiber can effectively enhance the bending properties and toughness of HPC at a certain content.

2.3. Thermogravimetric analysis

According to the thermogravimetric analysis results, the mass loss of sisal fiber is attributable to evaporation of water up to 110°C, while 225°C to 315°C is the decomposition temperature of hemicellulose and 315°C to 380°C is the decomposition temperature of cellulose. After 3 days of steam curing, the alkali hydrolysis of sisal fiber was slight, only hemicellulose hydrolysis occurred, and no significant hydrolysis of cellulose occurred. After 40 dry-wet cycles, the mass loss of sisal fiber in HPC decreased from 81.0% to 70.4%, compared with that in HPC without dry-wet cycle. Meanwhile, the peak strength of cellulose decomposition was reduced, suggesting that the amorphous components, such as hemicellulose and lignin in sisal fiber were further hydrolyzed, which led to an increase in the degree of cellulose hydrolysis. Additionally, after 40 dry and wet cycles, the peak temperature of the cellulose decomposition in sisal fibers within high-performance concrete (HPC) decreased from 355°C to 331°C, indicating a reduction in the thermal stability of sisal fibers and a weakening of the degree of polymerization of cellulose.

2.4. X-ray Diffraction (XRD)

XRD analysis of sisal fiber in HPC showed that the structure of the fiber did not change significantly under the condition of dry and wet cycling, However, the degradation of cellulose and hydrolysis of amorphous components to some extent affected the crystal structure of the fiber. According to the XRD results, the crystallinity of sisal fiber has decreased, indicating that its structure has become looser. This change might result in a reduction in the bonding performance of sisal fibers within the cement matrix.

In general, the mechanical properties of sisal fiber-reinforced high-strength concrete (HPC) are stable after dry and wet cycling, especially in compressive strength and bending strength, which shows that its long-term durability is good. Especially compared with other plant fibers, the properties of sisal fiber are maintained well. Although there are some fiber degradation cases, mainly in thermogravimetric analysis at high temperatures, sisal fiber can still provide some enhancement in HPC, especially in terms of bending resistance and toughness. In addition, the effect of sisal fiber on HPC is closely related to the content of sisal fiber and the compactness of cement matrix. An appropriate amount of sisal fiber helps to improve the toughness, crack resistance and durability of concrete, but too much fiber may reduce the compactness of concrete and affect its mechanical properties. Therefore, the addition of sisal fiber needs to be optimized according to the specific engineering needs to ensure its best performance in concrete.

3. The effect of raw bamboo fiber on concrete

As an environmentally friendly biomass material, bamboo's high tensile strength, short maturity period, and excellent toughness make it a potential concrete reinforcement material. Bamboo fiber has gradually become the focus in the application research of reinforced concrete, especially in the fields of bamboo reinforced concrete, bamboo mixed sandwich boards, and so on. Like other environmentally friendly fibers (such as flax, jute, etc.), raw bamboo fiber has good mechanical properties and is convenient for large-scale production [3].

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3.1. Compressive strength test

Many fine cracks can be observed on the surface of the BFC (raw bamboo fiber reinforced concrete) specimen after the test, although the specimen remains intact after failure. In contrast, the PC(ordinary concrete) specimens were subjected to brittle failure with severe penetration cracks. Because the cross action of bamboo fibers helps the concrete bear part of the load, it delays the propagation of microcracks until the fibers are pulled out or broken. The fiber bridging effect significantly increases the ultimate compressive strain of concrete and improves the deformation ability of concrete.

According to the test results of compressive strength in the experiment. Embodies the compressive strength of bamboo fiber-reinforced concrete under different curing ages. The compressive strength of bamboo fiber-reinforced concrete with different fiber volume ratios at 3 days, 7 days, and 14 days is 54.1%-60.2%, 66.8%-73.9% and 77.5%-84.8% of the 28-day strength, respectively, while the corresponding strength of PC specimen is 52.7%, 72.5% and 86.1%. This indicates that bamboo fiber concrete plays an important role in the early strength. Regarding the 28-day compressive strength, the strength of sample BFC1.0-20-10 is similar to that of PC-10,whereas the strength of sample BFC0.5-20-10 and BFC1.5-20-10 are 12.6% and 23.4% lower than that of PC, respectively. This occurrence is related to the equilibrium between the fiber bridging effect and degradation caused by fiber entanglement. Long fibers tend to aggregate, resulting in weak areas in the matrix, which reduces the compressive strength. Besides that,the effect of fiber length on compressive strength is very large of. The sample with fiber length of 10mm has the highest compressive strength, 4.1% higher than that of PC sample. However, specimens with fiber lengths of 20mm and 30mm had lower compressive strength by 0.6% and 5.4%, respectively. The uneven distribution and large aggregation of long fibers are the reasons for this phenomenon. The final maximum aggregate size has little effect on compressive strength. The compressive strength of sample BFC1.0-30-20 (1% fiber content, fiber length, maximum aggregate size) is only 81.2% of that of sample PC. The larger aggregate size provides more space for fiber aggregation, which leads to the decrease of matrix fiber strengthening effect.

3.2. Splitting tensile strength test

In the experiment, multiple little fractures were seen in the middle area of the splitting surface of the BFC sample. Compared with the failure mode of complete fracture of the PC sample, the BFC sample maintained better integrity. The bridge action of bamboo fiber effectively prevented the development of major cracks, so that the cracks replaced the large cracks with evenly distributed small cracks.

According to the test results of the splitting tensile strength, with the fiber content increasing from 0.5% to 1.5%, the splitting tensile strength of BFC sample increased by 15.1%, 19.8% and 8.4%, respectively, compared with that of PC sample. Appropriately increasing the amount of bamboo fiber is helpful to strengthen the bridging effect and enhance the tensile strength. In terms of fiber length, 20mm fiber has the most significant improvement effect on tensile strength. In contrast, the 10mm fiber failed to significantly improve the tensile strength due to insufficient anchoring length, while the 30mm fiber had a certain promotion effect on the tensile strength, but the effect was not as good as the 20mm fiber. This is because the longer fiber has more severe entanglement, which leads to its weakening of the strengthening effect. Next, the growth rate of the splitting tensile strength of BFC was reduced from 16.8%to 6.5%with the increase of the maximum aggregate size. The larger space between the large aggregate particles promotes the agglomeration of the fibers, which reduces the fiber strengthening effect.

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3.3. Flexural strength test

In the experiment, small longitudinal fractures were initially noticed around the pure curved portion of the BFC specimen. With the increase of load, the cracks gradually expanded, but did not extend to the entire section, so the sample maintained good integrity. In contrast, the PC sample showed wide cracks.

According to the load-deflection curve, the curves of BFC and PC samples showed two stages of increase. In the first stage, the slope of BFC samples was larger, indicating that bamboo fiber was helpful in improving the initial bending stiffness and limit the development of cracks. However, in the second stage, the fiber contributes less to the final bending strength of the concrete, because the fiber occupies the space of the concrete, resulting in the ultimate load and deflection of the BFC sample being slightly lower than that of the PC sample.

According to the test results of bending strength, the introduction of bamboo fiber usually leads to a decrease in bending strength, but with the increase of fiber consumption, the decrease in amplitude gradually becomes smaller. When the fiber content is 1.5%, the bending strength of BFC 1.5-20-10 is 93.6% of that of PC-10. This effect is due to the weakening effect of the fiber on the matrix, which increases the porosity of the matrix. However, the addition of fibers helps to provide resistance against crack growth, so there is a trade-off between this negative effect and the positive effect.

In terms of fiber length, the bending strength of BFC1.0-10-10 is increased by 1.5% compared to PC-10. However, when the fiber length was extended to 20mm and above, the bending strength was not significantly improved.

4. Other plant-based fibers

4.1. Straw fiber

The results show that the compressive strength of concrete decreases gradually with the increase of rape straw content. Specifically, the 7-day compressive strength decreases faster than the 28-day compressive strength [4]. This is because the incorporation of straw ash will reduce the amount of cement, thus inhibiting the hydration reaction, resulting in a decrease in the strength of the concrete [5]. However, with the proper dosage and fiber length, straw fibers have a positive effect on the strength and toughness of concrete. The research shows that when the fiber length of rape straw is 30-40 mm and the volume content is 0.1%, the compressive strength can be raised by 16.45%; When the fiber length is 20-30 mm and the volume content is 0.2%, the splitting tensile strength and bending strength are increased by 9.12% and 6.64%, respectively [6]. Moreover, straw concrete also possesses excellent thermal insulation characteristics[86].

4.2. Wood fiber

Wood fiber, as an environmentally friendly material, can effectively absorb and degrade carbon elements and reduce CO2 emissions [7]. However, when wood chips are mixed into concrete, the strength of concrete shows a certain downward trend. According to Yang's research, with the increase of wood chip content, the compressive strength of concrete showed a downward trend in both dry and saturated water absorption states, especially in the saturated water absorption state, the strength decline was more significant. When the sawdust volume content is 3 percent, the strength of the concrete decreases by about 38 percent; When the volume content reaches 10%, the concrete will appear segregated [8].

4.3. Coir fiber

Coir fiber has strong mechanical properties and heat and moisture resistance and is another common plant fiber. Studies have indicated that coir fiber had a considerable effect on the mechanical characteristics of recycled concrete. When the content of coir fiber is 0.5 kg/m^3, the 28-day bending strength can be increased by 5.13% to 23.19%, reaching 4.1-5.79 MPa. The addition of coir fiber can also improve the splitting tensile strength and wear resistance of concrete. Especially when the water-cement ratio is 0.4, coir fiber concrete shows better mechanical properties [9]. In addition, when coir fiber is woven into a network, the interfacial properties of concrete are also significantly improved.

5. Conclusion

Plant fiber concrete has many advantages, such as being lightweight, strong environmental protection, good toughness, excellent heat preservation, and so on. These advantages make plant fiber concrete in the field of construction have broad application prospects, especially in low-carbon buildings and green buildings. Nonetheless, the use of plant fibers in concrete continues to encounter several challenges. First, the addition of plant fiber may cause the phenomenon of expansion and dry shrinkage of wet concrete, which affects its binding performance with the cement matrix. In addition, the chemical reaction of plant fiber in an alkaline environment may cause the durability of concrete to decline. Therefore, how to improve the binding performance of plant fiber and concrete matrix and enhance its long-term durability is an important direction of future research.

The mechanical qualities and durability of concrete can be greatly increased by the use of natural plant fibers, sisal fiber, and bamboo fiber. Sisal fiber especially in strengthening the tensile strength, bending strength, and crack resistance of concrete has a unique advantage; Bamboo fiber has a good effect on improving the tensile strength, bending strength, and durability of concrete. Adding an appropriate amount of plant fiber can effectively improve the comprehensive performance of concrete, especially in crack resistance, freeze-thaw resistance, and corrosion resistance has a strong advantage.

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