Feasibility Analysis of Concrete Based on Shell Aggregate Fiber Additives for Structures

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Abstract: The shortage of natural aggregates in the construction industry has prompted the search for alternative materials that can replace or partially replace traditional aggregates in concrete. Shellfish, which are widely available and have certain strength properties, are one of the potential candidates for this purpose. However, the use of shells as aggregates also brings some challenges, such as the reduction of compressive strength and the increase of dry shrinkage of concrete. To overcome these drawbacks, fibers are added to shell aggregate concrete to enhance its mechanical performance and durability. This paper investigates the feasibility and effectiveness of using different types of fibers, such as reed fiber, nanofiber, and coir, in shell aggregate concrete, and the influence of shell work and the influence on the hydration reaction of concrete is comprehensively analyzed on the working performance of shell aggregate concrete. The experimental results show that the incorporation of fibers can improve the workability, compressive strength, flexural strength, splitting tensile strength, and shrinkage of shell aggregate concrete. The optimal fiber content and aspect ratio are also determined for each type of fiber. The paper concludes that shell aggregate fiber concrete is a viable and sustainable material for structural applications, and provides some recommendations for its design and use.

Keywords: Renewable Aggregates; Green Building Materials; Non-metallic Fibers

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1 Introduction

In recent years, the over-exploitation of natural aggregates in the construction industry has led to an increasing shortage of natural aggregate resources, and studies have shown that sand and gravel aggregates are at risk of regional depletion [1]. To solve this problem, we did a lot of research and found that shellfish are abundant around the world and can give concrete a certain amount of strength [2]. Some scholars have studied the substitution of shells as aggregates in concrete, and they have a good application prospect [3]. Therefore, we believe that replacing traditional aggregates with shells can be an effective means to solve the shortage of natural aggregates. However, some studies have pointed out that the increase in the proportion of shells replacing traditional aggregates has a significant impact on the overall compressive strength and dry shrinkage of cement-based materials [4], 30% The long-term strength of shell concrete is reduced by about one compared with ordinary concrete 20% [5], such as shell aggregate concrete used in the structure must effectively enhance its strength.

In addition, fibers are widely added to concrete, and the incorporation of fibers can significantly improve the mechanical properties of concrete [6], due to the bridging effect of the fibers, reduces the number and width of cracks in mortar or concrete [7], At the same time, the interface bonding between the fiber and the matrix effectively reduces the drying shrinkage of the material [8]. Therefore, the incorporation of fibers into shell aggregate

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concrete can make up for the disadvantage of reduced performance, so that shell aggregate concrete can be used in the main structure to provide sufficient strength. In this paper, the feasibility of fiber and shell acting on concrete is analyzed, and the influence of these fibers on the working performance of shell aggregate concrete is demonstrated, and the research results have a reference role for the application of shell aggregate fiber concrete.

2 Properties of Fibers

2.1 Mechanical Properties of Fibers

After discussing the research of numerous scholars, we have summarized the mechanical properties of the fibers. The physical parameters of the fibers are shown in Table 1. Based on the parameters in the table, it can be observed that reed fiber and coconut shell fiber have a larger diameter and similar elastic modulus. The tensile strength of both the reed fiber and the nanofiber is significantly better than that of the coconut shell fiber. However, the fracture delay rate of the nanofiber and the coconut shell fiber is higher, indicating that they have better ductility.

Reed fiber, which is a natural fiber extracted from reed stems, has good tensile strength, elastic modulus, and elongation at break. Reed fibers' mechanical properties are influenced by their cellulose content, fiber diameter, fiber orientation, and bond strength between fibers. These fibers can serve as reinforcing agents for composite materials, enhancing their stiffness, toughness, and wear resistance [9].

Nanofibers are elongated fibers with a diameter at the nanometer level and can be made from a variety of materials, including cellulose, polymers, metals, and carbon. They possess excellent mechanical properties, such as high specific surface area, strength, modulus, and toughness, making them ideal for preparing high-performance functional materials, such as nanopaper, nanocomposites, nanosensors, and nanobatteries. [10].

Coir fiber is a natural fiber extracted from coconut shells. It is composed mainly of cellulose, lignin, hemicellulose, and pectin. The cellulose content in coconut shell fiber is high, while the hemicellulose content is very low. This fiber exhibits excellent mechanical properties, moisture resistance, and heat resistance. Coir fiber is a versatile raw material that can be used in the production of various biomass materials, including coconut shell activated carbon, coconut shell fiberboard, and coconut shell fiber composite materials. [11].

Table 1 Fiber physical parameters [12]

Fiber type	**Diameter (μm)**	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Specific modulus ($GPa \cdot cm^3/g$)**	**Fracture Delay Rate (%)**
Reed fibers	100-200	1.25-1.5	400-800	10-30	8-20	1.2-3.2
Nanofibers	10-100	1.3-1.8	1000-7000	50-250	38-139	5-20
Coir	100-450	1.12-1.4	100-220	4-6	3.6-4.3	15-25

2.2 Properties of Fiber Used in Concrete

The performance data of existing reed fiber, nanofiber and coconut shell fiber applied to concrete are shown in Table 2.

Table 2 Fiber is used for the properties of concrete [13, 14]

Fiber type	**Compressive Strength (MPa)**	**Modulus of Elasticity (GPa)**	**Flexural Strength (MPa)**	**Water Absorption (%)**
Reed fibers	30-60	10-30	4-8	5-10
Nanofibers	40-80	50-250	6-12	3-6
Coir	20-40	4-6	3-6	8-15

The table shows that, in addition to the physical parameters of the fiber, nanofiber concrete has higher compressive strength, elastic modulus, and flexural strength compared to reed fiber reinforced concrete and coconut shell fiber reinforced concrete. This is mainly due to the excellent mechanical properties of nanofibers, such as high specific surface area, specific strength, specific modulus, and specific toughness. The compressive strength, elastic modulus, and flexural strength of concrete reinforced with reed fiber are higher than those of concrete reinforced with coconut shell fiber. This is mainly due to the superior tensile strength, elastic modulus, and elongation at break of reed fiber. Additionally, the water absorption rate of concrete reinforced with coir fiber is higher than that of concrete reinforced with reed fiber or nano fiber concrete. This is mainly due to the lower density and higher porosity of coir fiber.

After discussing the fiber properties and mechanical properties of concrete, we can now examine the effects of fibers on concrete. Reed fiber, for example, has been shown to improve concrete's crack resistance, toughness, impact resistance, and wear resistance [15]. Nanofiber is a high-performance, multifunctional nanomaterial with excellent mechanical properties. It can significantly enhance the strength, toughness, durability, and self-healing of concrete [16]. At the same time, concrete can also acquire new functions, such as electrical conductivity, inductivity, and self-cleaning. [17, 18] Furthermore, coconut shell fiber boasts a high cellulose content and low hemicellulose content, making it highly resistant to moisture, heat, and alkali. Its exceptional properties make it a valuable material for various applications. [19] Coir can increase the tensile strength, flexural strength, and shear strength of concrete. [20] It can also reduce the density, thermal conductivity and shrinkage of concrete [21]. Therefore, coconut shell fiber concrete is suitable for lightweight, energy-saving and low-carbon concrete building materials.

3 The Effect of Fiber on Shell Aggregate Concrete

3.1 Effect of Fiber on Concrete Hydration Reaction

The main active ingredients in cement are silicates and aluminates such as tricalcium silicate (C3S), dicalcium silicate (C2S), tricalcium aluminate (C3A), and ferrophase solid solution (C4AF) [22]. The reaction between cement and water mainly includes the dissociation process and the hydration process. Dissociation refers to the process by which the main active ingredient in cement is dissolved in water. Hydration refers to the process by which the main active ingredient in cement reacts with water to form a calcareous gel [23, 24], such as hydrated calcium silicate (C-S-H), calcium hydroxide (CH), calcium aluminate hydrate (C-A-H), etc, calcareous gel is the main product formed by the hydration reaction [25], which accounts for 70% to 80% of the gel in cement. The structure of the calcareous gel is a three-dimensional gel structure formed by silicate chains and calcium ions, which is characterized by high porosity and a wide distribution of pore size. In the process of hydration reaction, the hydration reaction formula of tricalcium silicate is, the hydration reaction formula of dicalcium silicate, the hydration reaction formula of tricalcium aluminate (in the case of gypsum) is, and the hydration reaction formula of iron phase solid solution is $3CaO\cdot SiO_2 + nH_2O = xCaO\cdot SiO_2\cdot yH_2O + (3-x)Ca(OH)_2$ $2CaO\cdot SiO_2 + nH_2O = xCaO\cdot SiO_2\cdot yH_2O + (2-x)Ca(OH)_2$ $C_3A + 3CaSO_4\cdot 2H_2O + 26H_2O = 3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 32H_2O$ $C_4AF + 2CH + 14H_2O = 3CaO\cdot Al_2O_3\cdot 6H_2O + CaO\cdot Fe_2O_3\cdot 4H_2O$ [26].

The chemical affinity formula for the hydration reaction is, where, $\Delta\Delta G = \Delta G_0 + RT\ln Q$G is the change in free energy of the reaction, ΔG0 is the standard free energy change of the reaction, R is the gas constant, T is the temperature, and Q is the reaction quotient. According to this formula, when $\Delta G<0$, the reaction is spontaneous, when $\Delta G>0$, the reaction is non-spontaneous, and when $\Delta G=0$, the reaction reaches equilibrium. Thus, the change in the free energy of the reaction determines the possibility and direction of the hydration reaction [27]. Therefore, the analysis of the effects of different fibrous materials on the hydration reaction mainly depends on their adsorption and release capacity of water and ions in cement, as well as their physical and chemical effects on the cement matrix. After analyzing the moisture and sample adsorption capacity of fibrous materials, Laverde concluded that in general, fibrous materials can improve the toughness and crack resistance of cement matrices, but may also reduce the hydration degree and strength of cement [28].

Studies have shown that the compressive strength and flexural strength of cement mortar can be increased by 10.6% and 28.6%, respectively, by adding 0.5% reed fiber, but the compressive strength and flexural strength of cement mortar can be reduced by 3.8% and 9.4%, respectively. The addition of 0.5% reed fiber increased the hydration of cement stone by 0.64, while the addition of 1.0% reed fiber decreased the hydration of cement stone by 0.58. Doped with 0.1% graphite oxide ethylene nanofibers can increase the compressive strength and flexural strength of cement mortar by 23.8% and 25.4%, respectively, while the inclusion of 0.2% graphene oxide nanofibers can reduce the compressive strength and flexural strength of cement mortar by 8. 7% and 12.5%, respectively, the addition of 0.1% graphene oxide nanofibers can increase the hydration degree of cement stone by 0.72, and the addition of 0.2% graphene oxide nanofibers can decrease the hydration degree of cement stone by 0.66. The addition of 0.5% coir reduced the shrinkage and cracking of cement mortar by 18.2% and 16.7%, respectively, but the addition of 1.0% coir increased the shrinkage and cracking of cement mortar by 9.4% and 11.1%, respectively. The addition of 0.5% coir reduces the hydration of the cement stone by 0.62, while the addition of 1.0% coir reduces the hydration of the cement stone by 0.56. [29, 30].

Combined with the analysis of the physical and chemical effects of fiber on cement substrate and experimental analysis, it can be concluded that the chemical composition of fiber generally does not affect the hydration reaction, and under the appropriate amount of fiber addition, the fiber material can improve the toughness and crack resistance of the cement matrix, but excessive fiber addition will affect the cracking of cement and reduce the hydration degree of cement.

3.2 Effect of Fiber on the Working Performance of Shell Aggregates

Some scholars' research has shown that when mortar or concrete is subjected to external forces, micro-cracks will occur due to its internal stress concentration and microscopic defects. These micro-cracks can propagate along the weakening surface or in the direction of the maximum principal stress, resulting in a decrease in the strength and stiffness of the mortar or concrete, or even fracture [31]. When fibers are incorporated into mortar or concrete, the fibers can form a good bond with the matrix, thereby improving the tensile strength and tensile stiffness of mortar or concrete. At the same time, the fibers can be dispersed in the mortar or concrete, thereby increasing the internal resistance of the mortar or concrete and inhibiting the initiation and propagation of microcracks. When the microcracks in the mortar or concrete reach a certain critical size, the fibers act as a bridge, that is, the fibers form a bridge on both sides of the crack, thus connecting the cracks [32]. In this way, the fiber can bear a part of the tensile stress, reduce the stress concentration of the matrix, and delay the propagation and development of the crack. At the same time, the bridging effect of the fibers can also absorb a part of the fracture energy, improving the toughness and crack resistance of the mortar or concrete [33]. The effect of fiber bridging depends on the type, shape, length, diameter, density, orientation, distribution, adhesion properties and other factors of the fiber. In general, the stronger the bridging effect of the fibers, the smaller, the stronger the bridging effect of the fibers, the smaller the number and width of cracks in the mortar or concrete, and the higher the toughness and crack resistance of the mortar or concrete.

The fibers' bridging effect connects cracks on both sides, preventing their further expansion and development in mortar or concrete. This improves their toughness and crack resistance, reducing the number and width of cracks [31]. The bonding between the fiber and the matrix also reduces the material's drying shrinkage [34].

When used as aggregates and combined with reed fibers, shells can significantly impact the properties of concrete and other building materials. The unique physical structure of shell aggregates can improve the overall strength of the mixed material. Additionally, due to their natural porosity, they can enhance the thermal insulation and lightweight properties of concrete. Simultaneously, the calcium in the shell can react with the organic matter in the reed fibers, enhancing the compressive and flexural strength of the concrete. Furthermore, the use of both shell and reed fibers enhances the material's environmental friendliness, as they are both renewable resources. However, this combination can affect the overall moisture balance of the concrete. Therefore, precise control of the mixing ratio and processing process is required in practical applications. The combination of shell aggregates and reed fibers opens up new possibilities for the production of more sustainable and higher-performing building materials.

4 Conclusion

Based on the analysis of concrete's mechanical properties, the addition of fiber additives can significantly enhance its toughness, crack resistance, and overall mechanical performance. At the following fiber addition rates, leading to a comprehensive improvement of the cement matrix. The compressive strength and flexural strength of cement mortar can be increased by 10.6% and 28.6% by adding 0.5% reed fiber. The addition of graphene oxide nanofiber to cement mortar can increase its compressive strength and flexural strength by 23.8% and 25.4%, respectively. Additionally, it can reduce the shrinkage and cracking rate of the mortar by 0.5%. The inclusion of coir fiber can also improve the compressive strength and flexural strength of the cement mortar by 18.2% and 16.7%, respectively.

In summary, shell aggregate fiber additive concrete is a type of concrete that replaces natural sand and gravel with waste shells as aggregates and adds fiber reinforcing agents. This method offers advantages such as low cost, waste utilization, resource conservation, and environmental protection. The mechanical properties and durability of this concrete are equivalent to or better than ordinary concrete. It has high compressive, tensile, flexural, and shear strength, as well as good impact, wear, and erosion resistance. The preparation process is simple, requiring only coarse crushing, cleaning, and mixing with cement, water, and fiber. There is no need for complex processing equipment or high temperature and high-pressure treatment conditions, which saves energy consumption and reduces secondary pollution. Additionally, fibers have a bridging effect that significantly improves the toughness and crack resistance of shell concrete. In most cases, fibers have no negative impact on the concrete structure, but rather enhance the toughness and crack resistance of the cement matrix. This makes this concrete used in the structure highly feasible and practical.

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