Comparative study on properties of different straw fiber cement composites

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Abstract. In order to explore the effect of several common crops (wheat, corn, rice) straw on the properties of cement-based materials, the straw fiber-cement composites were prepared by dividing the straw into cement. The physical and mechanical properties of the three composites were investigated by different pretreatment methods, fiber content and fiber length. The results show that the hemicellulose content in straw decreases greatly in three pretreatment methods (cold water, 4% NaOH solution and hot alkali), and the effect of straw on retarding time of cement is weakened obviously. The increase of dimension length is disadvantageous to the mechanical strength of the composites; after pretreatment, the physical and mechanical properties of the three kinds of straw fiber-cement composites are improved. The optimum order of the three kinds of straw as cement additives is wheat > corn > rice.

1. Background

China is a large agricultural country with an annual output of more than 600 million tons of crop straw [1, 2]. After the crops are harvested, in order to ensure the re-cultivation of the land, only a small part of the treatment of crop straws is used for livestock feed, most of which is disposed of by incineration, and a large amount of harmful gases and smoke are generated during the incineration, which increases the haze. In addition, the resources are relatively scarce in China, to pay attention to the full use of resources, increase the utilization of solid waste resources, and develop and promote new building materials actively, which will become the only way for the construction industry to achieve sustainable development.

The results show that [3, 4], crop straw (such as wheat, corn, rice, etc.) contains a large number of fibers, these fibers compared with asbestos and other fibers, with non-toxic and corrosion-resistant characteristics, and a wide range of sources, low cost, and can be combined with cement to prepare green building materials. Effective utilization of crop straw resources can not only turn the straw into a treasure, but also realize the purpose of saving energy and saving waste, developing economy and protecting environment. However, in many literatures, researchers have only studied the effects of certain straw on the performance of cement-based materials [5-8], but there have been few reports on comparative studies on crops with a wide range of crops such as wheat, corn, and rice.

Therefore, cement is used as the base material, wheat, corn and rice are selected as reinforcement materials to prepare green building composites, and the effect of three kinds of straw as cement reinforcement materials is investigated from the aspects of pretreatment method, fiber content and fiber length, so that suitable straw fiber can be selected as cement in the future. It also provides
guidance for adding materials, and also provides reference for the application of straw fiber cement composites.

2. Raw materials and test methods

2.1. Raw materials

(1) Wheat straw, corn straw and rice straw were all produced in Suzhou. Firstly the straw were cleaned, the dust was removed, the straw was dried and cut into 2-30 cm long with the haircutter, then screened out by grinding them in a feed mill. The length of the straw fibers is 2 mm, 4 mm, 6 mm and 8 mm, respectively. The bags are sealed and stored for use.

(2) Cement: the cement used for this work is Ordinary Portland cement of grade 42.5, the basic physical properties are shown in Table 1.

| Density (kg/m³) | Water consumption of normal Consistency (%) | Setting time (min) |
|----------------|--------------------------------------------|--------------------|
| 3000           | 26                                         | Initial 160        |
|                |                                            | End 210            |

(3) Sodium hydroxide: the sodium hydroxide is the analytically pure produced by Suzhou Chemical Reagent Factory.

2.2. Specimen preparation and characterization

(1) The preparation, curing and testing of straw fiber-cement composite specimens were referred to Testing method of cement mortar strength (ISO method) (GB/T 17671-1999), and the fiber content was the relative mass ratio of straw fiber to cement.

(2) Setting time: to select different pretreatment methods of straw fiber and cement, determine the impact on setting time. The determination were referred to Test methods for water requirement of normal consistency, setting time and soundness of the portland Cements (GB / T 1346 - 2001).

(3) Effect of fiber content and length on dry density and water absorption of composite materials: straw fiber and cement mixed with different dosages and lengths were selected and cured to the specified age to test the effect on the dry density and water absorption of straw fiber-cement composites. Those were measured according to Foam Mixture (JG/T 266 - 2011).

3. Test results and discussion

3.1. Pretreatment of straw fiber

3.1.1. Characteristics and pretreatment of straw fiber. The main components of crop straw are cellulose, hemicellulose and lignin. When straw are added to cement cementitious materials, alkaline environment caused by cement hydration will cause chemical erosion of straw, dissolve monosaccharide, oligosaccharide, starch and other substances, and the cement retard finally [9].

Due to the short molecular chains and poor crystallinity of pentosan in hemicellulose, it is easy to hydrolyze into monosaccharides such as glucose and mannose in alkaline environment, and form calcium gluconate with calcium ions produced by cement hydration, which is coated on the periphery of cement particles, forming a shell and hindering cement hydration [10, 11].

Therefore, in order to reduce the hindrance of small molecular sugars in straw fiber to cement hydration, the pretreatment methods were discussed firstly. The concrete methods were soaking straw with three solvents: cold water, 4% NaOH solution, hot alkali (60°C, 4% NaOH solution), soaking time was 24 hours, and the pretreatment methods were investigated. The effect of each component is shown in Table 2.
Table 2. Effect of pretreatment on components of straw.

| Processing method | wheat stalk | Rice stalk | wheat straw |
|-------------------|-------------|------------|-------------|
|                   | A | B | C | D | E | A | B | C | D | E | A | B | C | D | E |
| I                 | 38.9 | 30.7 | 13.9 | - | 5.6 | 35.7 | 27.1 | 12.0 | - | 13.0 | 37.7 | 27.4 | 14.3 | - | 4.2 |
| II                | 38.6 | 26.8 | 11.9 | 6.47 | 4.5 | 35.3 | 22.3 | 9.9 | 10.7 | 10.8 | 37.4 | 23.2 | 11.6 | 8.2 | 3.4 |
| III               | 37.7 | 8.3 | 4.11 | 30.7 | 3.0 | 34.6 | 5.3 | 3.3 | 28.1 | 4.1 | 36.4 | 7.3 | 4.6 | 29.3 | 2.7 |
| IV                | 37.6 | 3.1 | 1.16 | 43.9 | 1.4 | 33.8 | 2.8 | 2.1 | 36.8 | 2.6 | 36.1 | 3.4 | 1.4 | 39.5 | 1.5 |

I -Untreated, II -Cold water, III-4% NaOH, IV-Hot alkali, A-Cellulose, B-Hemicellulose, C-Lignin, D-Extract, E-Ash Content.

From the data in Table 2, it can be found that after pretreatment, the components of the straw were changed in varying degrees. After pretreatment, the percentage of hemicellulose and lignin in the straw components were decreased significantly, and the specific content changes were the lowest in cold water soaking, followed by 4% NaOH soaking, the highest in hot alkali soaking, and the changes of hemicellulose in the straw components were the most obvious. Hot alkali solution at 60°C has the best effect on the extraction of small molecular sugars from straw. This is because when immersed in an alkali solution, small molecules such as pentosans in hemicellulose are hydrolyzed to monosaccharides, and the amount of dissolution is larger, and the temperature is increased, the rate of hemicellulose hydrolysis is increased, and the hydrolysis is further improved fully. In addition, wheat straw components of the three kinds of straw were changed most obviously, hemicellulose loss were the largest, which will reduce its hindrance to cement hydration, but the amount of cellulose content will also have a certain degree of impact on the physical and mechanical properties of cement.

3.1.2. Effect of pretreatment on setting time. After pretreatment, the hemicellulose in the straw changed obviously. The effect of hemicellulose on setting time of cement was investigated. The results are shown in Table 3.

Table 3. Effect of different pretreatment methods on setting time of cement (min).

| Processing method | wheat stalk | Rice stalk | corn straw |
|-------------------|-------------|------------|------------|
|                   | Initial | End | Initial | End | Initial | End | Initial | End |
| I                 | 191 | 233 | 177 | 225 | 184 | 230 |
| II                | 181 | 225 | 174 | 218 | 177 | 220 |
| III               | 175 | 216 | 171 | 213 | 170 | 214 |
| IV                | 168 | 210 | 166 | 211 | 167 | 210 |

I -Untreated, II -Cold water, III-4% NaOH, IV-Hot alkali

The data in Table 3 were shown that the effects of three pretreatment methods on the initial setting time and final setting time of cement were different. The initial setting time of wheat straw, rice straw and corn straw soaked in cold water were 181 min, 174 min and 177 min, and the final setting time were 225 min, 218 min and 220 min, respectively. Compared with rice straw and corn straw, the initial setting time of wheat straw was prolonged by 7 min and 4 min, and the final setting time was prolonged by 7 min and 5 min. The initial setting time of three kinds of straw soaked in 4% NaOH was 175 min, 171 min and 170 min, respectively, and the final setting time was 216min, 213 min and 214 min. Compared with corn straw and rice straw, the initial setting time of wheat straw increased by 4 min and 5 min, and the final setting time increased by 3 min and 2 min.

After soaking in hot alkali solution, the initial setting time of the three kinds of straw were 168 min, 166 min, 167 min, and the final setting time were 210 min, 211 min and 210 min, respectively. At this time, the initial setting time and the final setting time of the three kinds of straw had little difference. From the point of view of the types of straw, the three kinds of straw fibers have different effects on the setting time of cement. The reason is that the components in the straw were different.
with the other two kinds of straw, wheat straw has higher hemicellulose content and more carbohydrates, so the retarding effect on cement was obvious.

In addition, it can be seen that the first two pretreatment methods will affect the setting time of cement because of the incomplete hydrolysis of carbohydrates in the straw, and after thermal alkali treatment, carbohydrates were removed thoroughly. Therefore, the final three straws have little effect on the setting time of cement.

As a whole, compared with untreated straw, the retarding effect of straw fiber soaked by three pretreatment methods on cement was weakened. Thermo-alkali treatment has the greatest weakening effect, the shortest initial setting time was 23 min, and the shortest final setting time was 23 min. The reason is that the carbohydrate in straw is decomposed sufficiently by thermo-alkali treatment. The straw was removed in the washing process, avoiding the adverse effects of carbohydrates on the setting time of cement.

3.2. Comparison of mechanical properties of three kinds of straw fiber cement composites

3.2.1. Effect of straw fiber content on compressive and flexural properties of composites. Figure 1 shows the effects of three kinds of pretreated and untreated straw fibers on the compressive strength and flexural strength of straw fiber-cement composites.

![Figure 1. Effect of fiber content on compressive strength and flexural strength of straw fiber reinforced cementitious composites.](image)

It is shown that the strength of the three kinds of straw fiber increases first and then decreases when the content of the three kinds of straw fiber increases from 1% to 4%, and the compressive strength and flexural strength reach the maximum when the content of the three kinds of straw fiber is 2%.

Therefore, the optimum content of straw fiber is 2%. When the content of straw fiber is low, it distributes evenly in cement base and forms a complete connection with cement. When the content of straw fiber increases, the distribution of straw fiber in cement base is not uniform, agglomeration occurs in the matrix, and there are defects in the interface between straw fiber and cement base, which leads to the loss of ‘bridge’ effect and the reduction of strength [12].

It can also be seen from Figure 1 that the mechanical properties of straw fiber-cement composites differ greatly before and after pretreatment. The pretreatment can significantly improve the compressive strength and flexural strength of straw fiber cement composites. This is due to the removal of fiber carbohydrates after thermal-alkali immersion, the influence of carbohydrates on cement hydration is greatly weakened. In addition, the waxy layer on the surface of straw fiber can be partly or completely eliminated after soaking with hot alkali, and the rough surface can be exposed, which increases the mechanical adhesive force between the cement paste and the surface of straw fiber [13-15], and reduces the effect on the adhesive strength of the straw fiber-cement interface. Finally, the intensity increases. Figure 1 shows that the mechanical strength of wheat straw is obviously better than that of corn straw and rice straw, and the order is wheat > corn > rice. This is because the cellulose content of wheat straw after pretreatment is higher than that of corn and rice, and the
interfacial bonding probability between wheat straw and cement is high, so the strength of the composite is improved.

![Figure 2. Effect of fiber length on compressive strength and flexural strength of straw fiber reinforced cementitious composites.](image)

3.2.2. Effect of straw fiber length on compressive and flexural properties of composites. Figure 2 shows the effect of different straw fiber length on the mechanical strength of straw fiber cement composites. It can be seen that when the fiber length changes from 2 mm to 8 mm, the compressive strength and flexural strength of the cement-based composite material tend to decrease with the increase of the fiber length. This is because the short fibers have favourable dispersibility in the cement slurry and are easy to mix with the cement. At the same time, short fibers can block part of the capillary channel in the matrix, and the water retention performance is excellent. The cement matrix is not easy to be separated, so that the cement is more hydrated [16]. The 2mm long fiber has the best effect on the mechanical properties of the composite.

It can be seen from Figure 2 that the mechanical properties of wheat straw fiber cement-based materials are better than those of corn stover and rice straw when changing the fiber length, which is closely related to the pretreatment method, and the sugar of wheat is compared with the latter two in the hot alkali treatment mode. The precipitation of the substances is more complete and the cellulose content is higher, so the effect of improving the mechanical properties of the composite material is better.

3.3. Effects of three kinds of straw fibers on physical properties of cement-based composites

3.3.1. Effect of straw fiber content on dry density and water absorption of composites. Figure 3 shows the variation of physical properties of straw fiber cement composites with the increase of straw fiber content.

![Figure 3. Effect of fiber content on dry density and water absorption of straw fiber reinforced cementitious composites.](image)
According to Figure 3, with the increase of straw content, the dry density of composite materials decreased and water absorption increased. The reason is that with the increase of straw content, the volume of straw in cement-based materials increases, and the density of straw is obviously lower than that of cement. Additionally, the increase of fiber content will reduce the dispersion of fiber in cement matrix, and the porosity in the matrix will gradually increase, eventually leading to the decrease of dry density. The higher the content of fiber is, the more fiber content in the composite is. Therefore, the water absorption of the composite increases with the increase of the content of fiber.

The data in Figure 3 shows that, under the same dosage, the dry density of the straw fiber-cement composite after pretreatment is greater than that of the untreated straw fiber-cement composite, and the water absorption is smaller than them also. The straw fiber saccharide after the hot alkali treatment is removed, and the structure formed by the cement is denser, the pores are reduced, and the bonding is more compact. Therefore, the dry density of the composite after pretreatment is increased, and the water absorption rate is reduced.

The results showed that the dry density and water absorption of the three straw composites were the best when the content of wheat straw was 1%. The dry density of wheat straw was 1.852 g/cm$^3$ and the water absorption rate was 12.32%. Compared with corn straw and rice straw, the dry density increased by 0.059 g/cm$^3$ and 0.129 g/cm$^3$ respectively, and the water absorption rate decreased by 0.54% and 1.27% respectively.

In the case of the same length, the wheat cellulose content was high, the volume in the matrix was small, the dispersion in the matrix was good, the pores formed were less, and the structure formed with the cement was denser, therefore, the dry density was larger, and the water absorption was greater. Excessive moisture will reduce the thermal insulation and moisture resistance of the material. Therefore, the influence of the water absorption rate on the durability of the material cannot be ignored, and the small water absorption rate can ensure the durable use of the material.

The experimental results show that the composite with low water absorption can be obtained by adding low amount of straw, and the addition of straw fiber further reduces the density of the material, which makes the lightweight composite material become one of the more practical building materials.

3.3.2. Effect of straw fiber length on dry density and water absorption of composites. Figure 4 shows the effect of straw fiber length on the physical properties of straw fiber cement composites.

![Figure 4](image-url)

**Figure 4.** Effect of fiber length on dry density and water absorption of straw fiber cement matrix composites.

It can be seen from Figure 4 that when the fiber length is increased from 2 mm to 8 mm, the physical properties of the cement-based composite material show different trends, the dry density decreases with the increase of the length, and the water absorption increases with the increase of the length. The longer the fiber length is, the worse the dispersion in the cement matrix is. It is easy to agglomerate in the matrix and form a network structure, which decreases the density of the cement matrix and increases the number of pores in the matrix. As a result, dry density decreases and water absorption increases. From the test results, it can be found that the dry density and water absorption of
straw fiber cement composites are inversely proportional. The characteristics and test results of the combined materials can be considered as the key factor to the phenomenon of true density, swell and dispersibility of straw fibers.

Figure 4 also shows that pretreatment can obviously improve the physical properties of straw fiber cement composites under the same fiber length. The experimental data show that the content of wheat cellulose after pretreatment is higher than that of other two kinds of straws under the same content of three kinds of straws. When the fiber length changes, the wheat straw fiber occupies a small volume in the matrix, and has a good dispersion, the matrix compactness is better, the porosity of the composite is lower, so its dry density is higher than corn straw and rice straw, but the water absorption is lower than the latter two.

4. Conclusions
(1) When three methods are used to pretreat wheat straw, corn stover and rice straw, the content of extracts by hot alkali treatment are high, and the sugar substances in straw are more fully dissolved.

(2) The pretreated straw fiber can improve the compressive strength, flexural strength, dry density and water absorption of the straw fiber-cement composite; the wheat straw can improve the performance of the composite better than corn straw and rice straw; the dry density and water absorption of the composites were inversely proportional, and the physical and mechanical properties of wheat straw fiber-cement composites were better than those of corn and rice.

(3) Adding straw fiber into cement cementitious materials can improve the physical and mechanical properties effectively, and the addition of straw fiber can greatly help to reduce the density of building materials and obtain lighter building materials.

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