Mechanical and Thermophysical Properties of Concrete with Straw Fiber and Straw Ash

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China has abundant straw resources; however, the utilization of straw waste resource remains challenging. In this work, corn straw fiber and corn straw ash were applied to concrete as raw material after pretreatment. Through mechanical and thermal conductivity tests, it was concluded that the tensile strength of the corn straw fiber was 160.5 MPa after alkali treatment. The corn straw fiber and corn straw powder did not enhance the compressive strength of concrete. Compared with original concrete, the thermal conductivity of concrete added with 1.5% corn straw powder decreased by 25.9%, and the thermal conductivity of concrete with 5% corn straw ash was reduced by only 5.2%. Through thermogravimetric analysis of the concrete, it was found that the internal weakly bound water and strongly bound water will be lost in the range 100 °C to 160 °C, $Ca(OH)_2$ will decompose from 420 °C to 500 °C, and $CaCO_3$ will decompose approximately at 800 °C. It is recommended that corn straw powder and corn straw ash can be added at 1.5% and 5% concentrations to ensure that the mechanical properties can meet the engineering requirements and achieve good insulation performance.

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Keywords: Corn straw ash; Corn straw fiber; Thermal conductivity; Thermogravimetric analysis; Concrete

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INTRODUCTION

In recent years, with increasing advancement of agricultural science and technology, grain production has experienced a significant increase. Consequently, the volume of agricultural residues has also been on the rise (Thomas *et al.* 2021; Yurt and Bekar 2022). The traditional method of directly burning the residues not only leads to a waste of straw resources, but it also causes environmental pollution, such as the produced harmful gases and particles that make people sick (Amin *et al.* 2021; Hamza Hasnain *et al.* 2021). Given the growing importance placed on environmental protection, it is crucial to provide an environmentally and resource-efficient approach for the waste (Abbas *et al.* 2022; Amaral *et al.* 2022).

Construction under high temperature conditions, such as the heat damage in deep mines, heat insulation properties, and mechanical properties of concrete materials, are of great significance for the prevention and control of heat damage (Huang *et al.* 2019). If full use is made of crop residue straw resources in concrete construction, this not only will save raw materials, but also make resource utilization of straw resources (Aksoğan *et al.* 2016; Martirena and Monzó 2018). This method broadens the comprehensive utilization of straw, and it helps to reduce the cost of concrete production. Straw fiber has a lower cost and significant economy compared with other concrete materials, which not only solves the problem of straw treatment, but it also realizes the reuse of resources, in line with the concept of sustainable development. However, because of its poor mechanical properties, chemical composition, and waxy surface layer characteristics, straw resources face challenges in achieving good compatibility with other materials, and the limitations significantly hinder the widespread application of straw in concrete materials. Additionally, biomass power generation produces substantial amounts of ash, which possesses certain activity, for example, active SiO_2 and active Al_2O_3 react with other components in concrete to form calcium silicate hydrate and calcium aluminate hydrate gel, which promote the performance of concrete to a certain extent. Meanwhile, concrete is a highly used material in construction, and the cost of raw materials in the production process accounts for a large proportion. As a low-cost, easy to obtain raw material, straw ash can partially replace traditional concrete raw material, reduce production costs, and improve economic benefits, and incorporating the ash into concrete offers an effective means for recycling straw ash (He *et al.* 2016; Wang *et al.* 2019).

The research on straw fiber and straw ash concrete in cement-based materials is still in its infancy. There is still no uniform standard for both test and application, but already there are some research results in this respect. Ammari *et al.* (2020) reported that the addition of straw to cement mortar can reduce the thermal conductivity and mechanical properties of mortar. Jian *et al.* (2014) realized that the optimum amount of rice straw fiber can enhance the flexural strength and dry shrinkage resistance of cement-based materials but reduce the compressive strength. Memon *et al.* (2019) reported that corncob ash instead of concrete fine aggregate can reduce the compressive strength of concrete and increase the water absorption rate and acid corrosion degree of concrete. Rosales *et al.* (2017) reported on the influence of different pretreatment of straw ash on the mechanical properties of cement mortar.

This method provides a new way for the utilization of straw resources. However, the current work considered the engineering application of straw resources in concrete, including the mechanical properties and durability. The authors studied both the mechanical and thermal properties of concrete by adding the corn straw fiber and corn straw ash. Such information will have a great significance to the utilization of straw resources, environmental protection, and increasing the functional properties of concrete materials.

EXPERIMENTAL

Materials

The corn straw fiber was obtained from straw core from Bozhou, Anhui Province, China. The corn straw fiber and the corn straw powder were specially treated, which can improve their physical properties. The corn straw ash was also specially calcined to enhance the activity of straw ash, the treatment methods have been introduced in the literature (Wen *et al.* 2023, 2024).

The cement was made of Bagongshan P.O 42.5. The setting time and the strength index are shown in Table 1, and the mineral composition is shown in Fig. 1. Coarse aggregate, the river sand, the water reducing agent, and water were the same as materials used by Wen *et al.* 2023, 2024.

Table 1. Cement Setting Time and Strength Index

Presetting Time (min)	Final setting Time (min)	Compressive Strength (MPa)		Flexural Strength (MPa)	
		3	28	3	28
194	243	25.8	-	5.6	-

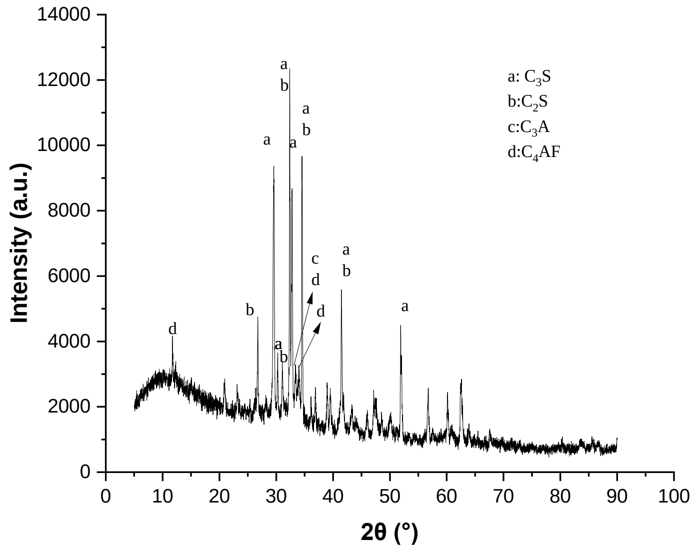


Fig. 1. XRD pattern of cement

Test Methods

Mechanical properties test

The mechanical properties of corn straw fiber after the pretreatment were tested according to GB/T 1040 (2006), the standard distance was 50 mm, and the loading speed was 50 mm·min^{-1}.

Concrete strength test

Cement, water, stone, and sand were added in accordance with the ratios 1:0.45:1.94:1.94, the added amount of corn straw fiber and corn straw powder was 1.5%, 2.5%, and 4% of the cement, and the replaced cement amount of corn straw ash was 5%, 10%, and 15%, respectively (Wen *et al.* 2023). The concrete sample of 100 × 100 × 100 mm^3 was made by adding an appropriate amount of water-reducing agent and stirring evenly. After resting for 24 h, the sample was demolded and placed in a standard curing box (humidity ≥ 95%, temperature 20 ± 2 °C) for a curing period of 28 days, and then the compressive strength test is carried out (Wen *et al.* 2023, 2024).

Thermal conductivity test

The plane heat source method was adopted, and the instrument (Hotdisk TPS 2500S, Sweden) was used for the tests. Preparation of the test specimen involves reshaping the sample. The sample was ground under the pressure of 30 MPa by keeping the pressure for

1 min, and then taking the thermal conductivity test specimen for testing according ISO 22007 (2015).

Thermogravimetric analysis test

The test adopted the comprehensive thermal analyzer (STA449 F5, NETZSCH, Germany), the heating rate was set at 10 ℃ /min, the maximum target temperature is 900 ℃, and the atmosphere is N_2.

RESULTS

Properties of Corn Straw Fiber and Corn Straw Ash

Tensile strength of corn straw fiber

It can be seen from Fig. 2 that the tensile strength of raw corn straw fiber was 90.6 MPa, and it was 160.5 MPa after alkali treatment. After alkali combined polyvinyl alcohol treatment, the tensile strength was 162 MPa. It is apparent that the alkali treatment can improve the tensile strength of corn straw fiber.

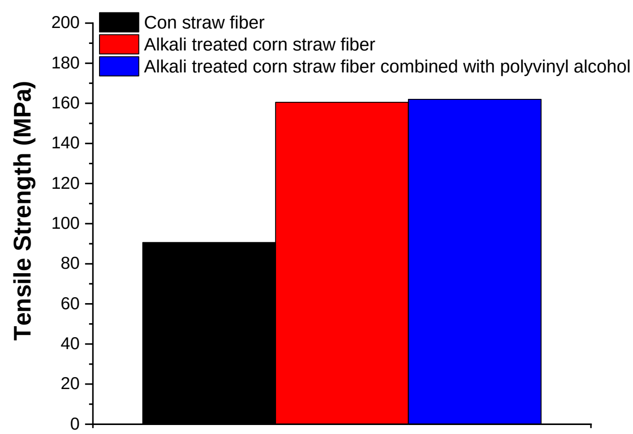


Fig. 2. The tensile strength of the corn straw fiber

Alkali treatment can increase the specific gravity of cellulose and improve the mechanical properties due to a strong force between the molecular chains of cellulose, which increases the tensile strength after alkali treatment (He *et al.* 2016; Ma *et al.* 2020; Wang *et al.* 2019; Wen *et al.* 2023). It is also known that the polyvinyl alcohol has limited effect on strength, but it may can improve the corrosion resistance of the corn straw fiber. The following sections will demonstrate this from the microstructure.

Microstructure of the corn straw fiber

To observe the effect of straw structure by polyvinyl alcohol, the cross-section of corn straw fiber was selected. It can be seen from Fig. 3 (a) that the internal void of the original cross-section corn straw fiber was bigger, and the structure was relatively loose, while in Fig. 3 (b), the internal void size of the corn straw fiber after alkali treatment was reduced. The cellulose and vascular bundle became tight, indicating that alkali treatment can improve the strength (He *et al.* 2015). In Fig. 3 (c), the authors found that the internal voids of corn straw were permeated, adsorbed, and filled by the polyvinyl alcohol. This also verified that polyvinyl alcohol treatment of corn straw after alkali treatment can improve the resistance to degradation (Huang *et al.* 2019;Li *et al.* 2012; Wen *et al.* 2023).

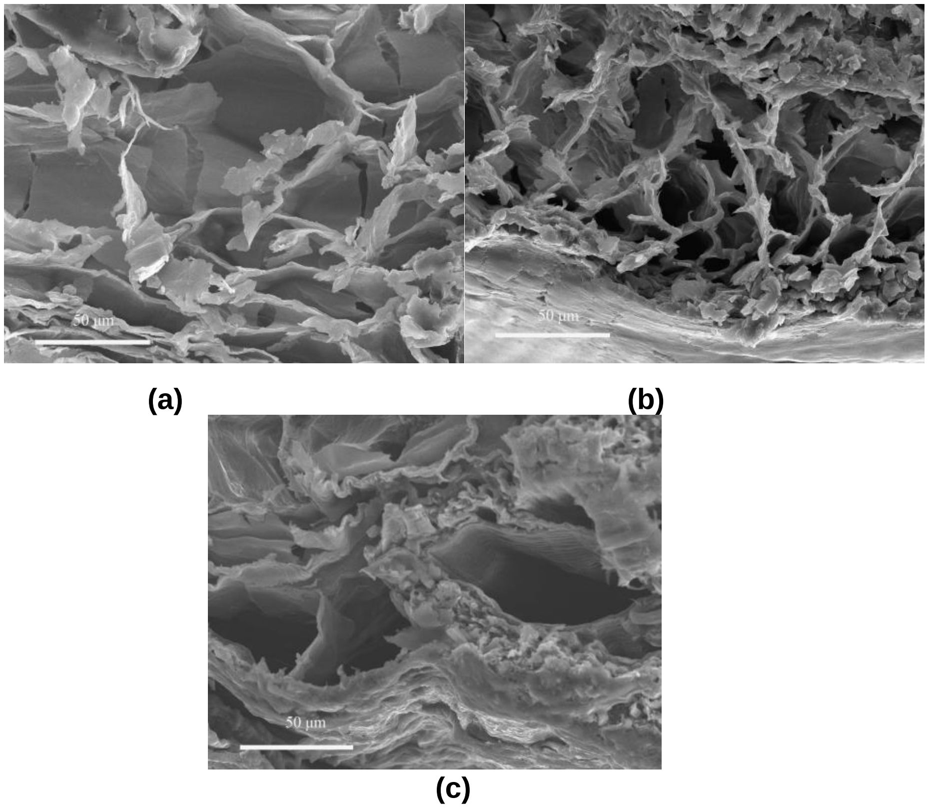


Fig. 3. SEM of different straw treatments: (a) Corn straw fiber, (b) Corn straw fiber after alkali treatment, and (c) Corn straw fiber after alkali combined polyvinyl alcohol treatment

Particle size of corn straw ash

Incomplete combustion of corn straw ash contains a higher amount of unburnt carbon. This affects the mechanical properties of concrete when added to concrete, while calcined corn straw ash can enhance the activity of corn straw ash (Santhosh *et al.* 2022). It can be seen from Fig. 4 that the surface topography of corn straw ash was uneven and there were some irregular small size particles. Based on the literature (Wen *et al*. 2024), it is apparent that the content of particles smaller than 41 μm accounted for 50% of the total amount.

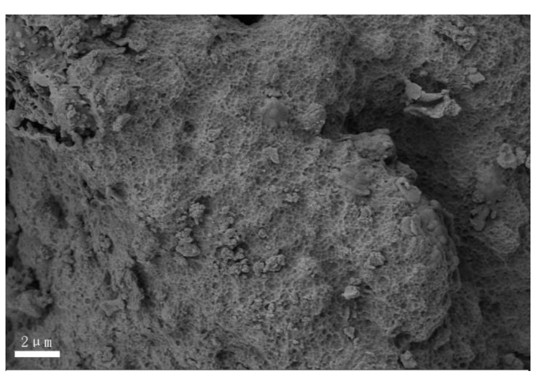


Fig. 4. SEM of treated corn straw ash

Concrete Properties

Compressive strength

It can be seen from Fig. 5 that the addition of corn straw fiber and corn straw powder can reduce the compressive strength of concrete. The compressive strength of concrete was reduced by 20.2% when adding 1.5% corn straw fiber, and it was reduced 19% with adding the same dosage as for the corn straw powder. As for the corn straw ash, the compressive strength of concrete was still remained above 30 MPa when it was added at a 5% dosage in the literature (Wen *et al.* 2024), which indicates that the application of straw waste to concrete is feasible (Zhang *et al.* 2017; Wen *et al.* 2024). The strength decrease of the concrete with corn straw fiber addition can be attributed to poor mechanical properties of the fiber. In addition, the proportion of cement in the concrete is reduced, which further contributes to reduced strength of the concrete.

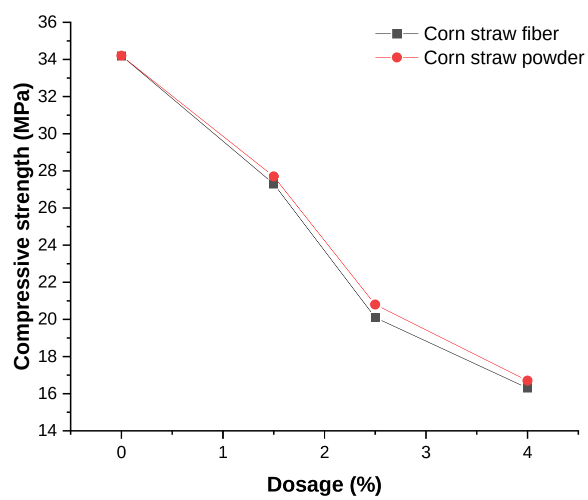
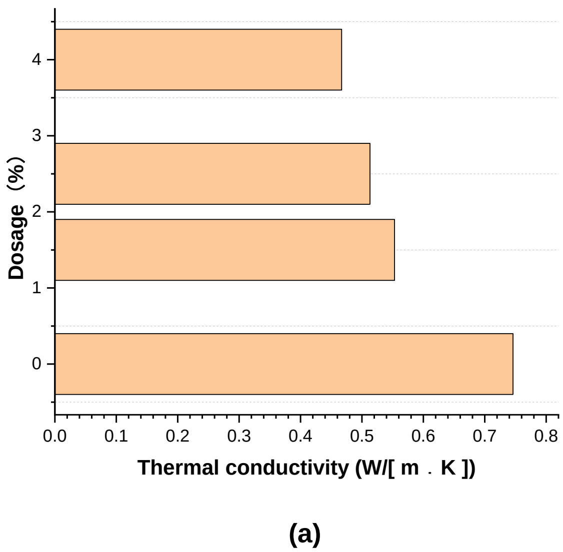


Fig. 5. Influences of corn straw fiber and corn straw powder on the concrete

When the straw fiber is processed into straw powder, the straw powder fills the internal pores of the concrete, and the compatibility with the concrete is better than the straw fiber, so the strength is greater than the straw fiber concrete. Corn straw ash as the addition to cement-based materials will also affect its mechanical properties (Khan *et al.* 2022), as for the corn straw ash in this paper, the result has been explained in the literature (Wen *et al.* 2024).

Thermal conductivity

Corn straw powder and corn straw fiber are in different forms, and this paper only studied the influence of corn straw powder on the thermal conductivity of concrete. It can be seen from Fig. 6 that corn straw powder and corn straw ash added to concrete had a great impact on the thermal conductivity of concrete. Compared with original concrete, the thermal conductivity of concrete added with 1.5% corn straw powder decreased by 25.9%, and the thermal conductivity of concrete with 5% corn straw ash was reduced by only 5.2%. There are many factors affecting the thermal conductivity of concrete, such as aggregate, porosity, water-cement ratio, and so on (Wang *et al.* 2012). The thermal conductivity of straw material is smaller than that of cement matrix, and corn straw powder and corn straw ash changed the thermal conductivity path of cement matrix. The low thermal conductivity of corn straw powder hinders the heat transfer between aggregates and mortar inside concrete, resulting in the decline of the thermal conductivity of concrete (Gao *et al.* 2022). Corn straw ash in concrete is similar to cement, but the thermal conductivity of straw ash concrete was also reduced. The solids and voids of concrete play a major role in the heat conduction of concrete; to enhance the thermal insulation performance of concrete, one can change the internal structure and composition of concrete (Gao *et al.* 2022).



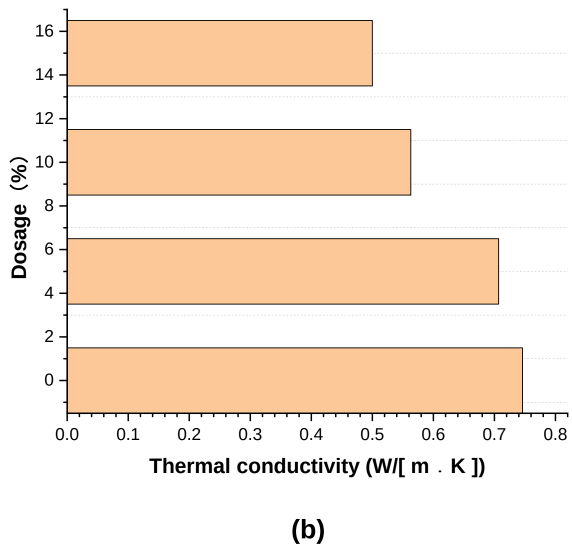


Fig. 6. Thermal conductivity of concrete with straw powder and straw ash: (a) Corn straw powder, (b) Corn straw ash

Thermogravimetric analysis

The TG curve represents the weight loss of concrete, whereas the DTG curve represents the weight loss rate of concrete. As shown in Fig. 7(a), as the temperature rose, the quality of concrete gradually decreased. When the temperature reached 800 °C, the TG curves of the concrete became stable. As shown in Fig. 7(b), there were some peaks in the DTG curve, indicating that the interior of concrete was affected by temperature. When the temperature was below 100 °C, the evaporation of free water accounted for the weight loss. In the temperature range of 100 to 160 °C, there were two downward peaks in the DTG curve, indicating that weakly bound water and strongly bound water were lost. In the range 420 to 500 °C, the concrete also exhibited a weight loss interval; this was attributed to the internal decomposition of $Ca(OH)_2$. When the temperature was around 800 °C, the downward peak was relatively clear, indicating that the $Ca(CO)_3$ inside the concrete began to decompose to CaO; thereafter the DTG curve of the concrete was stable.

Within the temperature range 420 to 500 °C, the chemical reaction of $Ca(OH)_2$ in the concrete occurs; it can be expressed as the follows (Liu *et al.* 2018):

$$\mathrm{Ca(OH)_2(s) = CaO_2(s) + H_2O(g)} \tag{1}$$

The chemical reaction of $Ca(CO)_3$ occurs inside the concrete at aboat 800 °C; it can be expressed as the follows (Liu *et al.* 2018):

$$\mathrm{Ca(CO)_3 = CaO_2(s) + CO_2(g)} \tag{2}$$

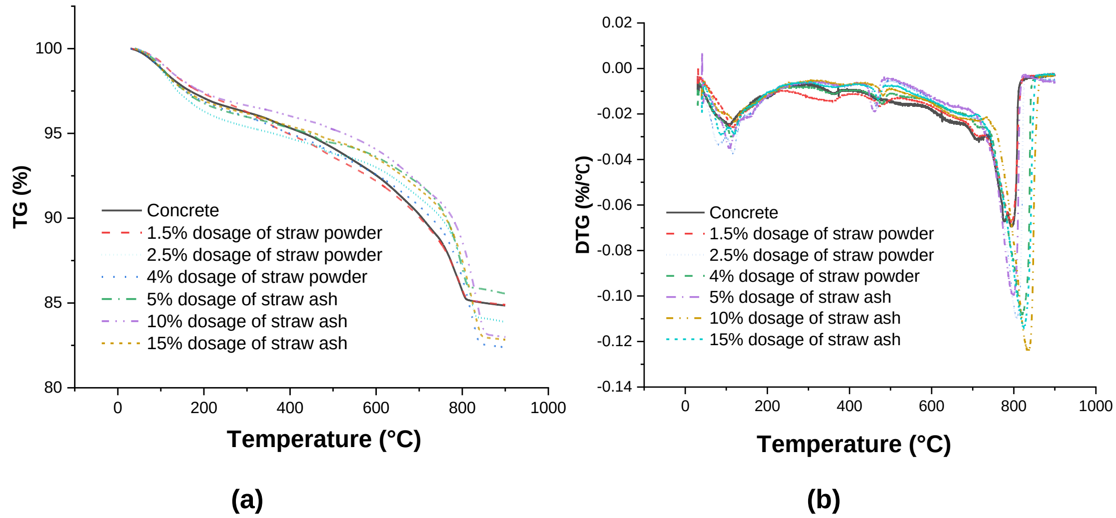


Fig. 7. Thermogravimetric analysis curve of corn straw concrete: (a) TG curve, (b) DTG curve

Microstructure of concrete

As shown in Fig. 8(a), fibrous and needle-like calcium silicate hydrate (C-S-H) in the original concrete diagram intersected with each other, and there was a certain void volume in the concrete structure.

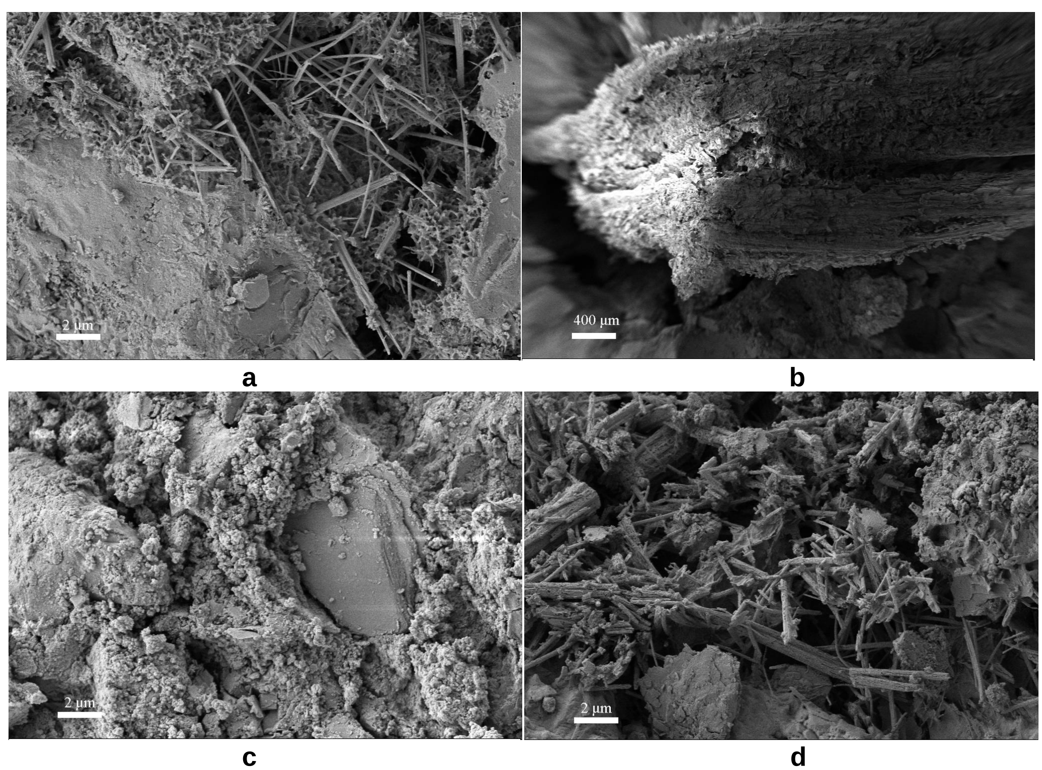


Fig. 8. SEM of the concrete: (a) Raw concrete, (b) Corn straw fiber concrete, (c) Corn straw powder concrete, and (d) Corn straw ash concrete

As shown in Fig. 8(b), corn straw fiber connected to the deconstructed surface of concrete, and the connection degree was not tight. There were certain pores in the middle, which indicates that corn straw fiber had poor compatibility with cement mortar and aggregate, and there were certain interfacial pores, which also led to the decline of the strength of corn straw concrete. In Fig. 8(c), it can be found that the internal pores of the concrete were filled with corn straw powder, which was in good contact with cement mortar and aggregate, and the pores were small. As shown in Fig. 8(d), a dense network C-S-H was present, this may be due to the secondary hydration of cement hydration products generated by corn straw ash.

DISCUSSION

The thermal conductivity is an important index to characterize concrete. The smaller the thermal conductivity, the better will be its thermal insulation performance. The production process of corn straw fiber and corn straw ash concrete in this paper is similar to that of ordinary concrete, but there are great differences in thermal conductivity, which can be attributed to the difference in the internal structure of concrete caused by the difference in the internal composition of concrete. Although the concrete thermal conductivity test in this paper adopts remolding compaction sample preparation, the results still can represent the thermal conductivity of concrete, and the effect on the influence of the corn straw powder and corn straw ash on the thermal conductivity of the concrete.

The heat transfer path inside the concrete passes through continuous and discontinuous layers of cement mortar and aggregate, accordingly, the thermal conductivity of concrete can be expressed as shown below (Campbell-Allen 1963; Zhu *et al.* 2015):

$$M = 1 - \sqrt[3]{1-P} \tag{3}$$

$$\kappa = k_m(2M - M^2) + \frac{k_m k_a (1-M)^2}{k_a M + k_m(1-M)} \tag{4}$$

where P is the volume fraction of concrete mortar (1); k_m is the cement mortar thermal conductivity (W/(m.K)); and k_a is the aggregate thermal conductivity (W/(m.K)).

Assume that the thermal conductivity of corn straw powder or corn straw ash mortar is expressed as,

$$k_m = v_1\lambda_1 + v_2\lambda_2 + v_3\lambda_3 \tag{5}$$

where v_1, v_2, v_3 represents the volume fraction of cement, fine aggregate, and corn straw powder or corn straw ash, respectively, and $\lambda_1, \lambda_2, \lambda_3$ represent the thermal conductivity of cement, fine aggregate, and corn straw powder or corn straw ash respectively.

$$\kappa = (v_1\lambda_1 + v_2\lambda_2 + v_3\lambda_3)(2M - M^2) + \frac{(v_1\lambda_1+v_2\lambda_2+v_3\lambda_3)\ k_a(1-M^2)}{k_a M + (v_1\lambda_1+v_2\lambda_2+v_3\lambda_3)(1-M)} \tag{6}$$

The thermal conductivity of concrete is not only related to the thermal conductivity of cement, corn straw powder, corn straw ash, fine aggregate, and coarse aggregate, but it is also related to the volume fraction of aggregate. In fact, the thermal conductivity of concrete is also related to water-cement ratio, sand content, pore distribution number, and interfacial thermal resistance. For corn straw powder concrete, corn straw powder thermal conductivity and cement mortar thermal conductivity and coarse aggregate, the thermal conductivity difference is large, and the temperature difference between the two sides of the interface is large, which implies that the interfacial thermal resistance is large. If the interface is not fully contacted, there are still some gases inside, which will also hinder the heat conduction inside the concrete. Meanwhile, the low thermal conductivity of the corn straw powder also reduces the thermal conductivity of the concrete. Corn straw ash will also reduce the thermal conductivity of concrete, which may be due to the poor thermal conductivity of corn straw ash, secondary hydration reaction, and particle filling effect after it is added to concrete, resulting in corn straw ash wrapped around the concrete aggregate. In addition, the micropores in straw ash concrete increase, which also has a bad effect on the thermal conductivity of concrete. Therefore, the overall thermal conductivity of corn straw ash concrete decreases.

CONCLUSIONS

1. Alkali treatment is able to increase the tensile strength of corn straw fiber and also can make the internal pores of corn straw fiber smaller. Polyvinyl alcohol can improve the resistance of the straw fiber to degradation by adsorbing on the internal pores of corn straw fiber.
2. The compressive strength of straw concrete decreased with the increase of the addition corn straw fiber and corn straw powder dosage. With the increase of corn straw powder and corn straw ash dosage, the thermal conductivity of concrete decreases gradually, and the thermal conductivity of concrete added with 1.5% corn straw powder decreased by 25.9%, the thermal conductivity of concrete with 5% corn straw ash was reduced by 5.2%. The effect of corn straw powder on reducing the thermal conductivity of concrete was better than that of corn straw ash.
3. According to the thermogravimetric analysis of concrete, free water evaporates when the temperature is below 100 ℃, bound water is lost in 100 to 160 ℃, calcium hydroxide is decomposed by heat in 420 to 500 ℃, and calcium carbonate is decomposed by heat approximately at 800 ℃.
4. When straw is used as a heat-insulating concrete material, it is recommended to add 1.5% corn straw powder or 5% corn straw ash under the requirements of the mechanical properties.

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