Experimental Study on Freeze-Thaw Properties and Thermal Conductivity of Green and Environment-Friendly Three-Admixture Concrete

Yuhao Song¹, Zhengchao Jin¹*, Zijie Tuo¹, Chao Li¹, Guangxiu Fang¹

¹Department of Civil Engineering, College of Engineering, Yanbian university, Yanji, Jilin, China

*Corresponding author’s e-mail: jinzhengchao@ybu.edu.cn

Abstract: Using straw powder (rice husk ash), fly ash, silicon powder and other three admixtures to prepare concrete can improve the ecological environment and promote the reuse of agricultural and industrial wastes. In this paper, 9 groups of freeze-thaw specimens and 9 groups of thermal conductivity specimens of green and environment-friendly three admixture-blended concrete were prepared with corn, wheat and rice husk powder, replacing cement with straw powder by 6% and 8% respectively and replacing cement with fly ash by 20% and silica fume by 10%. The test results show that the mass loss rate of the concrete ranges from 0.8% to 1.4% and from 3.5% to 4.4% after 25 and 50 freeze-thaw cycles, respectively. The thermal conductivity of the concrete falls within the range of 0.2901 w/(m·K)-0.5834 w/(m·K), which is suitable for the existing building reconstruction and new construction projects in cold and severe cold areas.

1. Introduction
In China, the quantity of straw resources and wastes from the crop production, occupies the first place in the world, but the utilization rate only reaches 33%. Since 1994, the amount of straw produced in China, though fluctuating, has shown an overall upward trend, reaching more than 640 million tons up to now, but a large amount of straw waste cannot be rationally utilized. Every year, nearly 200 million tons of crop straws are burned on the spot in China, resulting in a great waste of resources and environmental pollution [1]. In addition, due to the limitation of technology, capital and other factors, the utilization of straw resources in China is single and inefficient.

In order to further accelerate the resource utilization of agricultural straw, the state has issued a number of policies to plan and support the comprehensive utilization of straw since the 13th Five-Year Plan. In an active response to the national policy, Zhang Q [2] studied the mechanical properties and workability of concrete mixed with rape straw and silica fume. The results showed that with the increase in silica fume content, the cohesion and water retention of concrete became better, and when the silica fume content was 10%, the compressive strength of concrete increased by 24%. Chen D [3] explored the mechanical properties and thermal insulation properties of concrete mixed with different kinds of straw and fly ash, and found that the mechanical properties and thermal insulation properties of concrete mixed with rape straw were better than those mixed with wheat straw and corn straw. At present, the studies on straw concrete at home (China) and abroad have mainly focused on the influence of a certain kind of straw on its performance [4] the performances of concrete specimens mixed with different kinds of straw have been comparatively analyzed in few studies. On the other hand, modern concrete is mixed with a large amount of industrial solid wastes [5] such as fly ash and slag, while few studies have
involved the concrete performance under the interaction of straw and solid wastes.

In this paper, corn, wheat, rice straw and rice husk were used as raw materials, processed into powder, and mixed with fly ash and silica fume in a certain proportion, respectively. The frost resistance and heat preservation performance of new concrete with three different kinds of straw, fly ash and silica fume were studied, aiming to provide the reference for the application of this new concrete material in the existing building reconstruction and new construction projects in cold and severe cold areas.

2. Test Materials and Schemes

2.1. Test materials
1) Silicon powder: 92% domestic silicon powder from Henan Platinum Casting Material Co., Ltd;
2) Corn straw powder: 20-mesh crushed corn stalk experimental powder from Jiangsu Surui Straw Processing Factory;
3) Wheat straw powder: 20-mesh crushed wheat straw experimental powder from Jiangsu Surui Straw Processing Factory;
4) Rice straw powder: rice straw powder with specifications of 0.5-1cm from Shandong Yutai Jiayao Agricultural Products Co., Ltd.;
5) Grinding rice husk: 80-mesh low-moisture dried and dust removed rice husk powder from Chutian bran powder processing factory in Badong County, Enshi Prefecture, Hubei Province;
6) Cement: "Miaoling" P.O 42.5 ordinary Portland cement from Jilin North Cement Company;
7) Coarse and fine aggregate: The maximum particle size of natural crushed stone was 20 mm, the apparent density was 2,680 kg/m, and the water content was 0%; the natural sand was medium sand with qualified gradation, apparent density of 2,600 kg/m and water content of 0%.
8) Fly ash: ii fly ash from Tienan Heating Company in Yanji City, Jilin Province;
9) Water reducer: polycarboxylate water reducer from northern building materials market in Yanji City, Jilin Province;
10) Water: tap water;
11) Wooden board for mold making: 2 m × 2.4 m solid board from Beida Building Materials Market in Yanji City, Jilin Province.

2.2. Test scheme
1) Design indicators
The design strength grade of both green environment-friendly three-admixture concrete and ordinary concrete was C30. The slump required by the construction is T=30-50 mm and sand ratio was Sp= 35%.
2) Maintenance conditions
The concrete block was placed in a standard curing room at 20.2 ℃ and a relative humidity of over 80%.
3) Fabrication of test blocks
A total of 9-group test blocks were made, the first group was the concrete control group mixed with fly ash and silica fume; in the second to fifth groups, straw powder was used to replace cement by 6%; in groups 6 to 9, straw powder was used to replace cement by 8%. Among them, corn straw powder was chosen for the second group and the sixth group; wheat straw powder for the third and seventh groups; straw powder for the fourth and eighth groups; rice husk powder for the fifth and ninth groups. In all the 9 groups, fly ash was used to replace cement by 20%, and silica fume to replace cement by 10%.
4) Preparation strength and mix ratio
The formula of concrete preparation strength given in the Code for Mix Proportion Design of Ordinary Concrete (JGJ55-2011) was taken for reference as below:

\[ f_{cu,0} = f_{cu,k} + 1.645\sigma \]  

In which:
\( \sigma \) —— standard deviation of concrete strength (N/mm²);
\( F_{cu,0} \) —— preparation strength of concrete (N/mm²);
$F_{cu,k}$ —— standard value of compressive strength of concrete cube (N/mm²).

According to calculation, the mixing ratio of 1 m³ ordinary concrete is 215.6: 201.6:684.26:1272.73 (cement: water: sand: gravel). The experimental coordination of straw powder (rice husk powder), fly ash and silicon powder mixed with concrete is shown in Table 1.

Table 1. Test Mix Proportions of Green and Environment-friendly Three-admixture Concrete (mixed amount is 23 liters)

| group | Cement /kg | Water /kg | sand /kg | Natural crushed stone /kg | Silica fume /kg | Fly ash /kg | Straw powder (rice husk powder) / kg |
|-------|------------|-----------|----------|---------------------------|-----------------|-------------|-----------------------------------|
| 1     | 4.96       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0                                 |
| 2     | 4.66       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.30                              |
| 3     | 4.66       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.30                              |
| 4     | 4.66       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.30                              |
| 5     | 4.66       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.30                              |
| 6     | 4.56       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.40                              |
| 7     | 4.56       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.40                              |
| 8     | 4.56       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.40                              |
| 9     | 4.56       | 4.64      | 15.74    | 29.27                     | 0.71            | 1.42        | 0.40                              |

3. Test Equipment and Tests

3.1. Freeze-thaw test

According to the Standard for Test Methods of Long-term Performance and Durability of Ordinary Concrete (GB / T 50082-2009), 9 groups of specimens were prepared, as shown in Figure 1. After 25 and 50 freeze-thaw cycles, the mass loss rate was tested; the specimen dimensions were 100 mm × 100 mm × 400 mm; KDR type rapid freeze-thaw testing machine was used for the test. After 28 days of curing in the standard curing room, the test blocks were taken out, and the test blocks were numbered, and put into the freeze-thaw test instrument, as shown in Figure 2.

Figure 1. Freeze-thaw Specimens

Figure 2. Freeze-thaw Test

The water level in the test box was 5 mm higher than the top surface of each test block. The minimum and maximum temperatures of the specimen center were controlled between (- 16 ± 2) °C and (5 ± 2) °C, respectively. The single freeze-thaw cycle time was 3-4 h, the conversion time between freezing and thawing was not longer than 10 min, and the melting time was not less than 1/4 of the whole freeze-thaw cycle time. The mass loss rate of the test block was measured by a balance with an accuracy of 0.1 g; each time the set freeze-thaw cycles were completed for one specimen, the moisture on the surface was wiped off and weighed, and the mass loss rate of the specimen was calculated according to formula (2).
\[ \Delta W_n = \frac{G_0 - G_n}{G_0} \times 100\% \]  

Where:

\( \Delta W_n \) —— the mass loss rate (%) of concrete specimens after n freeze-thaw cycles;

\( G_0 \) —— the mass of concrete specimen before freeze-thaw cycle (g);

\( G_n \) —— the mass of concrete specimens after n freeze-thaw cycles (g);

3.2. Thermal conductivity test

Drh-300 thermal conductivity tester was used to test the thermal conductivity. The measurement range of thermal conductivity was 0.010-2 w/(m) · K, and the measurement accuracy was less than 1%; the measurement range of hot surface temperature was room temperature -99.99 °C, and the temperature resolution was 0.01 °C; the measurement range of cold surface temperature was 0- -60 °C, the temperature resolution was 0.01 °C, and the laboratory temperature was 20-25 °C. According to "Determination of Steady-state Thermal Resistance and Related Properties of Thermal Insulation Materials: Guarded Hot Plate Apparatus" (GB/T 10294-2008) [2] and the test requirements of, 9 groups of concrete blocks were prepared, with 4 blocks in each group and 36 blocks in total. A concrete plate specimen with the dimensions of 300 mm × 300 mm × 30 mm was used to measure the thermal conductivity, as shown in Figure 3.

![Figure 3. Thermal Conductivity Test Block](image1)

![Figure 4. Thermal Conductivity Test](image2)

In order to avoid the gap between the test block and the plate caused by the uneven surface of the test block, the customized steel template was used as the test mold. After each specimen was formed, the mold was removed after standing for 24 h. Afterwards, the concrete surface was grinded with sand paper to ensure that the thickness of the specimen was uniform, and the two surfaces were parallel. Then the thermal conductivity was tested after the standard curing in the curing room for 28 days, ensuring that all contact surfaces were flat and tight. In an effort to eliminate the influence of external factors on the value, it is necessary to close the protective cover and thus close the whole test system, as shown in Figure 4. The thermal conductivity test environment was kept dry. The hot plate control temperature was set at 35 °C, the cold plate control temperature at 15 °C, and the temperature difference between the cold and hot plates at 20 °C; the power supply was turned on to start the test. After a period of time, the test data converged stably, and the test equipment stopped automatically. The system displayed the specific value of thermal conductivity.

4. Test Results and Analysis

4.1. Analysis of freeze-thaw test data

After 25 and 50 freeze-thaw cycles, the appearance changes of the specimens are shown in Figure 5 and Figure 6; Table 2 shows the freeze-thaw test data of 9 groups of concrete specimens.
It could be seen from Table 2 that after 25 freeze-thaw cycles, the mass loss rate of green and environment-friendly three-admixture concrete was within 0.8% - 1.4%; after 50 freeze-thaw cycles, the mass loss rate was within 3.5% - 4.4%.

| Group/number of cycles | After 25 cycles | After 50 cycles |
|------------------------|-----------------|-----------------|
| 1 group                | 0.6%            | 2.5%            |
| 2 groups               | 0.8%            | 3.6%            |
| 3 groups               | 0.8%            | 3.5%            |
| 4 groups               | 1.1%            | 3.9%            |
| 5 groups               | 0.9%            | 3.8%            |
| 6 groups               | 1.2%            | 4.2%            |
| 7 groups               | 1.1%            | 3.9%            |
| 8 groups               | 1.5%            | 4.6%            |
| 9 groups               | 1.4%            | 4.4%            |

The relationship between mass loss rate and freeze-thaw cycles is shown in Fig. 7.
It could be seen from Fig. 7 that the mass loss rate of concrete specimens was positively correlated with the number of freeze-thaw cycles, that is, the mass loss rate increased with the increase in freeze-thaw cycles, because the specimens were gradually peeled off. When the content of different kinds of straw powder (rice husk powder) increased from 6% to 8%, the corresponding mass loss rate also increased, but the difference was not significant, and the mass loss rate did not exceed 5% after 50 cycles. By comparing the influence of three kinds of straw powder and rice husk powder on the mass loss rate of concrete, it was found that the frost resistance performance of green environmental protection concrete mixed with wheat straw powder was better than that of corn straw powder, rice straw powder and rice husk powder.

4.2. Analysis of thermal conductivity test data

The thermal conductivity of green and environment-friendly concrete specimens with three admixtures is shown in Table 3.

| Group thermal conductivity | Average value of the first and second blocks | Average value of the third and fourth blocks | Group n average |
|---------------------------|-----------------------------------------------|-----------------------------------------------|-----------------|
| 1 group                   | 0.8724                                        | 0.922                                         | 0.8972          |
| 2 groups                  | 0.6017                                        | 0.5651                                        | 0.5834          |
| 3 groups                  | 0.4983                                        | 0.4501                                        | 0.4742          |
| 4 groups                  | 0.4587                                        | 0.4631                                        | 0.4609          |
| 5 groups                  | 0.5193                                        | 0.4939                                        | 0.5066          |
| 6 groups                  | 0.3727                                        | 0.3795                                        | 0.3761          |
| 7 groups                  | 0.3155                                        | 0.3433                                        | 0.3294          |
| 8 groups                  | 0.2785                                        | 0.3017                                        | 0.2901          |
| 9 groups                  | 0.3755                                        | 0.3535                                        | 0.3645          |

Table 3 shows the measured values of thermal conductivity of group 1 to group 9 mixed concrete. It could be seen that the thermal conductivity of the first group of control concrete block without straw powder (rice husk powder) was 0.8972 W/(m·K). After the addition of straw powder (rice husk powder), the thermal conductivity of three-admixture concrete decreased greatly with the increase in the content of straw powder (rice husk powder). By comparing the effects of three kinds of straw powder and rice husk powder on the thermal conductivity of concrete, it was found that the decrease amplitude of the thermal conductivity of concrete mixed with straw powder was higher than that mixed with corn straw powder, wheat straw powder and rice husk powder, respectively. As the thermal conductivity was mainly affected by the apparent density, porosity and pore characteristics of materials, the addition of straw powder increased the porosity of concrete, thus reducing the thermal conductivity of concrete.

5. Conclusions

1) The addition of straw powder (rice husk powder) will degrade the frost resistance of concrete, while will be continuously decreased with the increase of the straw powder content, but the decrease amplitude is not large. The frost resistance of concrete mixed with wheat straw powder is better than that mixed with corn straw powder, rice straw powder and rice husk powder, respectively.

2) The results show that the thermal conductivity of concrete decreases obviously with the increase in the content of straw powder (rice husk powder) added. The thermal insulation performance of concrete mixed with straw powder is better than that mixed with wheat straw powder, corn straw powder and rice husk powder, respectively.

3) The green and environment-friendly three-admixture concrete is applicable to the existing building renovation and new construction projects in cold and severe cold areas.
Acknowledgements
This paper is supported by the Research on the Influence of Ground Straw and Recycled Aggregate on the Compressive Strength of Concrete of first class undergraduate major construction project of Yanbian University (Yanda jiaofa No. 2020-16), science and technology development program of Yanbian University (Yanda kehezi No. 2021-1) .and the key projects of science and technology development plan of science and Technology Department of Jilin Province (20170204032sf).

References
[1] Sun D H, Yang P Q, Zhang Y Z. Study on comprehensive utilization of crop straw. Anhui Agricultural Sciences, 2007(35):11587+11590.
[2] Zhang Q, Liu B H, Liu Q L, Liu F, Wei H. Influence of ash and silica fume of rape straw on concrete performance. Journal of Hunan Agricultural University (Natural Science Edition), 2014, 40(03):334-336.
[3] Chen D, Song X Y, Jiang Z P, He Z H. Influence of straw and fly ash on concrete performance. Concrete and Cement Products, 2020(04):100-103.
[4] Liu Y, Liu F S, Fan J, Qiu Q, Zhang P. Experimental study on thermal insulation performance of concrete straw block wall. New Building Materials, 2009,36(12):78-79.
[5] Zhang L S, He S H, Zhou H F, Li X, Xie Z L. Effect of slag content on high temperature performance of fly ash-based polymer concrete. New Building Materials, 2020,47(10):36-39+4.