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Mechanical Properties and Thermal Insulation of Straw Fiber-Reinforced Perlite Concrete

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ABSTRACT

Construction operations in the forest areas may damage the local environment to some degree. It's today's trend to achieve the ecological sustainable development of these areas. To this end, combined with the advantages of forest and grass environment materials, this paper studies the road concrete added with straw fiber and perlite. The perlite was added into the concrete, which enhances the insulation. Also, it compared the changes of concrete strength when adding the rod-shaped straw in natural state and alkalization-treated filamentous straw fibers respectively. The results showed that the volume weight of concrete reinforced with perlite was reduced and the insulation was improved; the strength of concrete was promoted by adding the filamentous straw fiber after alkalization. The Scanning Electron Microscope (SEM) found that perlite can be closely bonded with the products of cement hydration; in the interfacial transition zone between perlite, straw fiber and cement base there existed a gap between rod-shaped straw and concrete, while after alkalization treatment, the filamentous straw fiber was closely bonded with the cement-based material, which improves the ductility and strength of concrete. This study is of great significance for ensuring the suitable development and protecting the green environment in forest areas.

1. INTRODUCTION

China has many forest areas covered with mountain ranges and cold areas etc. The traffic roads between forest areas are the key links in these mountain ranges and cold areas. In order to meet the increasing production and living needs of forest areas year by year, abundant construction materials are required for the local transportation infrastructure [1]. Following the theme of green environment protection and the path of protecting the ecological sustainability in forest areas, it is the today's trend to select suitable local raw materials of transportation facilities [2]. Concrete is an important construction material in China. Currently higher requirements have been made for the concrete performance [3, 4]. Many new types of concrete, such as asphalt concrete and fly ash concrete, have been produced and used to some traffic roads etc. [5]. However, due to heavy texture and resulted environmental pollution, they cannot be widely applied. Oriented to the concept of "Lucid waters and lush mountains are invaluable assets", the related research on green concrete materials has started, e.g., as a new raw material in the concrete construction, perlite has the advantages of easy access, light texture, and good insulation [6]. Sengul et al. [7] found that the addition of perlite in concrete can reduce concrete mass and enhance thermal insulation. Fiber concrete as a new type of concrete has the advantages of high strength and easy access, such as steel fiber concrete, basalt concrete, etc. [8]. By adding soaked wheat straw, boiled wheat straw and wheat straw treated with 3% NaOH solution in the concrete, respectively, Farooqi and Ali [9] analyzed the straw and its microstructure bonded to concrete, and found a substantial increase in the strength of the alkali-treated straw fibers. The quality and cost of man-made fibers depend on the environment, and their effectiveness in certain environments is yet to be tested [10, 11]. In order to speed up the construction of green buildings, in the background of forest and grassland environment, people began to add plant fibers in concrete instead of artificial fibers [12]. As an important food product in China, the annual output of rice is accompanied by a large number of rice straw and other by-products output. Straw has the advantages of high toughness, easiness to take, and environmental protection [13]. The addition of straw fibers in concrete instead of traditional fibers provides a new path for the sufficient utilization of straw resources. Ataie [14] explored the effect on the compressive and flexural strength of concrete, drying shrinkage, and heat of hydration of cement by incorporating straw fibers, and concluded that there was no significant increase in compressive strength. Liu et al. [15] investigated how the shape of optimized straw fibers affected the strength of concrete. Farooqi and Ali [16] studied the structural properties of straw-reinforced cement concrete roads; taking the performance of plain concrete pavement as a standard, it also analyzed the microstructure of straw-concrete matrix, and determined the reasonable bonding and uniform dispersion of straw fiber as well as its destruction mechanism, thus improving the concrete road strength. Zhang et al. [17] found that the performance of light aggregate concrete added with straw fibers such as fly ash was improved. Kammoun and Trabelsi [18] studied the incorporation of straw into ultra-high-performance concrete and concluded that the density and thermal conductivity decreased with the increase in the amount of straw, respectively; the increased straw content reduced the mechanical strength of concrete. Yin et al. [19] proposed a simple and efficient method for straw-reinforced asphalt concrete, i.e., matching the particle size distribution of straw fibers with the aggregate spacing of the asphalt mixture, and the results showed that the flexural strength of the asphalt mixture increased by 6%. The mixing of straw fiber and perlite still belongs to the new field. This paper studies the straw fiber instead of artificial fiber which is Environmental-friendly, easy to get. The insulation of perlite has been widely studied by experts, but the mechanical properties of perlite concrete is weak. Through the change of straw fiber, this paper explores the method of improving the strength of perlite concrete.

This paper aims to study the basic mechanical properties and thermal insulation of straw fiber-based perlite concrete for forest roads. It mainly analyzes the effects of perlite admixture and straw fiber shape on the mechanical properties of concrete. Among the studies of straw fiber concrete, a lot of content is not contain coarse aggregate or remixed with straw fiber， so it is close to the blank in the study of perlite remixing. Through the experiment, the filamentous straw fiber can enhance the strength of concrete. The characteristics of perlite are good for reducing the weight of concrete and increasing the insulation of the wall. The remixed material can not only reduce its own weight, but also have a certain strength, which is a kind of wall filling material with excellent performance.

2. TEST MATERIALS

(1) Cement: No. 42.5R ordinary silicate cement (Yatianwan brand), in line with the test index.

(2) Straw: fine straw stalk from Fangzheng County, Harbin, with high quality rice straw, no decay and mildew, similar thickness and uniform texture; two kinds of rice straw fiber are selected: one is rod-shaped straw in natural state, washed and dried (Figure 1a); The reason for the reduction of straw concrete strength is hemicellulose and lignin and pectin. The crushed straw fiber still contains such substances, so the strength is still reduced. The other is filamentous straw fiber, which is shredded by crusher and dried after soaking in 3% concentration of sodium hydroxide solution for 6 hours and alkaline treatment (Figure 1b). After soaking straw fiber with different concentration of NaOH solution, it is found that the NaOH solution with above concentration 3% is too alkaline and the cellulose toughness of straw fiber is reduced. It loses its elastic performance and unable to play the effect of stretching. The NaOH solution with concentration below 3% has too long immersion time, and the dissolution of hemicellulose, lignin and pectin is not complete, so that the concrete strength is low.

(3) Sand: local natural river sand with good grading, conforming to all test indexes;

(4) Stone: 10-30 mm crushed stone with good grading, in line with the test indexes;

(5) Perlite: 20-30 mesh expanded perlite ore sand with good grading, in line with the test indexes (Table 1).

(a) Rod-shaped straw fiber (b) Filamentous straw fiber

Figure 1. Rod-shaped and filamentous straw fibers

Table 1. Chemical composition of perlite (%)

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O
75.39	10.13	2.57	0.06	0.14	0.05	0.84	8.75

3. CONCRETE MIX PROPORTION

The concrete mix proportion in this study was finally determined mainly according to the Specification for Mix Proportion Design of Ordinary Concrete (JGJ552011) and trial adjustment: cement: water: sand: gravel (450:180:630:1165), strength grade C40, and the shapes of straw fiber and perlite admixture as the control variables.

3.1 The effect of perlite on the concrete strength

Tests were conducted to explore the effect of perlite admixture on the strength and mass of concrete. Test groups A0-A3 (Table 2) were designed by replacing 0%, 10%, 20% and 30% of equal-volume sand with perlite, respectively to study the changes in strength, insulation and mass of concrete. Perlite has the characteristics of easy access, rich yield and small density, which can be perfectly combined with the hydration products of cement, replace fine aggregate and reduce the weight of concrete. It has been applied in building insulation.

Table 2. Perlite concrete mix parameters (g)

No.	Cement	Water	Sand	Stone	Perlite	Water reducer
A0	450	180	630	1165	0	1.8
A1	450	180	567	1165	9.7	1.8
A2	450	180	504	1165	19.4	1.8
A3	450	180	441	1165	31.1	1.8

3.2 Effect of straw fibers on the concrete strength

Firstly, to investigate the effect of rod-shaped straw admixture on the strength of concrete, test groups B0-B3 (Table 3) were designed. In this test, the straw was controlled to be 2 cm long and blended into concrete at 0%, 1%, 2% and 3% of the cement mass, respectively. Besides, test groups B4-B6 (Table 3) were designed to analyze the effect of the filamentary straw fiber admixture on concrete strength, in which the straw fiber was cut into 2 cm and then mixed into the concrete at 1%, 2% and 3% percentage of the cement mass, respectively. The mix proportions are shown in Table 3.

3.3 Effect of straw fiber on the strength of perlite concrete

Test groups C0-C3 were designed by mixing 0%, 1%, 2% and 3% percentage of the cement mass into the concrete to explore the effect of filamentary straw fiber on the perlite concrete strength. The mix proportions are shown in Table 4.

3.4 Thermal conductivity

Thermal conductivity was measured by the thermoconductivity measurer. The test results show that the thermal insulation of concrete is improved after adding perlite, and with the perlite concrete's volume weight decreasing, the strength and thermal conductivity of the components get worse. This indicates that when the material has less volume weight, there shall be more internal voids and higher thermal insulation. Due to its hydrophilicity and large specific surface areas, perlite has a high rate of water absorption. After absorbing water, the material density of perlite can reach about 7 times of itself. But the thermal conductivity of water is 24 times higher than air, which seriously affects the thermal insulation effect of the insulation layer, and the application effect of materials. Therefore, the insulation layer should be as dry as possible to reduce its water content. According to the insulation requirements of road concrete design, the volume weight of expanded perlite is generally controlled to be about 450 kg/m^3, and compressive strength is about 3kg/cm^2.

Table 3. Mix parameter of concrete and rod-shaped straw/filamentary straw fiber (g)

No.	Cement	Water	Sand	Stone	Rod-shaped straw	Filamentary straw	Water reducer
B0	450	180	630	1165	0	0	1.8
B1	450	180	630	1165	4.5	0	1.8
B2	450	180	630	1165	9.0	0	1.8
B3	450	180	630	1165	13.5	0	1.8
B4	450	180	630	1165	0	4.5	1.8
B5	450	180	630	1165	0	9.0	1.8
B6	450	180	630	1165	0	13.5	1.8

Table 4. Mix parameters of straw fiber-reinforced perlite concrete (g)

No.	Cement	Water	Sand	Stone	Perlite	Straw fiber	Water reducer
C0	450	180	504	1165	19.4	0	1.8
C1	450	180	504	1165	19.4	4.5	1.8
C2	450	180	504	1165	19.4	9	1.8
C3	450	180	504	1165	19.4	13.5	1.8

4. TEST PROCESS

The first group of specimens (A0-A3) was produced as follows: firstly, weigh the required mass of stone, sand, perlite and cement into the mixer for 90 s; secondly, add 70% of water and water reducer for 150 s, and then add the remaining water and mix for 120 s; finally mold the mixed concrete. The concrete was cured in the curing room for 3 days, 7 days and 28 days respectively, and tested for compressive and flexural resistance. The specimen of compressive test was 100×100×100 mm, and that of flexural test was 100×100×400 mm.

The second group of specimens (B0-B6) was produced: firstly, weigh the required weight of stone, sand, perlite and cement into the mixer for 90 s; secondly, add about 50% of water, rod-shaped straw fiber and water reducer for 120 s, add the remaining straw fiber and 30% of water for 120 s, and then add the remaining water and mix for 120 s; the mixed fiber concrete was molded and then pounded on the vibrating table for 120 s, and afterwards it's applied with cling film and then demolded after 24 h; finally, the fiber concrete was cured in the curing room for 3 days, 7 days and 28 days respectively, and tested for compressive and flexural resistance. The specimen of compressive test was 100×100×100 mm, and that of flexural test was 100×100×400 mm.

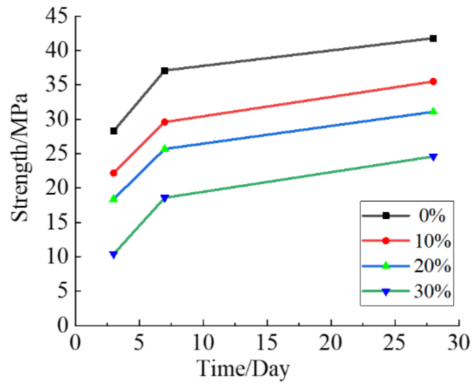
The third group of specimens (C0-C3) was produced as follows: firstly, weigh the required weight of stone, sand, perlite and cement into the mixer, and mix for 90 s; secondly, add about 50% of water, filamentary straw fiber and water reducer for 120 s, and then add the remaining straw fiber and water and mix for 120 s; thirdly, mold the fiber concrete mix, place it on the vibrating table and vibrate for 120 s, and demold it after applying the cling film for 24 h; finally the concrete was cured in the curing room for 3 days, 7 days and 28 days, and tested for compressive and flexural resistance. The specimen of compressive test was 100×100×100 mm, and that of flexural test was 100×100×400 mm.

5. RESULTS AND ANALYSIS

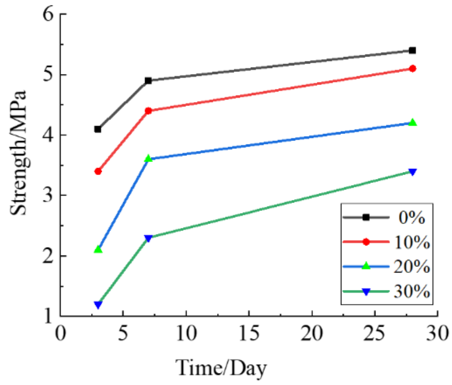
The tests followed the Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T50081-2016). The compressive and flexural tests was conducted on the 2000 kN hydraulic universal servo machine at the compressive loading rate of 0.5 MPa/sec and the flexural rate of 0.05 MPa/sec. The arithmetic mean of the compressive strength was taken from three cubes in each test group, while that of flexural strength was from three rectangular bodies in each group.

5.1 Basic mechanical properties of perlite concrete

When fine aggregates in concrete are replaced with perlite, the mechanical properties of perlite degrade, while the concrete strength decreases with increasing admixture. It can be found that the density of concrete replacing 10%, 20%, and 30% of fine aggregates decreased by 4.9%, 12.1%, and 14.7%, respectively, the compressive strength decreased by 12.2%, 24.6%, and 49.9% (Figure 2a), and the flexural strength decreased by 5.1%, 14.8%, and 37.6% (Figure 2b). When the perlite admixture was 30% of the equal-volume sand, the concrete strength decreased significantly.



(a) Compressive test of perlite concrete

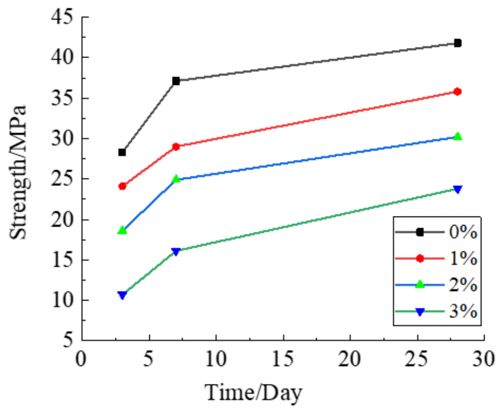


(b) Flexural test of perlite concrete

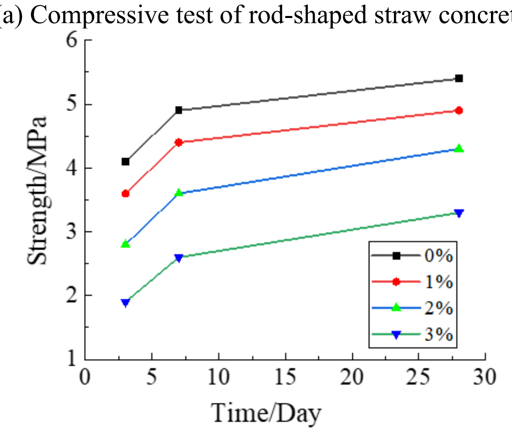
Figure 2. Strength test of perlite concrete

5.2 Test for basic mechanical properties of rod-shaped straw concrete

With the increase of rod-shaped straw admixture to the concrete in the test, the concrete strength decreased. When the straw admixture was 1%, 2% and 3% of the cement mass, the compressive strength was reduced by about 14%, 28% and 43% (Figure 3a), and the flexural strength was reduced by about 9%, 20% and 40%) (Figure 3b). As the admixture amount reached 3%, the concrete strength showed a significant reduction.



(a) Compressive test of rod-shaped straw concrete

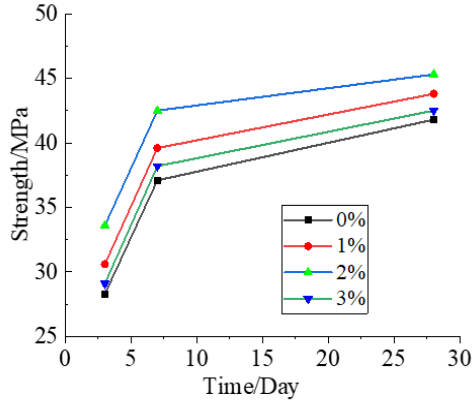


(b) Flexural test of straw concrete

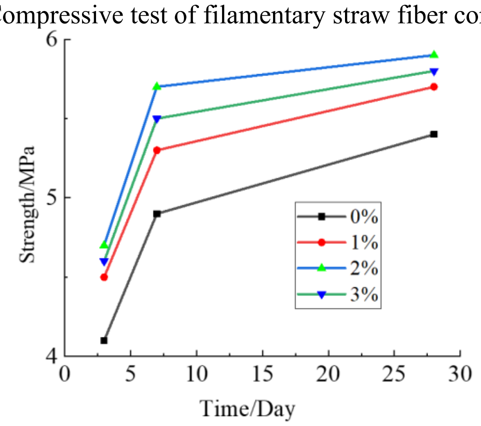
Figure 3. Strength test of rod-shaped straw concrete

5.3 Tests for basic mechanical properties of filamentary straw fiber concrete

The concrete strength was enhanced by soaking filamentary straw fibers in 3% NaOH solution for 6 hours (alkalization treatment), while it started to decrease when the admixture amount exceeds a certain range. The compressive strength of concrete increased by about 4.7%, 8.3%, and 1.6% (Figure 4a) and flexural strength increased by 5.1%, 9.4%, and 7.3% (Figure 4b) at 1%, 2%, and 3% admixtures of alkaline-treated filamentous straw fibers. The maximum concrete strength was achieved at the admixture level of 2%.



(a) Compressive test of filamentary straw fiber concrete

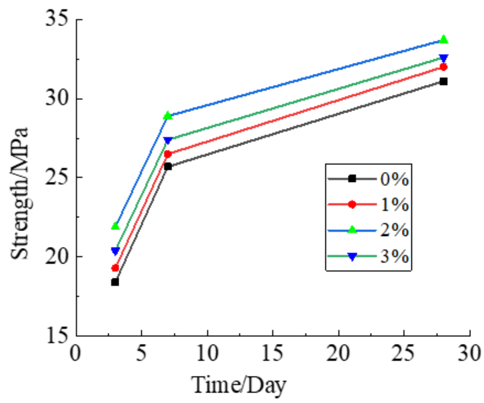


(b) Flexural test of filamentary straw fiber concrete

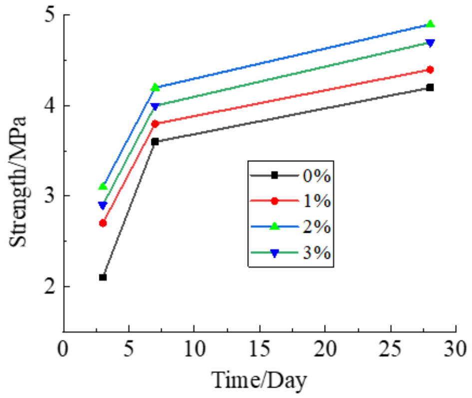
Figure 4. Strength test of filamentary straw concrete

5.4 Tests for basic mechanical properties of straw fiber-reinforced perlite concrete

Figure 5 shows that the strength of concrete was significantly reduced when perlite replaced 30% of equal-volume sand, and the optimal amount of admixture was 20%, i.e., the addition of certain amount of alkali treated straw fiber into the concrete (with the optimal mixing amount) will enhance the compressive and flexural strength of concrete. But its strength will decline after the admixture amount exceeds a certain range.



(a) Compressive test of straw fiber-reinforced perlite concrete



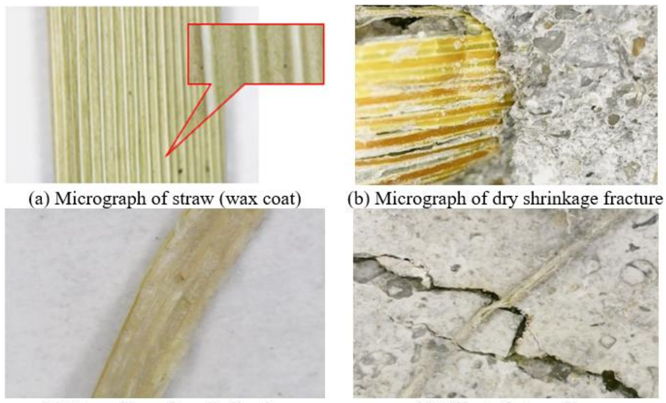
(b) Flexural test of straw fiber-reinforced perlite concrete

Figure 5. Strength test of straw fiber-reinforced perlite concrete

Figure 5 indicates that the concrete strength increased by about 3.4%, 9.1%, 5.1% (Figure 5a) and flexural strength increased by 5.7%, 12.2%, 9.4% (Figure 5b) at 1%, 2%, 3% of alkali-treated filamentary straw fibers. The maximum concrete strength was achieved at the admixture level of 2%.

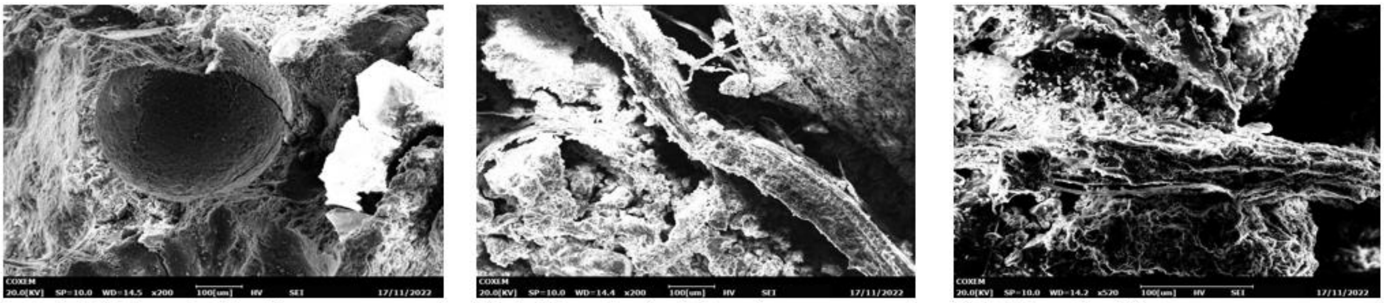
5.5 Micro-analysis

Natural straw has rich hemicellulose, lignin and pectin etc., which are very easy to dissolve and release in the concrete interior [20], affecting the concrete fluidity and hydration reaction. Besides, the surface of rice straw has a smooth wax coat (Figure 6a) with strong water absorption. After the concrete setting, the fiber size will decrease, while the gap between the fiber and the cementitious material will increase [21]. This leads to an increase of porosity in the transition zone of the fiber-cement interface and larger dry shrinkage cracks at the interface with the cementitious base (Figure 6b), thereby resulting in a reduction in the concrete strength. For the straw fibers alkaline treated with 3% concentration NaOH solution, the hemicellulose, lignin, and pectin have been dissolved internally, while the wax coat has been degraded (Figure 6c) and its water absorption was lost. The fibers act as a tensile force when the test block is stressed, which increases the concrete strength.



(a) Micrograph of straw (wax coat)
(b) Micrograph of dry shrinkage fracture
(c) Straw fiber after alkalization
(d) Effect of straw fiber

Figure 6. Micro analysis diagram



(a) SEM graph of perlite concrete
(b) SEM graph of rod-shaped straw concrete
(c) SEM graph of filamentary straw concrete

Figure 7. SEM analysis

5.6 SEM analysis

The Scanning Electron Microscope (SEM) (magnification 200x, 100 μm) was used to find that the perlite and the hydrated product were tightly bound (Figure 7a), and fine aggregates can be replaced. Figures 7b and 7c showed that there was a gap between the hydration products of concrete and rod-shaped straw fibers, leading to the reduction of concrete strength; when the hydration products of concrete were tightly bound to the filamentous straw fibers after alkaline treatment, the concrete strength is improved.

6. CONCLUSION

This paper studies the mechanical properties and thermal insulation of straw-reinforced perlite concrete materials for forest roads, and makes the following conclusions:

(1) By SEM it's found that the perlite added to concrete can bind closely with hydration products so that it can successfully replace fine aggregates and reduce the self-weight of concrete.

(2) Perlite density is low, so it is easy to float in the process of concrete vibration, resulting in uneven concrete force.The larger the floating perlite content is, the greater the strength of the concrete decreases.

(3) The straw has substances such as pectin that dissolve in alkalinity and wax coat that has strong water absorption. When it's added to the concrete, the fiber size will shrink after concrete setting and gaps appear between the fiber and concrete, leading to a reduction in concrete strength.

(4) It's found through SEM and microscope observation that the alkaline treated straw fibers can be tightly bonded with the hydration products of concrete and act as a tensile force when the specimen is stressed, which enhances the strength of concrete.

(5) The above tests show that the self-weight of concrete is reduced by 10% when perlite admixture is 20%; when the amount of admixture exceeds 20%, the strength of concrete shows a substantial decrease; the concrete strength is enhanced by 12% when the amount of filamentary straw fiber is 2% of

the cement mass in perlite concrete mixed with straw fiber; the concrete strength is weakened when the amount is more than 2%.

(6) To increase the insulation of concrete added with perlite, generally it's required to control the volume weight of cement expanded perlite in about 450kg/m^3, and compressive strength in about 3kg/cm^2.

(7) Through the characteristics of materials, perlite concrete mixed with straw fiber can be applied to the construction of temporary houses in farmland, and temporary grain storage, which not only enhances the strength of these type of houses, but also provides a new way for the treatment of rice straw.

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