Research Article
A New Heat Insulation Shotcrete Mixed with Basalt and Plant Fibers

Jin-kun Huang,1,2 Jian-yong Pang,1,2 Guang-cheng Liu,1,2 Yi-xin Mo,2 Ping-wei Jiang,2 and Qiang Su2

1State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mine, Anhui University of Science and Technology, Huainan 232001, China
2School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, China

Correspondence should be addressed to Jin-kun Huang; 550467503@qq.com

Received 23 January 2019; Revised 6 April 2019; Accepted 2 May 2019; Published 2 June 2019

1. Introduction

As the mining depths of coal mines increase, increases in the temperature of the original rock and the thermal conductivity of the deep rock mass have been observed [1]. The temperature increase due to increase in mining depths further affects the thermal stress increase in rock during roadway excavation. After roadway excavation, heat exchange between the rock and air results in thermal stress in the rock mass. Consequently, many new cracks form due to thermal stress, which changes the state of the stress distribution in the surrounding rock. Thus, the circumjacent tangential stresses, displacement, broken areas, and radius of the plastic zone of the roadway grow, affecting the safety of the roadway [2–4] and causing severe heat damage of the deep roadway [1–11].

As the most direct and important heat source in the roadway, heat dissipation of the surrounding rock accounts for about 48% of the heat [1]. Therefore, it is advisable to use a heat-insulating material with a smaller thermal conductivity than the surrounding rock and spray a coating on the rock wall to prevent the heat dissipation from the surrounding rock [12]. As a necessary means of roadway support, shotcrete can be improved by using admixtures to achieve both support strength and reduce the thermal conductivity [13,14], which can effectively block the heat dissipation of the surrounding rock and provide support for the roadway. At present, there are several commonly used methods. The first is to add aluminum powder to the cement to create a random pore structure in the concrete and increase the thermal resistance [15]. However, the strength and stiffness of the concrete decrease exponentially with the increase in the number and sizes of pores. The second method is to partially substitute the coarse and fine aggregates in concrete with various additives, such as ceramsite, pottery sand, glazed hollow beads, expandable polystyrene beads, and other lightweight porous materials, thereby reducing the thermal conductivity of the concrete.
[16–18]. However, ceramsite and pottery sand can lead to large water absorption. After mixing the aggregate, the brittleness of concrete increases, resulting in poor workability and difficulty in molding the material [16]. Furthermore, the surface hydrophobicities of glazed hollow beads and polystyrene beads cause them to float and separate during the processes of mixing, vibrating, and separating, which affects the processability and mechanical properties of the concrete [17, 18]. In the third method, plant fiber is mixed in the concrete to form a composite reinforced material, which can improve the strength of the concrete [19]. Due to the inherent multiscale cell walls of plant fibers, their inner cavity structures, and their low coefficients of thermal conductivity, the plant fibers can also reduce the coefficient of thermal conductivity of the concrete [20]. However, plant fibers are organic materials with poor corrosion resistances. They can be degraded easily by alkaline substances generated by the hydration of cement, which can reduce the durability of the concrete and the late strength.

To address the issues described above, based on previous studies [13, 21], the coarse and fine aggregates in ordinary shotcrete were partially substituted by ceramsite and pottery sand to reduce the thermal conductivity of the concrete in this study. Additionally, plant fibers, which received antiseptic treatment, and basalt fibers were mixed into the concrete. Due to the low thermal conductivity of the plant fiber [19] and the good compatibility between the basalt fiber and the concrete matrix [22], the thermal conductivity of concrete was further reduced after the ceramsite and pottery sand were mixed in. The resulting concrete possessed a mesh-like structure, which produced secondary strengthening effects. This improved the strength of the concrete and reduced the rebound degree of the ceramsite and pottery sand when they were injected. Therefore, an orthogonal experiment was designed to improve the working, mechanical, and heat insulating performances of the shotcrete, which can be used to block the heat dissipation of surrounding rock and provide effective support for roadways in coal mines.

2. Orthogonal Test: Materials, Methodology, and Specimen Preparation

2.1. Material Properties. Ceramsite, pottery sand, basalt fiber, and plant fiber were selected as additives to mix into the concrete in this study. To satisfy the requirements of the shotcrete, all the material properties are described in the following paragraphs.

Based on the use of plant fiber as a reinforcement material in silt soil in a previous study [23], cotton straw plant fiber was selected for this study. This fiber faces corrosion issues, which was mentioned in the literature review above [19, 23]. In the current work, modified polyvinyl alcohol (SH glue) was selected to address the corrosion problem [24]. Plant fibers were soaked for 3 days in modified polyvinyl alcohol solution, and then they were removed from the solution to dry naturally [24]. The surface topographies of the plant fibers before and after antiseptic treatment are shown in Figure 1. As shown in Figure 1(a), the surfaces of the plant fibers were rough and, there were many holes before the antiseptic treatment. Furthermore, Figure 1(c) shows that cured films formed and enveloped the surfaces of the plant fibers after treatment with the SH glue. The film prevented direct contact between the fiber, water, and air, which effectively improved the stabilities and corrosion resistances of the fibers.

Figure 2 shows the remaining admixtures of the shotcrete, other than the basic components. Figures 2(a)–2(d) show the basalt fiber, glazed hollow beads, ceramsite, and pottery sand, respectively.

The basalt fiber was composed of 15 mm long chopped fibers, and its material properties are shown in Table 1. The glazed hollow beads were hydrophobic and with closed pores, the material properties are shown in Table 2. Ceramsite and pottery sand were the main products used to substitute the coarse and fine aggregates in this concrete, respectively. Meanwhile, the pottery sand is a kind of fine aggregate which is one of the accompanying minerals of ceramsite, only in small size. Their properties are shown in Table 3.

The selection of the remaining materials in this experiment followed a standard composition [25]. These materials included P·O42.5 ordinary Portland cement, grade I fly ash, 5–10 mm melon seed stones as the coarse aggregate, fine sand as the fine aggregate, and ordinary drinking water.

2.2. Experimental Methods. The orthogonal experimental design accounted for the influence of multiple factors at multiple levels. Based on the orthogonal test table, various factor combinations were selected, and the data from the tests were analyzed to obtain the optimal solution quickly and efficiently, saving time and effort. The proportions of cement, sand, stone, water, and admixtures of shotcrete were determined following standard proportions [25]. The L9(34) orthogonal test table in the literature was used to design the experiments [26]. The orthogonal test scheme shown in Table 4 was designed to include four factors: the ceramsite content, pottery sand content, basalt fiber content, and plant fiber content. As shown in Table 5, three levels (the contents of each factor) were set for each factor, and the test proportions of the nine sets of concrete samples are listed. When the test was complete, the test results were processed and analyzed in combination with a data processing method [26] and the grey correlation analysis method [27] presented in the literature.

2.3. Specimens Preparation. In the orthogonal test, nine groups were designed, and the compressive strength, tensile strength, shear strength, and thermal conductivity of each group was measured. Following a test standard [28], 54 (6 × 9) test cubes with sizes of 100 mm × 100 mm × 100 mm were constructed to measure the compressive and tensile strengths, 27 (3 × 9) test cubes with sizes of 50 mm × 50 mm × 50 mm were constructed to measure the shear strength, and 54 (6 × 9) test cubes with sizes of 300 mm × 300 mm × 30 mm were
constructed to measure the thermal conductivity. The partially cured specimens are shown in Figure 3. After 28 days of curing, the mechanical properties and thermal conductivities of the concrete were measured at the State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mine, Anhui University of Science and Technology, China, using a WAW-2000 electrohydraulic servo universal tester and PDR-300 thermal conductivity instrument.

3. Presentation and Evaluation of Orthogonal Test Results

3.1. Experimental Results. The compressive strength, tensile strength, shear strength, and thermal conductivity values of nine sets of orthogonal test specimens were averaged, and the test results are shown in Table 6.

As shown in Table 6, the test result data are in haphazard distribution. Thus, as ceramsite, pottery sand, basalt fiber,
and plant fiber were the four control factors. The effects of the three levels (the contents of each factor) on the orthogonal test results could not be directly obtained. Therefore, the test results must be further analyzed.

3.2. Analysis of Variance and Contribution Rate. The variance and contribution rate of the 4 factors were calculated by comparing the $F$ value (value of normal distribution) obtained using values in the normal distribution table to determine the influence of each factor in the orthogonal tests for the same evaluation index. The value of the contribution rate can determine the order of influence of the individual factors. After determining the main influencing factors, they can be adjusted and controlled during tests for specific targets.

Using the variance and contribution rate equations from a previous report [26], the test results in the orthogonal test were calculated. The specific calculation equations are as follows.

Total sum of squares of deviations:

$$SST = \sum_{i=1}^{n} (y_i - \bar{y})^2. \quad (1)$$

Degree of freedom:

$$f_T = n - 1, \quad (2)$$

where $n$ is the number of rows of the orthogonal test table (the number of trials) and $\bar{y}$ is the average value of $n$ experimental indices.

Sum of squares of deviations of factor A:

$$SSA = \sum_{i=1}^{n} n_i (\bar{y}_i - \bar{y})^2. \quad (3)$$

Degree of freedom:

$$f_A = n_i - 1, \quad (4)$$

where $a$ is the number of levels of factor A, $n_i$ is the number of trials at level $i$, and $\bar{y}_i$ is the average value of the indicators.
at each level of factor A. The values of SSB, SSC, and SSD (i.e., the sum of squares of the deviations of factors B, C, and D, respectively) can be calculated in a similar manner.

Sum of squares of deviations of error:

\[ SSE = SST - SSA - SSB - SSC - SSD. \]  

(5)

Total pure sum of squares:

\[ SSPT = SSPA + SSPB + SSPC + SSPD + SSPE. \]  

(6)

The pure sum of squares of factor A:

\[ SSPA = SSA - f_A \times MSE. \]  

(7)

The values of SSPB, SSPC, and SSPD (i.e., the pure sum of squares of factors B, C, and D, respectively) can be obtained in a similar manner.

The pure sum of squared of error:

\[ SSPE = f_T \times MSE. \]  

(8)

The contribution rate of factor A:

\[ \rho_A = \frac{SSPA}{SSPT}. \]  

(9)

The values of \( \rho_B \), \( \rho_C \), and \( \rho_D \) (i.e., contribution rate of factors B, C, and D, respectively) can be obtained as well.

Using the test results in Table 6 and the equations above, the variance and contribution rate of the compressive strength were calculated and are shown in Table 7. The effects of factors A, B, and C were particularly significant to the compressive strength, and D was significant. Factor B had the largest contribution rate of 49.95%. The contribution rates of factors A and C were adjacent, 18.47% and 21.02%, respectively. But the contribution rate of factor D was the smallest, 9.83%. The error, with the contribution rate 0.73%, had the least influence on the test results and can be neglected. Thus, factor B had the largest influence on the compressive strength of the concrete, and its content should be controlled to achieve the highest possible compressive strength.

Based on the analysis of variance of the tensile strength shown in Table 8, the effects of factors A and C on the tensile strength were significant. Factor D also had an effect, but factor B had little effect. Based on the contribution rate, factor A was the greatest contributor, with a rate of 63.04%, followed by factor C with a rate of 21.74%. However, the contribution rates of factor B and the error were similar, 2.18% and 2.90%, respectively. Thus, the influences of factor B and the error on the tensile strength were negligible. Finally, factor A had the greatest influence on the tensile strength of the concrete, and its content should be controlled to achieve the highest possible tensile strength.

Based on the analysis of variance of the shear strength shown in Table 9, the influences of factors A, B, C, and D on the shear strength were significant. Factor B was the biggest contributor, reaching a contribution rate of 34.22%. Factors A and D followed, with rates of 27.28% and 25.43%, respectively. The rate of factor C was 12.60%. The contribution rate of the error was the smallest, 0.47%, and could be neglected. Thus, based on the shear strength, the contents of A, B, C, and D should be all controlled to achieve the highest possible shear strength.

Based on the analysis of variance of the thermal conductivity shown in Table 10, the effects of factors A and C were more significant than those of B and D on the thermal conductivity. Factor A was the biggest contributor, with a contribution rate of 54.84%, followed by Factor C, with a rate of 31.45%. The contribution rates of factors B and D and the error were small, 4.84%, 5.65%, and 3.22%, respectively, and the differences were not significant. Thus, based on the thermal conductivity, the contents of A and C should be controlled.

3.3. Analysis of Factor Indices. For the compressive strength of concrete, it is shown in Figure 4(a) that when the level of factor A (content) increased from A1 (5%) to A3 (15%), the compressive strength first decreased and then subsequently increased. While the levels of factors B, C, and D increased, the compressive strength first increased and subsequently decreased. The most obvious decrease occurred as factor B increased from B2 (10%) to B3 (15%), where the compressive strength decreased by 20.64%. Therefore, to ensure a high compressive strength of the specimen, the best combination of factor levels was A1B2C2D2.

For the tensile strength of concrete, Figure 4(b) shows that when the level of factor A increased, the tensile strength first decreased significantly and then increased significantly. It decreased by 27.03% as the level of factor A increased from A1 (5%) to A2 (10%), after which it increased by 32.8% as the level of factor A increased from A2 (10%) to A3 (15%). As factor B increased, the tensile strength...
strength decreased initially and subsequently increased. The total increase was greater than the total decrease. The tensile strength first increased and subsequently decreased as factors C and D increased. However, the dependence on factor C was greater. When factor C increased from C1 (0%) to C2 (0.15%), the tensile strength increased by 16.14%. In contrast, from C2 (0.15%) to C3 (0.3%), the tensile strength decreased by 16.22%. Therefore, based on the factor index analysis, the best combination of factor levels was A1B3C2D2 to ensure an adequate tensile strength of the specimen.

As shown in Figure 4(c), when the level of factor A increased, the shear strength initially decreased slightly and subsequently increased significantly. Factor C decreased sharply and subsequently increased slightly. The shear strength initially decreased as B increased, and from B2 (10%) to B3 (15%), the amplitude decreased rapidly. Meanwhile, factor D initially increased rapidly and subsequently decreased rapidly. Based on factors A, B, and C, the most dramatic increase or decrease in the shear strength occurred between levels 2 and 3. Therefore, the best combination of factor levels was A3B1C1D2 to ensure an adequate shear strength of the specimen.

For the thermal conductivity of concrete, Figure 4(d) shows that when the level of factor A increased, the thermal conductivity decreased abruptly and then increased slightly and that the biggest decrease was 22%. As factors B and C increased, the thermal conductivity increased first and subsequently decreased. The thermal conductivity continued to decrease with the level increase of factor D. Therefore, A2B1C1D3 was the best combination of factor levels to reduce the thermal conductivity of the specimen.

### Table 7: Analysis of variance of compressive strength.

<table>
<thead>
<tr>
<th>Factors</th>
<th>SS</th>
<th>f</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
<th>Critical value</th>
<th>SSP</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20.5</td>
<td>2</td>
<td>10.25</td>
<td>102.5</td>
<td>Particularly significant</td>
<td>$F_{0.1}(2,2) = 9$</td>
<td>20.3</td>
<td>18.47</td>
</tr>
<tr>
<td>B</td>
<td>55.1</td>
<td>2</td>
<td>27.55</td>
<td>275.5</td>
<td>Particularly significant</td>
<td>$F_{0.05}(2,2) = 99$</td>
<td>54.9</td>
<td>49.95</td>
</tr>
<tr>
<td>C</td>
<td>23.3</td>
<td>2</td>
<td>11.65</td>
<td>116.5</td>
<td>Particularly significant</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>23.1</td>
<td>21.02</td>
</tr>
<tr>
<td>D</td>
<td>11</td>
<td>2</td>
<td>5.5</td>
<td>55</td>
<td>Significant</td>
<td></td>
<td>10.8</td>
<td>9.83</td>
</tr>
<tr>
<td>Error</td>
<td>0.2</td>
<td>2</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
<td>0.73</td>
</tr>
<tr>
<td>Total</td>
<td>110.1</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>109.9</td>
<td></td>
</tr>
</tbody>
</table>

Note: SS indicates the sum of squares of deviations, f indicates the degree of freedom, MS indicates standard deviation, and SSP indicates total pure sum of squares. $F > F_{0.01}(2,2) = 99$ indicates that this factor has a particularly significant impact on the evaluation index. $F_{0.05}(2,2) = 19 < F < F_{0.01}(2,2) = 99$ indicates that this factor has a significant impact on the evaluation index. $F < F_{0.1}(2,2) = 9$ indicates that this factor has a small impact on the evaluation index. This notation is also suitable for subsequent tables showing analysis of variance results.

### Table 8: Analysis of variance of tensile strength.

<table>
<thead>
<tr>
<th>Factors</th>
<th>SS</th>
<th>f</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
<th>Critical value</th>
<th>SSP</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.88</td>
<td>2</td>
<td>0.44</td>
<td>88</td>
<td>Significant</td>
<td>$F_{0.1}(2,2) = 9$</td>
<td>0.87</td>
<td>63.04</td>
</tr>
<tr>
<td>B</td>
<td>0.04</td>
<td>2</td>
<td>0.02</td>
<td>4</td>
<td>Small impact</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>0.03</td>
<td>2.18</td>
</tr>
<tr>
<td>C</td>
<td>0.31</td>
<td>2</td>
<td>0.155</td>
<td>31</td>
<td>Significant</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>0.30</td>
<td>21.74</td>
</tr>
<tr>
<td>D</td>
<td>0.15</td>
<td>2</td>
<td>0.075</td>
<td>15</td>
<td>Some impact</td>
<td></td>
<td>0.14</td>
<td>10.14</td>
</tr>
<tr>
<td>Error</td>
<td>0.01</td>
<td>2</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td>0.04</td>
<td>2.90</td>
</tr>
<tr>
<td>Total</td>
<td>1.39</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.38</td>
<td></td>
</tr>
</tbody>
</table>

### Table 9: Analysis of variance of shear strength.

<table>
<thead>
<tr>
<th>Factors</th>
<th>SS</th>
<th>f</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
<th>Critical value</th>
<th>SSP</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.37</td>
<td>2</td>
<td>1.185</td>
<td>237</td>
<td>Particularly significant</td>
<td>$F_{0.1}(2,2) = 9$</td>
<td>2.36</td>
<td>27.28</td>
</tr>
<tr>
<td>B</td>
<td>2.97</td>
<td>2</td>
<td>1.485</td>
<td>297</td>
<td>Particularly significant</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>2.96</td>
<td>34.22</td>
</tr>
<tr>
<td>C</td>
<td>1.1</td>
<td>2</td>
<td>0.55</td>
<td>110</td>
<td>Particularly significant</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>1.09</td>
<td>12.60</td>
</tr>
<tr>
<td>D</td>
<td>2.21</td>
<td>2</td>
<td>1.105</td>
<td>221</td>
<td>Particularly significant</td>
<td></td>
<td>2.20</td>
<td>25.43</td>
</tr>
<tr>
<td>Error</td>
<td>0.01</td>
<td>2</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td>0.04</td>
<td>0.47</td>
</tr>
<tr>
<td>Total</td>
<td>8.66</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.65</td>
<td></td>
</tr>
</tbody>
</table>

### Table 10: Analysis of variance of thermal conductivity.

<table>
<thead>
<tr>
<th>Factors</th>
<th>S</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>Significance</th>
<th>Critical value</th>
<th>SSP</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0069</td>
<td>2</td>
<td>0.00345</td>
<td>69</td>
<td>Significant</td>
<td>$F_{0.1}(2,2) = 9$</td>
<td>0.0068</td>
<td>54.84</td>
</tr>
<tr>
<td>B</td>
<td>0.0007</td>
<td>2</td>
<td>0.00035</td>
<td>7</td>
<td>Small impact</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>0.0006</td>
<td>4.84</td>
</tr>
<tr>
<td>C</td>
<td>0.004</td>
<td>2</td>
<td>0.002</td>
<td>40</td>
<td>Significant</td>
<td>$F_{0.05}(2,2) = 19$</td>
<td>0.0039</td>
<td>31.45</td>
</tr>
<tr>
<td>D</td>
<td>0.0008</td>
<td>2</td>
<td>0.0004</td>
<td>8</td>
<td>Small impact</td>
<td></td>
<td>0.0007</td>
<td>5.65</td>
</tr>
<tr>
<td>Error</td>
<td>0.0001</td>
<td>2</td>
<td>0.00005</td>
<td></td>
<td></td>
<td></td>
<td>0.0004</td>
<td>3.22</td>
</tr>
<tr>
<td>Total</td>
<td>0.0125</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0124</td>
<td></td>
</tr>
</tbody>
</table>
Considering that the shotcrete must have sufficient strength and a small thermal conductivity, the overall analysis presented in Figure 4 shows the optimal range of various factors from the slopes of the evaluation indices as the level of each factor increased. The optimal contents of ceramsite, pottery sand, basalt fiber, and plant fiber were 10–15 mass% of the coarse aggregate, 5–10 mass% of the fine aggregate, 0–0.15 vol.% of the concrete, and 0.1–0.2 vol.% of the concrete, respectively.

3.4. Analysis of Grey Correlation. The above analysis only produced a rough range of factors, and it was not possible to determine which of the nine orthogonal tests produced the best results. Therefore, combined with the literature research [27], the orthogonal test data was normalized to obtain a grey relational coefficient. The grey relational coefficient of each evaluation index of the nine sets of orthogonal test schemes was obtained by combining the formulas (10)–(14). The results are shown in Table 11.

The results of the evaluation indices can be put into a matrix following equation (10):

\[
X = \begin{pmatrix}
    x_{11} & \cdots & x_{1m} \\
    \vdots & \ddots & \vdots \\
    x_{n1} & \cdots & x_{nm}
\end{pmatrix},
\]

where \( m \) is the number of evaluation indices and \( n \) is the number of experiment schemes.

For the factors that produced better evaluation indices when they had larger values (as the shotcrete studied is used to support the roadway, so the larger the strength like...
compressive strength, tensile strength, and shear strength, the better the support effect), the normalization was as follows:

\[ r_{ij} = \frac{x_{ij} - \min(x_{1j}, x_{2j}, \ldots, x_{nj})}{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - \min(x_{1j}, x_{2j}, \ldots, x_{nj})} \]  

(11)

And for the factor that produced better evaluation indices when it had a smaller value (as the shotcrete is also used for heat insulation, so the smaller of the thermal conductivity is, the effect of heat insulation will be better), the normalization was as follows:

\[ r_{ij} = \frac{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - x_{ij}}{\max(x_{1j}, x_{2j}, \ldots, x_{nj}) - \min(x_{1j}, x_{2j}, \ldots, x_{nj})} \]  

(12)

where \( i = 1, 2, \ldots, n \); \( j = 1, 2, \ldots, m \).

After the evaluation indices were normalized, an ideal reference scheme (usually the maximum value in each indicator) was constructed and can be expressed as follows:

\[ S^0 = [s^0_1, s^0_2, \ldots, s^0_m], \]  

(13)

where \( s^0_j = \max(r_{1j}, r_{2j}, \ldots, r_{nj}); j = 1, 2, \ldots, m \). Thus, the \( m \) evaluation indices in \( S^0 \) were the maximum values of the corresponding evaluation indices in the overall scheme.

The ideal scheme was used as a reference sequence, and each evaluation index value was used as a comparison sequence. The correlation coefficient corresponding to each index was obtained as follows:

\[ \xi_{ij} = \min, \min, \frac{\min, \min, |s^0_j - r_{ij}| + \rho \max, \max, |s^0_j - r_{ij}|}{\max, \max, |s^0_j - r_{ij}|} \]  

(14)

where \( \xi_{ij} \) is the correlation coefficient between the \( i \)-th \( (i = 1, 2, \ldots, n) \) comparison sequence and the \( j \)-th \( (j = 1, 2, \ldots, m) \) index in the reference sequence \( S^0 \), and the resolution coefficient \( \rho \in [0, 1] \) was \( \rho = 0.5 \).

As all the coefficients shown in equations (10)–(13) have been calculated, and other coefficients used in equation (14) have been given out, so the values in Table 11 could be finally resulted from equation (14).

The subjective weight assignment of the mechanical properties and thermal insulation properties of the concrete was considered. The compressive strength and thermal conductivity were the most important, followed by the tensile and shear strengths. Therefore, the weight coefficients of the subjective evaluation index were 0.3, 0.2, 0.2, and 0.3 for the compressive strength, tensile strength, shear strength, and thermal conductivity, respectively. Obviously, the weight coefficients 0.3, 0.2, 0.2, and 0.3 are user defined. According to equation (15), the degree of the grey correlation is calculated and shown in Table 12.

\[ r = \xi_{ij} \omega_j, \]  

(15)

where \( \xi_{ij} \) is obtained from Table 11, and \( \omega_j (j = 1, 2, \ldots, m) = [0.3, 0.2, 0.2, 0.3] \).

As shown in Table 12, as the value of the grey correlation degree tended to 1, the performance indices of the concrete became more ideal. In this test, the correlation degree of specimen series no. 2 was the largest at 0.7043. Thus, the ratio of no. 2 specimen was the best ratio, i.e., the sample with the composition \( A_1B_2C_2D_2 \). In this specimen, ceramsite replaced 5% of the mass of the coarse aggregate, pottery sand replaced 10% of the mass of the fine aggregate, the content of basalt fiber was 0.15% of the volume of the concrete, and the content of plant fiber was 0.2% of the volume of the concrete.

### 4. Microscopic Analysis

The strength and thermal conductivity of concrete can be obtained by the testing method described above. The data processing method of the orthogonal test can also be used to obtain the effect of the four factors, i.e., ceramsite, pottery sand, basalt fiber, and plant fiber, on the strength and thermal conductivity of the concrete. However, the interaction of the four factors with concrete in the concrete matrix, and their influence on the strength and thermal conductivity must be observed by microanalysis. Therefore, it is necessary to slice the concrete samples and directly observe the aggregate distribution inside the concrete. The components of the hydration reaction in concrete were analyzed using X-ray diffraction (XRD), and the appearance of the concrete matrix and the reinforced form of the fiber were observed using scanning electron microscopy (SEM).

#### 4.1. X-Ray Diffraction Analysis

For the nine groups of specimens for the orthogonal test, all the basic materials were selected in the same way. With the only difference being the content of ceramsite, pottery sand, basalt fiber, and plant fiber in the concrete mixture. Ceramsite is a stable...
coarse aggregate that exhibits good compatibility with cement and other cementitious materials. Therefore, a certain content (5 mass% of coarse aggregate) of ceramsite is required. The phase compositions of concrete mixed with the other three factors at different levels were examined. According to Table 4, the content of ceramsite was fixed in specimens 1, 2, and 3, while the levels of the other three factors varied but keep at a same increase. In specimens 4, 5, and 6 and specimens 7, 8, and 9, the content of ceramsite was also fixed, but the levels of the other three factors varied irregularly. Therefore, specimens 1, 2, and 3 were chosen for X-ray diffraction tests. The samples were sealed after they were ground and passed through a 400-mesh screen. X-ray diffraction analysis was carried out to determine the phase composition inside the concrete. The results are shown in Figure 5.

As shown in Figure 5 and combined with the research in the literature [29], ettringite (B-AFt) and calcium hydroxide (A-Ca(OH)2) peaks appeared in the XRD spectra for the three groups. The height of the ettringite peak in sample 2 exceeded that of calcium hydroxide, and thus, the content of ettringite was greater than that of calcium hydroxide. Compared with the peak height of ettringite in samples 1 and 3, the peak height of ettringite was the largest in sample 2. Consequently, the compressive strength of sample 2 was the largest, which is consistent with the compressive strength tests. Pottery sand contains a certain amount of clay minerals, which can react with the hydration products of cement (mainly calcium hydroxide) to produce ettringite, thereby increasing the content of ettringite and reducing the content of calcium hydroxide. In addition, as the concrete was mixed with ceramsite, pottery sand, fly ash, and other mineral admixtures, several free elements in each admixture reacted to form two polymers: Al(OH)3·AlPO4(F) and 2MgSO4·Mg(OH)2(G). As reported in [30, 31], these two polymers are flame retardant and possess high strengths, stable sizes, and anticracking properties. Their presence in the concrete matrix can effectively improve the strength of the concrete, prevent concrete cracking, and provide beneficial effects on the mechanical properties of the concrete.

4.2. Scanning Electron Microscopy Analysis. The scanning electron microscopy (SEM) images of a matrix section of the new heat insulation shotcrete of specimen 2 are shown in Figure 6. On the surface of the concrete, there were many holes with different sizes, which were intercalated in the concrete and evenly distributed in Figure 6(a). The size of indicative holes is enlarged, and the hole position is highlighted by a red circle position in Figure 6(b). The holes formed due to the presence of two porous materials in the concrete matrix: ceramsite and pottery sand. Since the two porous materials were uniformly distributed in the concrete matrix, a large number of uniformly distributed closed pores appeared. Due to the low thermal conductivity of the air inside the holes, the thermal conductivity of the concrete was effectively reduced, and the concrete exhibited better thermal insulation effects.

Although the thermal conductivity of concrete can be reduced by adding porous materials, such as ceramsite, pottery sand, and glazed hollow beads, the strength of the concrete can be simultaneously reduced due to the characteristics of the porous materials. When concrete failure occurred, the walls around the holes in the porous material first deformed, which caused stress flow in the spherical

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Ceramsite Contents (kg)</th>
<th>Pottery sand Contents (kg)</th>
<th>Basalt fiber Contents (kg)</th>
<th>Plant fiber Contents (kg)</th>
<th>Grey correlation degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53</td>
<td>34</td>
<td>0</td>
<td>0.075</td>
<td>0.5061</td>
</tr>
<tr>
<td>2</td>
<td>53</td>
<td>68</td>
<td>3.975</td>
<td>0.15</td>
<td>0.7043</td>
</tr>
<tr>
<td>3</td>
<td>53</td>
<td>102</td>
<td>7.95</td>
<td>0.225</td>
<td>0.4085</td>
</tr>
<tr>
<td>4</td>
<td>106</td>
<td>34</td>
<td>3.975</td>
<td>0.225</td>
<td>0.5535</td>
</tr>
<tr>
<td>5</td>
<td>106</td>
<td>68</td>
<td>7.95</td>
<td>0.075</td>
<td>0.4272</td>
</tr>
<tr>
<td>6</td>
<td>106</td>
<td>102</td>
<td>0</td>
<td>0.15</td>
<td>0.5796</td>
</tr>
<tr>
<td>7</td>
<td>159</td>
<td>34</td>
<td>7.95</td>
<td>0.15</td>
<td>0.6230</td>
</tr>
<tr>
<td>8</td>
<td>159</td>
<td>68</td>
<td>0</td>
<td>0.225</td>
<td>0.5962</td>
</tr>
<tr>
<td>9</td>
<td>159</td>
<td>102</td>
<td>3.975</td>
<td>0.075</td>
<td>0.4985</td>
</tr>
</tbody>
</table>
pores and led to stress concentration. This promoted the development of tensile stress and finally resulted in a crack, which destroyed the specimen. When basalt and plant fibers were mixed into the concrete, the two fibers formed a crisscrossed and disordered distribution in the concrete matrix. In Figure 7, the yellow rectangle highlights a basalt fiber and the red rectangle highlights a plant fiber. The two kinds of fibers formed a stable spatial network structure in the concrete matrix. When the pressure increased to the point of structural failure, the integrity of the specimen was better, which effectively inhibited the development of tensile stress caused by the failure of the porous materials in the concrete matrix and produced a secondary strengthening effect.

Figure 8(a) shows the state of the structural surface reinforced by the fibers enlarged 400 times. An alveolate hole structure can be observed beside the area reinforced by the plant fibers on the surface of the concrete. In Figure 1(b), the alveolate structure is enlarged 2000 times. The alveolate structure had a smooth sheet surface and a thickness of approximately 10–20 nm. They were connected by a central core and could be easily embedded into the concrete matrix to provide internal stress transfer for the structure. Based on the X-ray diffraction analysis results and previous reports [30], the honeycomb shell structure was the Al(OH)$_3$·AlPO$_4$ polymer. It was formed by covering the AlPO$_4$ flower-like microstructure with Al(OH)$_3$. Additionally, this structure provided flame retardant properties and improved the tensile strength of the composite [30]. Meanwhile, the above structure and fiber reinforcement worked together to improve the tensile strength of the concrete.

5. Conclusion

Based on the analysis of variance and contribution rate, and of all the four main admixtures like ceramsite, pottery sand, basalt, and plant fiber, the results show that the pottery sand content had the greatest influence on the compressive and shear strengths of the concrete, with contribution rates of 49.95% and 34.22%, respectively. The ceramsite content had the greatest influence on the tensile strength and thermal conductivity of the concrete, with contribution rates of 63.04% and 54.84%, respectively.

Figure 6: Scanning electron microscopy of the concrete matrix: (a) 200 times and (b) detail 400 times.

Figure 7: Scanning electron microscopy of the distribution of fibers in concrete matrix.

Based on the factor indices, the optimal range of additive contents was found to be as follows: ceramsite content 10–15% of the mass of coarse aggregate, pottery sand content 5–10% of the mass of fine aggregate, basalt fibers content 0–0.15% of the volume of concrete, and plant fibers content 0.1–0.2% of the volume of concrete.
Based on the grey correlation degree, and to balance the strength and thermal conductivity of the heat insulating shotcrete effectively, the best composition resulted by the specific number of specimen was as follows: 5% of the mass of coarse aggregate was replaced by ceramsite, 10% of the mass of fine aggregate was replaced by pottery sand, the content of basalt fiber was 0.15 vol.% of the concrete, and the content of plant fiber was 0.2 vol.% of the concrete. According to the above research, a general conclusion could apply to future research.

Microscopic test results showed that the hydration reaction of the cement slurry in concrete was not affected by the above admixture. Additionally, the strength of the concrete was high, and no harmful substances or adverse reactions appeared. Combined with mechanical performance analysis, the heat insulating shotcrete could be used for heat resistance of the surrounding rock and roadway support in deep and high-temperature mines.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors acknowledge the support from the Science and Technology Project Foundation of Key Technologies for Prevention and Cure of Major Accidents in Production Safety, General Administration of State Security Supervision (no. Anhui-0003-2016AQ), and the Innovation Fund of Postgraduate, Anhui University of Science and Technology (2017CX2021).

References

[13] J. Pang, J. Huang, W. Yao et al., "Experimental study on thermal conductivity and strength of thermal shotcrete in


