Research on the Crack Resistance and Bearing Capacity of Concrete Roadway Enhanced by Carbon Fiber Mesh and Carbon Fiber Short Cut Wire

Lei Chen

1School of Energy and Safety, Anhui University of Science and Technology, Anhui, Huainan, 232001, P.R. China

Abstract: Shotcrete support technology can play a certain role in strengthening and anti-permeability of underground roadway. However, the lack of crack resistance and bending resistance seriously affects the function of shotcrete support. In this paper, the crack resistance and bearing capacity of underground concrete shotcrete layer were improved by means of high density carbon fiber mesh (CFM) embedded in prefabricated layer and carbon fiber short cut wires (CFSC) with different content of uniform cloth, which was focused on the synergistic strengthening mechanism between CFM and CFSC. The results show that the addition of high density CFM can significantly improve the bearing capacity of concrete shotcrete layer, but the improvement of crack resistance is not obvious. The addition of CFSC (with a content of 2% and a length of 3 mm) can significantly increase the initial crack load of concrete shotcrete, thus improving the crack resistance performance, but it has no obvious effect on the bearing capacity. Adding CFM and CFSC together can further significantly enhance the bearing capacity and crack resistance of concrete shotcrete layer and give full play to the synergistic enhancement effect between the two.

1. Introduction
At present, shotcrete support has been widely used in underground engineering such as coal mine and tunnel, mainly playing the role of reinforcement and anti-permeability. Concrete is a kind of porous brittle material, and its tensile property is much less than the compressive property. With the increase of mining depth, the pressure and deformation of surrounding rock of roadway increased obviously. As a result, serious cracks appear in the concrete shotcrete layer in the service process, even causing concrete spalling and falling blocks, and losing the function of sealing and strengthening the surrounding rock, which leads to serious damage to the roadway and brings serious hidden trouble to the safety of coal mine. Therefore, the research and development of shotcrete support structures with high tensile and crack resistance, high elastic modulus and chemical stability has become the main direction of modern shotcrete development, which is used to solve such problems as cracking, excessive deformation of surrounding rock and instability failure of concrete support structures in tunnel and mine roadway engineering.

At present, although scholars at home and abroad have made some progress in the study of crack and crack resistance of reinforced concrete, there are still a series of problems. However, with the development of carbon fiber composites with high tensile properties, the problem of crack resistance and flexural resistance of concrete shotcrete has been solved. Carbon fiber is a kind of new fiber material with high strength and high modulus, which contains more than 95% carbon. It is made of organic fiber such as flake graphite microcrystalline along the direction of the fiber axial stacking,
through carbonization and graphitization and obtained from the microcrystalline graphite material. This material has the characteristic of "soft outside and strong inside", that is, the quality is much lower than that of metal iron, but the tensile strength is much higher than that of steel. At the same time, carbon fiber material also has the characteristics of high bond strength and modulus, low density, high specific performance, no creep, fatigue resistance and corrosion resistance. Therefore, the application of carbon fiber composite in concrete shotcrete layer will help to improve the crack and crack resistance of concrete materials.

In this experiment, the crack resistance and bearing capacity of concrete shotcrete layer was improved by means of pre-embedded CFM and CFSC. The effect of CFM density and layering number as well as the length and content of CFSC in the concrete shotcrete layer was analyzed, and the synergistic strengthening mechanism of both CFM and CFSC was analyzed. Finally, the concrete shotcrete supporting structure with excellent crack resistance and bearing capacity was obtained.

2. Materials and methods

2.1. Materials

(1) CFM and CFSC
The CFM and CFSC used in the experiment is woven from carbon fiber bundles provided by a new material science and technology co., ltd. in Cangzhou, Hebei province, and its performance parameters are shown in Table 1. As the CFM must be tied in the reinforcement net to stand in the concrete shotcrete layer, this test adopts HPB235 reinforcing bars with a diameter of 6 mm and a mesh density of 240 mm×240 mm, which its performance conforms to the national standard of steel for reinforced concrete (GB1499.1-2008). The density of CFM is 20 mm×20 mm, as shown in Figure 1. Due to the high tensile properties of CFSC, the experiment mainly adopted four kinds of admixture (0.5%, 1%, 2% and 4%) to improve the performance of the concrete shotcrete layer.

Table 1. Mechanical properties of carbon fiber.

| Types of materials | Test item          | Units | Performance requirements | Test result |
|--------------------|--------------------|-------|--------------------------|-------------|
| Carbon fiber bundle| Tensile strength   | MPa   | ≥4000                    | 4268        |
|                    | Modulus of elasticity | GPa   | ≥200                     | 226        |
|                    | Elongation         | %     | ≥1.5                     | 1.67        |
| CFSC               | Tensile strength   | MPa   | ≥4200                    | 4376        |
|                    | Modulus of elasticity | GPa   | ≥200                     | 232        |
|                    | Diameter           | um    | 6.9                      | 6.9         |

(a) Steel mesh; (b) CFM;

Figure 1. Steel mesh and CFM

(2) Concrete
P.O 32.5 Portland cement was used in the test, and its performance conforms to the national standard of universal Portland cement (GB 175-2016). The fine aggregate used for the test was medium coarse river sand, and the fineness modulus was 2.8. Coarse aggregate is gravel, saturated surface dry state, continuous grading, particle size range of 5-20 mm. The test water was ordinary tap water.
2.2. Methods
(1) Design of concrete shotcrete model
   Based on the laboratory conditions and the actual conditions of the coal mine roadway, the design was carried out according to the ratio of the engineering prototype to the test model of 2:1. The designed total width of concrete shotcrete layer is 2.7 m, and the total height is 2.15 m. The height of the straight wall is 0.8 m, and the concrete pouring thickness is 80 mm. The steel mesh and the CFM are tied together and placed in the middle of the concrete shotcrete layer (as shown in the dotted line in figure 2(a)). CFSC are uniformly mixed into the concrete shotcrete layer. The pouring height of concrete shotcrete layer is 300 mm. The placement of abrasive tools and the pouring of sample is shown in Fig. 2(b, c).

   (a) Sample model;                (b) Sample mold;           (c) Finished cast sample;

Figure 2. Model and preparation of sample

(2) Preparation and curing of concrete shotcrete layer
   The mix proportion of concrete shotcrete layer is shown in table 2. A-1 was used as the control group, only steel mesh was added, and no CFM and CFSC were added. CRM and CFSC were added into A-2 and A-3 respectively to test the enhancement of CRM and CFSC on concrete shotcrete layer. Both CFM and CFSC were added into A-4 to A-6 groups to test the synergistic enhancement.

   The preparation of concrete shotcrete layer refers to the preparation method of "Standard for evaluation of concrete compressive strength " (GB/T50107-2010). Take sample D-2 as an example: firstly, tie the CFM and steel mesh together and put them into the mold according to the predetermined position. According to the mix proportion in table 3, cement and CFSC were first added to the mixer and dry mixed quickly for 30 seconds, then sand was added and dry mixed quickly again for 30 seconds, which ensure that the CFSC could be evenly distributed in the concrete. Finally, gravel and water were added, slowly stirred for 30 seconds and then stirred quickly for 60 seconds and ready to be molded. Sample covered with wet dishcloth after demoulding, sprinkler maintenance on a regular basis. During the curing period, the temperature difference between day and night in the laboratory was between 16℃ and 26℃, and the bearing capacity test of sample was carried out until the specified age (28 d).

(3) Loading test of concrete shotcrete layer
   In this experiment, 9 hydraulic jacks were distributed on the concrete shotcrete layer for loading, which was used to approximate the stress state of roadway in the underground. The arrangement of hydraulic jacks is shown in figure 2(a and c). In the loading device, the maximum loading pressure of
each hydraulic jack is 100 t, and the starting load of the cylinder is 0.5 MPa. Meanwhile each stage is increased by 0.1 MPa for slow loading until the sample is completely destroyed. The calculation formula of the jack cylinder is shown in equation (1). M is the force exerted by the hydraulic jack on the concrete arch specimen, and the unit is KN. N is the pressure applied by each oil cylinder, and the unit is MPa. The load with the first visible crack appearing on the surface of the sample was recorded as the initial crack load, which was used to evaluate the crack resistance. In order to evaluate the bearing capacity of the sample, the ultimate load is recorded as the load when the sample is damaged.

\[ M = -10.551 + 30.823N \]  

(1)

3. Results and discussion

(1) Analysis of bearing capacity of concrete shotcrete layer

When the CFM and CFSC were not added, the initial crack load of sample A-1 was low, and obvious cracks appeared on the surface of sample A-1 loaded at 0.9 MPa. When the load rose to 2.4 MPa, the sample A-1 was damaged. Because concrete is a kind of brittle material, the lack of bending and crack resistance seriously affects the bearing capacity of the concrete shotcrete layer. Therefore, it is necessary to modify and enhance the concrete shotcrete layer to significantly improve its bending and crack resistance performance and weaken the shortcomings, so as to give full play to the excellent performance of concrete materials and realize the extensive application of concrete in roadway support.

(2) CFM strengthening the concrete shotcrete layer

When the CFM was added into the concrete shotcrete layer, the bearing capacity of the sample A-2 was significantly improved. The initial crack load of sample A-2 increased to 1.0 MPa and the ultimate load increased to 3.3 MPa, which increased by 11.1% and 37.5% respectively compared with sample A-1. It can be seen that the incorporation of CFM can significantly increase the ultimate load of the concrete shotcrete layer, while the enhancement of the initial crack load is not obvious. This is because the carbon fiber bundles have excellent tensile properties and the high density carbon fiber mesh can form a good bond with the concrete. Therefore, the addition of high density CFM can give full play to its excellent tensile properties, and significantly improve the bearing capacity of concrete
shotcrete layer. However, laminated CFM can only improve a layer crack resistance of concrete but it cannot improve the crack resistance of concrete shotcrete layer as a whole. When the concrete shotcrete is under load, the concrete in other locations cracks gradually due to the lack of crack resistance and expands into visible cracks. Therefore, the crack resistance of concrete shotcrete has not been significantly improved.

(3) CFSC strengthening the concrete shotcrete layer
When the CFSC was added into the concrete shotcrete layer, the initial crack load of sample A-3 increased to 1.5 MPa, but the ultimate load only increased to 2.6 MPa, which increased by 66.7% and 8.3% respectively, compared with sample A-1. It can be seen that the incorporation of CFSC can significantly increase the initial crack load of the concrete shotcrete layer, while the enhancement of the ultimate load is not obvious. This is because CFSC are distributed evenly in the concrete shotcrete layer, connecting the concrete into a whole. When the concrete shotcrete is subjected to load, the uniform distribution of CFSC can effectively inhibit the formation and expansion of micro-cracks, thus significantly increasing the initial crack load of the concrete shotcrete. However, due to the short length and small diameter of CFSC, tensile failure will occur under the action of lower load, and the overall enhancement effect cannot be achieved like that of CFM. Therefore, the incorporation of CFSC cannot significantly improve the ultimate load of concrete shotcrete layer.

(4) Both CFM and CFSC strengthening the concrete shotcrete layer
When both CFM and CFSC were added, the performance of concrete shotcrete layer has been further improved significantly. The initial crack load of sample A-4 increased to 1.7 MPa and the ultimate load increased to 3.8 MPa, which increased by 88.9% and 58.3% respectively compared with sample A-1. It can be seen that the incorporation of CFM and CFSC can both significantly increase the initial crack load and ultimate load of the concrete shotcrete layer, which the enhancement is even higher than that of CFM and CFSC separately. This is because the incorporation of SFM and CFSC together can play a synergistic role. In order to give full play to the excellent tensile properties of the carbon fiber mesh, it is necessary to ensure that the CFM and concrete can form a good bond. However, concrete is a brittle material that is prone to cracking. When the concrete shotcrete is under load, the bonding surface between the carbon fiber mesh and the concrete is prone to crack and constantly expands and extends under the action of load, which will lead to the weakening of the bonding force between the CFM and the concrete and hinder the performance of the high tensile strength. Uniform distribution of CFSC can effectively hinder the generation of micro-cracks and further inhibit the extension and expansion in concrete, improve the bonding force between CFM and concrete, and ensure the full play of the tensile properties of CFM.

When the total output of CFSC is kept at 2%, but the length of 1 mm and 3 mm of CFSC is mixed with 1% each, the mechanical properties of sample A-5 were further improved. The initial crack load of sample A-5 increased to 2.0 MPa and the ultimate load increased to 3.9 MPa, which increased by 17.6% and 2.6% respectively compared with sample A-4. It can be seen that mixing of 1 mm and 3 mm CFSC can further increase the initial crack load of concrete shotcrete, but the ultimate load does not increase significantly. This is because when the mixing amount of CFSC remains 2%, but the length of some CFSC is shortened from 3mm to 1mm, which increases the mixing amount. The increase content of CFSC will increase the content of CFSC in per unit volume and further enhance the crack resistance of concrete per unit volume. This undoubtedly improves the crack resistance of concrete shotcrete layer. However, due to the low length of 1mm CFSC, it is unable to form a strong enough cohesive force with the concrete, resulting in the failure of part of the CFSC pull out and not fully play out the tensile properties, so the content of 1 mm CFSC is only maintained at 1%. The most important thing is that adding CFSC of different lengths can play the role of step by step crack resistance in the concrete shotcrete layer, which is also the reason why the initial crack load of sample A-5 increases.

When adding a double layer of CFM at 20 mm and 40 mm below the surface of the concrete shotcrete layer, the bearing capacity of sample A-6 was further improved. The initial crack load of sample A-5 increased to 2.1 MPa, and the ultimate load increased to 4.7 MPa, which increased by 5%
and 20.5% respectively compared with sample A-5. It can be seen that the ultimate bearing capacity of concrete shotcrete can be further improved by adding the CFM at different locations, but the improvement of initial crack load is not obvious. This is because the addition of double CFM at different locations can ensure the formation of enough cohesive force between it and the concrete so as to further develop the tensile properties of the double-layer CFM. The most important thing is that the double-layer CFM and CFSC can connect the concrete shotcrete layer as a whole, significantly improving its toughness and overall bearing capacity. Therefore, the bearing capacity of sample A-6 can be further improved.

4. Conclusions

(1) Concrete is brittle and easy to crack, which makes concrete shotcrete prone to crack and insufficient bearing capacity.

(2) The addition of CFM can significantly improve the ultimate bearing capacity, but the effect is not obvious to the promotion of crack resistance of concrete shotcrete layer.

(3) The addition of CFSC can significantly improve the crack resistance, but the effect is not obvious to the promotion of ultimate bearing capacity of concrete shotcrete layer.

(4) Adding CFM and CFSC together can play a synergistic role in further enhancing the initial crack load and ultimate load of concrete shotcrete. The anti-cracking effect of mixing different lengths of CFSC is better than that of adding a single length. The enhancement effect of double CFM is better than that of single.

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