Development and Experiment Research on Multi-function Wire Rope for Manned Rescue Lifting Equipment

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Abstract: Starting from the introduction of the method of manned rescue lifting for deep hole with large diameter, a multi-function requirement was proposed for loading and communication transmission to develop a special wire rope for ZMK5200QJY40 rescue and lifting vehicle, and a built-in four-strand 4V × 39S non-rotating wire rope structure was established with the coal mines safety requirements. Through the combination of numerical calculation and experimental research, the specific parameters of the wire rope were calculated, the wire and the central cable material, the workshop production process were optimized, and a multi-function wire rope was trial-produced. Based on the failure tensile test, the wedge-shaped ring combination was preferred as the connection method between the wire rope and the lifting cabin, after a series of fatigue and insulation tests, actual working condition simulation tests, etc., a kind of wire rope with functions of manned lifting and communication has been successfully developed, the structure was reliable enough to ensure the safety of the manned rescue process, and it has a reference significance for the series of multi-functional wire ropes development.

1. Demand analysis of wire rope
The ground manned lifting and rescue for large-diameter hole was to construct a small-diameter life passage hole to provide life support for the trapped people after the underground accident, and then construct a large-diameter drilling hole and use the manned rescue lifting equipment to lift the trapped people to the ground. The rescue method can effectively avoid the collapse of roadways, prevent secondary accidents during the rescue process, and have high rescue efficiency. It is a new and effective method for emergency rescue in mines [1][2].

ZMK5200QJY40 type rescue lifting vehicle was developed by Xi’an Research Institute of China Coal Technology and Engineering Group Co., Ltd to meet the demand of manned rescue and lifting requirements (see as Figure 1.). In this paper, the development and test research process of the wire rope for the lifting equipment were specially studied. For the wire rope, manned lifting function should be the first considered, a stable and uninterrupted information transmission channel constructed for the communication system should also be provided. In terms of structure, the multi-function wire rope is preferably non-rotating structure to meet the safety requirements for coal mine safety regulations and to ensure that the wire rope does not rotate or weakly rotate during the lifting process. In terms of the relationship between the communication cable and the wire rope, there will be 4 (2 pairs) cables with outer insulation material as the internal design, the wire rope and inner cable will be good without damage, deformation and cracking under the load, to avoid the conduction of the copper core of the cable and the wire rope, affecting the communication performance, so material and thickness [3][4] of the insulation material for internal cable should be specially studied.
Wire rope forging production process was used, forging process should be controlled with reasonable forging rate to ensure the internal cables no-damaged during production. Considering the high humidity characteristics of coal mine rescue environment, wire rope with certain anti-corrosion function was realized through hot-dip galvanized steel wire coupled with some use of grease.

Fig.1 ZMK5200QJY40 type rescue lifting vehicle

2. Wire rope scheme establishment
In the design of coal mine rescue wire rope, the first problem to be solved was that the wire rope cannot rotate during use. There are two types of non-rotating wire rope structures, one is a multi-strand non-rotating structure, such as 19 × 7, and the other is a few-strand non-rotating structure, such as 4V × 39S. From the perspective of flexibility, 4V × 39S is worse than 19 × 7; from the perspective of wear resistance, 4V × 39S has better wear resistance compared with 19 × 7 because of larger diameter of the outermost steel wire. In general, from the perspective of wire rope, 4V × 39S is more suitable for coal mine rescue use conditions. The copper cable was coated with plastic insulation, which was placed in the outer layer of 4V × 39S rotating with the strand, which is a relatively optimized and feasible scheme[5].

In this end, the structure of the wire rope (shown as Figure 2.) was established, and four special communication cables were respectively buried in four-strand wire rope center.

Fig. 2  4V × 39S + 5FC type wire rope structure

3. Calculation of wire rope parameters

3.1. Wire rope selection factor

\[ C = \sqrt[4]{\frac{n}{k \omega \phi \sigma_b}} \]  

Where, \( n \) — safety factor, article 400 of the Coal Mine Safety Regulations suggests the promotion of manned lifting 9;
\( k \) — Reduction factor of twisting wire rope, 0.92;
\( \omega \) — Wire rope fullness factor, 0.46;
\( \sigma_b \) — Nominal tensile strength of wire rope, N/mm², 1770;
\( C \) — Wire rope selection coefficient, substitute the above data, 0.124.
3.2. Calculation of wire rope diameter

\[ d = C \sqrt{F_{\text{max}}} \]  

(2)

Where,  
- \( C \) — Wire rope selection coefficient;  
- \( F_{\text{max}} \) — Wire rope design maximum pulling force, N, choose 20000, the actual pulling force is 8300;  
- \( d \) — Wire rope diameter, mm. Substitute the above data, select 18 according to the calculation result.

3.3. Wire rope diameter check

\[ F_c \geq nF_{\text{max}} \]  

(3)

Where,  
- \( n \) — safety factor, choose 9;  
- \( F_{\text{max}} \) — Wire rope design maximum pulling force, N, choose 20000;  
- \( F_c \) — The minimum breaking tension of the wire rope, kN, GB/T8918-1996, 4V×39S-5FC, diameter of 18 mm, 1770 N/mm\(^2\) was chosen for nominal tensile strength, steel core of wire rope, choose 204 kN; substitute the above data, 204 \( \geq \) 180, wire rope diameter was qualified.

3.4. Calculation of outer strand diameter of wire rope

The diameter of the outer strand of the wire rope was calculated as follows:

\[ d = \frac{DK_1}{m} \]  

(4)

Where,  
- \( D \) — wire rope diameter, mm, choose 18;  
- \( K_1 \) — rope design factor, choose 1.035;  
- \( m \) — twisting factor, query the twisting coefficient in m table, choose 2.432;  
- \( d \) — Outer strand diameter of wire rope, mm, substitute the above data, choose 7.67.

3.5. Diameter calculation of each layer of the outer strand for the wire rope

The outer strand of the wire rope was composed of the outermost layer wire, the secondary outer layer wire and the strand core, which were a combination structure type of 15 + 15 + strand core, in which the outermost layer diameter was calculated as follows:

\[ d_1 = \frac{d}{m_1} \]  

(5)

Where,  
- \( d \) — Outer strand diameter of steel wire rope, mm, choose 7.67;  
- \( m_1 \) — Coefficient of twisting of outermost wire, 6.173 was taken by looking up the table;  
- \( d_1 \) — Outer wire diameter, mm, choose 1.24.

query the design parameter table of line contact round strands, when k is 6.5, the ratio of the diameter of the three-layer steel wires were:

\[ d_1 : d_2 : d_3 = 1.000 : 0.7418 : 3.0484 \]  

(6)

Where,  
- \( d_1 \) — outermost steel wire diameter of outermost strand, mm, choose 1.24;  
- \( d_2 \) — secondary steel wire diameter of outermost strand, mm, substitute the above data, get 0.92;  
- \( d_3 \) — Outer strand core wire diameter, mm, substitute the above data, get 3.78.
4. Trial production
Based on the above theoretical calculation results, the hot-dip galvanized steel wire 70 # and 80 # were used, and the central cable was made of PA12 with a diameter of 2.70 ~ 2.80 mm, coated with nylon insulation material. The specific production process of the wire rope was shown in Table 1.

Table 1. Production process of steel wire rope

| Structure      | After-pressing diameter (mm) | before-pressing diameter (mm) | Steel wire strength (MPa) | Wire diameter | Fiber core (mm) | Cable lay | Length of lay (mm) |
|----------------|-------------------------------|-------------------------------|--------------------------|---------------|----------------|----------|--------------------|
| 4V39S+5FC      | 18.20                         | 19.20                         | 1870                     | /             | hemo core 5.6  | Z        | 144-150            |
| 15+15+(18+0)   | 7.70                          | /                             | 1.24+0.92                | /             | /              | S        | 50-52              |
| 18+0           | 3.78                          | /                             | 0.53                     | /             | cable          | S        | 38                 |

5. Series of experimental research

5.1. Breaking tensile test
The wire rope was woven by hand to form a buckle, and then plastic safety protection was carried out, see Figure 3 (a); the wire rope was formed by an aluminum pressure sleeve to form a buckle, see Figure 3 (b); the wire rope was combined by hand weaving and an aluminum pressure sleeve, see Figure 3 (c); the combination of wire rope pulleys, see Figure 3 (d).

![Fig. 3 Breaking tensile test plan](image)

5.2. Fatigue test
The test method was refered to the fatigue standard requirement of 8.0 mm elevator rope. After 5000 fatigue tests, there was no broken wire on the surface of the strand, and the insulation was above 500 megohms, the wire rope will be ok. Wire rope of 7 m was taken to split and straighten, load of 380 kg on the wire rope was tested on the test machine of elevator rope static fatigue, 5000 times were simulated in one direction. If the insulation resistance was above 500 megohms, the wire rope will pass the test of fatigue.

5.3. Whole wire rope of 750 m insulation test
A 500 range megohmmeter and whole wire rope of 750 m were used to conduct resistance insulation test. The strand wire and the cable were connected to the "line" and "ground" ports of the megohmmeter respectively. The test will pass if the insulation resistance test results were all above 500 megohms.
5.4. Rotation performance test
The 50 cm end of the wire rope was fixed in half on the driving hook (not rotated), and it was fixed with a wire rope chuck; the other end was folded in half at 50 cm and fixed with a wire rope chuck. The above two wire rope rings were connected to the I-shaped wheel. 3 mm hemp rope with length of 5 m was attached at the middle of the two chucks. After the wire rope was lifted, I-wheel rotates until stopping, and the wire rope rotates 1.75 turns in total.

5.5. Live test of rescue wire rope simulation
A 1.5 t heavy object was hung by a two-section braided rope for 24 h, and its conductivity was also tested, and it was still fully insulated. Lift up and down 50 times to load and unload, check its conductivity, and still fully insulated. A two-piece wedge-shaped ring combination rope was used to suspend a 1.5 t weight for 24 h, and its conductivity was tested and all insulated. Lift up and down and load and unload 100 times, check its conductivity, all tests were insulated. Through the above optimization, theoretical calculation, trial production and various tests, the coal mine rescue wire rope was successfully developed, the product parameters were shown in Table 2 [8][9].

Table 2. Multi-function wire rope product parameters

| Diameter (mm) | Nominal strength (MPa) | Surface condition | Minimum breaking tension (kN) | Linear density (kg/m) |
|---------------|------------------------|-------------------|-------------------------------|---------------------|
| 18.00         | 1770                   | Galvanized / Grade B | 204                           | 1.217               |

6. Summary
Based on the large-diameter hole used ground manned rescue and lifting method, in order to develop a special wire rope for the ZMK5200QJY40 rescue and lifting vehicle, multi-function requirements of manned lifting and providing a stable and uninterrupted information transmission channel for the communication system were established. Built 4 cables in four-strand of 4V × 39S non-rotating wire rope structure to satisfy safety requirements of coal mines was brought forward. Through theoretical calculation, the parameters such as wire rope selection coefficient, wire rope diameter and other parameters, the wire rope and the central cable material were selected, production process was optimized, and a 750 m of wire rope was trial produced. On this basis, the destructive tensile test was carried out, and the wedge-shaped ring combination method was preferred as the connection method between the steel rope and the lifting cabin, and a series of tests such as fatigue test, tests of 750 m whole rope insulation, rotating performance, rescue wire rope simulation live, etc. were carried out. In the end, a multi-function wire rope structure that meets the requirements for manned lifting and communication was successfully developed, which reliably guarantees the working safety of the ZMK5200QJY40, it has reference significance for the development of a series of wire ropes with multi-function.

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