Research on Anti-abrasion Property of Waterborne Epoxy Mortar Based on Underwater Steel Ball Method

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Abstract. Waterborne epoxy emulsion modified mortar has been paid more and more attention and applied in the field of hydraulic construction. Its physical and mechanical properties, especially the anti-erosion properties, are the key influencing parameters applied to the drainage structures such as sand tunnel and spillway dam surface. A high-speed underwater steel ball punching tester was used to simulate the impact of pushing mass on the abrasion resistance of water-borne epoxy mortar. In this paper, the abrasion resistance of mortar under different rotational speeds and different grades of grinding steel balls are analyzed, and the test parameters of underwater steel ball method suitable for waterborne epoxy mortar are explored, then a method for predicting the punching and grinding life of mortar is well proposed. The research results provide a basis for the application of water-borne epoxy mortar to hydraulic structures required by anti-impact abrasion.

1. Introduction

It is a difficulty and academic research hotspot for engineering researchers to take the anti-abrasion protection measures for hydraulic outlet structures. At present, there are two ways to protect hydraulic outlet structures and repair abrasion and cavitation erosion of them: (1) anti-abrasion concrete lining can be used, such as high strength concrete, silica fume concrete, high flyash concrete and fiber concrete, in the construction period or when the depth and scope of the scour pool are large, etc. (2) When abrasion and cavitation erosion occurs in the hydraulic outlet structures, steel plate, cast stone slab and polymer mortar can be used as the surface thin layer protective material. The application of steel plate and cast stone slab is limited due to the easy occurrence of overall peeling, complex construction process and high cost[1,2]. Polymer modified mortar takes polymer as cementitious material, which takes advantage of the good cohesive force and low modulus of elasticity of polymer itself to improve the mechanical properties, abrasion resistance, durability and cohesive force with base concrete of ordinary mortar [3]. Epoxy resin mortar is the most widely used polymer modified mortar in the reinforcement of hydraulic concrete structures and has the best effect[4]. However, the traditional epoxy mortar uses oily epoxy resin, which has some shortcomings in the application process.
Waterborne epoxy resin has some advantages of traditional epoxy resin and breaks through its shortcomings, so it has broad application prospects. However, the research of waterborne epoxy resin started late, and its application in hydraulic engineering is still rare, which limits its application in repairing hydraulic outlet structures.

The anti-abrasion property of waterborne epoxy mortar is the key influencing parameter for its application in outlet structures such as sediment-flushing tunnel and spillway face, and it is also the premise for its wide application in the hydraulic outlet structures. Now, the underwater steel ball method, air sand gun method and disc method are often used to test the anti-scouring and abrasion performance. However, the test parameters of these methods are based on concrete research results and can not be directly applied to the abrasion test of waterborne epoxy mortar. Therefore, it is necessary to carry out appropriate anti-abrasion test methods to study the anti-abrasion performance of waterborne epoxy mortar.

2. Material and Methods

2.1. Material

Waterborne epoxy mortar was prepared with P·C32.5R cement and green silicon carbide as sand. The mixture ratio and mechanical properties of mortar are shown in table 1-2.

| Table 1. Mixture ratio |
|------------------------|
| Polymer cement ratio (%) | Water cement ratio | Cement sand ratio | 36eye sand:46eye sand |
| 12 | 0.35 | 1:2 | 1:1 |

| Table 2. Mechanical properties |
|--------------------------------|
| Age | Compressive strength /MPa | Flexural strength /MPa | The ratio of compressive strength to flexural strength | Tensile strength /MPa |
| 7d | 40.99 | 10.62 | 3.86 | 3.66 |
| 14d | 46.99 | 12.96 | 3.63 | 4.30 |
| 28d | 51.02 | 14.60 | 3.50 | 3.06 |

2.2. Test Scheme

According to the “Hydraulic Concrete Test Rules” (DL/T 5150-2001), underwater steel ball method was used to simulate the abrasion process of mortar under bed load. In this paper, the abrasion resistance of waterborne epoxy mortar is studied by using a High-speed Underwater Steel Ball Abrasion Tester developed by Nanjing Hydraulic Research Institute. The test machine can adjust the speed of impeller, and the maximum speed can reach 4200r/min. Two kinds of impeller rotational speeds, 1200r/min and 1800r/min, were used in the test. The steel ball grading is shown in table 3. The standard gradation is the standard steel ball gradation stipulated in the “Hydraulic Concrete Test Rules” (DL/T 5150-2001).

| Table 3. Steel ball gradation |
|-------------------------------|
| Diameter/mm | Number | Total mass/g |
| Standard | 70 | 1859 |
| 12.7±0.1 | 224 | 1859.2 |
| 19.1±0.1 | 67 | 1882.7 |
| 25.4±0.1 | 28 | 1870.4 |

2.3. Test Piece Preparation

The underwater steel ball method is originally used to test the abrasion resistance of concrete. It needs to make cylindrical abrasion specimen with a thickness of 10cm and a diameter of 30cm and the specimen is large and heavy. However, the production cost of epoxy mortar is much higher than that...
of concrete. If the waterborne epoxy modified mortar is made according to the size of the original specimen, it will lead to more material consumption and lower utilization rate. In order to improve the test efficiency, reduce the test cost and make it more suitable for the abrasion test of mortar, the test device has been improved in this paper.

The improved abrasion specimen is shown in figure 1, including base (1), waterborne epoxy mortar test block (2), screw for outside hex bolt (3), nut for outside hex bolt (4) and nut (5). The fabrication process of the specimen device is as follows:

1) Making a cylindrical mortar block with a thickness of 8cm and a diameter of 30cm as the base of the mortar test block.

2) Inserting the nut for outer hexagonal bolt tightly into the nut to form a nut assembly to enhance the firmness of the connection between the nut for outer hexagonal bolt and the base, then installing the nut assembly into the hole drilled in the center of the base and filling it with cement mortar.

3) After drilling a hole in the center of the water-borne epoxy mortar test block, place it on the base and connect it with the base by the screw for outside hex bolt. After the installation of the water-borne epoxy mortar test block, it can be put into the underwater steel ball abrasion tester for testing.

3. Results

3.1. Results analysis

The abrasion speed is calculated as follows:

$$f_a = \frac{M_o - M_f}{T}$$  \hspace{1cm} (1)

In formula: $f_a$ is the abrasion rate, kg/h; $M_o$ is the quality of specimen before test, kg; $M_f$ is the quality of specimen after test, kg; $T$ is the test time, h.

The abrasion rate is calculated as follows:

$$L = \frac{M_o - M_f}{M_o}$$  \hspace{1cm} (2)

In formula: $L$ is the abrasion rate, %; $M_o$ is the quality of specimen before test, kg; $M_f$ is the quality of specimen after test, kg.

Figures 2-3 show the changes of the abrasion speed and abrasion rate of mortar over time under different rotational speeds and different grades of steel balls.

It can be seen from the figures that the abrasion speed of the specimen in the first and two stages is basically equal at the speed of 1200r/min. From the third stage, the abrasion speed of the specimen tested with 12mm steel ball began to increase sharply. The abrasion rate of the specimen tested with another three gradations of steel ball increases relatively slowly.
It can be seen from the figure that the abrasion speed of the specimen in the first and two stages is basically equal at the speed of 1200r/min. From the third stage, the abrasion speed of the specimen tested with 12mm steel ball began to increase sharply. The abrasion rate of the specimen tested with another three gradations of steel ball increases relatively slowly. At the rotational speed of 1200r/min, the steel ball gradation corresponding to the abrasion efficiency of mortar from high to low is 12mm, standard gradation, 19mm and 25mm. At the rotational speed of 1800r/min, the abrasion speed in the first stage of the specimen tested with 19mm and 25mm steel ball is basically the same, but the abrasion rate of specimen tested with 12mm steel ball increases sharply from the first stage. It can be seen from the results that the surface of mortar has high abrasion strength. With the continuous abrasion, the surface of the specimen is worn, the abrasion develops to the interior of the specimen and the abrasion speed begins to increase gradually.

3.2. The influence of water flow velocity on the abrasion of mortar

It can be seen from the figure that the abrasion speed of the specimen in the first and two stages is basically equal at the speed of 1200r/min. From the third stage, the abrasion speed of the specimen tested with 12mm steel ball began to increase sharply. The abrasion rate of the specimen tested with another three gradations of steel ball increases relatively slowly. At the rotational speed of 1200r/min, the steel ball gradation corresponding to the abrasion efficiency of mortar from high to low is 12mm, standard gradation, 19mm and 25mm. At the rotational speed of 1800r/min, the abrasion speed in the first stage of the specimen tested with 19mm and 25mm steel ball is basically the same, but the abrasion rate of specimen tested with 12mm steel ball increases sharply from the first stage. It can be seen from the results that the surface of mortar has high abrasion strength. With the continuous abrasion, the surface of the specimen is worn, the abrasion develops to the interior of the specimen and the abrasion speed begins to increase gradually.
Figure 4 shows the abrasion rate of mortar at the rotational speed of 1200r/min and 1800r/min. The gradation of steel ball is standard gradation, 12.7mm, 19.1mm and 25.4mm, the test time is 72h, 24h, 54h and 45h, respectively. It can be seen from the results that the change of flow velocity has more obvious effect on single particle size steel ball. The results of underwater steel ball abrasion test for concrete show that [5], using 19mm and 25mm steel ball, when the rotational speed increases from 1200r/min to 1800r/min, the abrasion rate of concrete decreased. It can be seen that the water-borne epoxy mortar is more obviously affected by the change of flow velocity. The reason is that mortar is composed of fine particles such as cement and sand. The damage of bedload to materials is mainly impact damage. The impact and friction of abrasive media lead to the wear and separation of fillers. Concrete consists of cement, sand and coarse aggregate. The surface of concrete is mostly a layer of mortar with low abrasion resistance. In the process of abrasion, the cement paste is first abraded and the aggregate is gradually exposed. The hardness of aggregate is higher than that of cement paste, so the cutting wear is much less than that of cement paste. When the cement paste between the coarse aggregate is further taken away by the water flow, the aggregate is subjected to a greater force of the water flow, resulting in further development of damage. Therefore, the impact of steel ball size on concrete abrasion is greater. Using mixing particle size steel ball, the cement paste between aggregates is easier to be worn. Relevant study has shown that [6] under the condition of 1200r/min rotational speed, standard gradation steel ball is used, and the abrasion efficiency of concrete is higher than using single particle size.

3.3. Analysis of test results of traditional epoxy mortar
Based on the test results of waterborne epoxy mortar, at the rotational speed of 1800r/min, using 12.7mm, 19.1mm and 25.4mm single particle steel ball, the abrasion tests of traditional epoxy mortar were carried out. The test results are shown in Figures 5-6.

Figure 5. The change of abrasion speed over time. Figure 6. The change of abrasion rate over time.

Compared with waterborne epoxy mortar, the abrasion resistance of traditional epoxy mortar is quite different. There are loose particles on the surface of traditional epoxy mortar, which leads to a large mass loss at the beginning. When the loose particles are peeled off, the real abrasion resistance of mortar is reflected. From the second stage, no matter what particle size steel ball is used, the abrasion speed of traditional epoxy mortar at all stages remains basically stable. This shows that the abrasion resistance of traditional epoxy mortar is uniform. According to the abrasion results of 19.1mm and 25.4mm steel ball, the anti-abrasion strength of the surface layer of waterborne epoxy mortar is close to that of traditional epoxy mortar.

3.4. Analysis of test results of traditional epoxy mortar
At the rotational speeds of 1200r/min and 1800r/min, the abrasion rate of waterborne epoxy mortar has a parabolic relationship with test time. The relationship between abrasion rate and test time can be fitted as shown in table 4. Where: y is the abrasion speed, kg/h; x is the test time, h; R^2 is the correlation coefficient.
Table 4. The fitting formula of abrasion rate and time of waterborne epoxy mortar

| Rotation speed (r/min) | Gradation | Fitting formula |
|------------------------|-----------|----------------|
|                        | standard gradation | y=3E-05x^2-0.0003x+0.0013, R^2=0.9956 |
|                        | 12.7      | y=2E-04x^2+0.0024x+0.0052, R^2=0.9967 |
|                        | 19.1      | y=4E-05x^2-0.001x+0.0075, R^2=0.9689 |
|                        | 25.4      | y=2E-06x^2+0.0002x+0.0014, R^2=0.9523 |

Table 5. The fitting formula of abrasion rate and time of traditional epoxy mortar.

| Rotation speed (r/min) | Gradation | Fitting formula |
|------------------------|-----------|----------------|
|                        | standard gradation | y=1E-05x^2+0.0028x-0.0083, R^2=0.99 |
|                        | 12.7      | y=5E-04x^2+0.0041x-0.0028, R^2=0.9984 |
|                        | 19.1      | y=2E-04x^2-0.0021x+0.004, R^2=0.9995 |
|                        | 25.4      | y=5E-05x^2+0.0023x-0.0006, R^2=0.9943 |

The abrasion rate of traditional epoxy mortar has a linear relationship with test time. The relationship between abrasion rate and test time can be fitted as shown in table 5. Where: y is the abrasion speed, kg/h; x is the test time, h; R^2 is the correlation coefficient.

According to the test results, the relation of abrasion rate and test time of different types mortars can be expressed by a fitting formula. This can provide a reference for predicting the anti-abrasion life of mortar under the action of bed load. When predicting the anti-abrasion life of new mortar under the action of bed load, the Underwater Steel Ball Method test can be carried out first, then the relationship between abrasion rate and time can be fitted. The fitting formula can be compared with that of the existing mortar, the anti-abrasion life of the new mortar under the same conditions can be inferred according to the life of the existing mortar in different practical projects.

3.5. Influencing factors of abrasion resistance of waterborne epoxy mortar

In order to analyze the influence of mechanical strength on the abrasion resistance for mortar, P·O42.5 ordinary Portland cement was used to make abrasion specimens. The test results were compared with that of waterborne epoxy mortar. The mixture ratio and mechanical properties of ordinary Portland cement mortar are shown in tables 6-7. The rotational speed is 1200r/min, using 12.7mm single particle size steel ball, the number of steel balls was 112, the test results are shown in Figures 7-8.
The maximum abrasion speed of cement mortar is 3.23 times of the minimum, while the maximum washing rate of waterborne epoxy mortar is 10.77 times of the minimum. This shows that waterborne epoxy mortar has a greater difference in surface and internal abrasion resistance. The possible reason is that there are more porous in the waterborne epoxy mortar. After 72 hours of abrasion, the abrasion rate of waterborne epoxy mortar is 30.5% lower than that of cement mortar. Compared with cement mortar, waterborne epoxy mortar has 10.1% higher compressive strength, 64.8% higher flexural strength, 33.1% lower the ratio of compressive strength to flexural strength and 30.3% higher maximum tensile strength. It can be seen that the abrasion resistance of mortar has a strong correlation with the ratio of compressive strength to flexural strength and tensile strength, the abrasion resistance of mortar has a negative correlation with the ratio of compressive strength to flexural strength and a positive correlation with tensile strength. The ratio of compressive strength to flexural strength reflects the toughness of the material. The better the toughness of the material is, the less likely it is for the mortar to have microcrack under the impact of the steel ball. The tensile strength reflects the bonding force of the mortar fillers. The higher the tensile strength is, the more difficult it is for the filler particles to fall off from the matrix under the impact of steel balls.

In order to further study the influence of the internal characteristics of waterborne epoxy mortar on the abrasion resistance, the water cement ratio of waterborne epoxy mortar was increased to 0.4, and the other ratios were unchanged. The rotational speed is 1200 r/min, using 12.7mm single particle size steel ball, the number of steel balls was 112, the test results are shown in Figures 9-10.

The abrasion rate of mortar with water cement ratio 0.4 is 15.9% lower than that of mortar with water cement ratio 0.35. The density of mortar with water cement ratio 0.35 is 2327.9 kg/m$^3$ and that of mortar with water cement ratio 0.4 is 2456.2 kg/m$^3$. The increase of water cement ratio leads to the increase of the consistency of mortar and the decrease of internal pores, the improvement of the compactness increases the abrasion resistance of the mortar. Therefore, the compactness of waterborne epoxy mortar is also an important factor affecting the abrasion resistance.

4. Conclusion
In this paper, a high-speed underwater steel ball abrasion tester was used to simulate the impact of bed
load on the abrasion resistance of waterborne epoxy mortar. In this paper, the abrasion characteristics of mortar under the action of different rotational speeds and different gradations of steel ball are analyzed, and the suitable test parameters of the underwater steel ball method for the waterborne epoxy mortar are explored. A simple method for predicting the abrasion resistance life of waterborne epoxy mortar is proposed. The main conclusions are as follows:

(1) At the rotational speeds of 1200r/min and 1800r/min, using 12.7mm single particle steel ball, the abrasion efficiency is higher than that of standard gradation, 19.7 mm and 25.4mm single particle steel ball, and it can better reflect the abrasion resistance of different layers of waterborne epoxy mortar.

(2) The waterborne epoxy mortar is more obviously affected by the change of flow velocity compared with concrete.

(3) The abrasion rate of traditional epoxy mortar and waterborne epoxy mortar has different change trend with test time. The fitting formula between the abrasion rate of mortar and test time can be obtained through the test results to predict the service life of different mortars under the same conditions.

(4) The abrasion resistance of mortar has a strong correlation with the ratio of compressive strength to flexural strength and tensile strength; the abrasion resistance of mortar has a negative correlation with the ratio of compressive strength to flexural strength and a positive correlation with tensile strength; the compactness of waterborne epoxy mortar is also an important factor affecting the abrasion resistance.

Acknowledgements
This work was financially supported by the national natural science foundation of China (51779101), the postgraduate research & practice innovation program of Jiangsu province (SJCX18_0178), the fundamental research funds for the central universities (2018B752X14), and fundamental research funds for the central nonprofit research institutions (HKY-JBYW-2018-01).

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