

Research Article

Hydraulic Abrasion-Resistant Elastic Epoxy Resin Materials

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The abrasion of hydraulic concrete structures caused by the washing action of flowing water is a common problem and cannot be solved by simply increasing the strength of the concrete. To ensure safe operation, increase in service life and reduction of maintenance costs of hydraulic concrete structures and the development of abrasion-resistant materials are required. In this work, polyurethane-modified epoxy resin was synthesized using the interpenetrating network technology (IPN). After many mixing experiments, the ratio of polyether amine to alicyclic amine in Component B was determined to be 29:14 and the ratio of Component A to Component B was 7:3. With these ratios, elastic epoxy achieved a tensile strength of more than 15 MPa and an elongation rate of more than 20%, thus balancing strength and toughness. The effects of the curing conditions, the ratio of Component A to Component B, and diluents and fillers on tensile strength and elongation of the elastic epoxy resin were analyzed. The results of the analysis indicated that the curing duration should be over 7 days, the optimal proportion of Component A to Component B should be 7:3, and the diluent of the elastic epoxy material should be the bifunctional butanedioldiglycidyl ether (622). The reliability of this material was determined by pull-out testing, adhesion, and tensile strength testing. The underwater steel ball test and ring test were adopted as the abrasion-resistance tests for the elastic epoxy resin material. The results showed that the abrasion-resistance performance of elastic epoxy coating improved hundreds of times over that of common concrete. Although the wearing strength was reduced with pressure, the elastic epoxy coating still retained excellent abrasion-resistance performance. At last, future application prospects of elastic epoxy improvement products are introduced and need further reach.

1. Introduction

1.1. Preface. Outlet structures, such as overflow dams and spillway tunnels, are commonly subjected to abrasion, and thus, damage to concrete caused by cavitation erosion and grinding is quite common, particularly when high-velocity water carries sediments and rocks. After 30 years of operation, more than 75% of dams require some degree of repair. The inspection of 32 large concrete dams revealed that 22 suffered from cavitation erosion and grinding problems. Due to sediment content and bed load, coupled with high velocity water flow, abrasion and cavitation have become the main problems for outlet structures of large hydropower stations that have already been built or will be built on the Yellow River and in southwest China. The abrasion and cavitation erosion may affect safety, so repair or reinforcement of these outlet structures is necessary [1].

Hydropower stations, such as Baihetan (China), Jinping (China), and Laxiwa (China), have high water heads (over 200 m) and high flow velocities (up to 40–50 m/s), while the discharge volumetric flow rate of a single spillway tunnel can reach 3000 m³/s to 4200 m³/s. High flow velocities with solid particles have high kinetic energy, which leads to increased erosion damage; thus, it is necessary to improve the anti-abrasion performance of the material of the outlet structures. Therefore, the abrasion-resistance tests should be performed to evaluate solutions to the problem.

To repair the damaged dams and improve the reliability, safety, durability, and service life of the structures, the development of hydraulic antiabrasion materials with anti-cavitation and abrasion resistance under the condition of high flow velocity with solid particles is required. This research addresses the theory and application of hydraulic antiabrasion materials.

1.2. Research Progress. The research of antiabrasion materials is mainly focused on two aspects: the increase in the strength of the concrete and the increase in the toughness of the concrete. High-strength concrete uses additives, such as admixture and a water reducer, which reduce the abrasion but may cause brittleness and a lack of toughness. A new type of concrete cover for toughness is an organic material layer, which can absorb the sediment's kinetic energy and avoid erosion, thus providing antiabrasion qualities. In addition, the concrete cover can avoid the direct scouring of the concrete by water flow with sediments. To date, the main antiabrasion materials are high-strength concrete [1], such as steel fiber-reinforced concrete [2–7] and silicon powder concrete; multicomponent cementitious materials concrete [8–11], while adding an active admixture, such as I or II fly ash and silicon powder [12–15] and adding fibers producing antiabrasion concrete [16–20]; fly ash concrete [21–25]; and new types of concrete covers, such as epoxy slurry, epoxy coating, polyurea, and polyurethane elastic-coating materials, as well as other concrete coating materials [26].

1.2.1. Epoxy Resin. Epoxy resins, such as epoxy coatings and epoxy mortars, are widely used in hydropower engineering. An epoxy coating, a type of epoxy resin composite, has good performance for anticavitation and abrasion resistance. In addition, epoxy coatings have many advantages, such as the ease of application, low cost, no heat sensitive zones, and minimal deformation. Epoxy mortar consists of an epoxy resin, a curing agent, a plasticizer, a thinner, a pigment, and a filler. A modified epoxy mortar has many advantages, such as minimal shrinkage, strong adhesion to concrete, high mechanical strength, and high resistance to abrasion [26–30].

In the early 1960s, epoxy mortar was applied to protect the concrete of an overflow plant from cavitation and abrasion in the Xin'anjiang Power Station (China) [31]. In the 1980s, an elastic epoxy mortar, developed by the China Institute of Water Resources and Hydropower Research, was found to have good deformation characteristics and strong adhesion. This elastic epoxy mortar can be used even at the temperatures of 3–5°C. In recent years, Shu-fang et al. [32] studied the abrasion-resistance performance of epoxy resins with a sea island structure. Based on this experiment, it was concluded that this epoxy resin has high fracture toughness, it can be used as an abrasion-resistance material in hydraulic structures, and it can be used as the material for concrete cover. Wei-cai and Ju-tao [33] studied the mechanical strength and impact strength of epoxy mortar with different doses of toughening agents and different sand-binder ratios. The results showed that epoxy resin with the sea island structure can improve the fracture toughness of epoxy mortar and abrasion resistance, while its tensile strength is positively related to the abrasion resistance.

1.2.2. Polyurea Materials. Polyurea elastomer technology is a new kind of solvent-free, pollution-free, green construction technique, developed to meet environmental protection needs. The polyurea materials have excellent abrasion

performance, permeability, and corrosion resistance [30, 34]. There are two main types of polyurea elastomer technologies, including sprayed polyurea and hand-scraped polyurea. The spray polyurea technology was developed by Texaco Chemical Corporation (USA) in the early 1990s. After this technology was applied in several engineering projects, such as the overflow of the Xin'anjiang Dam (China), it was found that the problem of adhesion between spraying polyurea and base surface had not been satisfactorily resolved [35]. The hand-scraped polyurea technology solves the problem of the rapid reaction of the polyurea components. Based on the field experiment results from the No. 2 desilting tunnels of the Xiaolangdi Water Conservancy Project (China), the hand-scraped polyurea technology showed excellent abrasion resistance. The polyurea elastomer technology has been successfully applied in abrasion protection work of many projects.

At present, additional hydraulic antiabrasion materials have been developed, and further studies of their performance are still needed.

- (1) There are many advantages of organic coating materials, such as lower cost, lower toxicity, and simpler construction, but there are many problems, such as poor adhesion to the base, low intensity and toughness, and poor abrasion resistance under high water flow velocities with solid particles. It is necessary to improve the toughness and adhesion performance, and then the organic coating materials will meet the requirements of anticavitation and abrasion resistance.
- (2) Organic abrasion-resistant materials, such as epoxy resin mortar (concrete) and epoxy mastic (paint), have improved mechanical properties. However, due to the increased cost, complexity, low efficiency in construction, and poor compatibility with the existing concrete, organic abrasion-resistant materials are still only applied in thin layers on construction repairs.

Through this experimental study of epoxy abrasion-resistant materials, a long-term, flexible, reliable, protective layer was developed, which can be applied in concrete repairs and dam construction to resolve cavitation and abrasion problems.

2. Materials and Methods

2.1. Mechanism of Material Synthesis. Through the interpenetrating network technology (IPN) and the molecular design process (such as the molecular synthesis process or molecular grafting process), the toughness of the epoxy material can be improved by connecting suitable flexible chain segments directly to the epoxy molecule. This method is usually achieved by inserting a flexible segment between epoxy resins or its hardener molecules. It is necessary to choose the appropriate polyurethane flexible chain segment, which allows the polyurethane-modified epoxy to achieve a balance between rigidity and elasticity, which improves the structure for abrasion resistance. The chemical reaction is shown in Figure 1.

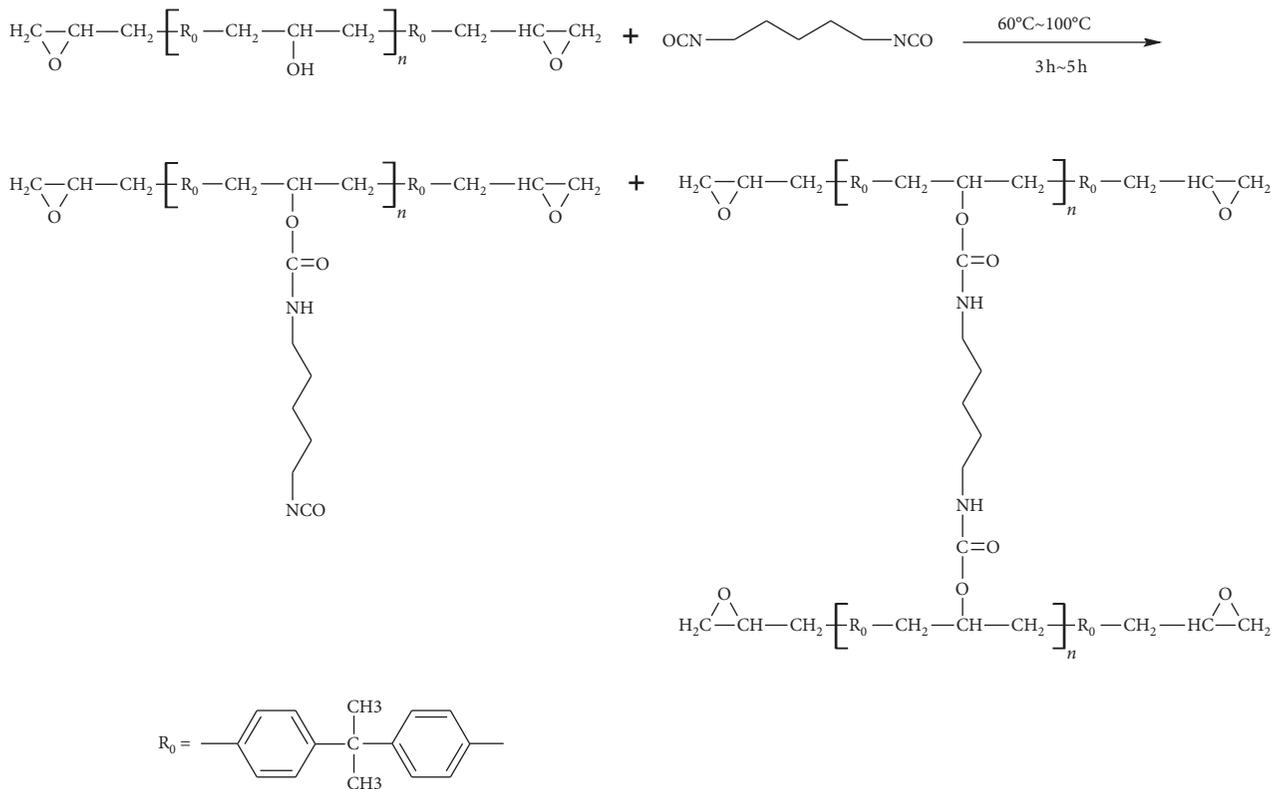


FIGURE 1: Principle of the chemical reaction.

2.2. Raw Materials of the Sample and Synthesis Process.

The raw materials include the epoxy resin, polyether polyol, and 4, 4'-diphenylmethane diisocyanate (MDI), as shown in the above chemical reaction. The epoxy resin adopts bisphenol A epoxy resin and diphenol-propane epoxy resin. The low relative molecular mass of the liquid epoxy resins is cured due to the effect of the epoxy group. With the increase of the relative molecular mass of the epoxy resin, the effect of the epoxy group is decreased, and the effect of the hydroxyl group is increased. If the relative molecular mass of the bisphenol A epoxy resin is high enough, a tough film can be formed without using any oxygen resin-curing agents. The epoxy resin used in this sample was CYD-128, and its epoxy is 0.51. The polyether polyol is a type of oligomer, which has a main chain containing an ether bond (-R-O-R-), and its end or side group contains more than two hydroxyl (-OH) groups. Given the low-molecular weight polyols, multiple amine, or compounds containing active hydrogen as starting agents and given the oxyalkylene as a catalyst, the polyether polyol is formed by ring-opening polymerization. The oxyalkylene is mainly composed of propylene oxide and ethylene oxide, with propylene oxide being most important. The polyol starting agent is mainly composed of the glycols (propylene glycol and ethylene glycol), a ternary alcohol (glycerin trimethylolpropane), and the polyols (pentaerythritol, four alcohols, xylitol, sorbitol, and sucrose). The amine starting agent is mainly composed of diethylamine and ethylene triamine. This sample adopts the MR-220 polyether polyol and MDI-50, which is the most important raw material for producing polyurethane.

The elastic epoxy synthesis test was divided into Component A synthesis and Component B screening. The procedure for Component A synthesis was the following: the epoxy resin, the polyether alcohol, and the MDI in proportion were placed in 3 flasks, the condensed water was piped in, the contents were mixed until the temperature reached 40°C, and the temperature was maintained at 60°C to 100°C for 3 h to 5 h. Component A was obtained after cooling. The selection of Component B was based on its acceptable toughness as a curing agent from among the following malleable compounds: polyamide, polyether amine, fatty amine, alicyclic amine, and phenolic amine. The screening tests of Component A and Component B were then carried out.

2.3. Preliminary Determination of Polyurethane-Modified Elastic Epoxy Performance. Based on the above raw material (3.2), the tensile test was carried out to analyze the performance of the different compositions of the components. According to the China standard GB/T 1040-2006, the tensile speed of the test is 50 mm/min. The test results are shown in Tables 1 and 2.

2.4. Determination of Material Formulation. According to the test results shown in Table 1, when the polyether amine D400 was chosen as Component B, the elongation of the material at 18 days can reach 77%. The tensile strength of this material is too low at only 2.1 MPa at 18 days. Thus, this material is extremely soft and flexible. When polyether

TABLE 1: Performance of different polyurethane-modified elastic epoxy.

No.	Component A (g)	Component B (g)	Component B dosage (g)	Diluter (g)	Promoter A/B (g)	Age (d)	Tensile strength (MPa)	Elongation
1	100	Polyether amine D400	60	0	2/4	18	2.1	77%
2	100	Polyamide	47	15	2.35/0	7	25.6	8%
3	100	Alicyclic amine	30	15	0/0	7	24.4	7%
4	100	Polyether amine D230	34	0	1.7/0	/	Failed	Failed
5	59	Phenolic aldehyde amine	31.21	0	0/0	5 36	24.8 21.2	5.5 6.7

TABLE 2: Performance of polyurethane-modified elastic epoxy.

No.	Component A (g)	Component B	Component B dosage (g)	Diluter (g)	Age (d)	Tensile strength (MPa)	Elongation
1	100	Polyether amine D400	23	0	9	22.9	14~21%
		Alicyclic amine TE80	15		51	16.3	14~20%
2	100	Polyether amine D400	29	0	9	18.3	21~26%
		Alicyclic amine TE80	14				
3	100	Polyether amine D400	35	0	9	14.1	31~37%
		Alicyclic amine TE80	13				

amine D230 is chosen, it was too hard to dismantle the mold, and thus, this material cannot meet the requirements. When polyamide and lipids were tested, the tensile strength of the material greatly increased. However, due to their unsatisfactory extension rates, both are considered to be rigid materials. Therefore, to achieve a balance between toughness and rigidity, the combination of rigid materials and flexible materials should be considered. According to the results in Table 1, the D400 polyether amine should be chosen when a flexible material is required, and when a rigid material is required, less alicyclic amine and no accelerator are needed; thus, alicyclic amine should be chosen.

Based on the results in Table 1, polyether amine D400 and alicyclic amine TE80 were chosen for the composition of Component B. After multiple tests, whose results are showed in Table 2, it was confirmed that the optimum proportion of the elastic epoxy resin was Component A: 100 g, Component B: 29 g polyether amine, and 14 g alicyclic amine. In these proportions, that is, Component A to Component B is being 7 : 3, and the material reached a balance between strength and toughness. The tensile strength was greater than 15 MPa, and the extension rate was greater than 20% for this composition.

2.5. Adhesion and Tensile Performance Test of Elastic Epoxy Materials. The elastic epoxy material was made into a standard dumbbell specimen, with each end measuring 12 mm * 12 mm and the center 5 mm in width, with the overall length of 50 mm. The specimen was then tested for tensile strength performance. The tensile stress-strain curve of the elastic epoxy is shown in Figure 2, where X is the strain (%) and Y is the stress (MPa).

The tensile stress-strain curve is a basic graph of the mechanical behavior of materials. As shown in Figure 2, the elastic epoxy tensile stress-strain curve is the uniform yield type. When the stress reached 18.1 MPa, there was an obvious physical yield point, and after the point, the stress

dropped and the stress plateaued. The curve showed that, under a sustained load, the material showed no obvious elastic-plastic deformation, absorbing part of the mechanical energy to thermal energy. According to the results above, the elastic epoxy resin absorbed mechanical energy well.

2.6. Sensitivity Analysis of Elastic Epoxy Materials

2.6.1. Effect of Curing Conditions. According to the results shown in Table 2, the optimum ratio for the elastic epoxy resin was epoxy Component A to Component B (A : B) at 7 : 3 (quality ratio). For an elastic epoxy, the tensile properties are the most sensitive indicators of quality. To study the change in sample performance with age, the tensile property tests of the elastic epoxy materials contained 7 sets of samples, with ages from 1 to 90 days and curing temperatures of $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$. The results are shown in Figure 3.

As shown in Figure 3, after 3 days of curing, the tensile properties of the elastic epoxy materials were stable. In consideration of complex actual working conditions and variability, the curing age should be more than 7 days.

2.6.2. Effect of Component A : B Ratio. Although the theoretical formula ratio of elastic epoxy materials of A : B is 7 : 3 (mass ratio), there may be some errors in weighing. In practical engineering applications, the problem is more likely. Therefore, the changes in the properties of elastic epoxy materials when the ratio of A and B deviated from theoretical values were tested and analyzed. The results of the tensile properties test are shown in Figure 4.

As shown in Figure 4, the ratio of elastic epoxy materials had a great impact on the tensile properties. When A : B = 7 : (2.7~3.3), the index requirements are met (tensile strength greater than 12 MPa and breaking elongation greater than 20%). Thus, in actual construction, when the ratio of

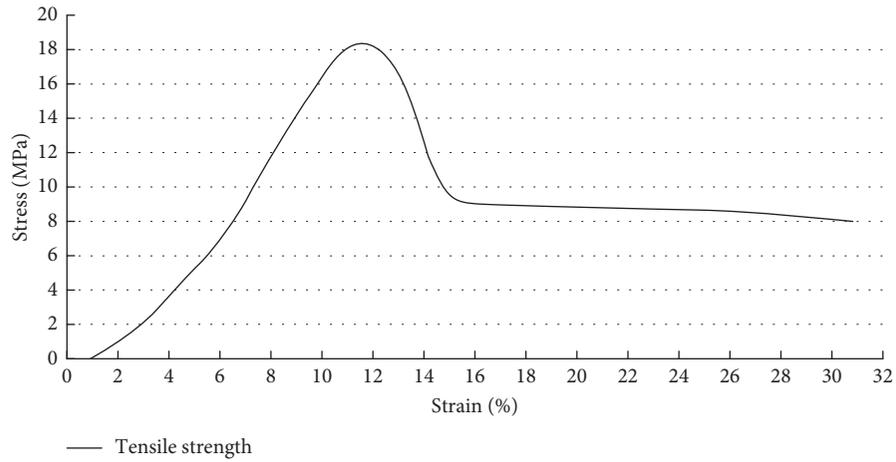


FIGURE 2: Tensile stress-strain curve of the elastic epoxy.

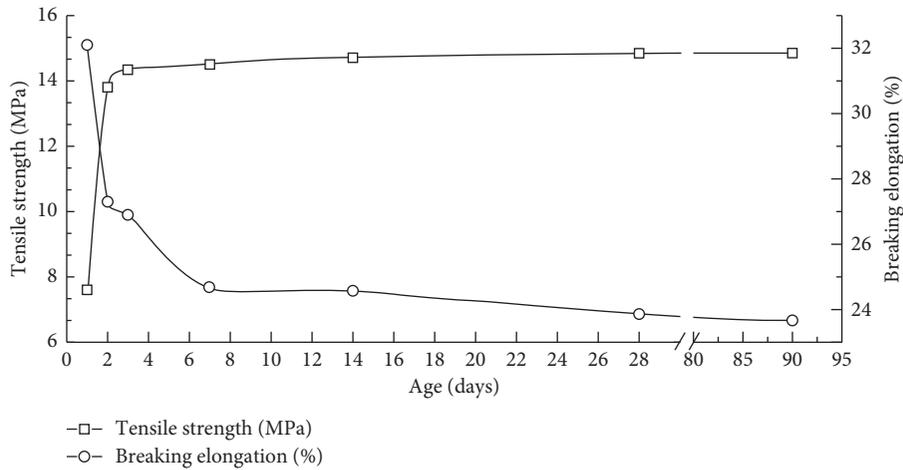


FIGURE 3: Influence of curing time on elastic epoxy material's tensile properties with the A/B ratio 7:3.

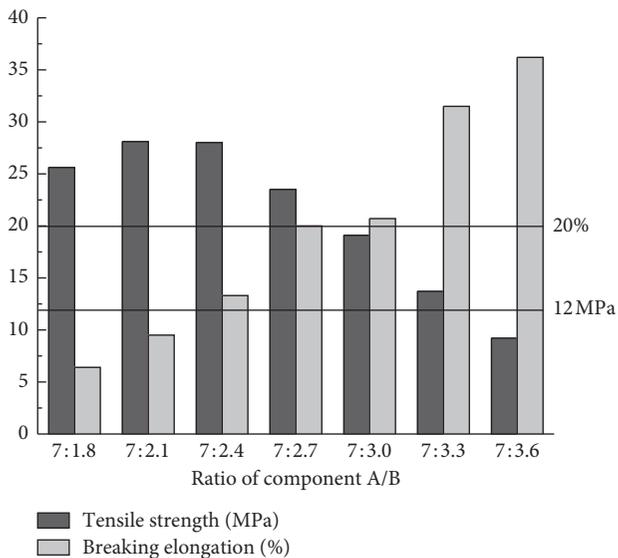


FIGURE 4: Proportioning effect of Component A:B ratio on material's tensile properties after 28 day's curing.

Component A/B is 7:3, the maximum allowable deviation of Component B is plus or minus 10% deviation.

2.6.3. Effect of Diluent. Due to the high viscosity of the epoxy resin, its operability is poor when applied without a diluent. Although the addition of inactive diluents is beneficial, there are disadvantages, such as volatility, unpleasant odors, environmental impacts, inflammability, explosiveness, and safety issues. In addition, the inactive diluents do not participate in the epoxy curing reaction, so products will continue to be volatile after curing, which causes shrinkage and cracking. Thus, reactive diluents were chosen for this test. Active diluents containing epoxide active groups can participate in the curing reaction with the epoxy resin. According to the number of diluent molecules in the epoxy groups, they are divided into monofunctional diluents, bi-functional diluents, and polyfunctional diluents. Benzyl glycidyl ether (692) was chosen as a monofunctional diluent due to its low-molecular weight, excellent dilution effect, and low odor production. Butanedioldiglycidyl ether (622)

was chosen as a bifunctional diluent due to its low-molecular weight and because it had the best dilution effect of the bifunctional diluents. No polyfunctional diluent was chosen in this experiment due to nonideal dilution effects. The effects of different diluents on tensile properties of materials are shown in Figure 5.

As shown in Figure 5, by adopting butanedioldiglycidyl ether (622), both ends of the molecular chain of the bifunctional diluent participated in the curing reaction. Thus, the influence of the tensile strength on the properties of epoxy resin is less than monofunctional diluent, and subsequent experiments mainly adopted the bifunctional diluent (622).

Using a spray test, the effects of different amounts of diluent (622) on the performance of the elastic epoxy materials are shown in Table 3.

As shown in Figure 6, excessive diluent degraded the performance of the elastic epoxy materials. After 10 times of diluent (622) were added, the elastic epoxy materials were able to be sprayed, and its performance met the requirements.

2.6.4. Effect of Pigments and Fillers. The elastic epoxy is an amber transparent liquid material, which has no capacity to cover the color of the base and easily flows, so that it is difficult to achieve the required thickness. Therefore, the influence of pigments, fillers, and thixotropic agents on the performance of the elastic epoxy was examined. The tensile test was conducted after the elastic epoxy materials (the elastic epoxy mixture of A:B=7:3) were mixed with the pigments and fillers. The results of the samples mixed with pigments and fillers are shown in Table 4.

As shown in Table 4, after the pigments, fillers, and thixotropic agents were mixed, the breaking elongation of the elastic epoxy material was less than 20%. In addition, the greater the amount of the pigments, fillers, and thixotropic agents, the less the breaking elongation. This outcome occurred due to the addition of defects in the pigments and fillers, which caused concentrated stress and prevented elongation. On the contrary, after adding the pigments, fillers, and thixotropic agents, the elastic epoxy materials turned from a pure resin into a type of gray paint with thixotropy so that it was not easily self-leveling when casting the specimens and contained many bubbles. The tensile strength and breaking elongation performance of sample no. 4 (material ratio 81.1:13.7:5.2) were acceptable.

2.7. Summary of Properties of Flexible Epoxy Coating. After the elastic epoxy coating was industrially produced by applying the methods above, the performance indices of the elastic epoxy coatings were measured and are shown in Table 5.

Based on the results above, along with the premise that the elastic epoxy coating met tensile strength and tensile elongation requirements, the elastic epoxy coating's abrasion resistance under different conditions was studied below to verify its reliability.

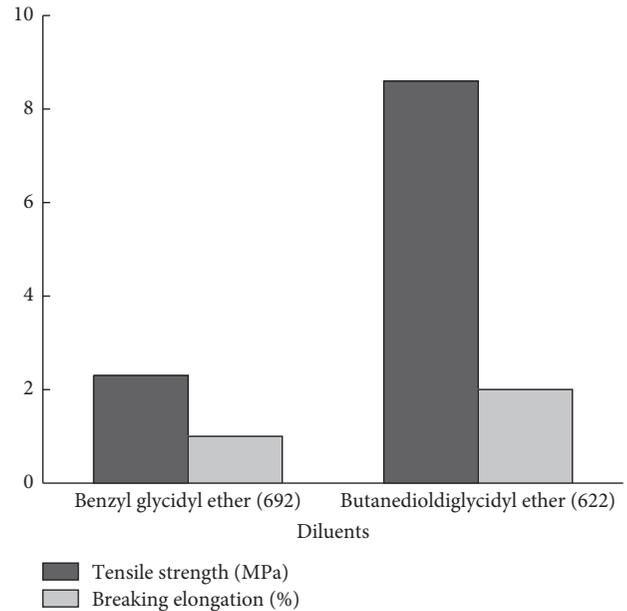


FIGURE 5: Effect of different diluents on tensile properties.

TABLE 3: Effect of different ratios of Component A/diluent on tensile properties after 7 days.

Experiment no.	A	622	B	A/622
1	95	5	45	95:5
2	90	10	47	90:10
3	85	15	49	85:15
4	83	17	50	83:17

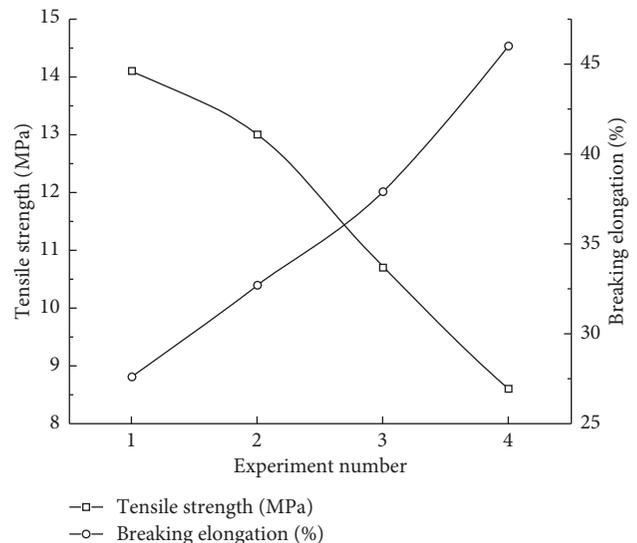


FIGURE 6: Effect of different ratios of Component A/diluent on tensile properties after 7 days.

3. Experimental Study

3.1. Pull-Out Test on Wet Surface. After soaking C20 concrete specimens of 150 mm * 150 mm * 150 mm in water for 24 hours, the water was wiped, and the specimens were

TABLE 4: Test of samples mixing with pigments and fillers after curing for 7 days.

Sample	Elastic epoxy	Pigments and fillers	Thixotropic agent	Tensile strength (MPa)	Breaking elongation (%)
1	64.5	28.7	6.8	13.7	4.6
2	66.5	29.6	3.9	14.2	6.4
3	70.0	29.0	1.0	11.9	7.4
4	81.1	13.7	5.2	16.3	10.5
5	85.1	13.7	1.2	11.2	16.3
6	90.0	8.5	1.5	12.5	16.9

TABLE 5: Properties of flexible epoxy coating.

Items	Indexes	Measured value
Appearance	Component A	Gray paste body
	Component B	Amber sticky liquid
Solid content	100%	100%
Surface drying time (h)	≤8	2
Compressive strength (MPa)	≥40	55.8
Tensile strength (MPa)	≥12	16.3
Bond strength (MPa)	≥4 (or mortar destruction)	5.99
Tensile ductility (%)	≥10%	12.0

coated with the elastic epoxy material. After the specimens were cured under standard conditions for 3 days, the concrete specimens were tested in the high and low temperature tensile tester at -10°C, 25°C, and 50°C. Results of the pull-out test are shown in Figure 7, and a sketch of the test is shown in Figure 8. A picture of the testing block after pulling is shown in Figure 9.

As shown in the results of pull-out testing, the damage occurred within the concrete, and there was no destruction of the bonding surface between the epoxy resin and the concrete. This outcome proves that, under different temperatures, the adhesive force of the elastic epoxy and the concrete was greater than the strength of the concrete itself.

3.2. Underwater Steel Ball Test. The HKS-II concrete anti-scouring machine was applied in the underwater steel ball test, as shown in Figure 10, with a maximum rotation speed of 1250 r/min. The abrasion-resistance performance of concrete was measured by the abrasion on the concrete surface caused by a certain size, the number of steel balls in a specified time, and the speed of the steel balls.

The steel balls in the water in the steel container were provided kinetic energy by the stirrer and were used as the abrasive material to impact and wear the specimen at the bottom to simulate the grinding process. The quality loss of the specimen was determined after a certain time period of grinding, and the abrasion-resistance strength was calculated by Equation (1). The wearing strength is characterized by the time consumed per unit mass per unit area:

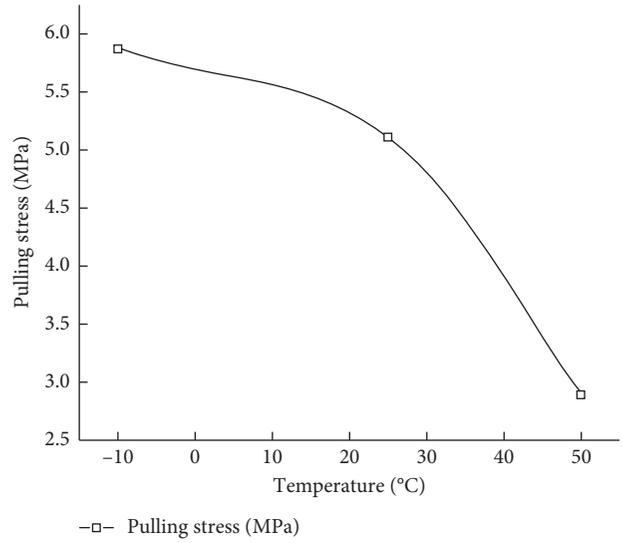


FIGURE 7: Pull-out test at different environmental temperatures. All interface destructions of specimens were 100% concrete failure.

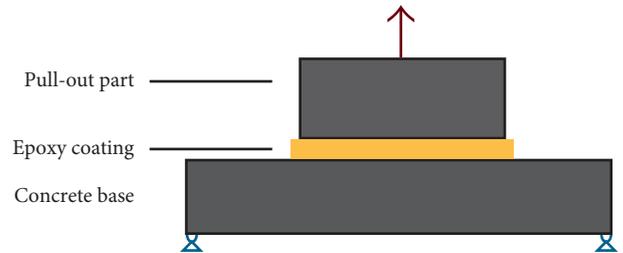


FIGURE 8: Sketch of the pull-out test.



(1) Bonding surface
(2) Concrete fracture surface

FIGURE 9: The bonding surface remained intact, and the concrete was cracked.

$$f_a = \frac{AT}{\Delta M}, \tag{1}$$

where f_a is the abrasion-resistance strength, A is the wearing area, T is the wearing time, and ΔM is the the lost mass after massing.

Comparison tests were conducted on C60 concrete, elastic epoxy coating, and silicon powder concrete using the steel ball method, and the surface after grinding of each

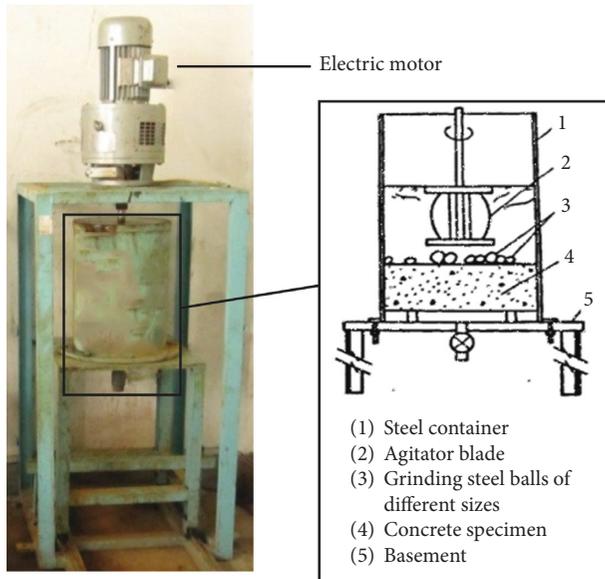


FIGURE 10: Underwater steel ball mill test apparatus.

material was recorded to compare their grinding performance. Test results of the abrasion resistance of each material are shown in Table 6 and Figure 11.

Through the underwater steel ball grinding tests, we know that ordinary concrete is brittle and hard. However, with fiber, silicon powder and polymer latex were added, the grinding resistance of silica-formed concrete improved up to several times, and the abrasion resistance of the concrete with elastic epoxy coating increased by tens times, which has been shown in Figure 11, due to the elastic epoxy coating which absorbed the impact mechanical energy. After grinding, the elastic epoxy coating was still smooth, and compared with the rough surface of concrete after grinding, it was more resistant to the abrasion. It must be noted that the underwater steel ball test is a simulation of the impact damage by the bed load, but it cannot represent the anti-abrasion performance in rivers with sediment and bed load.

3.3. Ring Test. The underwater steel ball test confirmed the antiabrasion performance of the elastic epoxy coating, and the ring test was applied to confirm the antiabrasion performance of the testing material in high-speed flow, as well as in silt-carrying flow. The abrasion-resistance performance testing machine used in this test, as shown in Figure 12, was developed based on the machine for the ring test of abrasion-resistance performance in SL352-2006 (Hydraulic Concrete Test Regulations).

To simulate material grinding in the sediment laden flow, sandy soil was used as an abrasive material and kinetic energy was supplied by the power in the grinding system ring test. By adjusting the motor speed and the amount of sand, the surface of the specimen was ground under a certain angle of impact and velocity of sand. The loss of mass was determined after a period of time, and the wearing strength or wear rate (the loss of mass per unit area per unit time) was calculated. By calculating these two parameters, the materials

TABLE 6: Material abrasion-resistance test results summary.

Specimen	72 h abrasion loss (g)	Wear rate (%)	Surface	Average wearing strength (kg/m ² /h)
C60 concrete	1489	9.66	Roughness	221×10^{-3}
Silicon powder polypropylene fiber C60 concrete	946.1	5.57	Roughness	184.1×10^{-3}
Elastic epoxy coating	30.0	0.20	Smooth	6.19×10^{-3}
Elastic epoxy coating (coat multiple times)	14.1	0.07	Smooth	1.93×10^{-3}

were evaluated for antiabrasion performance. Wearing strength and wearing rate are calculated by

$$f_a = \frac{AT}{\Delta M}, \quad (2)$$

$$L = \frac{\Delta M}{AT},$$

where f_a is the wearing resistance strength, L is the wearing rate, A is the wearing area of the specimen, T is the wearing time, and ΔM is the lost mass after wearing.

According to the hydraulic concrete test procedures (SL 352-2006), the abrasion-resistance performance of elastic epoxy coating should be tested in three wearing conditions (under pressure at 20 m/s, under pressure at 15 m/s, and no pressure at 40 m/s). The test results are shown in Figure 13.

The ring test results showed that when the free flow has a velocity of 40 m/s, the wearing strength of the elastic epoxy coating reached more than 100 h/(g/cm²). Under 15 m/s of pressure flow, the wearing strength of elastic epoxy coating reduced sharply, by approximately 50%. Under 20 m/s of pressure flow, the wearing strength further declined, being 50% lower than the previous measurement. Therefore, the increasing velocity of the silt-laden flow significantly affected the abrasion-resistance performance of the elastic epoxy coating, but in a comprehensive way, elastic epoxy coating can still be applied as protection under high-speed silt-laden flow.

4. Discussion and Conclusions

4.1. Future Application Prospects of Elastic Epoxy Improvement Products. Through research and development, the elastic epoxy resin has demonstrated improved toughness. In addition to being used as a flexible protective coating, elastic epoxy resin can be combined with other materials and can also be used as an epoxy base fluid to produce improved performance of "epoxy +" materials.

4.1.1. The Elastic Epoxy Mortar. The elastic epoxy mortar was composed of the elastic epoxy materials and powder, thixotropic agents, quartz sand, and C component containing a lightweight filler. The mortar's characteristics were low density, compressive strength similar to C30 concrete, low elastic

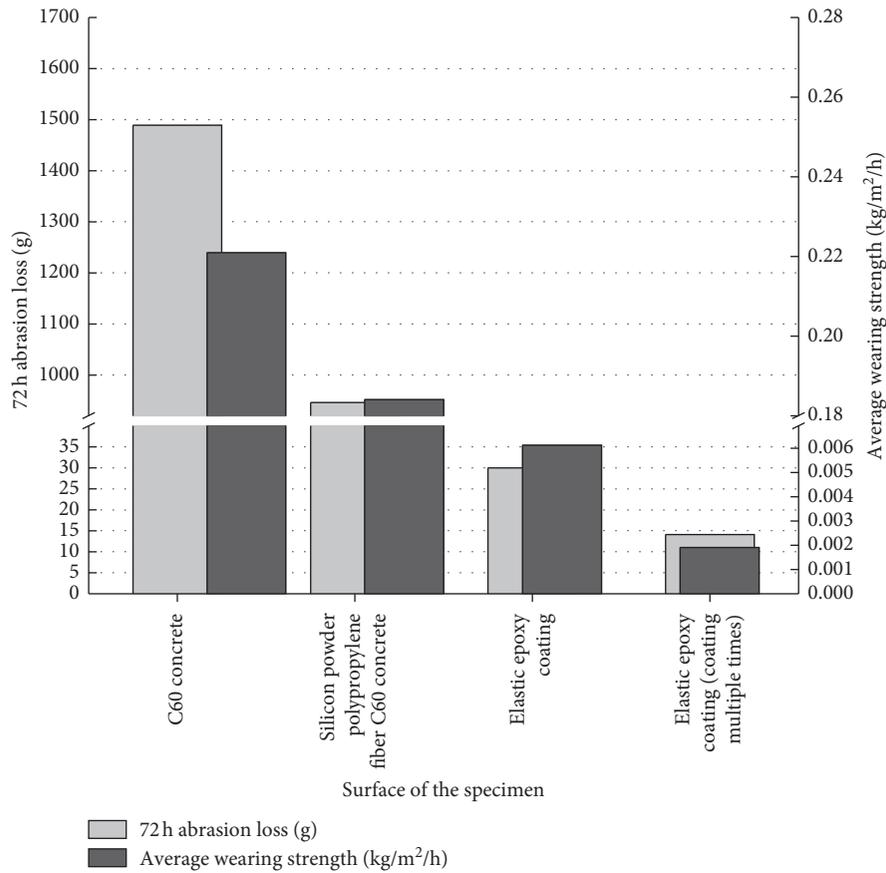


FIGURE 11: Average wearing strength and 72 h abrasion loss of the specimens.

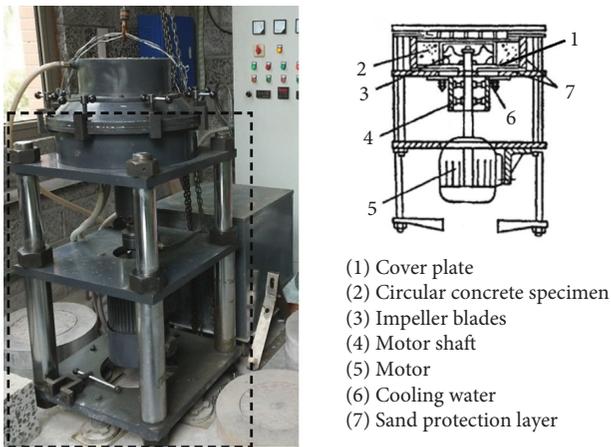


FIGURE 12: Abrasion-resistance apparatus.

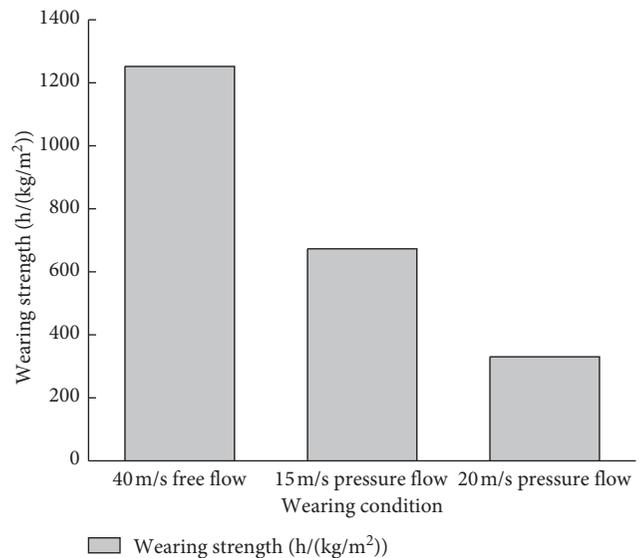


FIGURE 13: Abrasion-resistance performance of elastic epoxy coating under different conditions.

modulus, and excellent malleability. The elastic epoxy mortar can be applied to repair facades or top surfaces without using a mold, and the construction thickness can be greater than 8 cm.

The elastic epoxy material can also be used as a liquid, and when mixed with dry, common Portland cement and dry sand in appropriate proportions for tough mortar, it can be applied to repair the holes of old concrete to achieve matching and durability.

4.1.2. *Elastic Epoxy Concrete.* Elastic epoxy concrete is prepared by mixing elastic epoxy materials, dry common Portland cement, sand, and gravel in certain proportions. This concrete has excellent self-leveling and

self-compaction characteristics, as well as good toughness after solidification. It can be applied to repair large concrete pit holes and has better matching and durability compared with ordinary polymer concrete.

4.2. Conclusions. In this study, the elastic epoxy material (elastic epoxy resin) was synthesized by applying the method of polyurethane-modified bisphenol A epoxy resin, which has an elongation rate of over 20%, and a tensile strength close to polyurea. This synthesis is a breakthrough over traditional epoxy toughening. Based on the elastic epoxy material, after several adjustments of color, thixotropy, and aggregate gradation, an elastic epoxy coating material that can be directly used in the form of spraying or coating has been developed, and it can be used as a permanent protection layer attached to the protected surface of concrete in order to resist abrasion. The detailed conclusions are as follows:

- (1) After many mixing experiments, the ratio of Component B, composed of polyether amine and the alicyclic amine compound in the proportion of 29:14, and Component A at the ratio A:B=7:3 was determined to be optimal. In the ratio mentioned above, polyurethane-modified epoxy resin synthesized by the IPN technology achieved a tensile strength greater than 15 MPa and the elongation rate greater than 20% so that it achieved the balance of strength and toughness.
- (2) Through the experiments, it was seen that the performance of the elastic epoxy was stable after 3 days of curing, but since the conditions in the actual application are changeable, the curing age should be over seven days. The optimum ratio of the two components of A to B was 7:3, but in engineering practice, a 10% error in the amount of Component B is allowed. The diluent of elastic epoxy materials should be the bifunctional butanedioldiglycidyl ether (622).
- (3) The underwater steel ball grinding experiment showed that the elastic epoxy coating had good antiabrasion performance, an improvement of almost a hundred times over the performance of normal concrete. The surface was still smooth after grinding, which indicated its effectiveness in protection against abrasion. The ring test results showed that when free flow had a velocity of 40 m/s, the wearing strength of the elastic epoxy coating reached 100 h/(g/cm²), but under the condition of pressure flow, the wearing strength was greatly reduced. For example, under 15 m/s of pressure flow, the wearing strength of elastic epoxy coating dropped to approximately 50% but can still be applied as the abrasion-resistant material in high speed flow carrying silt.
- (4) Considering that the epoxy resin material can act as an epoxy base fluid with greater toughness, it is possible to produce a better performance of “epoxy +” materials after being combined with other materials. The performance of this material needs further research.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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