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Jiapeng Li
Chang'an University

Xiao Huan
Chang'an University

Shubing Wang
Gaode Highway Construction (Dezhou) Co. Ltd

Yanping Sheng
Chang'an University

Dahui Xu
Gaode Highway Construction (Dezhou) Co. Ltd

See next page for additional authors

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Performance of optimized composition of epoxy resin adhesive used in High Friction Surface Treatment

Jiapeng Li [a], Xiao Huan [a], Shubing Wang [b], Yanping Sheng [a,c,*], Dahui Xu [b], Zhanping You [c]

[a] School of Material Science and Engineering, Chang'an University, Xi'an 710064, China
[b] Gaode Highway Construction (Dezhou) Co. Ltd, Dezhou, China
[c] Department of Civil, Environmental, and Geospatial Engineering, Michigan Technological University, Houghton, MI 49931,United States

A R T I C L E I N F O

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A B S T R A C T

The High Friction Surface Treatment (HFST) paving technique is widely employed in engineering practices globally, serving to enhance the long-term anti-skid performance of pavements. However, there still exist significant gaps in research regarding the modified and optimized composition and corresponding content of the polymer binding materials used in HFST, as well as the performance of the pavements laid with modified and optimized blended aggregates during service. To address these issues, this research first modified and optimized the composition ratio of traditional epoxy resin materials. Subsequently, a toughened, high-flow epoxy bonding system suitable for the maintenance of concrete pavements was prepared. Additionally, the study explored the bonding performance of this system with both the cement base surface and aggregates. The results established that the optimal ratio range for the modified epoxy adhesive system is E51 epoxy resin to curing agent to toughening agent to diluent in the proportions of 100: 30–35: 20–30: 5. The experimental group used a high-flow epoxy resin adhesive ratio of E51 epoxy resin: curing agent: toughener: diluent = 100:30:20:5. For control group 1, the ratio of epoxy resin adhesive was E51 epoxy resin: curing agent = 100:30, and for control group 2, the ratio was E44 epoxy resin: curing agent = 1:1. Compared with control groups 1 and 2, the modified epoxy system with the cement base demonstrated a 149 % increase in average pull-off strength and an 18 % increase in average shear strength. Similarly, in comparison with control groups 1 and 2, the modified epoxy system with aggregates exhibited a 174 % increase in average pull-off strength and a 541 % increase in average shear strength. Based on the pull-off and shear test results, it was ultimately determined that the dosage of modified epoxy binder for HFST mixtures should be controlled at 1.0–1.2 kg/m^2, and the dosage of aggregate should be controlled at 3.3–4.3 kg/m^2. These findings provide valuable insights into optimizing HFST pavement compositions for improved performance and longevity.

1. Introduction

Currently, road traffic safety is a common challenge faced by countries worldwide [1,2]. One crucial reason for the frequent

* Corresponding author at: School of Material Science and Engineering, Chang'an University, Xi'an 710064, China.
E-mail address: syp@chd.edu.cn (Y. Sheng).

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occurrence of traffic accidents is the inadequate friction between tires and road surfaces [3,4]. The high traffic capacity and wheel loads, particularly of heavy vehicles, hasten the polishing and wear of the road surface aggregates, leading to a rapid decline in skid resistance and exacerbating traffic safety issues. Pavement skid resistance is a vital technical aspect for ensuring road safety and comfort and facilitating high-speed travel [5–7].

Cement concrete paving encompasses airport runways, port surfaces, and roadways, constituting one of the major pavement styles in China. As of 2020, the total length of cement concrete pavements worldwide was approximately 3.098 million kilometers, and in China, expressways contribute over 3000 kilometers to this total [8]. However, a reduction in the skid resistance of cement concrete pavements gives rise to various issues. The anti-skid structure wears out, and the friction coefficient persistently drops. This leads to a severe decline or complete loss in pavement performance far earlier than its intended lifespan. Such degradation not only impacts driving comfort but also compromises safety, necessitating prompt maintenance.

The general approach for improving the skid resistance of concrete pavements involves applying a wearing layer [9,10]. Common methods include applying polymer-modified cement mortar skid-resistant layers, SMA (Stone Mastic Asphalt) pavements, ultra-thin asphalt wearing courses, and High Friction Surface Treatment (HFST). HFST paving technology, known for its superior wear and skid resistance, high bonding strength, good water stability, unrestricted construction temperature, and rapid traffic reopening capability, has been researched and implemented in numerous countries globally [11–14]. HFST is particularly effective in enhancing skid resistance on road sections with high anti-skid requirements, including long steep gradients, bridge decks, tunnel approaches, and snow-prone areas [15,16]. The paving sequence of HFST maintenance technology involves several key steps. First, a layer of polymer adhesive material is applied, followed by the spreading of aggregate before the adhesive material sets. Subsequently, compaction is performed using compaction equipment. After allowing the adhesive material to cure, any loose, unbound aggregate is removed, and the road can be opened for traffic. A structural diagram of HFST is shown in Fig. 1.

The primary binder material for HFST paving is epoxy resin. However, studies have shown that in practical HFST projects, existing epoxy resin's poor workability leads to problems like aggregate flaking, bond failure, and delamination during its service life [17]. Additionally, old cement concrete pavements, situated in open natural environments and possibly afflicted with cracks [18], necessitate the modification of epoxy binders used in HFST. This modification aims to achieve suitable workability, bonding performance, weather resistance, and permeability, fulfilling the needs for the upkeep and repair of concrete pavements.

A wide range of scholars around the globe have delved into enhancing and refining the properties of epoxy resin adhesives by examining their natural attributes and addressing common concerns. Wang et al. [19] devised an innovative "rigid-flexible" interlayer aimed at concurrently boosting the interface's durability and resilience in carbon fiber/epoxy resin composites. Their research demonstrated that this unique approach to toughening the carbon fiber/epoxy resin boundary facilitated an even application of MWCNT and TPU across the carbon fiber surface. Relative to a baseline group, this adjustment led to a 163.3 % and 52.8 % uptick in shear strength and pull-off displacement at the carbon fiber/epoxy resin juncture, respectively, underscoring the beneficial impact of the "rigid-flexible" layer in fortifying the interface's robustness and flexibility. In a separate study, Wu et al. [20] explored how phenolphthalein polyarylether sulfone (PES-C) bolsters the toughness of E51/DETDA epoxy resin and its carbon fiber composite. SEM analysis revealed that blending PES-C with epoxy resin resulted in a bifurcated structure characterized by isolated regions. Incorporating 15 parts per hundred resin (phr) of PES-C led to notable enhancements in bending strength, impact resistance, and crack resistance of the composite, with increases of 41.1 %, 186.2 %, and 42.7 %, respectively. Moreover, integrating a PES-C film as a middle layer significantly elevated the Mode II fracture toughness (GIIC) of the carbon fiber composite. Specifically, the GIIC metric for composites toughened with a 7 μm PES-C film surged by 80.3 % in comparison with the baseline laminate.

Simultaneously, significant strides have been made in researching the toughening mechanisms and interlaminar enhancements of epoxy resins. Han et al. [21] developed carbon fiber-reinforced composites through the method of hot pressing layers of carbon fiber pre-pregs, incorporating graphene oxide (GO)-enhanced epoxy resin as the bonding matrix. Their findings indicated that adding 0.10 wt% GO into the epoxy resin resulted in a maximal interlaminar shear strength (ILSS) of 96.14 MPa for the laminates, marking an 8.05 % increase over laminates devoid of GO. This ILSS enhancement is ascribed to the toughened epoxy resin and better adhesion at the carbon fiber-epoxy matrix interface. In another study, Wu et al. [22] boosted the interlaminar fracture toughness of carbon

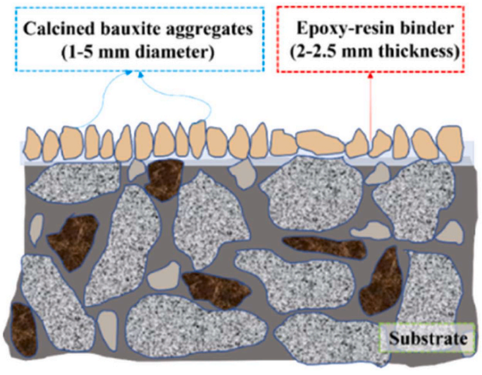


Fig. 1. Schematic diagram of HFST structure [16].

fiber-reinforced resin-based composites (CFRP) by integrating highly aligned carbon nanotube (CNT) fiber yarns within the interlayer zones. Adhering to ASTM standards, they assessed the Mode I and Mode II interlaminar fracture toughness of the enhanced samples. Through a combination of optical microscopy of cross-sections and scanning electron microscopy of fracture surfaces, they mapped the crack propagation pathways and elucidated the interlaminar toughening effect of CNT fiber yarns. Their results showcased a 37.4 % and 41.8 % increase in Mode I and Mode II interlaminar fracture toughness, respectively, in samples fortified with CNT fiber yarns.

Furthermore, research and application of epoxy resin in the field of anti-skid road surface coatings are gradually increasing. Chen et al. [23] employed alumina sand and water-based epoxy resin to develop a novel High Friction Surface Treatment (HFST). The research findings indicate that this low-cost HFST application exhibits performance comparable to or even superior to traditional HFST. Additionally, due to the finer aggregate used compared to traditional HFST, this novel HFST material resembles mortar, capable of filling small cracks on old road surfaces and delaying further crack propagation. Liu et al. [24] developed a cold-mix Ultra-Thin Anti-Skid Surface (UTASS) to enhance the skid resistance of Epoxy Asphalt Concrete (EAC) pavements. They evaluated the performance of four types of epoxy resin-based binders, selected the optimal binder type, and determined the UTASS preparation procedure. The results indicate that the texture depth of EAC-UTASS is nearly ten times greater than that of pavements constructed using EAC overlay structures. Additionally, EAC-UTASS exhibits outstanding resistance to high-temperature rutting, low-temperature cracking, and interlayer bonding stability. Chen [25] conducted research on waterborne epoxy resin modified emulsified asphalt and its fog seal layer performance. They found that the addition of waterborne epoxy resin significantly increased the high-temperature performance, low-temperature performance, and emulsion viscosity of modified emulsified asphalt. The dosage of waterborne epoxy resin curing agent and curing temperature are the main factors influencing the curing time of the fog seal layer. Waterborne epoxy resin fog seal layers outperform traditional fog seal layers in terms of wear resistance and skid resistance, and the fog seal layer material exhibits water dilution capability and better adhesion to coarse aggregates. Wei et al. [26] investigated the physical and mechanical properties of epoxy-alumina sand mortar used in HFST. The research findings indicate that the Coefficient of Thermal Expansion (CTE) of HFST epoxy-alumina sand mortar is significantly higher than that of Hot Mix Asphalt (HMA) and Portland Cement Concrete (PCC). Consistent results from fracture energy, tensile strength, and crack propagation rate (CPR) tests demonstrate that HFST epoxy-alumina sand mortar exhibits excellent crack resistance.

Although there has been extensive research on the modification and optimization of epoxy resin bonding materials, much of it has focused on studying the microstructure and mechanical properties of the modified materials. There has been relatively little research on the performance of modified epoxy resin bonding materials, especially regarding their bonding performance when used in High Friction Surface Treatment (HFST) to restore the skid resistance of concrete pavement substrates. Addressing the limitations of traditional epoxy resin modification optimization research, this research systematically conducted various experimental studies. First, through tensile performance tests, research was conducted on both traditional epoxy resin modification and composition optimization design. Based on the conclusions drawn from the research, a highly flowable toughened epoxy resin bonding material suitable for cement pavement maintenance was prepared according to the optimal ratio. Further research was conducted on the bonding performance between the high-flow epoxy resin binder and aggregates, as well as the cement substrate, through pull-off and shear tests. Finally, the dosage of modified epoxy bonding agent for HFST mixtures was determined. This study has theoretical and practical significance in promoting research on epoxy resin modification and improving the application of HFST in preventive maintenance of cement concrete pavement in China.

2. Materials and methods

2.1. Raw materials

2.1.1. Epoxy resin

Epoxy resin, a polymer prepolymer, is characterized by having at least two epoxide functional groups in its structure. The main chain is predominantly formed of aliphatic, alicyclic, or aromatic segments [27]. Among various epoxy resins, the most extensively produced and applied is the Bisphenol A type epoxy resin [28].

In this study, we employ the most frequently used Bisphenol A type epoxy resins, E44 and E51 [29–31], chosen for their common industrial usage and specific properties. The primary technical parameters of these resins are presented in Table 1.

2.1.2. Curing agent

Epoxy resin belongs to thermosetting resins and cannot cure naturally, making direct application difficult. When heated, it undergoes a chemical reaction, gradually solidifying into the desired shape. Once cured, it remains unaffected by temperature changes. However, achieving curing through heating is challenging in practical engineering applications, leading to increased construction costs and difficulty. Therefore, the curing agent is required in combination with epoxy resin to achieve curing at room temperature within a predetermined time. The active epoxy functional groups in epoxy resin react with the curing agent to form a cured product

Table 1
Technical specifications of Bisphenol A type E51 and E44 epoxy resins.

Category	Epoxy equivalent/(g mol^{-1})	Viscosity(25 ℃)/(mPa s)	Softening point/℃	Color/number
E51	184–195	10,000–16,000	12–20	≤ 1
E44	210–240	20,000–40,000	14–23	≤ 2

with a three-dimensional spatial network cross-linked structure.

The curing agent selected for E51 epoxy resin in this study was the modified amine curing agent (593B), which is an adduct of diethylene triamine and butyl glycidyl ether; the curing agent for E44 epoxy resin was the low-molecular-weight polyamide resin 650, which also has a toughening effect, with technical parameters shown in Table 2.

2.1.3. Toughening agent

After curing, epoxy resin and curing agent form a high crosslink density, but the cured system often exhibits drawbacks such as brittleness, low toughness, poor fatigue resistance, and impact resistance [32,33]. When used as a pavement bonding material, it is prone to cracking under traffic loads, leading to cracking at the interface of the adhesive layer. To address these shortcomings, it is necessary to toughen the curing system without compromising its other properties as a pavement bonding material. An effective method to toughen the epoxy resin matrix is to incorporate elastic rubber as a second-phase component [34].

In this experiment, the toughening agent used was hydroxyl-terminated polybutadiene liquid rubber (HTPB), with its technical parameters detailed in Table 3.

2.1.4. Diluent

Epoxy resin has a high viscosity at room temperature, and mixing it only with a curing agent and toughening agent makes it difficult to stir. Therefore, a diluent is needed to reduce the viscosity of the epoxy resin adhesive.The inclusion of a diluent containing epoxy groups in the epoxy resin bonding agent system can consume some of the curing agent, slowing down the curing process and providing ample working time. Additionally, the addition of the diluent facilitates mixing and application during construction. It enhances the penetrability of the epoxy bonding system, making it suitable for filling cracks in old pavement surfaces. Furthermore, it improves the system's wetting properties, thereby enhancing the bonding strength between the adhesive and the existing pavement.

We chose the active diluent glycidyl ether 12–14 alkyl (AGE) as the modified diluent for the epoxy system, and its technical indicators are presented in Table 4.

2.1.5. C30 cement concrete slabs

The experiment employed Grade 42.5 cement, with limestone crushed stone chosen as the coarse aggregate and river sand selected as the fine aggregate. The mix ratio was set to cement:water:sand:crushed stone = 3.8:1.85:6.48:11.98. This mixture was used to prepare C30 concrete. The concrete was cast into molds measuring 450 mm × 350 mm × 50 mm and into cubic molds with 100 mm sides. The surfaces were leveled and covered with plastic film. All concrete specimens were cured under standard conditions of 20 ± 2 ℃ and relative humidity ≥ 95 % for 28 days before demolding and then used as the concrete base for high friction surface treatment in subsequent experiments. The parameters of the limestone, 42.5 cement, and river sand used in the experiment are listed in Tables 5–7, respectively.

2.2. Experimental methods

2.2.1. Optimization of epoxy resin adhesive

2.2.1.1. Tensile test. The equipment used for the tensile performance test of the cured epoxy resin system in this experiment was the CMT5105 microcomputer-controlled electronic universal testing machine, as shown in Fig. 2. It measures tensile strength, elongation at break, and tensile modulus of elasticity. The viscosity testing equipment for the epoxy resin system was a Brookfield digital programmable viscometer, as shown in Fig. 3.

The specific test steps are as follows: The curing agent, toughening agent, and diluent were thoroughly mixed with 100 parts of epoxy resin in various blending ratios to form a mixture. The mixture was then allowed to stand until no bubbles were present. The thoroughly mixed liquid was poured into a sample container. The rotor model and speed were determined according to Appendix X1.1 in the 'ASTM D 2556-14 Standard Test Method for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties Using Rotational Viscometry' [35]. The viscometer's controlled temperature furnace was set to maintain the temperature at 23 ± 1 °C. According to the specifications for resin tensile tests in the 'Resin Casting Body Performance Test Methods' (GB/T 2567-2021) [36], tensile performance tests of the epoxy resin adhesive were conducted. Casting was carried out under conditions of room temperature between 15 °C and 30 °C, with a relative humidity not exceeding 75 %. The mixed adhesive liquid was poured into the mold groove along the pouring mouth, closely adhering to the edge of the mold. Once the mixture self-leveled, the excess protruding part was scraped off. The standard tensile specimen is shown in Fig. 4, and the actual tensile specimen is shown in Fig. 5.

At room temperature (25 ℃), the specimens were cured for 7 days after demolding. Tensile performance test data include tensile strength, fracture elongation, and tensile modulus of elasticity. Tensile strength and fracture elongation were directly obtained using a universal testing machine, while the tensile modulus of elasticity required the use of relevant specimens and test parameters,

Table 2
Technical parameters of two curing agents.

Category	Amine value/(mgKOH g^{-1})	Viscosity(25 ℃)/(mPa s)	relative density	Available time (25 ℃)/min
593B	550–700	70–150	0.985	30
650	200 ± 20	30,000–65,000	1.045	-

Table 3
Technical parameters of toughening agent.

Hydroxyl number/ (mmol g^{-1})	Peroxide Quality score/ %	Viscosity (40 ℃)/ (Pa s)	Molecular weight ($\times 10^3$) (POV) (GPC)	Solubility parameter/(cal/cm^3)^(1/2)
0.71–0.80	$\leq$ 0.05	$\leq$ 3.50	2.70–3.30	8.2

Table 4
Technical parameters of diluent.

Viscosity (25 ℃)/ (mPa s)	Epoxy value eq/ 100 g	Saponification of chlorine/%	Inorganic chlorine value/ (mg kg^{-1})	Moisture content/%	Solubility Parameter/(cal/ cm^3)^(1/2)
4–10	0.32–0.34	$\leq$ 0.15	$\leq$ 20	$\leq$ 0.1	8.3

Table 5
Performance parameters of limestone.

Performance	Unit	Technical requirements	Test results	Test methods
Apparent Relative Density	-	$\geq$ 2.60	2.635	AASHTO T84
Water Content/%	-	$\leq$ 0.2	0.001	AASHTO T255
Water Absorption Rate/%	-	$\leq$ 1.5	1.235	AASHTO T84
Los Angeles Abrasion Loss/%	-	$\leq$ 20	21.30	AASHTO T96
Polished Stone Value	-	$\geq$ 45	53	AASHTO T279
Impact Value	-	$\leq$ 20	23.25	AASHTO T96
Crushing Value/%	-	$\leq$ 26	23.79	T 0316
Alumina Content/%	-	$\geq$ 87	2.53	ASTM C25

Table 6
Performance parameters of 42.5 portland cement.

Performance	Unit	Technical requirements	Test results	Test methods
Fineness	%	$\leq$ 10	8	ASTM C204
Setting Time - Initial	min	$\geq$ 60	90	ASTM C191
Setting Time - Final	min	$\leq$ 600	480	ASTM C191
Compressive Strength - 3 days	MPa	$\geq$ 22	24	ASTM C109
Compressive Strength - 28 days	MPa	$\geq$ 42.5	45	ASTM C109
Flexural Strength - 28 days	MPa	$\geq$ 6.5	7	ASTM C348
Soundness	mm	$\leq$ 10	8	ASTM C151
Specific Gravity	-	3.15	3.14	ASTM C188

Table 7
Performance parameters of river sand.

Performance	Unit	Technical requirements	Test results	Test methods
Fineness Modulus	-	2.3–3.1	2.7	ASTM C136
Silt Content	%	$\leq$ 3.0	2.5	ASTM C117
Clay Lumps and Friable Particles	%	$\leq$ 1.0	0.8	ASTM C142
Specific Gravity	g/cm^3	$\geq$ 2.5	2.6	ASTM C128
Water Absorption	%	$\leq$ 2.0	1.8	ASTM C128
Moisture Content	%	$\leq$ 0.5	0.4	ASTM C566
Organic Impurities	-	Not darker than standard	Pass	ASTM C40

calculated using appropriate formulas. The standard resin tensile performance specimens are illustrated in Fig. 4. The specific experimental procedures are as follows: specimens were numbered, and the width and thickness of three locations within the gauge length (segment L_0 in Fig. 4) were measured, and the arithmetic mean was taken. Dumbbell-shaped specimens were clamped to align the central axis of the specimen with the centerline of the upper and lower fixtures. The tensile speed of the universal testing machine was set at 10 mm/min for uniform continuous loading until fracture occurred. Test data including tensile strength, fracture elongation, failure load, and maximum deformation were recorded and documented.

Tensile modulus of elasticity is calculated using Eq. (1):

$$E_t = \frac{L_0 \times \Delta p}{b \times h \times \Delta L} \tag{1}$$

Fig. 2. CMT5105 microcomputer-controlled electronic universal testing machine.

Fig. 3. Brookfield digital programmable viscometer.

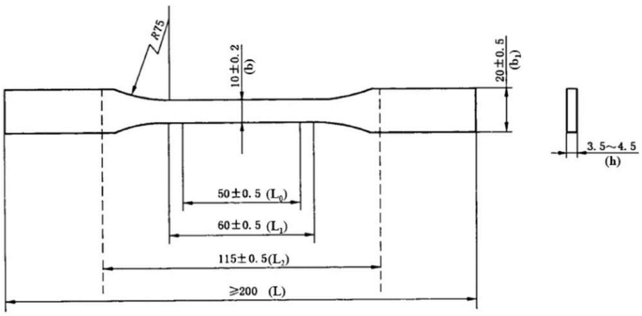


Fig. 4. Standard specimen of tensile test (Units of length: mm).

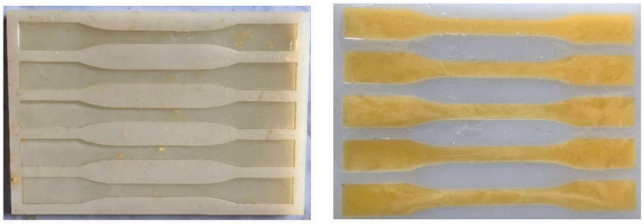

(a) E51 epoxy resin adhesive (b) E44 epoxy resin adhesive

Fig. 5. Actual specimen of tensile test.

where : E_t——Tensile modulus of elasticity, MPa;
Δp——Load increment in the initial segment of the load-deformation curve, N;
L_0——Gauge length, mm;
ΔL——Deformation increment within the gauge length corresponding to the load increment, mm;
b——Specimen width, mm;
h——Specimen thickness, mm.

2.2.1.2. Mixing ratios design. To determine the optimal dosage range of the curing agent, toughening agent, and diluent in the modified high-flow toughened epoxy resin adhesive system, the proportion design was carried out. Five parallel tensile specimens were prepared under each proportion for tensile performance tests. The proportion design is shown in Table 8.

2.2.1.3. Microscopic morphology. Based on the conclusion of the tensile test, the fracture surface of the dumbbell-shaped specimen fracture corresponding to the optimal amount of epoxy resin binder was tested by scanning electron microscope to observe the microscopic morphology of the fracture surface.

2.2.2. Performance of epoxy resin adhesive

2.2.2.1. Pull-off test. The thoroughly mixed epoxy adhesive was evenly applied to the test area on the surface of a 450 mm × 350 mm × 50 mm C30 cement concrete slab and the bonding head of the pull-off unit (that is spindle for pull-off test) using a scraper. The spindle was placed on the test area where the epoxy adhesive was applied and allowed to stand for 3 h to allow the adhesive to cure. The pull-off tester used in the experiment was the PosiTest AT-A fully automatic pull-off adhesion tester, as shown in Fig. 6. The dimensions of the spindle were 20 mm, with a measurement range of 0–20 MPa and a measurement accuracy of 0.01 MPa. During the experiment, the pull-off head sleeve was placed over the top of the spindle in the test area, securing the top of the spindle within the sleeve's snap-fit structure. A 20 mm cutter was used to cut the cured epoxy adhesive along the edge of the spindle, separating the adhesive in the pull-off area from the adhesive outside the pull-off area. The pull-off test was initiated using the pull-off tester until failure occurred, and the data displayed on the pull-off tester were recorded. The pull-off test procedure is illustrated in Fig. 7.

The pull-off test specimens are shown in Fig. 8.

2.2.2.2. Shear test. C30 cement concrete blocks with a molding side length of 100 mm were formed and cured for 28 days. The optimum dosage of epoxy adhesive determined from previous pull-off test results was uniformly applied to the test faces of two 100 mm cubic concrete blocks in each test group. These blocks were then bonded together to form a shear specimen and allowed to stand for 3 h. Shear tests were conducted using a universal testing machine, with one end of the shear specimen completely fixed while the pressure head of the universal testing machine applied force near the bonding interface at the other end. The shear application

Table 8
Design of mixing ratios for epoxy resin adhesive materials.

Experimental group	E51 epoxy resin/g	593B curing agent/%	Tougheners/%	Diluent/%
1	100	25	0	0
2	100	30	0	0
3	100	35	0	0
4	100	40	0	0
5	100	30	10	0
6	100	30	20	0
7	100	30	30	0
8	100	30	40	0
9	100	30	20	5
10	100	30	20	10
Control group	E44 Epoxy resin 100 g	650 Curing agent 100 g	-	-

Note 1: The curing agent, toughening agent, and diluent are added externally, and their dosages are all percentages of the dosage of epoxy resin used.

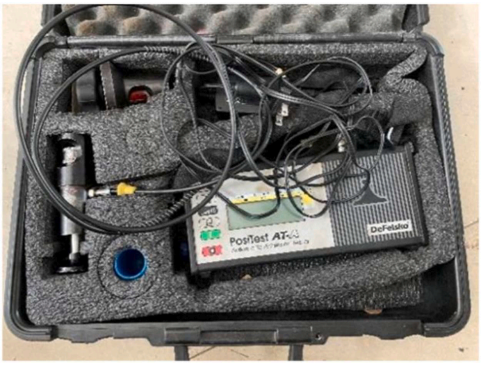


Fig. 6. PosiTest AT-A automatic pull-off tester.

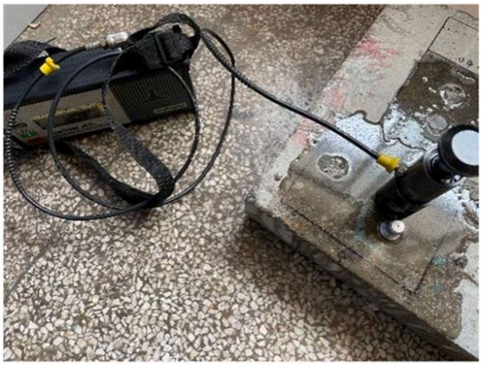
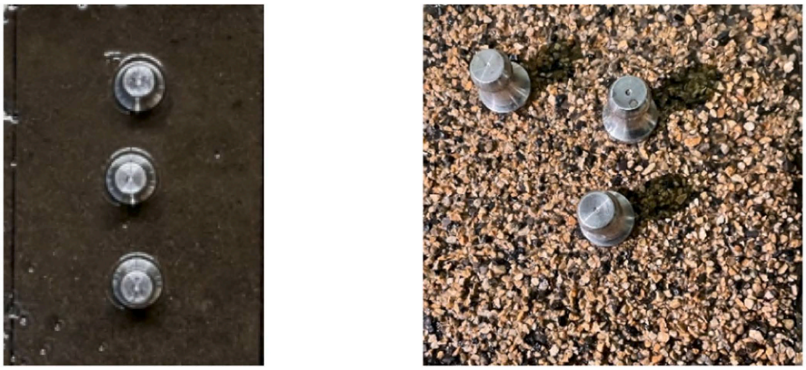


Fig. 7. Pull-off testing.



(a) Epoxy resin adhesive with old pavements (b)Epoxy resin adhesive with aggregates

Fig. 8. Specimen of pull-off test (The dimensions of the spindle were 20 mm).

velocity was controlled at 10 mm/min until shear failure occurred at the bonding interface of the specimen. The application of shear force was stopped upon occurrence of shear failure, and the maximum failure load was recorded. The shear test procedure is illustrated in Fig. 9.

The shear test specimens are shown in Fig. 10.

The shear strength is calculated according to Eq. (2):

$$\tau = \frac{F}{10} \tag{2}$$

where: τ——Shear strength, MPa;

Fig. 9. Shear test.

Fig. 10. Specimen of shear test.

F——Shear failure load, kN.

3. Results and discussion

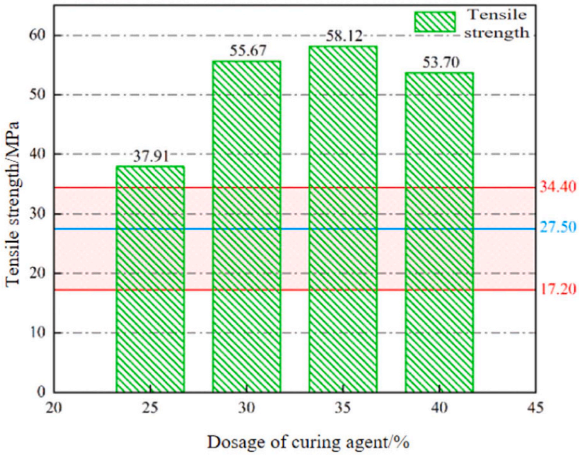
3.1. Optimization of epoxy resin adhesive

3.1.1. Curing agent

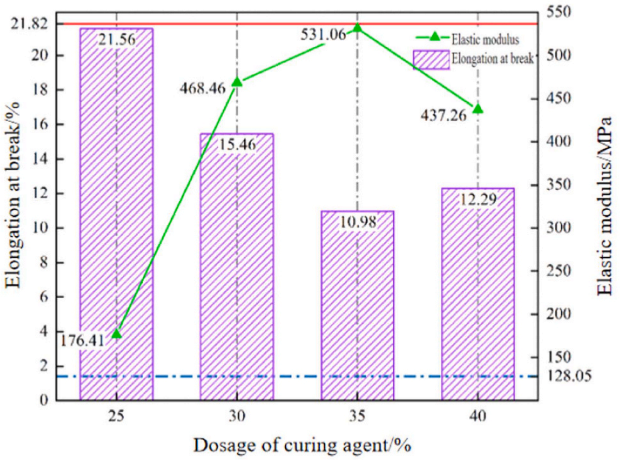
E51 epoxy resin was used as the base resin and mixed with varying dosages of curing agent (593B) for curing. The results of the tensile tests on the cured products are shown in Fig. 11.

In Fig. 11(a), the red area indicates the range of tensile strength requirements for epoxy adhesive materials as specified in the American "Standard Practice for High Friction Surface Treatment for Asphalt and Concrete Pavements" (AASHTO PP 79-2014) [37], which is 17.2–34.4 MPa (2500–5000 psi). The blue line represents the tensile strength of the control group E44 epoxy resin system, which is 27.5 MPa. In Fig. 11(b), the red solid line shows the elongation at break of the control group E44 epoxy resin system, which is 21.82 %; the blue dotted line indicates the tensile modulus of elasticity of the control group E44 epoxy resin system, which is 128.5 MPa.

With the increase in the dosage of 593B, the change in tensile strength of the cured products of the E51 epoxy resin adhesive system first increases and then decreases, as illustrated in Fig. 11. Within the entire range of designed curing agent dosages (25–40 %), the cured products of the E51 epoxy resin adhesive system demonstrate high tensile strength, significantly exceeding the 17.20–34.40 MPa



(a) Tensile strength



(b) Elongation at break and tensile modulus of elasticity

Fig. 11. Impact of curing agent dosage on the tensile performance of epoxy resin adhesive.

required by the AASHTO PP 79-2014 standard.

The tensile modulus of elasticity indicates the ease with which the cured epoxy resin undergoes tensile elastic deformation. A higher tensile modulus of elasticity signifies increased material rigidity, meaning that under the same level of stress, the material exhibits less tensile elastic deformation. As the dosage of curing agent (593B) increases, the tensile modulus of elasticity initially increases and then decreases. Combined with the results of the elongation at break, when the curing agent dosage is between 25 % and 35 %, the increase in 593B leads to more complete curing reactions and more cured products. Therefore, the rigidity of the cured products of the E51 epoxy resin adhesive system increases, making it less prone to deformation, and the elongation at break decreases. When the 593B dosage exceeds 35 %, some excess 593B, unable to react, remains in a liquid state within the cured epoxy system, thereby weakening the overall strength. Although it slightly raises the elongation at break and lowers the rigidity, in practical applications, this excess liquid 593B within the epoxy resin system can negatively impact the system.

Considering the three tensile performance indicators comprehensively, particularly the tensile modulus of elasticity, when the content of 593B reaches 30 %, the cured product exhibits higher tensile strength and rigidity. It provides a strength foundation for subsequent toughening and fluidity modifications and leaves considerable room for further improvements. Therefore, an appropriate range for the dosage of 593B is between 30 % and 35 % by weight.

3.1.2. Toughening agent

Using E51 epoxy resin as the matrix resin and blending with a curing agent at a concentration of 30 %, the tensile test results of epoxy resin cured products with various concentrations of the toughening agent (HTPB) were analyzed. The results are shown in Fig. 12.

As the dosage of the HTPB increases, the tensile strength generally shows a decreasing trend, with the rate of decline gradually diminishing, as illustrated in Fig. 12. When the HTPB dosage reaches 20 % or above, the tensile strength of the epoxy resin system can meet the requirements of the AASHTO PP 79-2014 standard.

With the increase in the dosage of the HTPB, the tensile modulus of elasticity also shows an overall decreasing trend, with the rate of decline gradually diminishing. The elongation at break is the most direct indicator of the flexibility of the epoxy resin adhesive. When the dosage exceeds 20 %, the increase in elongation at break slows down. This suggests that around a 20 % dosage of the HTPB, the physical miscibility toughening by HTPB is saturated, and there are enough terminal hydroxyl groups to fully react chemically with the epoxy resin, resulting in the optimal toughening effect. When the dosage exceeds 20 %, the toughening effect gradually weakens. Although the test results show an increase in flexibility, this not only increases modification costs and wastes material, but also the liquid, free-state HTPB can have negative effects similar to those of the aforementioned excess curing agent.

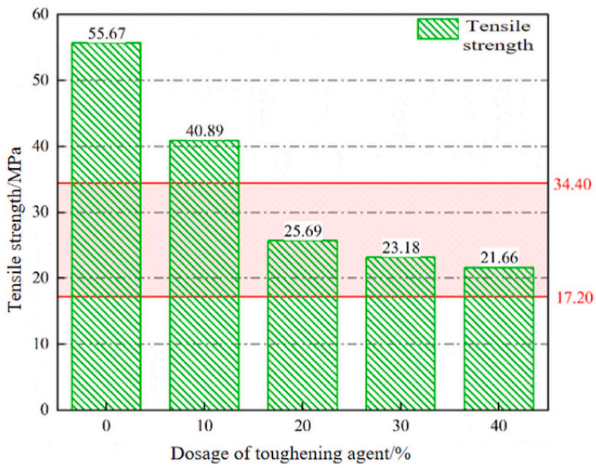
Considering the three tensile performance parameters and cost, a 20 % HTPB dosage is recommended. With this proportion, the overall tensile strength of the epoxy adhesive system is 25.69 MPa, and the elongation at break is 35.99 %, both complying with the AASHTO PP 79-2014 standard.

3.1.3. Diluent

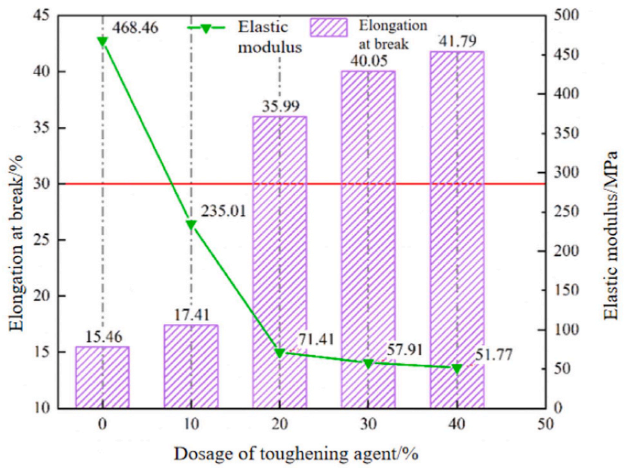
Using E51 epoxy resin as the matrix resin, a mixture was prepared by adding a 30 % dosage of curing agent (593B) and a 20 % dosage of toughening agent (HTPB). The viscosity tests of this epoxy system involved varying the dosage of the diluent (AGE), and the tensile test results of its cured products were analyzed. The experimental results are shown in Fig. 13.

With the increase in AGE dosage, both the tensile strength and tensile modulus of elasticity of the epoxy resin system continually decrease, as illustrated in Fig. 13. When the dosage increases from 5 % to 10 %, the tensile strength no longer meets the minimum standard requirements, and the elongation at break of the epoxy resin system also increases with the AGE dosage.

The viscosity index is used to evaluate the fluidity of the epoxy adhesive and the modification effect of the AGE. In Fig. 13(c), the purple area represents the viscosity range required by the AASHTO PP 79-2014 standard. As the AGE dosage increases, at a 5 % dosage,



(a) Tensile strength



(b) Elongation at break and tensile modulus of elasticity

Fig. 12. Impact of toughening agent dosage on the tensile performance of epoxy resin adhesive.

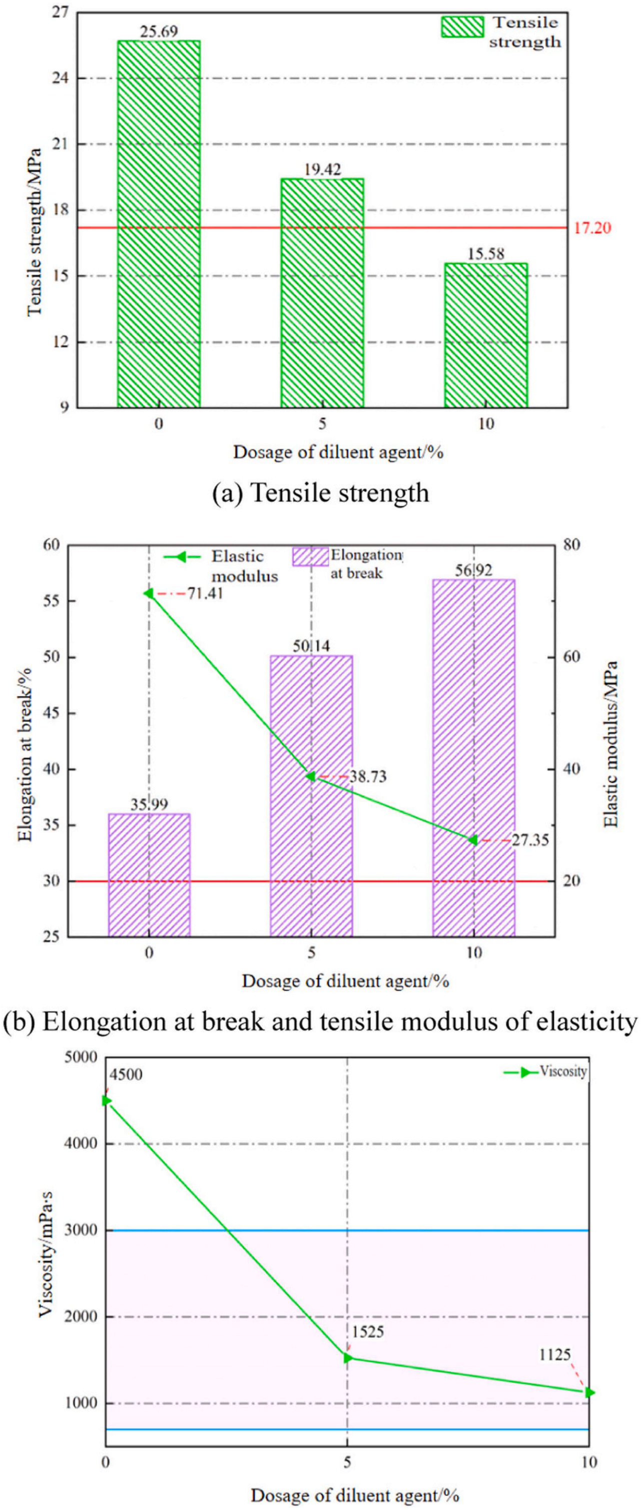


Fig. 13. Impact of diluent dosage on the tensile performance and viscosity of epoxy resin adhesive.

the viscosity value of 1525 mPa s meets the standard requirements. The viscosity of the E44 epoxy resin adhesive system was tested and found to be over 30,000 mPa s.

Considering the three tensile performance metrics of the cured substance, the pre-curing viscosity of the epoxy resin system, and the performance criteria outlined in the AASHTO PP 79-2014 standard, an AGE dosage of 5 % is deemed suitable.

Based on the experimental exploration of the optimal dosages of various additives mentioned above, the optimal dosages of additives and other technical performance indicators of the modified and optimized epoxy resin adhesive have been summarized in Table 9.

3.1.4. Microscopic morphology

The microscopic morphology of the fractured surface of the epoxy resin after modification and curing is depicted in Fig. 14. Upon observation, it is noted that the fractured surface of the epoxy system after curing appears smooth and uniform, with dispersed patterns and scattered white rubber particles. Locally, there are fibrous protrusions indicative of tensile fracture at the edges. Prior to curing, the modified epoxy system consisted of a four-phase structure, with distinct interfaces between phases. Upon initiation of the reaction, chemical reactions occurred between the phases, disrupting their initially independent structures. The edges of the phases gradually faded and merged together, while HTPB phases began to crystallize and precipitate rubber particles. Upon completion of the reaction and curing, the four-phase structure disappeared, resulting in a two-phase structure where the epoxy system serves as the continuous phase and the rubber particles act as the dispersed phase, presenting a semi-transparent appearance. When the epoxy system is subjected to stress and internal cracks initiate, the rubber particles present in the system act as stress concentrators, which can halt crack propagation or control crack development. If internal cracking occurs, the rubber particles can bond the cracks. Furthermore, when the epoxy system undergoes elongational deformation due to tensile stress, the rubber particles also act as connectors, impeding the formation of cracks and voids in the epoxy system, thus achieving toughening and modification effects.

3.2. Performance of epoxy resin adhesive

3.2.1. Selection of mixing ratios

The preferred ratio range for high-flow epoxy resin adhesive, as determined in Section 3.1, is E51 epoxy resin: curing agent: toughener: diluent = 100: (30–35): (20–30): 5. This ratio results in a lower viscosity before curing and higher fluidity, making the application process easier. After curing, it possesses sufficient strength and enhanced toughness, making it suitable for repairing and maintaining old road surfaces.

Therefore, the experimental group in this section used the high-flow epoxy resin adhesive ratio of E51 epoxy resin: curing agent: toughener: diluent = 100:30:20:5. For control group 1, the ratio of epoxy resin adhesive was E51 epoxy resin: curing agent = 100:30, and for control group 2, the ratio was E44 epoxy resin: curing agent = 1:1.

3.2.2. Bonding performance with old pavements

3.2.2.1. Pull-off test results. On the surface of cement concrete slabs, a bonding test area of 15 mm$\times$10 mm was marked, and different dosages of epoxy adhesive, specifically 0.4 kg/m^2, 0.8 kg/m^2, 1.2 kg/m^2, and 1.6 kg/m^2, were then applied to the marked bonding test areas. For each quantity of epoxy adhesive, three pull-off spindles were placed in the bonding area for parallel pull-off tests and left to set for 3 h. The results of the pull-off test are shown in Fig. 15, where the red solid line in Fig. 15 represents the minimum bonding strength required by the AASHTO PP 79-2014 standard, which is 1.7 MPa.

For both E51 epoxy adhesive systems (the test group and control group 1), the pull-off strength initially increases and then decreases with the dosage used, as illustrated in Fig. 15. The reason is that as the dosage of E51 type epoxy adhesive gradually increases to 1.2 kg/m^2, the pull-off test area is progressively fully contacted, saturated, and bonded by the adhesive. At a dosage of 1.2 kg/m^2, the dosage of adhesive applied to the bonding test interface reaches the critical point for fully and uniformly bonding the test interface. At this stage, the pull-off strength is at its maximum. The maximum pull-off strength of the modified epoxy adhesive system with the cement substrate surface is 6.66 MPa, representing an increase of 149 % and 18 % compared with control groups 1 and 2, respectively.

The pull-off strength of the E44 type epoxy adhesive (control group 2) decreases with increased dosage. The reason is that at low dosages, E44 type epoxy adhesive is relatively easier to spread, allowing it to fully contact the test area. Its bonding performance and toughness provide higher pull-off strength. In scenarios of higher dosages, the pull-off strength of control group 2 is lower than the pull-off strength of the test group, indicating a significant effect for toughening modification on the E51 epoxy system.

In summary, the pull-off strength between the epoxy adhesive and the cement concrete surface is influenced by the dosage of adhesive used at the bonding interface and its bonding performance, toughness, and cohesion. The modified E51 epoxy adhesive has enhanced bonding performance, toughness, and cohesion, offering bonding strength significantly surpassing standard requirements, and is capable of withstanding greater pull-off loads compared with control groups 1 and 2.

3.2.2.2. Shear test results. Based on the pull-off test results, the test group and control group 1 applied epoxy adhesive at a rate of 1.2 kg/m^2 on the concrete block surfaces, while control group 2 applied it at 0.4 kg/m^2. Three specimens were prepared for each group for parallel testing. The results of the shear test are shown in Fig. 16.

The test group's epoxy adhesive has the highest shear strength, as illustrated in Fig. 16. The modified epoxy adhesive system with the cement base achieved a maximum shear strength of 2.52 MPa, which is 58 % and 82 % higher than control groups 1 and 2, respectively. This demonstrates the superior shear bonding performance of the modified epoxy adhesive. The higher shear strength of the modified E51 epoxy adhesive is due to significant improvements in its toughness, allowing it to withstand greater shear stress and enhancing its shear bonding performance.

The difference in shear strength between control groups 1 and 2 is not significant, with control group 2 having slightly lower shear

Table 9
Technical performance indicators of modified epoxy resin adhesive.

Performance	Unit	Technical requirements	Test results	Test methods
Viscosity	Poises	7–30	15.25	ASTM D 2556
Gel Time/23 ℃	min	≥ 10	20	AASHTO M 235M
Ultimate Tensile Strength	psi	2500–5000	2861.6	AASHTO M 235M
Elongation at Break	%	30–70	50.1	AASHTO M 235M
Compressive Strength/3 h	psi	≥ 1000	6628.2	ASTM C 579
Curing Time	h	≤ 3	2	ASTM D 1640
Water Absorption Rate/24 h	%	≤ 1	0.11	AASHTO M 235M

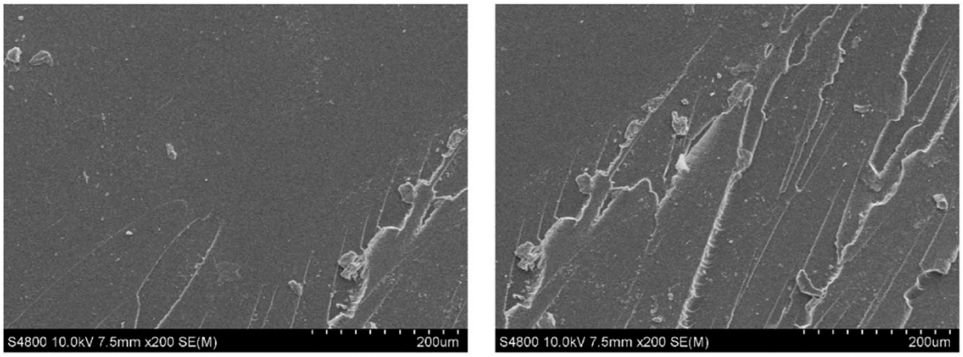


Fig. 14. The SEM image of the fractured surface of the epoxy resin after modification.

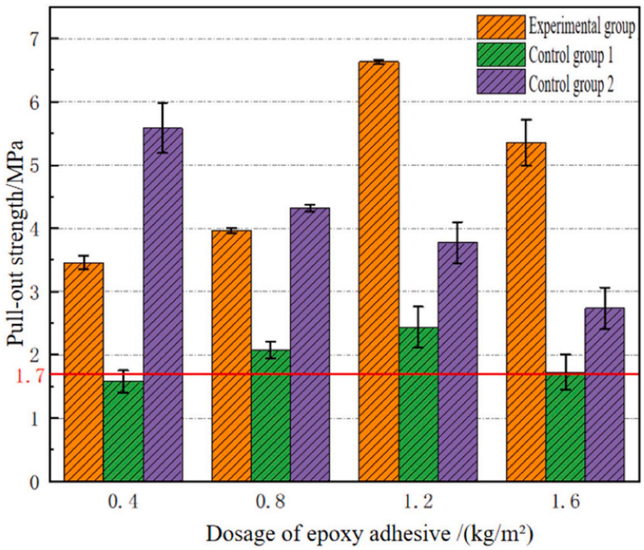


Fig. 15. Pull-off strength of various dosages of epoxy resin adhesive with cement concrete base.

strength primarily due to the lower epoxy equivalent of E44 epoxy resin. Hence, its cured toughness is poorer, and at low dosages, the shear strength between the adhesive and concrete surface mainly depends on the adhesive's bonding performance.

3.2.3. Bonding performance with aggregates

3.2.3.1. Pull-off test results. The surface of the cement concrete slab was divided into four equal parts. A fixed dosage of epoxy adhesive was applied, followed by spreading different dosages of 88# calcined alumina aggregate with a grain size of 1–3 mm. After curing for 7 days, HFS with various resin-to-aggregate ratios was prepared. Based on the results of Section 3.2.2 of this paper, the dosage of epoxy adhesive for the three HFS groups was fixed at 1.2 kg/m^2, with resin-to-aggregate ratios of 0.26, 0.28, 0.30, 0.32, and 0.34. On the epoxy adhesive of HFST pull-off test surfaces with varying resin-to-aggregate ratios, three pull-off spindles were bonded. The results of

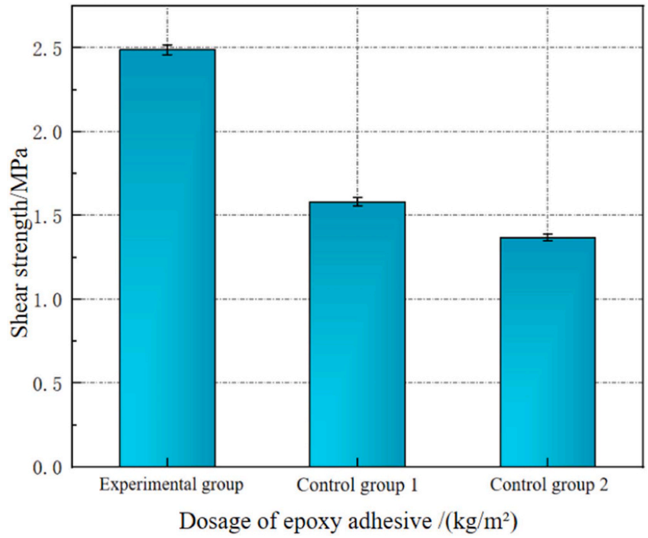


Fig. 16. Shear strength between epoxy resin adhesive and cement concrete base.

the pull-off test are shown in Fig. 17.

The pull-off strength of the experimental group is significantly higher than that of control groups 1 and 2, as illustrated in Fig. 17. The maximum pull-off strength between the modified epoxy adhesion system and aggregate is 14.36 MPa, with an average pull-off strength increase of 174 % and 541 % over control groups 1 and 2, respectively. This could indicate that the modified E51 epoxy adhesive has better bonding and adhesion performance with the aggregates. Another reason might be that the modified epoxy resin adhesive has a lower viscosity and higher fluidity, allowing the aggregates that are spread on top to easily sink through the adhesive due to their own weight.

As the resin-aggregate ratio increases, the pull-off strength of the test group first increases and then decreases, reaching a maximum at a ratio of 0.30. This indicates that the modified epoxy adhesive has fully encapsulated and bonded the aggregate into a cohesive whole. As the resin-aggregate ratio increases, the pull-off strength of control groups 1 and 2 gradually decreases. The increase in this ratio causes more pull-off forces to act directly on the epoxy adhesive, which cannot withstand greater forces, leading to earlier pull-off failure of the adhesive.

Based on the results of the Section 3.2.2.1, it can be determined that the modified epoxy adhesive dosage for a single layer of HFS should be controlled at 1.0–1.2 kg/m^2, and the aggregate dosage should be between 3.3 and 4.3 kg/m^2.

3.2.3.2. Shear test results. A layer of 1.2 kg/m^2 epoxy resin adhesive was coated on one side of a 100 mm cubic C30 cement concrete

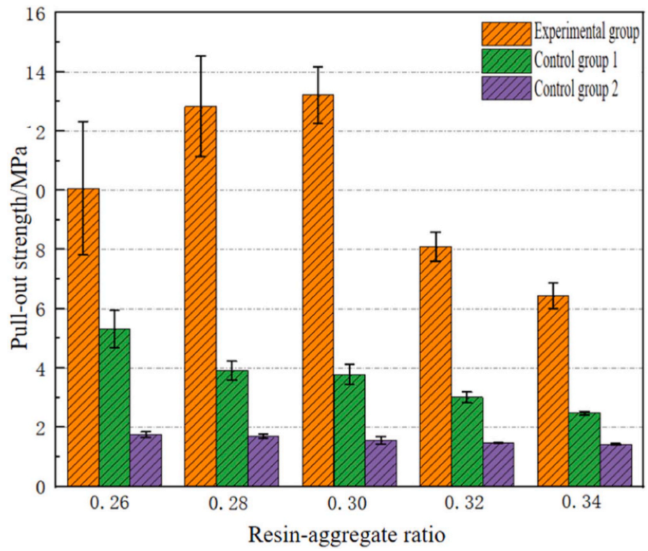


Fig. 17. Pull-off strength between epoxy resin adhesive and aggregate.

block and then sprinkled with 88# calcined alumina aggregate having a grain size between 1 and 3 mm. The test group HFS used a resin-aggregate ratio of 0.30, while control groups 1 and 2 used a resin-aggregate ratio of 0.26, and after curing for 7 days, the HFS for shear testing was obtained. Three shear test specimens were prepared for each group for parallel testing. The results of the shear test are shown in Fig. 18.

The test group has the highest shear strength, as illustrated in Fig. 18. The maximum shear strength between the modified epoxy adhesive system and the aggregate is 2.15 MPa, with an average shear strength increase of 77 % and 31 % over control groups 1 and 2, respectively. This indicates that the test group HFS has superior shear bonding performance. The modified E51 epoxy adhesive shows significant improvements in adhesion with the aggregate, effectively handling shear loads and being more suitable for practical road surface applications. Control group 1 exhibits inferior shear resistance; control group 2, which used E44 epoxy resin, has better toughness after curing than E51 epoxy resin, thus showing better shear resistance than control group 1.

Comparing the results of the Section 3.2.2.2, the bond shear strength between the three groups of epoxy adhesives and the aggregates is less than the interlayer bond shear strength between the adhesive and the cement concrete substrate. This is primarily due to the tighter contact and firmer bond between the epoxy adhesive and the surface of the cement concrete substrate. As a result, interlayer shear failure is less likely to occur between the High Friction Surface (HFS) and the cement concrete substrate.

4. Conclusions

This article aims to ensure a notable enhancement in road surface functionality while maintaining the long-term service performance of HFST in good condition. The objective is to extend their service life and to achieve a greater extent of high-quality promotion and application of this maintenance technology. To achieve this, a systematic approach was taken to modify and optimize the component ratios of traditional epoxy resin materials. Subsequently, a toughened, high-flow epoxy adhesive system suitable for concrete pavement maintenance was developed, and its bonding performance with the cement base and aggregate were further explored. Several conclusions were drawn as follows:

(1) Using E51 epoxy resin as the base, a gradual blending of modifying components was carried out, followed by tensile testing. Based on the results of the tensile tests, an analysis was conducted for optimizing the composition ratio of the modified E51 epoxy system. The optimal range of component proportions was determined to be E51 epoxy resin: curing agent: toughening agent: diluent = 100:30–35:20–30:5.

(2) The experimental group was designed with a ratio of E51 epoxy resin to curing agent to toughening agent to diluent of 100:30:20:5. Control group 1 had a ratio of E51 epoxy resin to curing agent of 100:30, while control group 2 had a ratio of E44 epoxy resin to curing agent of 1:1. Through tensile and shear tests, it was found that the modified epoxy bonding system exhibited an average tensile strength on the cement substrate surface 149 % higher than control group 1 and 18 % higher than control group 2. The average shear strength was increased by 58 % compared with control group 1 and 82 % compared with control group 2. Furthermore, the average tensile strength between the modified epoxy bonding system and the aggregate was 174 % higher than control group 1 and 541 % higher than control group 2, while the average shear strength was increased by 77 % compared with control group 1 and 31 % compared with control group 2.

(3) Guided by the pull-off and shear test outcomes, the optimal usage dosage of modified epoxy adhesive for HFST mixtures was established at 1.0–1.2 kg/m^2, with the aggregate dosage maintained at 3.3–4.3 kg/m^2.

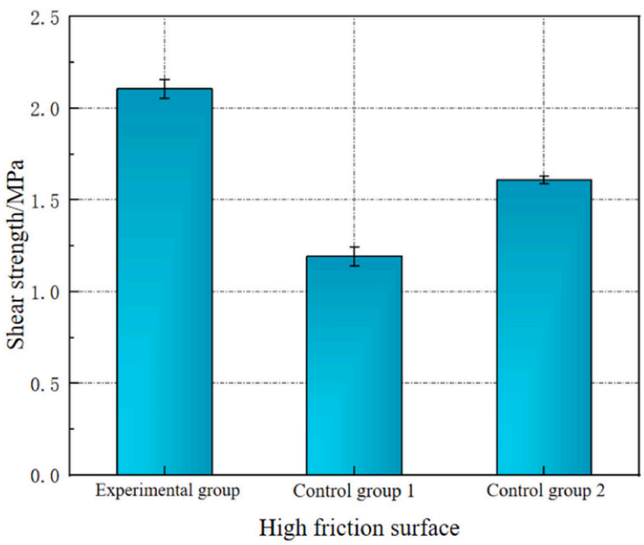


Fig. 18. Shear strength between epoxy resin adhesive and aggregate.

CRediT authorship contribution statement

Dahui Xu: Project administration, Methodology. **Yanping Sheng:** Resources, Methodology. **Shubing Wang:** Validation, Project administration. **Zhanping You:** Visualization, Investigation. **Xiao Huan:** Validation, Supervision. **Jiapeng Li:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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