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Research Article

Development and Performance Evaluation of Thin-Layer Color Antiwearing Paving Materials

Zhaohui Liu,[1] Xiangming Deng,[1,2] Hao Guo,[3] Yingchun Zhang,[3] Di Wei,[1] and Dongmei Zhang[1,4]

[1]*School of Traffic and Transportation Engineering, Changsha University of Science & Technology, Changsha 410114, Hunan, China*
[2]*Guangxi Communications Investment Group Corporation Ltd, Nanning 530007, Guangxi, China*
[3]*Hunan Provincial Communications Planning, Survey and Design Institute Co., Ltd, Changsha 410200, Hunan, China*
[4]*Hunan International Scientific and Technological Innovation Cooperation Base of Advanced Construction and Maintenance Technology of Highway, Changsha University of Science and Technology, Changsha 410114, Hunan, China*

Correspondence should be addressed to Dongmei Zhang; dmzhang@csust.edu.cn

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To develop a color antiwearing wear layer based on epoxy resin adhesives, the effect of single formula composition on the properties of adhesives was analyzed through drawing strength tests, shear strength tests, and bending strength tests. It was found that when the mass ratio of the epoxy resin curing agent and the dosage of the toughening agent increased, the bonding performance and toughness of the adhesive firstly increased and then decreased. With the increase of the mass ratio of phenolic aldehyde amine to polyamide, the bonding performance and toughness of the adhesive were improved, but the effect was significantly reduced when the ratio was more than 2. With the increase of diluent content, the bonding performance and toughness of the adhesive were reduced. Based on response surface optimization, the optimum formulation was recommended. The content of the mass ratio of the epoxy resin to the curing agent and mass ratio of curing agent phenolic amine to polyamide, toughening agent content, and diluent content was determined to be 2.971%, 1.887%, 2.455%, and 1.000%, respectively. And, the dosage of each material was consistent with the effect of the dosage of a single formula on the properties of adhesives. The performance of the color antiwearing thin layer was tested by the adhesion test and antiwearing durability test. It was found that temperature had a significant effect on the adhesion, the adhesion of the thin layer was significantly reduced at low temperature, and the sensitivity to impact load was enhanced, while the adhesion and sensitivity to impact load were effectively improved at more than 20°C. At the same time, the antiwearing of the thin layer decreased rapidly at the initial stage under the reciprocating load but tended to be stable when the load exceeds 500 times.

1. Introduction

Road traffic safety has always been the focus of scientific research workers [1, 2]. The State Council's "Thirteenth Five-Year Modern Comprehensive Transportation System Development Plan" pointed out that future highway construction should be "innovation-driven, green, and safe" as the basic principles, firmly establish the concept of safety first, and comprehensively improve the safety and reliability of transportation, and to ensure the safety of users to reach the destination has become the basic property of the highway [3]. However, the road traffic accident is still a difficult problem that cannot be avoided all over the world. According to the data of "road traffic and transportation safety development report (2017)," there are 8.643 million traffic accidents in China in 2016, resulting in direct property losses of 1.21 billion yuan [4]. The analysis of the causes of a large number of traffic accidents shows that, in addition to the vehicle and the climate, the driver is also one of the important accident risk factors. For example, long-term driving distraction can easily cause visual fatigue. Besides, some expressways contain a lot of curved road sections, appearing in the form of a combination of curved road sections and long downhills. The "nonorthogonality" of these linear designs bury hidden dangers for driving stability and safety [5, 6]. It is urgent to improve road traffic safety. The color antiwearing thin layer provides a new idea for improving road driving safety. It coats the road surface with adhesives and colored antiwearing aggregates to form a 4–10 mm thick structural layer, and through the change of color and the improvement of vibration, the driver is reminded to enter the dangerous road section from the visual and tactile aspects, respectively. Also, the structure layer has good antiwearing performance, which improves driving safety in a diversified way [7].

The research and application of the color antiwearing thin layer originated from Europe, the United States, and other developed countries in the 1950s, and it is applied to traffic engineering fields involving safety management [8–11], such as parking lot, tunnel entrance and exit, ramp, and deceleration belt. However, the research in this field started late in China; until the beginning of the 21st century, color pavement technology is applied to public places such as carriageway and residential area. With the maturity of the preparation, production, and construction technology of colored paving materials, the colored pavement is developing towards lightness, high performance, and safety [12]. The development of color thin layer binder has experienced three stages; they are color coating, color asphalt, and polymer resin [13]. At present, epoxy resin, polyurethane, and methyl methacrylate are widely studied. Chen et al. [14] developed a kind of antiwearing layer adhesive material for pavement, which was composed of epoxy resin, curing agent, toner, and quartz sand. The bonding material had excellent mechanical properties, deformation properties, and durability. Quan et al. [15] developed a one-component polyurethane adhesive, which was composed of polyaspartic resin, DOP, and MD polyether prepolymer, and had the characteristics of transparency, wears resistance, and good sealing performance. Wu [16] prepared a thermoplastic elastomer-modified polymethyl methacrylate color nonslip coating, which mainly included modified MMA resin liquid, rubber particles, dibutyl phthalate, and formyl peroxide, and had nonpolishing, nonslip, quiet, and other characteristics. With the development of the types of adhesives, the pavement properties of adhesives have been paid more and more attention. Zhong et al. [17] adopted pure shear strength test methods to compare the shear strength of epoxy resin and modified emulsified asphalt under different temperature conditions to evaluate the interlayer adhesion. They found that epoxy resin had good adhesion to asphalt concrete, and its shear strength was higher than emulsified asphalt. Xue et al. [18] measured the adhesion between color antiwearing thin layers under different resin coating amounts by paint and varnish pull-apart adhesion test method. It was found that, with the increase of resin adhesive coating amount, the adhesion between layers gradually tends to a fixed value. Li et al. [19] compared the interfacial bond strength of the original pavement with or without groove through the pull-out test and shear test, which found that the shear strength and pull-out strength can be increased by one-third under the groove condition. Wu et al. [20] determined that the structure depth of the colored antiwearing wearing course was 1.81 mm and the friction coefficient BPN was 59.8, which was higher than that of the general asphalt pavement. Zhang et al. [21] compared the friction coefficient of the color antiwearing thin layer with SMA-13 and AC-13 pavement under dry and wet conditions and found that the epoxy color antiwearing wear layer had the best performance and could shorten the braking distance by 40%. Liu et al. [22] compared the skid resistance performance of colored antiwearing thin layers from different aggregate sources and found that the antiwearing performance of bauxite particles, ceramic particles, quartz sand, and colored sand decreased in turn.

To sum up, there is still a need for further research in formulation development, thin-layer material adhesion, and skid resistance durability. Therefore, this paper through the single factor studied epoxy resin curing agent mass ratio, mass ratio of two types of curing agents, toughening agent dosage, and diluent dosage on the properties of adhesive, and then, the response surface method was used to obtain the optimal ratio. Finally, the adhesion between epoxy resin adhesive and ceramic particles was explored, and the antiwearing durability was evaluated.

2. Experimental

2.1. Materials. Since the adhesive of the epoxy resin was generally composed of epoxy resin and curing agent, to improve its comprehensive performance, it needed to be realized by adding tougheners, diluents, etc. The information on epoxy resin, curing agent, toughening agent, diluents, and other materials selected is shown in Table 1.

The color ceramic was the aggregate in the test, and its main technical indexes are shown in Table 2.

2.2. Test Methods

2.2.1. Drawing Strength Test. The microdrawing instrument of Shijiazhuang Zhuopu Technology Co., Ltd. was used. The epoxy resin adhesive was evenly stirred and applied on the surface of the clean steel plate, and then, the drawing head with a diameter of 100 mm was placed. After standing at room temperature and curing for 24 hours, the drawing strength was tested with a tensile rate of 10 mm/min. The principle of the equipment is shown in Figure 1.

The calculation formula is shown in the following formula:

$$\tau = \frac{4 \times F}{3.14 \times D^2}. \tag{1}$$

In formula (1), τ is drawing strength (MPa), F is the maximum drawing value (N), and D is the diameter of the puller (mm).

2.2.2. Shear Strength Test. The epoxy resin adhesive was evenly applied on the 100 mm × 100 mm surface of three 100 mm × 100 mm × 50 mm cement concrete specimens. After 24 hours of static curing at room temperature, it was

Table 1: Materials.

Type	Name	Manufacturer
Main agent	Epoxy resin (E−51)	Zhenjiang Danbao Resin Co. Ltd
Curing agent	Polyamide (650 low molecular weight) Phenolic aldehyde amine (T−31)	Zhengzhou Xinjiuda Chemical Products Co. Ltd
Toughening agent	Dibutylphthalate	Shandong Yousseo Chemical Technology Co. Ltd
Diluent	Butyl glycidyl ether	Changzhou Runxiang Chemical Co. Ltd
Coupling agent	Silane coupling agent (KH550)	
Filler	Nano-SiO_2 Nano-$CaCO_3$	Tianjin Jinxi Chenguang Chemical Welfare Factory Tianjin Tianchenggong Chemical Co. Ltd

Table 2: Technical indicators of the color ceramic.

Technology index	Test results
Apparent specific gravity	2.51
Moisture content (%)	1.1
Mohs hardness	6.5
Grain size (mm)	1~3

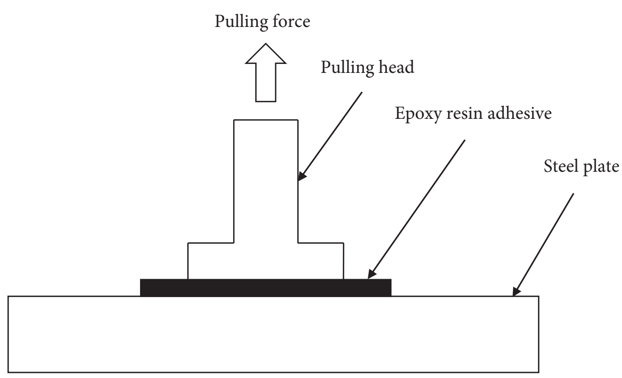

Figure 1: Drawing strength test principle.

placed in a self-made shear fixture, and its shear strength was tested at 1 mm/min:

$$\tau = \frac{F}{S}. \quad (2)$$

In formula (2), τ is shear strength (MPa), F is shear force (kN), and S is the stress area (m^2).

The test principle is shown in Figure 2.

2.2.3. Bending Strength Test. Based on “test method of resin casting performance (GB/T 2567–2008),” cuboid epoxy resin castables were prepared, and then, a three-point bending test was carried out.

2.2.4. Adhesion Test. According to the low-temperature adhesion test of asphalt and aggregate (T0660-2000), a 2 mm thick epoxy resin adhesive was applied on the central surface of the clean steel plate. Afterward, the color ceramic particles were evenly spread at a spreading amount of 1.8 kg/m^2 to form a circle with a radius of 70 mm. After curing at room temperature for 24 hours, the steel balls were dropped from different heights to observe the number of ceramic particles dropped after impact.

2.2.5. Antiwearing Durability Test. The self-made indoor accelerated wear equipment (Figure 3) was used, which was mainly composed of a drive system, temperature control system, wheelset system, and control system. The asphalt mixture rut board specimen (300 mm × 300 mm × 50 mm) was prepared, and the surface was laid with a color anti-wearing thin layer. The frequency conversion and wear times were set according to the test speed requirements, and the texture depth in the circular wear zone and the mass loss per unit area of the specimen were measured after different wear times.

3. Development of Epoxy Resin Adhesive

3.1. Effect of Single Material Composition on the Properties of Adhesives. To get a good application in the pavement, the thin layer material should have excellent bonding performance and effectively deform with the pavement structure without damage. Therefore, a single factor test was designed to analyze the effects of the mass ratio of the epoxy resin to the curing agent (phenolic amine and polyamide) and mass ratio of phenolic amine to polyamide, toughening agent, and diluent on the drawing strength, shear strength, and bending strength of the adhesive. In the test, the content of silane coupling agent (KH550), nano-SiO_2, and nano-$CaCO_3$ were 0.5% (extra-mixing). The test factor level design and test results are shown in Table 3, and the following conclusions are drawn .

(1) When the mass ratio of the epoxy resin curing agent increased, drawing strength, shear strength, and bending strength of adhesive firstly increase and then decrease (Figure 4). The reason is that, at the beginning of the mass ratio increase, the amine group in the curing agent causes the epoxy group in the epoxy resin to form a hydroxyl group and then react with the epoxy group to form a network polymer, which improves the overall performance of the adhesive [23, 24]. However, when the mass ratio is further increased, the excess epoxy resin makes the curing agent not have enough amine groups to cure and crosslink with it, and the epoxy resin itself has a low viscosity, which reduces the bonding performance and toughness. In this respect, the mass ratio of the epoxy resin to the curing agent should be about 3.

(2) As the mass ratio of phenolic amine to polyamide increases, the drawing strength and shear strength of

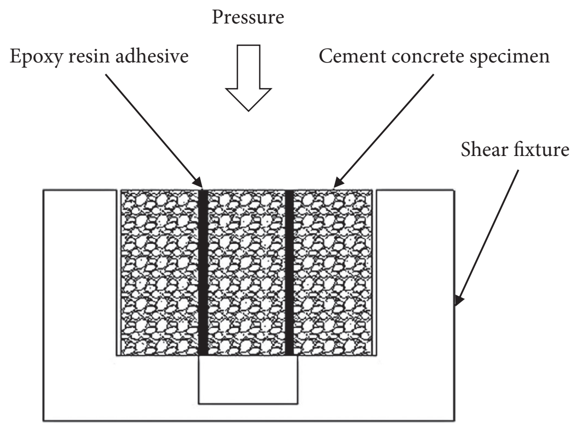

Figure 2: Shear strength test principle.

Table 3: Single factor test.

Serial number	Mass ratio of epoxy resin to curing agent	Mass ratio of phenolic amine to polyamide	Toughening agent dosage (%)	Diluent content (%)	Drawing strength (MPa)	Shear strength (MPa)	Bending strength (MPa)
1	2.0	1.5	3	2	4.13	1.84	59.66
2	3.0	1.5	3	2	6.22	2.89	75.69
3	4.0	1.5	3	2	5.19	2.34	62.3
4	5.0	1.5	3	2	3.88	1.77	48.6
5	3.0	1.0	3	2	5.34	2.23	72.5
6	3.0	1.5	3	2	6.22	2.89	78.36
7	3.0	2.0	3	2	6.54	2.95	80.69
8	3.0	2.5	3	2	6.46	2.77	81.1
9	3.0	1.5	2	2	5.88	2.44	76.2
10	3.0	1.5	3	2	6.22	2.89	80.36
11	3.0	1.5	4	2	6.01	2.84	77.6
12	3.0	1.5	5	2	4.87	2.56	69.1
13	3.0	1.5	3	1	6.41	3.04	79.65
14	3.0	1.5	3	2	6.22	2.89	75.6
15	3.0	1.5	3	3	5.51	2.55	68.45
16	3.0	1.5	3	4	3.84	1.76	54.14

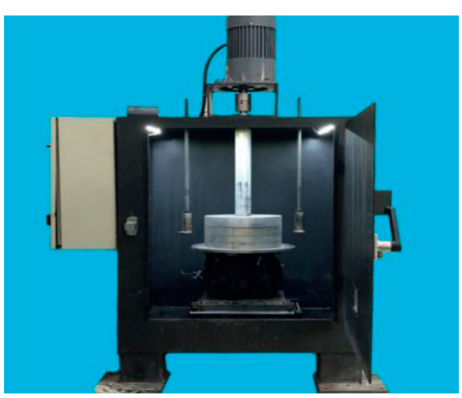

Figure 3: The accelerated wear equipment.

the adhesive gradually increase at the initial stage, but slightly decrease when the mass ratio exceeds 2 (Figure 5). On the contrary, the bending strength gradually increases, but the increase rate slows down when the mass ratio exceeds 2. This is due to the synergistic effect of polyamide and phenolic amine, which can improve the curing degree of the epoxy system and make the network structure formed by the reaction of active groups and epoxy firmer. However, it is possible that phenolic amine can only enhance the performance of the epoxy system within a certain dosage range, and the brittleness of the cured product beyond this range is gradually reflected [25, 26]. Therefore, from this perspective, the mass ratio of phenolic amine to polyamide should not exceed 2.

(3) With the increase in the amount of the toughening agent, the drawing strength, shear strength, and bending strength of the adhesive first increase and then decrease (Figure 6). The reason is that, at the initial stage of the increase in the amount of the toughening agent, the molecular weight of dioctyl phthalate (DBP) is relatively small, which can intersperse between the molecular chains of the epoxy cured product, increasing the mobility of the molecular chains and the spatial freedom of the epoxy resin molecular chain, and improve the toughness

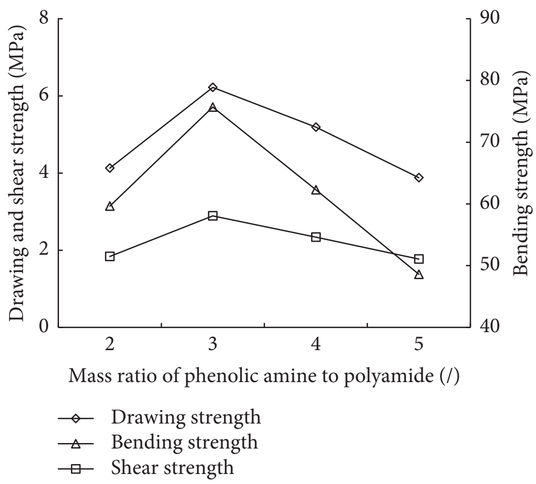

Figure 4: Mass ratio of the epoxy resin to the curing agent.

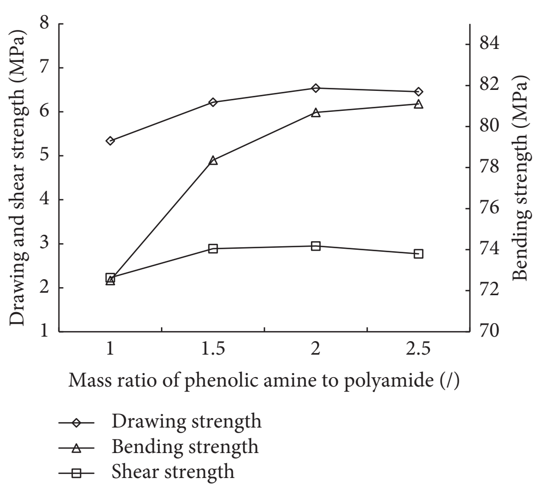

Figure 5: Mass ratio of phenolic amine to polyamide.

and strength. When the dosage is further increased, excessive DBP is incorporated into the epoxy system, and it cannot participate in the curing reaction of the epoxy resin, and there are a large number of small molecules in the cured product. Due to the low viscosity, the mechanical properties of adhesives are reduced to some extent [27]. Therefore, the optimal content of diluent is 3%.

(4) The increase of the content of diluent harms the properties of epoxy resin adhesive. With the increase of the diluent content, the drawing strength, shear strength, and bending strength of the adhesive all show a decreasing trend (Figure 7). This may be because the butyl glycidyl ether diluent belongs to a linear small molecule compound, and the linear chain segment in the molecule after curing reaction weakens the rigid structure of the whole crosslinking network and reduces the mechanical properties. However, from the perspective of construction workability, it is still recommended to add an appropriate amount of diluent [28].

3.2. Optimization of Adhesive Formulation Based on Response Surface Methodology. Response surface method is a statistical method of experimental design, which uses a reasonable experimental design to obtain the mathematical expression between design variables and response values through limited experiments, and obtains the optimal number of parameter groups through regression equation analysis, which is widely used in biology, chemistry, industry, engineering, and other fields [29–31]. To optimize the composition ratio of the epoxy resin adhesive, the drawing strength, shear strength, and bending strength are used as response values, and the three-level response surface with four factors including the mass ratio of the epoxy resin to the curing agent, the mass ratio of phenolic amine to polyamide, the content of toughening agent, and the diluent is designed. The factor levels are shown in Table 4, and the test results are shown in Table 5.

Since the single factor method cannot explain the interaction between factors and cannot give a clear model between factors and response values, the Design Expert software is used to perform multiple fitting regression on the test results in Table 5 to obtain the quadratic multinomial regression model which is the model of drawing strength (X), shear strength (Y), and bending strength (Z) on the mass ratio of the epoxy curing agent, the mass ratio of phenolic amine to polyamide, the content of toughening agent, and the diluent:

$$\begin{aligned}
X &= -12.51925 + 8.6345\mathrm{A} + 4.53733\mathrm{B} + 1.05617\mathrm{C} \\
&\quad + 0.743\mathrm{D} + 0.09\mathrm{AB} + 0.0475\mathrm{AC} + 0.0525\mathrm{AD} - 0.15\mathrm{BC} - 0.44\mathrm{BD} \\
&\quad + 0.18\mathrm{CD} - 1.512\mathrm{A}^2 - 1.048\mathrm{B}^2 - 0.21825\mathrm{C}^2 - 0.26575\mathrm{D}^2, \\
Y &= -7.351 + 4.92233\mathrm{A} + 2.378\mathrm{B} + 0.54317\mathrm{C} + 0.36767\mathrm{D} - 0.02\mathrm{AB} \\
&\quad - 0.0075\mathrm{AC} - 0.0225\mathrm{AD} - 0.045\mathrm{BC} - 0.185\mathrm{BD} + 0.0975\mathrm{CD} \\
&\quad - 0.81358\mathrm{A}^2 - 0.55433\mathrm{B}^2 - 0.10733\mathrm{C}^2 - 0.11233\mathrm{D}^2, \\
Z &= -183.50475 + 119.314\mathrm{A} + 66.373\mathrm{B} + 18.22067\mathrm{C} + 9.466\mathrm{D} \\
&\quad + 1.11\mathrm{AB} + 0.1775\mathrm{AC} + 1.0375\mathrm{AD} - 3.334\mathrm{BC} - 6.045\mathrm{BD} + 2.945\mathrm{CD} \\
&\quad - 20.69025\mathrm{A}^2 - 14.376\mathrm{B}^2 - 3.234\mathrm{C}^2 - 4.10025\mathrm{D}^2,
\end{aligned} \tag{3}$$

where X is the drawing strength, MPa, Y is the shear strength, MPa, Z is the bending strength, MPa, A is the mass ratio of the epoxy resin to the curing agent, B is the mass ratio of phenolic amine to polyamide, C is the amount of the toughening agent, %, and D is the dilutant dosage, %.

To test the validity of the regression equation and further determine the influence degree of various factors on the drawing strength, shear strength, and bending strength, the regression equation is analyzed by variance with the drawing strength as an example. The results are shown in Table 6, and from this, we can see the following conclusions.

(1) Model $P < 0.0001$, indicating that this model has a significant effect on the drawing strength. The regression model $R^2 = 0.9814$ indicated that 98.14% of the variation of the response value of the model comes from the selected factors. The model fits well,

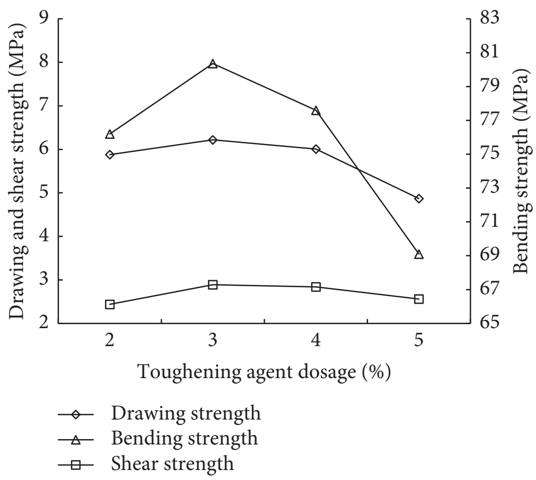

Figure 6: Toughening agent dosage.

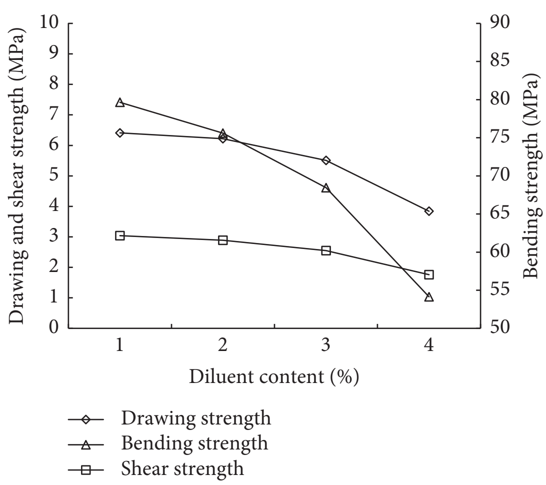

Figure 7: Diluent content.

Table 4: Experimental factors and levels of the response surface.

Factors	Level		
	−1	0	1
Mass ratio of epoxy resin to curing agent	2.0	3.0	4.0
Mass ratio of phenolic amine to polyamide	1.0	1.5	2.0
Toughening agent dosage (%)	2.0	3.0	4.0
Diluent content (%)	1.0	2.0	3.0

and the regression equation can describe the relationship between the various factors and the response value. The test method is reliable.

(2) According to the *P* value in the regression model, the influence of a single factor on the response value from large to small is D, B, A, and C. The *P* value of D is less than 0.0001, which indicates that it has the most significant impact on the drawing strength, the interaction term BD has a more significant impact, and the others are not significant. The quadratic term A^2 has the most significant impact, and the others are highly significant, which indicates that various factors have an interactive impact on the drawing strength, rather than a simple linear relationship.

The response surface graph can vividly describe the interaction between the factors. The steeper slope of the response surface indicates that the response value is more sensitive to changes in the ratio. On the contrary, the slope of the curve is gentler, and the change of the ratio has little influence on the response value. The influence of factor interaction on the response value is shown in Figures 8–13 , and from this, we can see the following conclusions.

(1) The interaction surface of the epoxy curing agent mass ratio and phenolic polyamide mass ratio, epoxy curing agent mass ratio and toughening agent content, epoxy curing agent mass ratio, and diluent content is steep, which indicates that the interaction effect on drawing strength is significant. The reason is that the mass ratio of the epoxy resin to the curing agent plays a leading role in the performance of the adhesive, and the effects of different levels of toughener and diluent depend on the level of the mass ratio of the epoxy resin to the curing agent.

(2) The interaction surface of phenolic polyamide mass ratio and toughening agent content, phenolic polyamide mass ratio and diluent content, toughening agent content, and diluent content is gentle, indicating that the interaction on drawing strength is not significant.

As shown in Figure 14, the drawing strength is compared by the test results and the prediction results of the response surface curve model. The results show a good linear relationship, so the model can predict the drawing strength under unknown conditions and seek the optimal solution. Therefore, A is 2.969%, B is 1.903%, C is 2.502%, and D is 1.000%.

In the same way, the shear strength regression equation is analyzed by variance, and based on the model prediction equation, A is 2.977%, B is 1.823%, C is 2.497%, and D is 1.000%. The bending strength regression equation is analyzed by variance, and based on the model prediction equation, the optimal ratio was A is 2.971%, B is 1.940%, C is 2.352%, and D is 1.000%.

On comprehensive consideration of drawing strength, shear strength, and bending strength, using Design Expert software, the three quadratic regression equations are combined. The maximum response value is solved within the variable range of factors, and the optimal ratio of epoxy resin binder is finally obtained. A is 2.971%, B is 1.887%, C is 2.455%, and D is 1.000%.

4. Study on Road Performance of Color Antiwearing Thin Layer

4.1. Adhesion. The adhesion between adhesive and aggregate is an important index to evaluate the antiwater damage and antiloose ability of the color antiwearing thin layer. Therefore, the steel plates are placed in −15°C, 20°C, 60°C, and 70°C environmental boxes for heat preservation, and the

Table 5: Response surface experimental results.

Serial number	Mass ratio of epoxy resin to curing agent	Mass ratio of phenolic amine to polyamide	Toughening agent dosage (%)	Diluent content (%)	Drawing strength (MPa)	Shear strength (MPa)	Bending strength (MPa)
1	3.0	1.5	3.0	2.0	6.14	2.94	81.35
2	3.0	1.5	2.0	1.0	5.98	2.84	79.14
3	2.0	1.0	3.0	2.0	4.36	1.96	55.96
4	3.0	1.0	3.0	1.0	5.47	2.68	71.63
5	2.0	1.5	3.0	3.0	4.14	1.99	52.69
6	3.0	2.0	4.0	2.0	5.56	2.61	72.45
7	3.0	1.5	3.0	2.0	6.07	2.95	80.11
8	3.0	1.5	3.0	2.0	6.10	2.96	81.33
9	3.0	2.0	3.0	1.0	6.49	3.12	86.34
10	3.0	1.5	2.0	3.0	5.05	2.44	65.23
11	3.0	1.5	3.0	2.0	6.11	2.76	81.45
12	3.0	1.0	4.0	2.0	5.51	2.59	74.35
13	4.0	1.5	3.0	1.0	4.28	2.01	56.3
14	3.0	1.5	4.0	3.0	5.62	2.68	74.10
15	4.0	2.0	3.0	2.0	4.39	1.88	58.60
16	4.0	1.5	4.0	2.0	4.44	2.01	57.44
17	2.0	1.5	2.0	2.0	4.41	1.95	58.63
18	2.0	1.5	3.0	1.0	4.57	2.06	60.14
19	4.0	1.0	3.0	2.0	4.08	1.77	54.20
20	4.0	1.5	2.0	2.0	4.36	1.93	57.36
21	3.0	1.5	4.0	1.0	5.83	2.69	76.23
22	3.0	2.0	3.0	3.0	5.25	2.45	69.36
23	2.0	2.0	3.5	2.0	4.49	2.11	58.14
24	3.0	1.0	3.5	3.0	5.11	2.38	66.74
25	3.0	2.0	2.5	2.0	5.76	2.77	75.98
26	2.0	1.5	4.5	2.0	4.30	2.06	56.86
27	3.0	1.0	2.5	2.0	5.41	2.66	71.2
28	4.0	1.5	3.5	3.0	4.06	1.85	53.00
29	3.0	1.5	3.5	2.0	6.00	2.88	80.00

Table 6: Variance analysis of the regression model.

Source	Quadratic sum	Degrees of freedom	Mean square	F-value	P
Model	16.5698	14	1.1836	52.6813	< 0.0001
A-a	0.0363	1	0.0363	1.6158	0.2244
B-b	0.3333	1	0.3333	14.8370	0.0018
C-c	0.0070	1	0.0070	0.3119	0.5853
D-d	0.9577	1	0.9577	42.6272	< 0.0001
Ab	0.0081	1	0.0081	0.3605	0.5578
Ac	0.0090	1	0.0090	0.4017	0.5364
Ad	0.0110	1	0.0110	0.4907	0.4951
Bc	0.0225	1	0.0225	1.0015	0.3339
Bd	0.1936	1	0.1936	8.6173	0.0109
Cd	0.1296	1	0.1296	5.7686	0.0308
A^2	14.8290	1	14.8290	660.0569	< 0.0001
B^2	0.4453	1	0.4453	19.8189	0.0005
C^2	0.3090	1	0.3090	13.7526	0.0023
D^2	0.4581	1	0.4581	20.3903	0.0005
Residual error	0.3145	14	0.0225		
Mismatch items	0.3032	10	0.0303	10.7141	0.0176
Pure error	0.0113	4	0.0028		
Total deviation	16.8843	28			

steel balls are allowed to fall freely from 50 cm to 100 cm heights, respectively. The number of ceramic particles falling is observed. The test results are shown in Figure 15, and from this, we can see the following conclusions.

(1) Ambient temperature has an important influence on the adhesion of epoxy resin adhesive and ceramic particles, and the adhesion of the thin layer decreases at low temperature. At −15°C, the number of ceramic

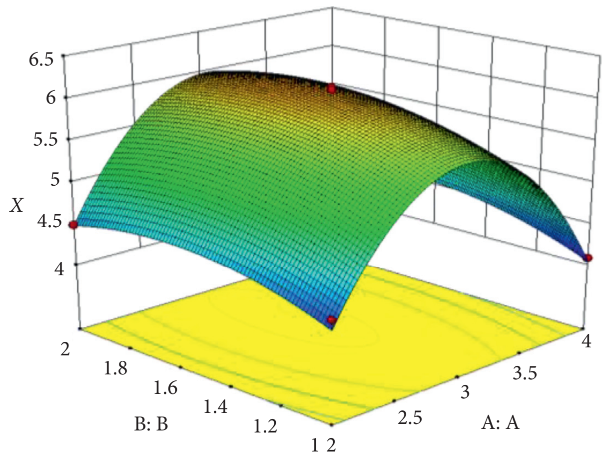

Figure 8: The interaction term AB.

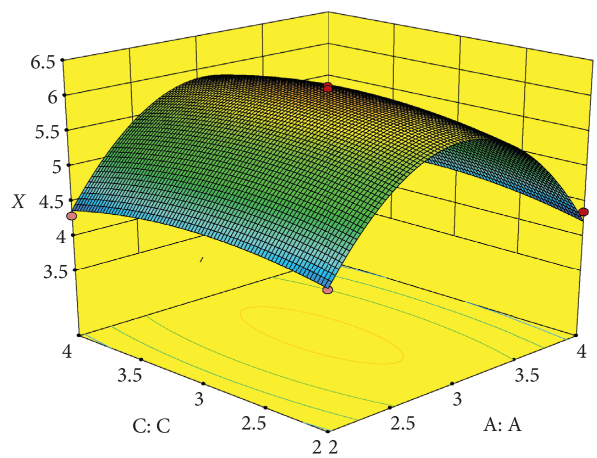

Figure 9: The interaction term AC.

particles falling is 2–10 times that of 20°C, 60°C, and 70°C. This is mainly because the macromolecular chain in the adhesive is frozen under a low-temperature environment, and the crack propagation ability is reduced, and it shows brittle failure under external force. Therefore, winter is the main period for the spalling of the antiwearing thin layer, and the temperature range in an unfavorable season should be considered in the performance evaluation of the antiwearing thin layer.

(2) When the impact load is increased, the adhesion between the epoxy resin adhesive and the ceramic particles decreases, showing that the number of ceramic particles dropped increases. The impact load has a certain temperature sensitivity on the adhesion of epoxy resin adhesive and ceramic particles. When the drop height of the steel ball increases from 50 cm to 100 cm, the number of falling ceramic particles increases by 11 at −15°C. When the temperature exceeds 20°C, the number of ceramic particles dropped increases by 1-2 with the increase of impact load, and the effect of impact load on adhesion decreases.

4.2. Antiwearing Durability. The color antiwearing thin layer is affected by wheel impact and other effects in the use process, and the aggregate will drop and polish, which will affect its use effect, so its antiwearing durability is one of the important performances. Therefore, based on the self-made indoor accelerated wear simulation equipment, different degrees of accelerated wear tests are carried out to test the texture depth and mass loss per unit area after wear. The weight ratio of binder to aggregate is 60 : 40. In the test, the ambient temperature is 30°C, the grounding pressure is 0.7 MPa, and the rotation speed is 60 r/min. The test results are shown in Table 7, and from this, we can see the following conclusions.

(1) With the increase of wear times, the wearing resistance of the color antiwearing thin layer decreases gradually. The texture depth decreases from 1.52 mm to 1.14 mm with only 500 times of wear at the initial

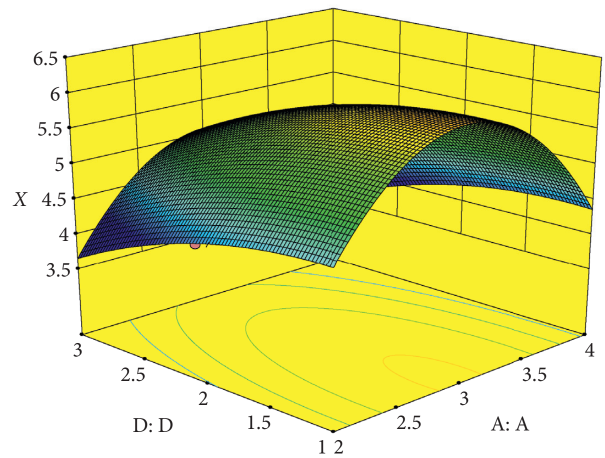

Figure 10: The interaction term AD.

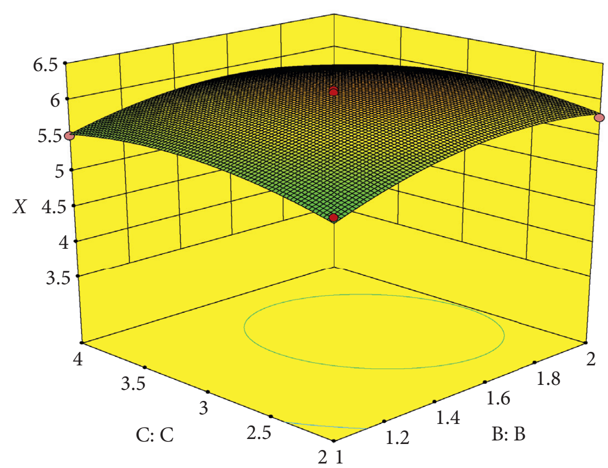

Figure 11: The interaction term BC.

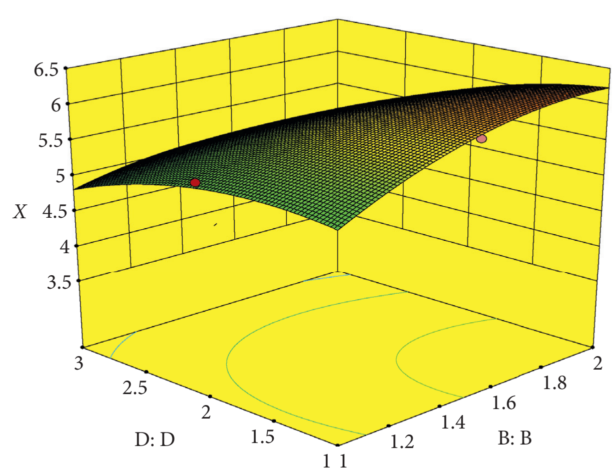

Figure 12: The interaction term BD.

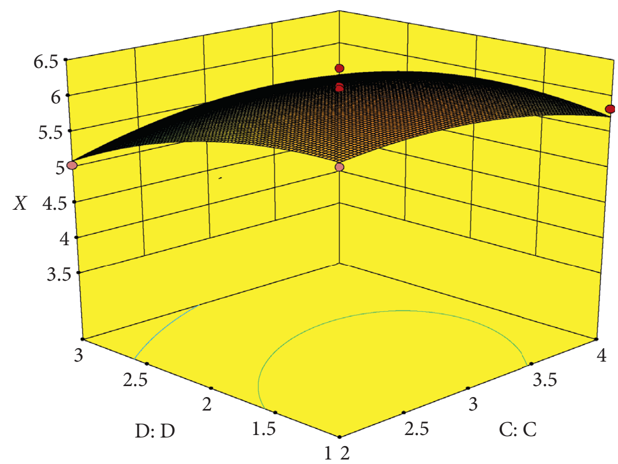

Figure 13: The interaction term CD.

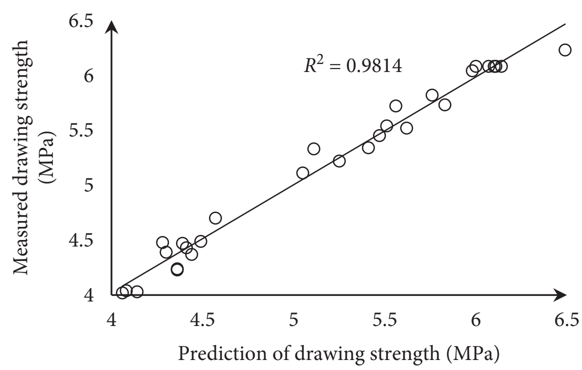

Figure 14: The drawing strength of the test results and the prediction results.

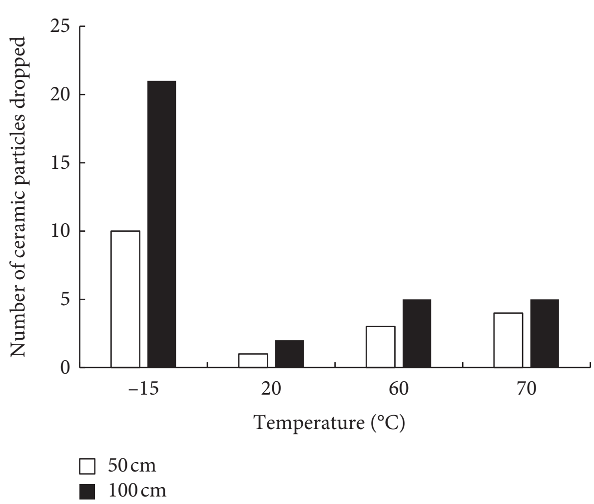

Figure 15: The adhesion of epoxy resin adhesive and ceramic particles.

stage. However, in the later stage, the wear rate is significantly slower, increasing from 500 times to 20,000 times of wear, and the texture depth decreased from 1.14 mm to 0.99 mm (Figure 16). Therefore, the design and evaluation of the antiwearing thin layer should pay attention to the changes in the wear process, rather than focusing on the antiwearing performance at the initial stage.

Table 7: Test results of antiwearing durability.

Wear times	Texture depth (mm)	Mass loss per unit area (g/cm^2)
0	1.52	—
500	1.14	0.015
2000	1.08	0.022
5000	1.03	0.026
10000	1.01	0.028
20000	0.99	0.029

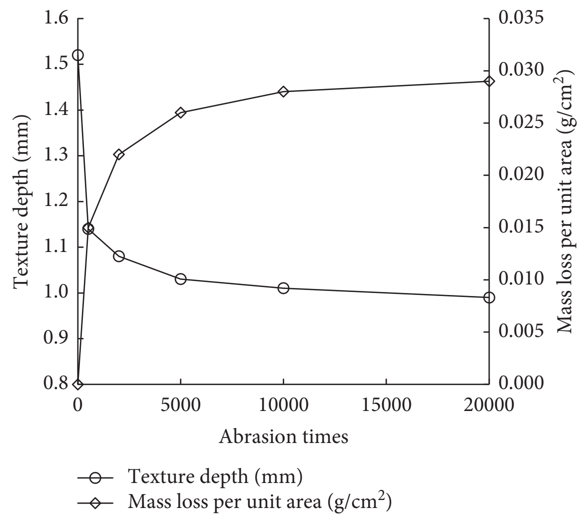

Figure 16: The texture depth and mass loss per unit area of the color nonslip layer under different wear times.

(2) Under the action of traffic load, the wearing resistance performance of the color antiwearing thin layer decreases, which is mainly caused by the drop of aggregate particles in the initial stage, and the mass loss per unit area increases significantly. The mass loss per unit area increases from 0 to 0.015 g/cm^2 after 500 wear times. With the further increase of wear times, the mass loss per unit area slows down, which is mainly caused by the surface structure polishing of ceramic particles.

5. Conclusion

(1) With the increase of the mass ratio of the epoxy resin to the curing agent and the dosage of the toughening agent, the bonding properties and toughness of epoxy resin adhesives were firstly improved and then decreased. The toughening effect of phenolic amine in the curing agent was only reflected in a certain range. When it exceeded this range, the increase of bending strength was limited, while the drawing strength and shear strength decreased slightly. Diluent harmed the mechanical properties of epoxy resin adhesive, but it was recommended to add an appropriate amount of diluent to improve the construction workability.

(2) Based on the response surface optimization results, the recommended mass ratio of the epoxy resin to a curing agent, mass ratio of phenolic amine to polyamide, toughening agent, and diluent were 2.971%, 1.887%, 2.455%, and 1.000%, respectively.

(3) Adhesion tests showed that temperature had a significant effect on the adhesion between the adhesive and the painted ceramic particles. The adhesion of the thin layer was decreased at low temperature, and the sensitivity to impact load was enhanced. However, both aspects were improved when the temperature exceeded 20°C. The accelerated wear test showed that, with the increase of wear times, the structure depth of the color antiwearing thin layer specimen first decreased rapidly and then decreased slowly, and the mass loss per unit area first increased rapidly, then increased slowly, and finally tended to a certain value. This showed that the color antiwearing thin layer could still maintain good skid resistance performance after repeated wear, which provided a guarantee for driving safety.

Data Availability

All the data in this paper are checked, which are obtained from tests in this study, and no other data were used to support this study.

Conflicts of Interest

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

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