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Optimized Proportioning Techniques and Roadway Performance Evaluation of Colored Asphalt Pavement Materials

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Abstract: This study systematically investigated the formulation optimization, performance evaluation, and practical application of epoxy-based composite materials for colored asphalt pavement. By conducting comprehensive experiments, we optimized the composition of epoxy-based composites, verifying their excellent bonding performance, good heat resistance, and UV aging resistance under various temperature conditions. The key optimized component ratios were determined as a 1:1 blend of Type I and Type II epoxy resins, 30 phr of curing agent, 10 phr of toughening agent, 5 phr of diluent, 10% filler, 12% flame retardant, and 10% pigment. At the recommended dosage of 2.0 kg/m^2 of epoxy binder, the composite structure exhibited the best reinforcement effect, improving low-temperature performance significantly. Compared to ordinary asphalt mixtures, the colored pavement composite structure showed superior mechanical strength, deformation capacity, high-temperature stability (dynamic stability approximately three times higher), and water stability (TSR values up to 95.5%). Furthermore, its fatigue life decay rate was significantly lower, with fatigue limit loading frequencies more than three times those of ordinary asphalt mixtures, demonstrating excellent fatigue resistance. This study provides strong technical support and a theoretical basis for the development and practical application of colored asphalt pavement.

Keywords: colored asphalt pavement; pull-out test; fatigue performance; pavement performance evaluation

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1. Introduction

The emergence of colored pavements represents a technological innovation compared to the long-standing tradition of black and white pavements (asphalt and cement concrete). In recent years, driven by the nation's economic development and subsequent improvement in living standards, people have gradually developed visual fatigue towards the monotonous pavement colors in cities. The coordination between uniform pavement colors and the surrounding environment is relatively poor [1]. Under intense work pressure, individuals have begun to demand higher levels of harmony between roads and the environment, thus giving birth to colored pavements. As a novel pavement technology, colored pavements not only alleviate driving fatigue but also enhance road comfort and safety, garnering widespread attention both domestically and internationally [2,3]. Currently, colored pavements have been extensively applied in developed countries abroad, breaking the long-held tradition of black and white asphalt and cement concrete pavements with their rich palette of colors. Especially in urban settings, colored pavements not only beautify the environment and provide a pleasant visual experience but also guide traffic, making urban transportation more user-friendly [4,5].

Colored pavements can be classified into three categories based on construction techniques: hot-mix colored asphalt concrete, colored resin ceramic particle anti-skid thin-layer, and colored micro-surfacing [6]. Among these, colored micro-surfacing is the most economical in terms of cost. However, it has been challenging to effectively promote this technology due to difficulties in emulsifying light-colored synthetic asphalt, particularly given the low selectivity of resins and the need for improvement of the performance of light-colored emulsified asphalt [7]. As a new pavement technology, colored pavements originated in Europe and the United States in the 1950s and gradually spread to other countries [8,9]. Currently, colored asphalt pavements are widely used in economically developed countries abroad, with notable examples including the United Kingdom, France, and the Netherlands. In South Korea, Rang W. Lee and Ju Won Kim developed a light-yellow polymer epoxy adhesive, demonstrating its good compatibility with colored aggregates through comparative experiments, such as Marshall stability tests, rutting tests, and accelerated aging tests [10]. The Strategic Highway Research Program (SHRP) in the United States analyzed various methods for bridge deck repair, concluding that the application of epoxy anti-skid layers can extend the deck's lifespan by at least ten years [11]. Liu et al. studied the paving methods and performance of epoxy anti-skid layers used in bridge deck paving, confirming their excellent practicality and mechanical strength for pavement applications [12,13]. Based on research conducted in the United States and other developed countries, Japan proposed innovative solutions and improvements tailored to actual road environments. They conducted extensive research on epoxy pavement layers, focusing on their application in particular, and introduced guidelines for the construction of colored anti-skid thin layers to facilitate their use in certain areas, such as sharp road curves, steep highway slopes, tunnel entrances and exits, and highway tollbooth entrances [14,15]. Additionally, Aliha et al. studied the causes of early-stage failures in colored pavements, such as aggregate detachment, surface discoloration, and delamination. They proposed further improvements to colored anti-skid surface paving technology, effectively enhancing the construction process using the fusion spray method [16,17].

Tang conducted research on the aging composition and performance of colored asphalt. They studied the performance changes of self-made 90# colored road asphalt during aging at different temperatures (150 °C, 163 °C, 180 °C) within 30 h using the asphalt four-component analysis method [18]. Yang and others investigated the influencing factors of surface color changes in colored asphalt with different pigment contents under various aging conditions. The analysis results showed that bright asphalt and a 5% pigment content exhibited better color effects, with red pigments demonstrating stronger resistance to ultraviolet radiation [19,20]. Petrukhina conducted Marshall tests, which indicated that certain pigments could cause asphalt mixtures to loosen after being immersed in water, which had a significant impact on their water stability. Through indoor ultraviolet radiation simulation tests, it was found that the influence of ultraviolet radiation on the color of asphalt mixtures was more pronounced in the early stages of the experiment. After 4 days of exposure, the color of the test pieces gradually became darker and duller, but after that, the color changes were no longer significant and tended to stabilize [21,22]. Gao used colored SBS-modified emulsified asphalt as a binder, added a certain amount of colored mineral aggregate and admixtures to prepare the colored micro-surfacing, and conducted mix design, road performance tests, and test section paving. The test results showed that its road performance was good and met the requirements of urban roads [23]. Chen analyzed the factors affecting the color durability of colored pavements and conducted conventional asphalt and aggregate adhesion tests as well as aging tests on colored asphalt, stone types, and environmental impacts. The results indicated that improving the adhesion between colored binders and aggregates was beneficial for improving the color durability of colored asphalt pavements [24]. Liu studied the application performance of bisphenol A epoxy adhesives and analyzed the key influencing factors of the performance of epoxy-based composites [25]. Mirzaei and others investigated the performance of epoxy anti-skid pavement materials, estimated the fatigue life, and explained how external environments, vehicle loads, and friction affected the degree of colored aggregate spalling. Increasing the temperature, load, and friction can aggravate the loss of colored aggregates [26]. Mirzaei conducted pull-out tests and accelerated wear tests on polyurethane epoxy resin wear test pieces. The research showed that the epoxy thin layer exhibited excellent pull-out strength, interlayer adhesion, and anti-skid performance, meeting the requirements of heavy traffic for overlay applications and being suitable for various concrete pavement overlays [26]. Sun conducted a follow-up investigation on the use of epoxy resin materials in the Gezhouba project, and the results showed that the epoxy adhesive had good waterproof performance [27]. Lee studied the fatigue resistance, adhesion, and low-temperature performance of bridge deck pavement layers using DLERA epoxy glue, demonstrating its wide application value in the field of bridge deck pavement [28].

Currently, there is a lack of national guidelines in China for quality control and construction technology guidance for colored pavement overlays. The performance of road binders and colored aggregates shows difficulty meeting the practical engineering application requirements, which is mainly due to poor mechanical properties, bonding properties, workability, road durability, and UV aging resistance. After colored pavement overlays are applied, diseases, such as rutting, cracking, spalling, and delamination, often appear within one to two years, indicating a certain gap between domestic and foreign paving materials and construction technologies. Therefore, based on previous research experience, this article comprehensively considers certain issues, such as traffic loads, tunnel environments, and economic applicability. The purpose of this study is to systematically explore the application of epoxy-resin-based composite materials in colored asphalt pavement, including formula optimization, performance evaluation, and practical application effects. The specific scope covers the following aspects: firstly, optimizing the proportion of epoxy resin composite materials through comprehensive experimental methods in order to obtain materials with excellent bonding performance, good heat resistance, and UV aging resistance; secondly, evaluating the physical and mechanical properties of the composite material under different temperature conditions, including tensile performance, low-temperature crack resistance, high-temperature stability, water stability, and fatigue performance; and, finally, combined with engineering practice, verifying the practical application effect of the material in colored asphalt pavement and thus providing a theoretical basis and technical support for its promotion and application in road traffic construction. This study not only contributes to improving the overall performance of colored asphalt pavement but also promotes technological progress and innovative development in the field of road engineering.

2. Materials and Methods

2.1. Materials

The epoxy-based composite material that was used in colored pavements was a multi-component system consisting primarily of epoxy resin, curing agent, toughening agent, diluent, filler, flame retardant, and trace amounts of additives. The rational proportioning of these components constituted a curing system that was not only outstanding in toughness and high in strength but also highly reactive. This optimized combination ensured that the epoxy binder exhibited good viscosity in its initial state, thereby enhancing its adhesion to asphalt pavements.

2.1.1. Epoxy Resin

Epoxy resins, named for the presence of two or more epoxy groups within their molecules, were widely used as the fundamental components of polymeric materials, such as adhesives and coatings. When combined with a curing agent, epoxy resins underwent chemical reactions that resulted in the formation of a robust three-dimensional cross-linked network, classifying them as thermosetting polymers. Among the various types of epoxy resins, bisphenol A-type resins stood out due to their cost-effectiveness, low curing shrinkage, and excellent corrosion resistance. However, Type I bisphenol-A-based epoxy resin exhibited low viscosity and was prone to crystallization when used alone, while Type II resin had higher viscosity and poor workability during construction. To address these issues, this study employed a blending strategy that involved the combined use of two epoxy resins with different molecular weights in a specific ratio. This blending approach not only enhanced the bond strength but also effectively inhibited crystallization and reduced shrinkage. The material used is produced by South Asia Epoxy Resin (Kunshan) Co., Ltd., Suzhou. Detailed technical specifications for both types of epoxy resins are provided in Table 1.

Table 1. Main technical parameters of epoxy resins [28].

Test Items	I	Technical Requirements	II	Technical Requirements
Epoxy equivalent (g/eq, 0.1 mm)	72.3	60~80	92.6	80~100
Volatile matter (%)	0.091	≤2.2	0.236	≤2.2
Viscosity (mPa·s, 25 °C)	42,210	30,000~50,000	36,520	≥100

2.1.2. Curing Agent

The curing agent, also known as the hardener, played a crucial role in epoxy binders. It chemically reacted with the epoxy groups and hydroxyl groups in the epoxy resin, initiating cross-linking. It is worth noting that the epoxy resin itself was a thermoplastic polymer that did not possess curing capabilities under normal or heated conditions and thus could not directly exhibit mechanical strength and durability. To impart practical value to the epoxy resin, it had to undergo a curing process in the presence of a curing agent and other additives to form a cured product with a three-dimensional, cross-linked network structure. In this study, a modified polyamine known as T31 was selected as the curing agent. The materials used are produced by Jiaxing Nanyang Wanshixing Chemical Co., Ltd. This curing agent significantly enhanced the curing speed of the epoxy resin, meeting the requirements of practical processes. Detailed technical parameters of the curing agent are provided in Table 2. The curing agent chemically reacted with the epoxy groups in the epoxy resin, forming a robust, three-dimensional, cross-linked network structure. This reaction not only imparts mechanical strength but also enhances the durability and heat resistance of the cured product.

Table 2. Main technical parameters of the T31 curing agent.

Test Items	Measured Values	Technical Indicators	Test Method [29]
Viscosity (mPa·s, 25 °C)	340	Measured	GB/T 2794-2013
Density (g/cm^3, 20 °C)	1.08	Measured	GB/T 29617-2013
Flash point (°C)	75	Measured	JTG F40-2004
Amine value (mKOH/g)	360	Measured	Chemical titration
Volatile matter	0.286	Measured	GB/T 30982-2014

2.1.3. Toughening Agent

To optimize the performance of the epoxy binder, particularly in reducing its brittleness after curing and enhancing the bond strength while maintaining the stability of other properties, the addition of an appropriate toughening agent was crucial. In this context, 700 low-molecular-weight polyamide was selected as the toughening agent. Its molecular ends also contained primary and secondary amine hydrogens, which could effectively react with epoxy groups to generate stable, cured products. Furthermore, 700 low-molecular-weight polyamide contained unsaturated bonds and longer fatty acid carbon chains, resulting in larger intermolecular spacing. Therefore, during the curing process, its product exhibited a lower density, imparting good toughness and flexural resistance to the cured product. These characteristics made 700 low-molecular-weight polyamide an ideal choice for improving the performance of epoxy binders. The addition of a low-molecular-weight polyamide toughening agent improved the flexibility and toughness of the cured epoxy resin by increasing its elongation and reducing brittleness. The toughening agent used is produced by South Asia Epoxy Resin (Kunshan) Co., Ltd. The molecular ends of the toughening agent react with the epoxy groups, contributing to the formation of a more ductile cured product. Detailed technical parameters of this toughening agent are provided in Table 3.

Table 3. Main technical parameters of curing agent [25].

Test Items	Measured Values	Technical Indicators	Test Method
Viscosity (mPa·s, 40 °C)	22,000	15,000~30,000	GB/T 2794-2013
Amine value(mg KOH/g)	245	210~250	Chemical titration method
Density (g/cm^3, 20 °C)	0.95	Measured	GB/T 29617-2013
Solids content (%)	98	96~100	GB/T 6740-1986

2.1.4. Diluent

To enhance the fluidity and coating performance of the binder and to improve the wetting and penetration capabilities of the epoxy adhesive on the pavement surface, leading to increased bond strength, the addition of a diluent was an effective solution. In this study, 1,6-Hexanediol diglycidyl ether (Y-162) was selected as the diluent. The diluent enhances the fluidity of the epoxy mixture, facilitating its application and penetration into the asphalt surface. However, excessive diluent can reduce the cross-link density of the cured product, impacting its mechanical properties. The diluent is produced by Jinan Chenwang Chemical Technology Co., Ltd. Detailed technical parameters of this diluent are provided in Table 4.

Table 4. Main technical parameters of diluent [30].

Test Items	Actual	Technical Indicators
Appearance	Colorless, transparent liquid	Colorless, transparent liquid
Viscosity (mPa·s, 25 °C)	15~25	Measured
Epoxy value (eq/100 g)	0.65~0.69	Measured
Organ ochlorine (eq/100 g)	0.012	≤0.02
Moisture content (%)	0.03	≤0.1

2.1.5. Flame Retardant

In this study, a composite halogen-based flame retardant (DBDPE/AO) was employed. This flame retardant combined the advantages of multiple flame retardant components, providing stable flame retardant effects in various environments. Fillers increase the viscosity and cohesive force within the asphalt mixture, improving its stability at high temperatures. The flame retardant provides additional safety by inhibiting the spread of fire in case of an incident. The flame retardant is produced by Dongguan Taiyang New Material Technology Co., Ltd. Tables 5 and 6 outline the technical specifications of the flame retardant material, including key parameters, such as its physical properties, chemical properties, and flame retardant performance.

Table 5. Main technical parameters of Decabromodiphenylethane [15].

Test Items	Technical Requirements	Actual
Bromine content (%)	≥81	82.8
Whiteness (%)	≥88	93.6
Thermal loss on weight (0.5%, °C)	≥305	329
Melting point (°C)	≥340	353
Average particle size (µm)	≤5.0	2.9

Table 6. Main technical parameters of antimony trioxide [23].

Test Items	Technical Requirements	Actual
Sb_2O_3 content (%)	≥99.8	99.9
Whiteness (%)	≥95	96.7
Melting point (°C)	≥650	659
Average particle size (µm)	0.5–1.3	0.7

2.1.6. Pigment

Due to the unique nature of colored pavement materials, the selection of pigments had to meet a series of demanding conditions, including high temperature resistance, good light stability, and strong hiding power and coloring power. In this study, a high-performance inorganic pigment, iron oxide pigment, was selected. The materials used are produced by Hefei Lantu Pigment Co., Ltd. The technical specifications are shown in Table 7.

Table 7. Main technical parameters of iron oxide pigments [22].

Test Items	Technical Requirements	Actual Measurement Value
Fe_2O_3 content (%)	≥86	91
Density (kg/cm^3)	400~600	465
Melting point (°C)	350~400	384
PH	3~7	4.5
Particle size (mesh)	600~700	632
Coloring strength (%)	95~105	100

2.2. Preparation Process of Epoxy-Based Composite Materials

2.2.1. Preparation Process

To prepare the colored epoxy binder, a high-shear emulsification and polymer compositing method was utilized. Initially, two types of epoxy resins were warmed to 4 °C for two hours to improve their fluidity, which facilitated the subsequent mixing steps. Following this thermal treatment, the required amount of epoxy resin was precisely measured based on the predetermined formulation ratio and introduced into the reaction vessel. Next, the diluent and toughening agent were sequentially added to the vessel, adhering to the specified proportioning requirements.

Manual stirring was initially performed for approximately four minutes to obtain an initial mixture, referred to as Epoxy Mixture I. However, due to the significant increase in viscosity after the addition of flame retardants and fillers, manual stirring became insufficient to achieve uniform dispersion. Therefore, the temperature was carefully maintained at approximately 35 °C, and a high-shear mixer was employed at a rotational speed of around 4500 r/min. After about eight minutes of high-shear mixing, it was verified that the smaller particle size fillers and components were evenly distributed in the mixture, designated as Epoxy Mixture II.

Finally, a specified quantity of curing agent and pigment were introduced into the mixture, and high-shear stirring was continued for an additional six minutes. This additional stirring step aimed to ensure complete dissolution and homogeneous distribution of all components within the mixture. Upon achieving a uniformly colored epoxy binder, stirring was promptly halted.

2.2.2. Compounding of Epoxy Resins

As shown in Table 8, when the proportion of Type II epoxy resin gradually increased (from 1:4 to 4:1), the tensile strength exhibited an overall decreasing trend. It is worth noting that when Type I epoxy resin was used alone (0:1), the tensile strength was the lowest at only 11.0 MPa. However, when compounded with Type II epoxy resin, even at a lower proportion, the tensile strength was significantly improved. This indicates that the addition of Type II epoxy resin has a positive effect on enhancing the tensile strength of the epoxy resin material. As the proportion of Type II epoxy resin increased, the elastic modulus also showed a gradually decreasing trend. This suggests that the addition of Type II epoxy resin makes the material more prone to deformation under stress, i.e., the material's flexibility is improved. However, it should be noted that when the proportion of Type II epoxy resin is too high (e.g., 1:0), the elastic modulus increases again, which may be due to the greater stiffness of Type II epoxy resin itself. With the increase in the proportion of Type II epoxy resin, the elongation showed a clear downward trend. This indicates that the addition of Type II epoxy resin can significantly improve the ductility of the epoxy resin material, allowing it to undergo larger deformations without breaking during the stretching process.

Table 8. Relationship between the dosage of two types of epoxy and tensile properties.

Distribution (II:I)	Tensile Strength (MPa)	Elastic Modulus (MPa)	Elongation (%)
1:0	20.6	516	5.1
4:1	20.1	489	6.0
3:1	19.3	449	6.5
2:1	18.3	420	7.8
1:1	17.0	365	9.7
1:2	15.1	312	10.9
1:3	14.1	265	12.3
1:4	13.2	232	13.2
0:1	11.0	216	13.5

An analysis of Table 8 reveals that the addition of Type II epoxy resin has a positive impact on enhancing the tensile properties and ductility of the epoxy resin material. However, an excessively high proportion of Type II epoxy resin may lead to an increase in the material's stiffness. Therefore, compounding Type I and Type II epoxy resins in a 1:1 ratio achieves greater strength and toughness while balancing the mechanical properties and processability of the material. Lee et al. [10] developed a light-yellow polymer epoxy adhesive in Korea that demonstrated good compatibility with colored aggregates. That adhesive shares similarities with the one used in this study in terms of using an epoxy-based material to enhance the durability and mechanical properties of colored pavement. However, this study focused on optimizing the formulation to achieve specific performance targets, including UV aging resistance and heat resistance, which were not explicitly mentioned in the work by Lee et al.

Another relevant study by Mirzaei et al. [26] investigated the fatigue life and performance of epoxy anti-skid pavement materials. Although their focus was not directly on colored pavement, the results provide valuable insights into the fatigue behavior of epoxy-based materials under varying conditions. The colored epoxy pavement exhibited a comparable fatigue life to the epoxy pavement materials, with further advantages at lower temperatures.

2.2.3. Dosage of Curing Agent

The experiment employed phr (parts per hundred parts of resin, referring to the ratio unit of adding 1 g of additive per 100 g of epoxy resin) as the unit for measuring the proportion of the curing agent. Epoxy binders were prepared, and tensile test specimens were produced to evaluate the effects of varying curing agent content on the tensile properties and curing time. The experimental results are presented in Figure 1.

Upon analyzing the data, a subtle relationship between the amount of curing agent and the tensile performance of the epoxy resin was observed, along with a trend in curing time as a function of the curing agent dosage. As the amount of curing agent increased, the tensile strength exhibited a marked upward trend, rising from 5.8 MPa at 5 phr to 18.1 MPa at 45 phr. This significant improvement in tensile strength can be attributed to the curing agent's ability to open the epoxide rings, initiate chemical reactions, and form a cross-linked network structure, thereby enhancing the mechanical properties of the material.

Similarly to the tensile strength, the elastic modulus also increased with the addition of more curing agent, rising from 30 MPa at 5 phr to 474 MPa at 45 phr. This increase indicates that the material's stiffness increases as the cross-linked network structure becomes more pronounced, making it more resistant to deformation under stress.

Concurrently, as the amount of curing agent increased, the elongation showed a decreasing trend, dropping from 16.1% at 5 phr to 7.9% at 45 phr. This suggests that the material's flexibility decreases with the addition of more curing agent. Taking into account the tensile test results, the curing time, and economic considerations, a dosage of 25 phr for the T31 curing agent was selected.

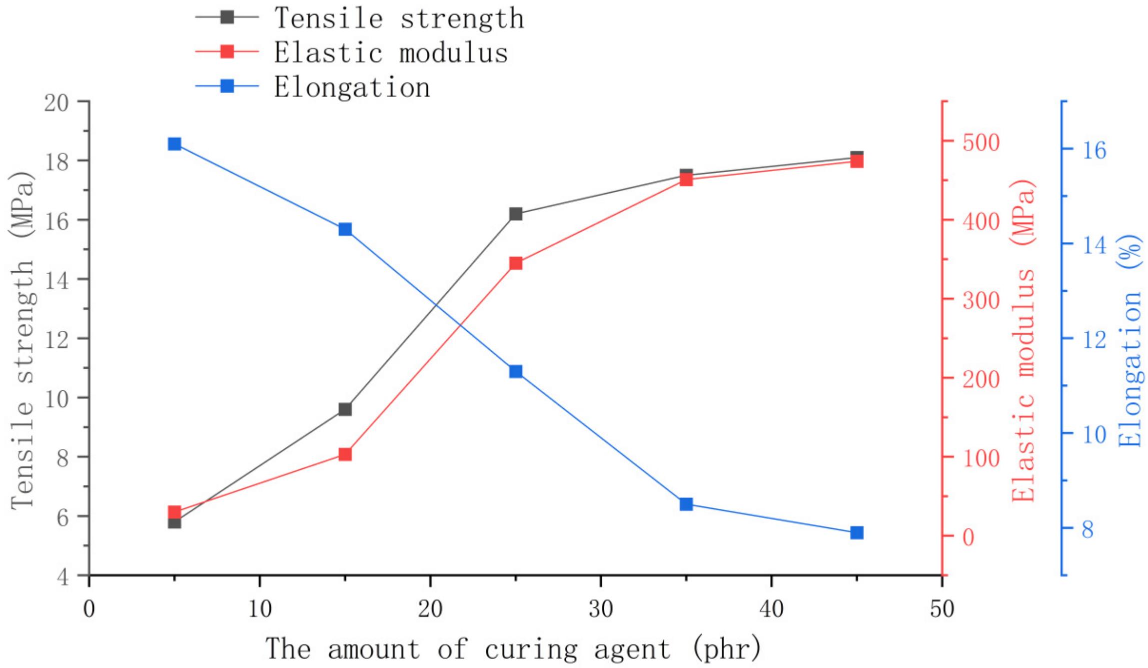

Figure 1. Relationship between curing agent content and tensile properties.

2.2.4. Dosage of Toughening Agent

In the experiment, a 1:1 mixture of epoxy resins I and II was used as the matrix, with a fixed curing agent dosage of 25 phr. Different amounts of toughening agent (0 phr, 10 phr, 20 phr, 30 phr) were added for preparation. The results are presented in Figure 2.

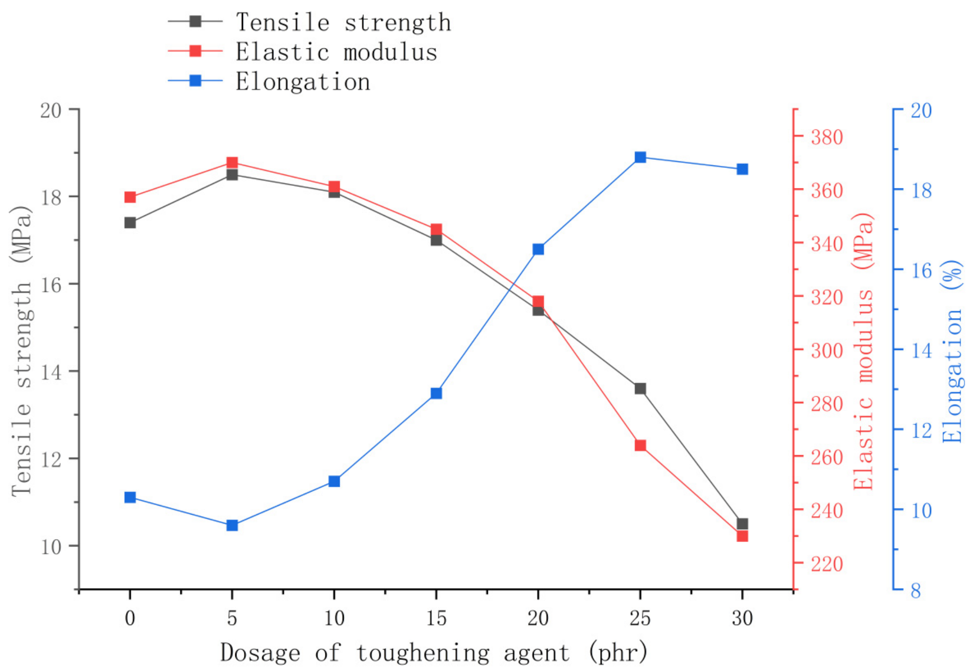

Figure 2. Relationship between the amount of toughener and tensile properties.

With increasing toughening agent content, the tensile strength exhibited an initial increase followed by a decrease. At a toughening agent dosage of 5 phr, the tensile strength reached a maximum of 18.5 MPa, which was an improvement compared to the control group without any toughening agent (17.4 MPa). However, as the toughening agent content continued to increase, the tensile strength began to gradually decrease, reaching a minimum of 10.5 MPa at 30 phr. This indicates that an appropriate amount of toughening agent can enhance the tensile strength of epoxy resin, but excessive addition can lead to a significant decline in its tensile properties.

Similarly to the tensile strength, the elastic modulus also showed an initial increase followed by a decrease with increasing toughening agent content. It reached a maximum of 370 MPa at 5 phr and then gradually decreased. The decrease in the elastic modulus became more pronounced when the toughening agent content exceeded 15 phr. This suggests that the addition of the toughening agent altered the stiffness characteristics of the epoxy resin to some extent, making it more prone to deformation under stress.

As the amount of toughening agent increased, the elongation exhibited a continuous increasing trend. It rose from 10.3% in the control group to 18.5% at 30 phr of toughening agent, indicating a significant improvement. This demonstrates that the addition of the toughening agent effectively enhanced the flexibility of the epoxy resin, allowing it to undergo greater deformation without fracturing during the tensile process.

However, after exceeding a certain range of toughening agent content, the increase in elongation may no longer be significant, while the decrease in tensile strength and elastic modulus may become the dominant concern. Polyamide, as a toughening agent for epoxy resin, can significantly improve the toughness of the cured product. Taking into account certain factors, such as the comprehensive strength, elongation, and the economy, it was determined that the optimal dosage of the toughening agent is 15 phr.

2.2.5. Dosage of Diluent

According to the results presented in Figure 3, it is observed that tensile strength gradually decreases with an increase in the amount of diluent used. Specifically, the tensile strength decreased from 16.2 MPa without any diluent to 14.9 MPa with the addition of 20 phr of diluent. This suggests that the incorporation of the diluent, to some extent, diminishes the tensile strength of the epoxy cured product. This could be attributed to changes in the cross-link density or molecular structure of the epoxy cured product induced by the addition of the diluent, thereby affecting its mechanical properties.

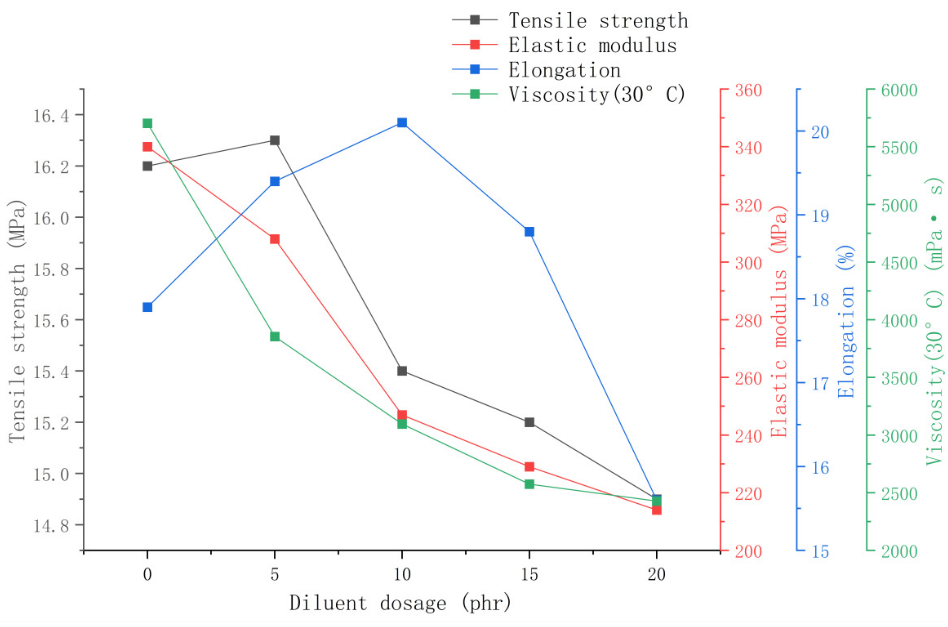

Figure 3. Relationship between the amount of diluent and tensile properties and viscosity.

Similarly to the tensile strength, the elastic modulus also exhibits a decreasing trend with increasing diluent content. It decreased from 340 MPa without any diluent to 214 MPa with 20 phr of diluent. This indicates that the addition of the diluent makes the epoxy cured product more prone to deformation under stress, i.e., its stiffness is reduced.

The elongation initially increases and then decreases with increasing diluent content, reaching a maximum of 20.1% with the addition of 10 phr of diluent before gradually declining. This suggests that an appropriate amount of diluent can enhance the flexibility of the epoxy cured product, but excessive addition can lead to a decrease in flexibility.

Concurrently, there is a notable decrease in viscosity with increasing diluent content. The viscosity decreased from 5703 mPa·s without any diluent to 2428 mPa·s with 20 phr of diluent. This demonstrates that the incorporation of the diluent effectively reduces the viscosity of the epoxy cured product, improving its flowability. This is of significant importance for the application and curing process of epoxy binders in engineering construction.

In summary, the diluent has a significant impact on the tensile properties and viscosity of the epoxy cured product. With increasing diluent content, there is a gradual decrease in the tensile strength and the elastic modulus, with an initial increase followed by a decrease in elongation and a marked reduction in viscosity. Therefore, in practical applications, it is necessary to consider both mechanical properties and construction requirements to select an appropriate amount of diluent. Taking into account certain factors, such as comprehensive mechanical properties and economic indicators, it is determined that the optimal dosage of the diluent is 10 phr.

2.2.6. Dosage of Flame Retardant

Figure 4 illustrates the relationship between the dosage of flame retardant and tensile properties. As the amount of flame retardant increases, the tensile strength exhibits a trend of initial increase followed by a decrease. At a flame retardant dosage of 10 wt%, the tensile strength reaches a maximum of 21.5 MPa, which is an improvement compared to the control group without any flame retardant (20.2 MPa). However, when the amount of flame retardant continues to increase, the tensile strength begins to gradually decrease, reaching a minimum of 11.6 MPa at 40 wt%. This suggests that an appropriate amount of flame retardant can enhance the tensile strength of the epoxy binder to some extent, but excessive addition can lead to a significant decline in its tensile performance.

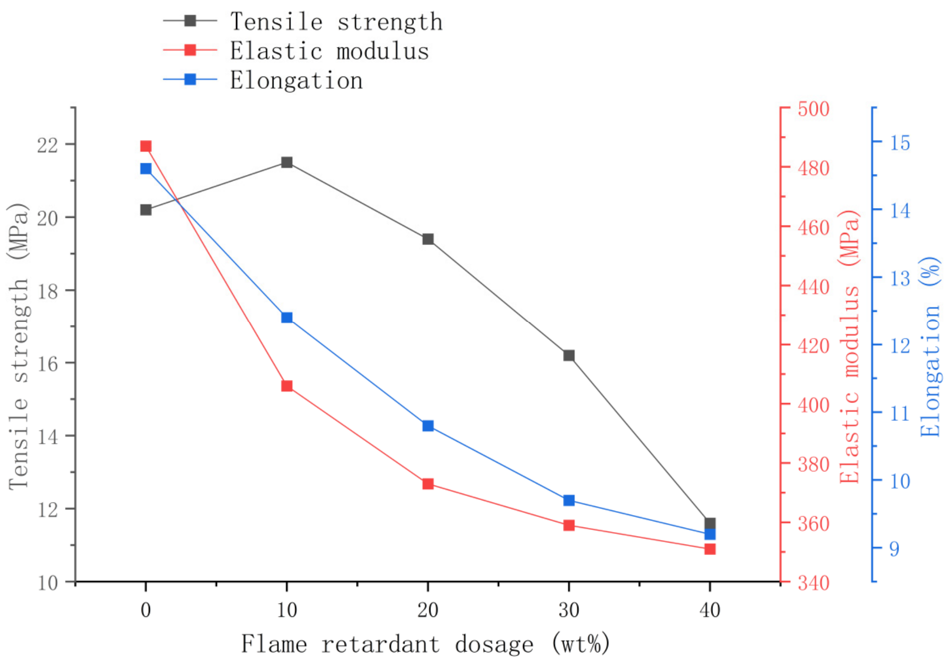

Figure 4. The relationship between the amount of flame retardant and tensile properties.

Concurrently, as the flame retardant dosage increases, the elastic modulus exhibits a continuous decreasing trend. It decreases from 487 MPa in the control group to 351 MPa at a 40 wt% flame retardant dosage, indicating a significant reduction. This suggests that the incorporation of the flame retardant has a certain degree of negative impact on the stiffness of the epoxy binder, making the material more prone to deformation under stress.

Similarly, the elongation also shows a decreasing trend with increasing flame retardant dosage. It decreases from 14.6% in the control group to 9.2% at a 40 wt% flame retardant dosage, which is a notable reduction. This indicates that the addition of the flame retardant reduces the flexibility of the epoxy binder, making it more susceptible to fracture during the stretching process.

Although the incorporation of composite flame retardants can have an impact on the mechanical properties of epoxy binders, by controlling the dosage of flame retardant within the range of 10~20%, a minimal impact on the mechanical properties of epoxy binders can be achieved.

2.3. Experimental Methods

2.3.1. Tensile Test

The tensile properties of the epoxy resin binder, including the tensile strength, elongation, and tensile modulus, were measured using a SUNS universal testing machine. Additives, such as diluent, filler, toughening agent, and curing agent, were incorporated into the epoxy matrix in specific proportions and mixed thoroughly. To eliminate air bubbles in the mixture, it was allowed to stand for 6 min. Subsequently, Vaseline was applied as a release agent inside of the dumbbell-shaped test mold, and the prepared mixture was poured into the mold while controlling the thickness of the colloid. The test mold was then placed on a leveled test bench, relying on the fluidity of the colloid to self-level, as shown in Figure 5.

Figure 5. Dumbbell-shaped specimen after pouring.

At least five sets of test samples were formed under the same experimental conditions. After curing the samples for 7 days at room temperature (25 ± 3) °C, tensile tests were conducted according to the standard GB/T 1040-2006 “Plastics—Determination of Tensile Properties”. During the tensile process, a tensile grip with a gauge length of 50 mm was used, and the cross-sectional area of the sample was calculated by measuring the thickness and width at three different locations within the gauge length. To ensure the accuracy of the test, the centerline of the tensile grip was aligned with the central axis of the sample to minimize the impact of eccentric forces on the test results.

During the tensile test conducted at room temperature, the sample was stretched at a constant mechanical speed of 5 mm/min until fracture. By recording the maximum failure load, the elongation, and the load increment and corresponding deformation increment in the initial linear region of the load–deformation curve, the tensile properties of the epoxy resin binder could be comprehensively evaluated, as shown in Figure 6.

Figure 6. Tensile experiment.

2.3.2. Low-Temperature Bending Test

To evaluate the performance of the colored pavement composite structure with different amounts of epoxy binder at low temperatures, an asphalt mixture bending test method was adopted. Dosages of 1.0 kg/m^2, 1.5 kg/m^2, 2.0 kg/m^2, and 2.5 kg/m^2 were used, respectively. Based on construction experience, 3 kg/m^2 of colored ceramic aggregate was evenly spread on the surface of the test specimens as the epoxy anti-slip layer. Subsequently, the specimens were cured at room temperature for 24 h to ensure they met the specified strength requirements. The specimens were then placed in a refrigerator at −10 °C and continuously monitored until they fully reached the desired low-temperature state for the test. After removing the specimens from the refrigerator, they were installed on the test support, and a load was applied at a rate of 50 mm/min while continuously observing the deformation and failure of the specimens.

2.3.3. Water Stability Performance

The water stability performance of colored pavements with different amounts of epoxy binder was evaluated using a freeze–thaw splitting test. This test used the freeze–thaw splitting strength ratio (TSR) as the main evaluation index to effectively measure the water stability of the pavement. Cylindrical test specimens of AC-13 asphalt mixture with a diameter of 100 mm and a height of 50 mm were prepared using the compaction method. After the specimens cooled, a colored epoxy anti-slip surface layer was applied to ensure that the specimens' dimensions and the preparation process met the standards. The prepared specimens underwent freeze–thaw cycling to simulate the harsh environments that real pavements may encounter.

2.3.4. Fatigue Performance

An indirect tensile splitting test method was adopted to evaluate fatigue performance. This method tests the ability of pavement materials to resist repeated loads without failure by simulating the actual force conditions they encounter during use. Composite structure samples consisting of a colored epoxy surface layer and an asphalt mixture were prepared. The size and shape of the samples should meet the test requirements to ensure the accuracy of the test results. The samples should be cured under standard conditions to the specified strength to ensure that their state during testing is similar to that of actual pavement use. The UTM-30 multifunctional asphalt material testing machine was used for the fatigue loading test. This equipment can precisely control the loading rate and the load size, thus simulating the repeated loads that actual pavements endure. The samples were installed on the testing machine, ensuring alignment with the loading device to eliminate the influence of eccentric loading on the test results. Cyclic loads were applied according to a predetermined loading program. The size and frequency of the loads should simulate the actual pavement usage conditions. During loading, the deformation and failure of the samples were monitored in real time. Displacement sensors and force sensors are typically used to measure the displacement and load of the samples, thus recording the stress–strain curve of the samples during loading. Fatigue tests were conducted at different temperatures to assess the impact of temperature on the fatigue performance of the composite structure. Representative temperature points of 10 °C, 30 °C, and 50 °C were chosen, representing low, ambient, and high-temperature environments, respectively. The test loading rate was set at 50 mm/min to study the fatigue life of the composite structure under different stress levels. The stress ratio is defined as the ratio of the minimum stress to the maximum stress during loading. Four parallel tests were conducted under different stress and temperature conditions. Before the tests, the samples were kept at the test temperature for at least 3 h.

3. Results and Discussion

3.1. Pull-Out Test

As indicated in Figure 7, with the increase in the application rate of epoxy binder, the pull-out strength also exhibits an increasing trend. However, under all test conditions, adhesive failure occurred between the epoxy coating and the asphalt surface layer. This suggests that under the current experimental conditions, the interfacial bond strength between the epoxy binder and the asphalt mixture is a critical factor limiting the overall adhesive performance.

When the epoxy binder dosage is 2 kg/m^2, the average bond strength of the coating reaches 2.62 MPa, showing significant growth compared to lower dosages. This indicates that increasing the amount of epoxy binder within a certain range can significantly improve the adhesive performance of the epoxy anti-slip surface layer. This may be because a greater amount of epoxy binder can better wet and cover the surface of the asphalt mixture, forming a stronger adhesive force and thus increasing the bond strength. However, when the epoxy binder dosage exceeds 2 kg/m^2, the growth in the bond strength gradually slows down. This may be due to the saturation of the epoxy binder coverage on the asphalt mixture's surface after reaching a certain dosage, and further increasing the dosage does not lead to a significant improvement in bond strength. In addition, excessive epoxy binder may result in an overly thick coating, which can somewhat reduce the adhesive performance.

It is worth noting that all failures in the pull-out tests of the epoxy pavement layers are adhesive failures. This failure mode directly reflects the interfacial bond performance between the epoxy anti-slip surface layer and the asphalt mixture. Therefore, these test results provide valuable insights for analyzing the adhesive performance of the epoxy anti-slip surface layer and further confirm the effectiveness of improving adhesive performance by increasing the amount of epoxy binder. Considering both the cost of epoxy coating materials and the improvement in adhesive performance, it is reasonable to select an epoxy binder application rate of 2 kg/m^2. This dosage ensures sufficient bond strength for the epoxy anti-slip surface layer while avoiding unnecessary material waste and cost increases.

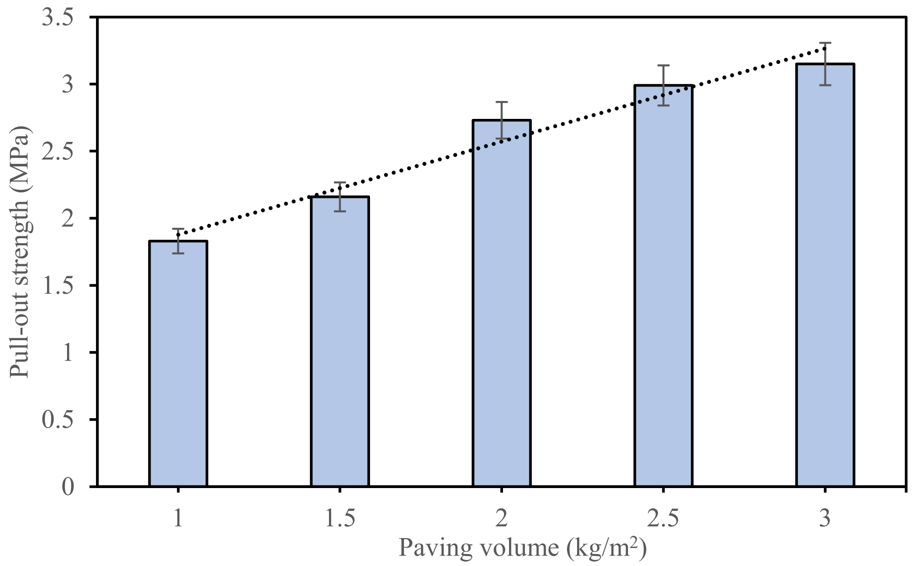

Figure 7. Results of epoxy binder pull-out tests with different paving amounts.

3.2. Tensile and Shear Test Results

The tensile and shear test results of the epoxy binder at different curing temperatures are presented in Figure 8. As the curing temperature increases, the shear strength of the specimens exhibits a noticeable downward trend. At 10 °C, the shear strength is 3.83 MPa; however, when the temperature rises to 50 °C, the shear strength decreases to 1.24 MPa. This characteristic change indicates that the epoxy binder possesses higher shear strength at lower temperatures and experiences a significant reduction in shear strength at elevated temperatures.

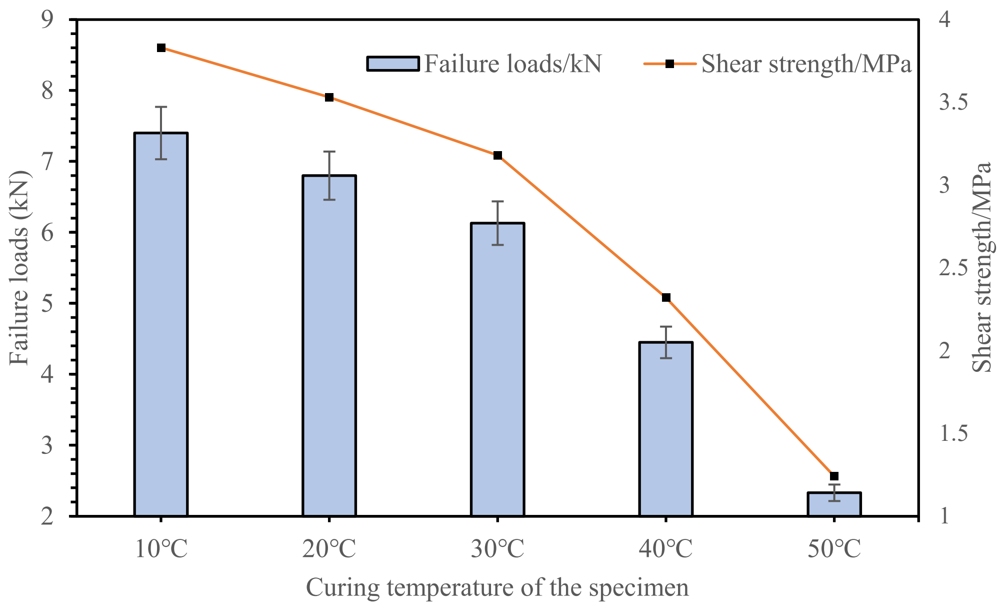

Figure 8. Tensile and shear test results of epoxy binders at different curing temperatures.

Concurrently, the failure modes of the specimens vary with different curing temperatures. At 10 °C, 20 °C, 30 °C, and 40 °C, adhesive failure occurs in the specimens, meaning that the failure takes place at the interface between the epoxy binder and the aggregate. This suggests that the adhesive force between the epoxy binder and the aggregate is relatively strong at these temperatures and capable of withstanding substantial shear forces. Nevertheless, when the curing temperature increases to 50 °C, the failure mode of the specimens shifts to mixed failure, indicating that the epoxy binder itself also undergoes failure. This change further corroborates the phenomenon of reduced shear strength in the epoxy binder at high temperatures. The optimized formulation of epoxy resin composites achieved a high tensile strength, which is comparable to or exceeds that reported in previous studies using different epoxy-based materials [25,29]. Specifically, the use of a 1:1 blend of Type I and Type II epoxy resins and an optimized curing agent dosage (30 phr) significantly contributed to the improved tensile properties.

The epoxy binder forms a three-dimensional network structure through the chemical reaction between epoxy resin and the curing agent. At lower temperatures, the curing reaction proceeds slowly, resulting in a denser three-dimensional network structure and higher shear strength for the epoxy binder. However, as the temperature increases, the curing reaction rate accelerates, leading to a more porous three-dimensional network structure and reduced shear strength of the epoxy binder. Additionally, high temperatures can adversely affect the interfacial adhesive force between the epoxy binder and the aggregate. At elevated temperatures, the thermal expansion and contraction differences between the epoxy binder and the aggregate increase, potentially causing stress concentration and microcracks at the interface, which in turn reduce the adhesive force and shear strength. In practical applications, it is essential to select an appropriate curing temperature based on the specific usage environment and requirements to ensure the performance of the epoxy binder.

3.3. Low-Temperature Crack Resistance

To gain a deeper understanding of the performance of epoxy binders at low temperatures, a bending test was conducted, and the results are presented in Table 9. It can be observed that as the amount of epoxy binder increases, the deflection of the specimens gradually increases, indicating an improvement in the material's flexibility. Simultaneously, both the flexural tensile stress and flexural tensile strain exhibit an increasing trend, reflecting the material's enhanced ability to resist deformation at low temperatures. However, when the amount of epoxy binder increases beyond a certain point, this increasing trend begins to slow down. This could be attributed to the excessive epoxy binder leading to an increase in the mixture's stiffness, thereby limiting its deformation capability [30].

With the increase in epoxy binder content, the flexural stiffness modulus generally exhibits an increasing trend, suggesting an enhancement in the material's stiffness, which is beneficial for improving the load-bearing capacity of the pavement. Nevertheless, it is important to note that excessively high stiffness may make the pavement more prone to cracking at low temperatures.

The excellent performance of epoxy binders at low temperatures is primarily attributed to their unique chemical structure and curing characteristics. The epoxy resin in the epoxy binder can undergo a chemical reaction with the curing agent, forming a three-dimensional network structure. This structure can maintain good stability and flexibility at low temperatures, effectively resisting the shrinkage deformation caused by temperature stress. Additionally, components, such as fillers and tougheners in the epoxy binder, can also play a role in enhancing and toughening, thus further improving the material's performance at low temperatures. As a crucial component of colored pavement materials, epoxy binders exhibit superior performance at low temperatures. Through reasonable proportioning and design, their performance at low temperatures can be further optimized, thereby enhancing the service life and driving comfort of the pavement.

Table 9. Traverse bending test results.

Dosage	Deflection (mm)	Flexural Tensile Stress (MPa)		Flexural Tensile Strain (με)		Flexural Stiffness Modulus (MPa)	
		Single Value	Average Value	Single Value	Average Value	Single Value	Average Value
Control group	0.536 0.54 0.557	10.64 10.21 9.05	9.97	2996.3 3026.24 3114.09	3045.55	3551.03 3373.82 2906.15	3277
1.0 kg/m^2	0.608 0.623 0.637	12.92 12.38 12.17	12.49	3420.68 3487.5 3561.92	3490.03	3777.03 3549.82 3461.7	3581.18
1.5 kg/m^2	0.655 0.665 0.681	14.51 14.08 13.26	13.95	3682.25 3741.13 3830.53	3751.3	3948.73 3763.57 3461.69	3724.66
2.0 kg/m^2	0.694 0.709 0.73	15.26 15.03 14.24	14.84	3902.38 3965.63 4083.55	3983.85	3910.43 3790.07 3487.16	3729.22
2.5 kg/m^2	0.728 0.711 0.746	15.25 15.5 14.72	15.16	4060.95 3976.38 4198.77	4078.7	3755.28 3898.02 3505.79	3719.7
Technical indicators	-	-		>2500		-	

3.4. High-Temperature Stability

According to the rutting test results presented in Figure 9, the dynamic stability of the asphalt concrete composite structure with the addition of colored epoxy anti-slip surface layers (1.0 kg/m^2, 1.5 kg/m^2, 2.0 kg/m^2, and 2.5 kg/m^2 groups) is significantly higher than that of the control group. The average dynamic stability of the control group is 7223 cycles/mm, while the average dynamic stability of the groups with colored epoxy anti-slip surface layers reaches 18,900 cycles/mm, 20,348 cycles/mm, 21,482 cycles/mm, and 21,973 cycles/mm, respectively. The results indicate that the incorporation of colored epoxy anti-slip surface layers significantly improves the rutting resistance of the asphalt concrete composite structure at high temperatures.

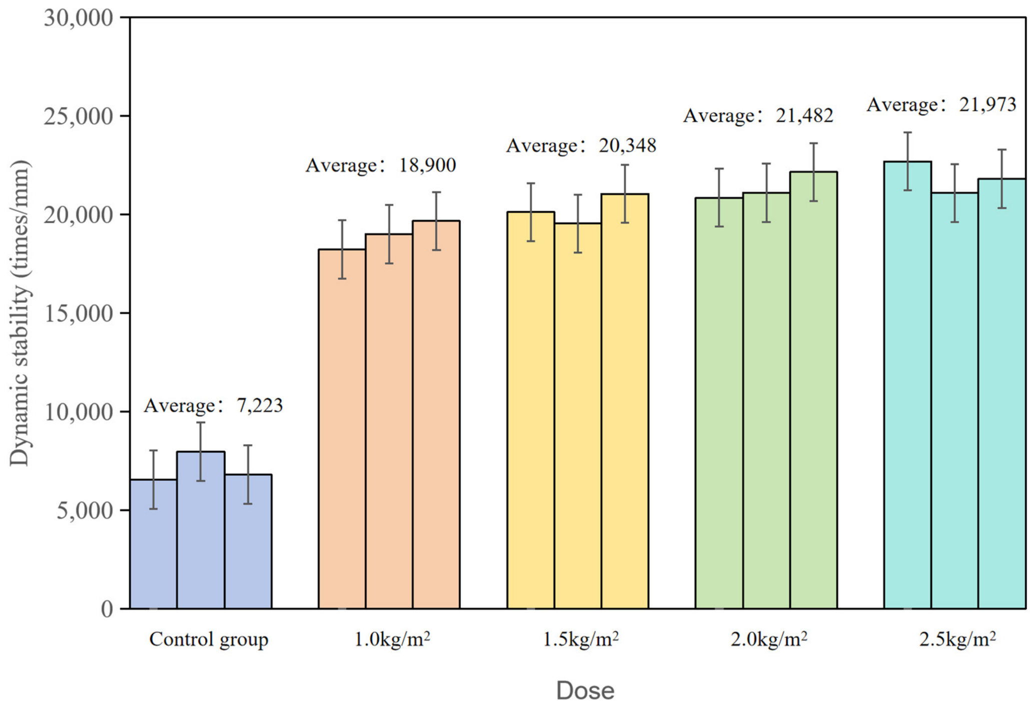

Figure 9. Rutting test results.

Further analysis reveals that as the amount of colored epoxy anti-slip surface layer increases, the average dynamic stability initially increases and then slightly decreases. Specifically, the 2.0 kg/m^2 group achieves the highest average dynamic stability of 21,482 cycles/mm. This may be because, within a certain range, increasing the amount of colored epoxy anti-slip surface layer can improve its bonding performance with asphalt concrete, thereby enhancing the overall stability of the composite structure. However, when the addition amount exceeds a certain limit, fluctuations in the performance of the mixture may occur due to the presence of excessive epoxy binder, which in turn affects the stability of the composite structure [31].

The large amount of filler in the epoxy binder has a large specific surface area, and its good fluidity allows it to deeply penetrate into the internal structure of the asphalt mixture. This deep penetration significantly increases the viscosity and cohesive force between asphalt and mineral aggregates, effectively preventing the deformation of the asphalt mixture at high temperatures. After curing, the epoxy binder can form a solid three-dimensional network structure. This structure not only has high mechanical strength itself but also undergoes an irreversible formation process, meaning it can maintain its stability for a long time. This stable structure provides excellent high-temperature deformation resistance for the colored epoxy anti-slip surface layer. Meanwhile, the unit area dosage of the epoxy binder has a relatively small impact on the dynamic stability of the colored pavement composite structure. Increasing its dosage does not significantly improve the high-temperature deformation resistance of the colored pavement composite structure. This may be because within a certain range, the amount of epoxy binder is sufficient to exert its stabilizing effect, and excessive addition does not bring further performance improvement. The high-temperature stability of the colored pavement was evaluated through rutting tests and compared to other studies. The dynamic stability achieved (approximately 21,000 cycles/mm) is notably higher than the values reported by Tang et al. [18] for light-colored synthetic asphalt binders, highlighting the effectiveness of the formulation in resisting rutting at high temperatures.

The composite structure of the colored epoxy anti-slip surface layer and the asphalt concrete exhibits good stability performance at high temperatures. By adding an appropriate amount of colored epoxy anti-slip surface layer, the rutting resistance of asphalt concrete can be significantly improved, prolonging the service life of the road. In practical engineering applications, the appropriate amount of addition should be selected according to specific requirements and environmental conditions to achieve the best use effect.

3.5. Water Stability Performance Result Analysis

Table 10 presents the results of freeze–thaw splitting tests conducted on different types of pavement materials, including the control group and colored pavements with varying addition amounts. In terms of compressive strength (RT1 and RT2), an increasing trend is observed as the amount of colored pavement added increases from 1.0 kg/m^2 to 2.5 kg/m^2. This indicates that the addition of colored pavement contributes to improving the compressive performance of the pavement material. In contrast, the compressive strength of the control group is relatively low, suggesting that materials without colored pavement additives exhibit poor compressive performance.

Furthermore, considering the standard deviation and coefficient of variation (C_v), the addition of colored pavement leads to an increase in data dispersion. This may be attributed to the introduction of more variables, such as particle size and distribution, resulting in greater data fluctuation. The TSR values of the colored pavement are higher than those of the control group, and they exhibit an increasing trend with increasing addition amounts. This demonstrates that colored pavement can better maintain its original performance and that it has higher durability under harsh environmental conditions, such as freeze–thaw cycles. The addition of colored pavement not only improves the compressive strength of the pavement material but also enhances its durability under the effects of freeze–thaw cycles. This is because the additives in the colored pavement may improve the internal structure of the material and increase its compactness and water resistance, thereby enhancing its durability. Freeze–thaw splitting tests revealed the superior water stability of the colored pavement compared to control samples and other studies. The TSR values (up to 95.5%) are significantly higher than those reported by Mirzaei et al. [26] for non-colored epoxy pavement materials, indicating that colored epoxy binder contributes positively to the overall water resistance.

Table 10. Freeze–thaw split test results.

Type of Mixture	RT_1 (MPa)	RT_2 (MPa)	Standard Deviation	Coefficient C_v (%)	TSR (%)
Control group	1.29	1.14	0.051	5.0	88.4
1.0 kg/m^2 colored pavement	1.37	1.25	0.17	14.9	91.6
1.5 kg/m^2 colored pavement	1.44	1.32	0.16	13.2	92.1
2.0 kg/m^2 colored pavement	1.49	1.39	1.19	14.8	93.9
2.5 kg/m^2 colored pavement	1.53	1.45	0.17	12.7	95.5

The improved water stability of the colored epoxy anti-slip surface material can be attributed to several factors. Firstly, the epoxy binder can penetrate into the voids of the asphalt mixture, enhancing the adhesion between the asphalt and the aggregate and thus improving the overall cohesion of the mixture. This reinforcement helps resist the erosion and damage caused by water to the asphalt pavement. Secondly, the three-dimensional network structure of the epoxy binder can form a dense oil film on the surface of the mixture, effectively preventing water infiltration. This oil film significantly reduces the corrosive effect of water on the asphalt mixture, further improving the water stability of the pavement. Lastly, the colored epoxy anti-slip surface layer exhibits good mechanical properties and can directly bear most of the wheel load, thereby reducing damage to the asphalt pavement. This protective effect helps prolong the service life of the pavement and improve the traffic quality of the road.

3.6. Fatigue Resistance Performance

To investigate the fatigue resistance of this composite structure at different temperatures, relevant experiments were conducted. By comparing and analyzing the test results at various temperatures, a more comprehensive understanding of the impact of temperature on the fatigue performance of pavement materials can be obtained [32]. This will aid in guiding the design and optimization of pavement materials to better adapt to complex traffic environments and variable climatic conditions, prolong the service life of pavements, reduce maintenance costs, and, ultimately, enhance the safety and comfort of road traffic. The test results are presented in Figure 10.

The fatigue test results of the control group and the composite material structure of the colored pavement at different temperatures (10 °C, 30 °C, 50 °C) can be observed. Firstly, at the test temperature of 10 °C, the fatigue life of the colored pavement is significantly higher than that of the control group. For example, at a stress ratio of 0.3, the fatigue life of the colored pavement is 38,811 cycles, while that of the control group is only 13,642 cycles, indicating that the fatigue life of the colored pavement is nearly three times that of the control group. As the stress ratio increases, this gap gradually narrows, but at all tested stress ratios, the colored pavement exhibits a longer fatigue life. This suggests that the composite material structure of the colored pavement has better fatigue resistance at lower temperatures.

At the test temperature of 30 °C, the fatigue life of the colored pavement is still higher than that of the control group, but the difference is not as significant as at 10 °C. For instance, at a stress ratio of 0.3, the fatigue life of the colored pavement is 29,903 cycles, while that of the control group is 9283 cycles, indicating that the fatigue life of the colored pavement is approximately 3.2 times that of the control group. As the stress ratio increases, the gap between the two groups gradually decreases. This indicates that the fatigue resistance of the colored pavement is still superior to that of the control group at moderate temperatures, but the advantage is somewhat weakened.

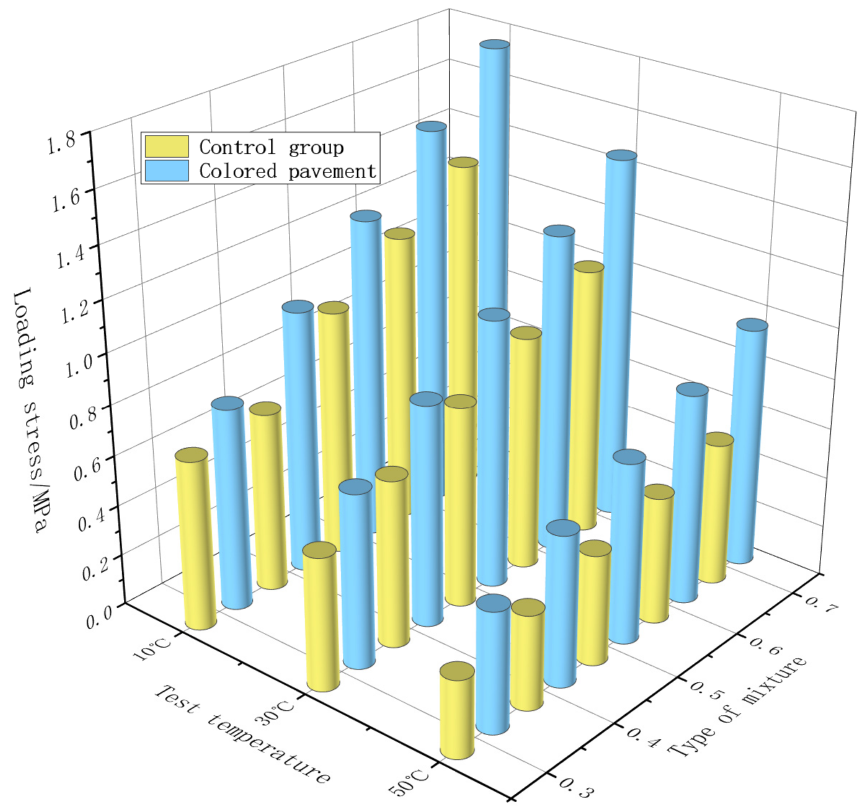

Figure 10. Comparison of load stress between control group and color pavement fatigue test.

At the test temperature of 50 °C, the fatigue life of the colored pavement remains higher than that of the control group, but the difference is further reduced. For example, at a stress ratio of 0.3, the fatigue life of the colored pavement is 23,921 cycles, while that of the control group is 5247 cycles, indicating that the fatigue life of the colored pavement is approximately 4.5 times that of the control group. However, as the stress ratio increases, the gap between the two groups rapidly decreases. At a stress ratio of 0.7, the fatigue life of the colored pavement is only 2328 cycles, while that of the control group is 326 cycles, indicating that the colored pavement is only about seven times that of the control group. This suggests that although the fatigue resistance of the colored pavement is still superior to that of the control group at high temperatures, the advantage has been greatly weakened. The fatigue life of the colored pavement under varying stress ratios and temperatures was compared to those reported in other studies. While the fatigue life decreased with increasing temperature, the results still outperformed those of ordinary asphalt mixtures, as well as some epoxy-based pavement materials reported in the literature [26]. This suggests that the optimized formulation provides better fatigue resistance under challenging conditions.

The composite material structure of the colored pavement exhibits good fatigue resistance at different temperatures. However, as the temperature increases, its advantage gradually diminishes. This may be related to changes in material properties at high temperatures. Therefore, in practical applications, it is necessary to select appropriate pavement materials based on specific usage environments and temperature conditions. Meanwhile, for the composite material structure of the colored pavement, further optimization of material ratios and design can be considered to improve its fatigue resistance at high temperatures. As the temperature rises, both the colored pavement and the control group show a decreasing trend in fatigue life. This may be due to changes in the mechanical properties of the materials at high temperatures, leading to reduced fatigue resistance. Nevertheless, at all tested temperatures, the fatigue life of the colored pavement remains higher than that of the control group, indicating that the composite material structure of the colored pavement has certain advantages in terms of fatigue resistance performance.

4. Conclusions

This paper systematically discusses the formula optimization, performance evaluation, and practical application effects of epoxy-based composites for colored pavement. The main conclusions are as follows.

(1) The composition of the epoxy-based composite formula has been successfully optimized. The key component ratios determined are as follows: a 1:1 blending ratio of EI and EII epoxy resins, a curing agent addition of 30 phr, a toughening agent of 10 phr, a diluent accounting for 5 phr, a filler accounting for 10%, a flame retardant accounting for 12%, and a pigment accounting for 10%. This novel formula ensures the basic performance of the material while also considering environmental friendliness and cost-effectiveness.

(2) Under low and normal temperature conditions, the binder exhibits excellent adhesive properties. Even in a high-temperature environment of 50 °C, it can maintain sufficient tensile shear strength, indicating good heat resistance. In addition, the binder demonstrates outstanding resistance to ultraviolet aging, showing its long-term stability in practical pavement applications.

(3) The performance of the composite structure of the colored epoxy anti-slip surface and asphalt concrete has been deeply studied. As the amount of epoxy binder increases, the low-temperature performance of the composite structure significantly improves. The best reinforcement effect is achieved when the amount is 2.0 kg/m2. Compared with ordinary asphalt mixtures, the colored pavement composite structure exhibits significant advantages in terms of mechanical strength and deformation capacity.

(4) The high-temperature stability of the composite structure of the colored epoxy anti-slip surface and asphalt concrete is far superior to that of ordinary asphalt mixtures. Its dynamic stability is approximately three times that of asphalt mixtures, demonstrating excellent high-temperature resistance to deformation.

(5) Through freeze–thaw splitting tests, it was found that the water stability of the colored pavement composite structure is significantly better than that of ordinary asphalt mixtures. In terms of anti-stripping performance, the colored pavement composite structure exhibits excellent durability, and no stripping phenomenon occurred during the test.

(6) Temperature has a significant impact on the fatigue life of the colored pavement composite structure. However, compared with ordinary asphalt mixtures, the fatigue life decay rate of the colored pavement composite structure is significantly lower. Under the same stress ratio, its fatigue limit loading frequency is more than three times that of ordinary asphalt mixtures, showing ideal fatigue resistance.

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