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Theoretical and Experimental Study on the Waterproofing Performance of Polymermodified Emulsified Asphalt Coatings

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Abstract

Emulsified asphalt boasts good waterproofing performance and aging resistance, but its comprehensive engineering performance, e.g., low bond strength and insufficient flexibility at low temperatures, can result in material detachment and water permeability in waterproofing projects. In order to improve its comprehensive waterproofing performance, this study proposed a waterproofing coating prepared by incorporating an acrylic emulsion, fillers, and additives into an emulsified asphalt polymer. The proportions of acrylic emulsion to emulsified asphalt, the filler content, and the dispersant dosage were selected as the main variables. Single-factor tests were conducted on the silica content and defoamer dosage, and the properties of waterproofing materials were analyzed under different temperature treatments. The optimal ratio of each component of the polymer-modified emulsified asphalt waterproofing coating was determined. Results demonstrate that, (1) the polymerization state of the acrylic emulsion with emulsified asphalt is stable. (2) When the mass ratio of acrylic emulsion to emulsified asphalt is 2:1, the physical and mechanical properties of the waterproofing coating can reach the optimal balance. (3) The appropriate amount of silica can enhance the physical properties, stability, and durability of the coating, with the optimal comprehensive performance at the mixing amount of 0.3%. (4) As the defoamer content increases, the coating surface becomes smooth, internal structural defects are reduced, the elongation at break can reach up to 1180%, and the bond strength can be improved up to 1.29 MPa. This study provides a good reference and basis for the theoretical research and engineering application of polymer-modified emulsified asphalt waterproofing coatings.

Keywords: Emulsified asphalt, Acrylic emulsion, Physical and mechanical properties, Waterproofing performance

1. Introduction

Polymer-modified asphalt waterproofing coatings present advantages such as high elongation, good waterproofing performance, and excellent aging resistance, as well as environmental and safety benefits. They have been extensively applied in building waterproofing, bridge waterproofing, and base treatment in waterproofing projects [1-3]. With the advancement of building waterproofing projects, modified asphalt waterproofing coatings have undergone vigorous development, and related technical research has achieved swift progress. Numerous scholars have devoted efforts to the research, preparation, and application of modified asphalt coatings [4]. Most modified asphalt rolls go through complex construction processes and require high-temperature heating treatment. Incomplete thermal fusion can lead to voids, resulting in insufficient bond strength and reduced waterproofing performance. Chen [5] developed a waterborne asphalt waterproofing and antirust coating prepared by blending an elastic acrylic emulsion with emulsified asphalt, achieving the requirements of convenient construction, safety, and environmental protection for modified asphalt materials.

However, modified asphalt materials are developing toward multifunctionality following the prolonged operation

of modified asphalt materials, with improved physical and mechanical properties. Along with the enhancement in the performance of modified asphalt materials, their cost has increased. In the design process, polyurethane, epoxy resin, or SBS is often used to modify emulsified asphalt. This process involves numerous design factors, such as waterproofing, high- and low-temperature performance, and physical and mechanical properties, presenting significant technical challenges to the research of modified asphalt materials.

On this basis, scholars have conducted extensive studies on improving the bond strength and elongation at break of modified asphalt waterproofing coatings and revealing their physical and mechanical properties [6–8]. However, issues remain with the research on the bond strength performance of polymer-modified asphalt waterproofing materials, which does not align with actual working conditions. Thus, how to accurately predict the elongation at break of waterproofing materials, address the issue of coating bond strength, and clarify the coupling relationship between waterproofing coatings and substrates in the actual working state of modified asphalt materials is an urgent problem that needs to be addressed.

Therefore, this study develops a waterproofing coating made from acrylic emulsion-modified emulsified asphalt. It establishes a testing model for polymer-modified asphalt waterproofing coatings to analyze the impermeability,

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physical and mechanical properties, and characteristics of polymer-modified asphalt waterproofing materials. This study elucidates the properties of polymer-modified asphalt waterproofing materials, tackles the problem of water permeability caused by the insufficient bond strength of waterproofing materials, and offers guidance for the development and refinement of such materials.

2. State of the art

Polymer-modified emulsified asphalt improves the performance limitations of raw asphalt by adding different polymer materials to the emulsion to meet its technical requirements in buildings. However, challenges have been encountered in the enhancement of its material properties and engineering applications [9]. With the improvement of living standards, people's demand for waterproofing materials is increasing day by day. These materials are essential to prolong the service life of buildings and ensure the safety of people's property. They can significantly improve aging resistance, bonding performance, and resistance to high and low temperatures. Scholars have carried out considerable work on polymer-modified asphalt materials. Hadavand [10] modified emulsified asphalt with polyurethane nanoclay composites and studied its permeability and softening point but did not discuss the physical properties. To enhance the fracture resistance of modified asphalt, Pirmohammad [11] used nano-Fe2O3 and carbon nanotubes to modify the asphalt mixture, but the analysis of asphalt properties was relatively simple. Taylan [12] employed nanocomposites to modify asphalt, which could significantly improve the stiffness of asphalt within a certain range, but the waterproofing performance of the material was not considered. Rooholamini [13] investigated the effects of nanoclay and its binding with SBS on bitumen to improve the fatigue and thermal cracking resistance of unaged and aged mixtures, but the addition of excess nanoclay was not discussed. Huang [14] explored the rheological properties of nano-organic montmorillonitemodified asphalt and nano-montmorillonite compound polymer-modified asphalt but lacked an analysis of bond strength.

Many studies have been conducted on the improvement of aging resistance, such as the blending of different types of polymers and asphalt, the addition of various antiaging agents and parameters, and the incorporation of organic materials. To reveal the aging characteristics of asphalt materials, Diab [15] blended different types of polymers with asphalt. They found that aging was largely dependent on the type of polymer and the level of modification. However, no further analysis of mechanical properties was conducted. Cong [16] explored different antiaging agents and parameters to improve the aging resistance of SBSmodified asphalt binders and determined the optimal combination of antiaging agents, but the addition of antiaging agents did not improve the physical properties. He [17] analyzed the waterproofing performance of organic montmorillonite to enhance the waterproofing of styrenebutadiene-styrene-modified asphalt. Their study provided a reference for the aging resistance of modified asphalt waterproofing materials, but the influence on the lowtemperature properties of the materials was not discussed.

Few studies exist on the enhancement of adhesive performance, mainly including composite modification and nanomaterial modification. Mirabdolazimi [18] modified an asphalt emulsion by adding nanosilica, which improved the cohesion of the asphalt and the adhesion between the asphalt and aggregate. However, they did not extensively investigate its elongation at break. Liu et al. [19, 20] discussed the composite modification of emulsified asphalt. They found that as the content of water-based epoxy resin increased, the curing time of the composite-modified emulsified asphalt shortened, while the tensile strength and adhesion improved. However, the improvement of high- and low-temperature performance requires further investigation. Zhang [21] studied the effect of the distribution ratio of each component in waterborne asphalt waterproofing coatings on coating performance through experiments. However, technical guidance for formula design and a comprehensive analysis of the results are still needed. Ma [22] developed a highviscosity antihydroplaning polymer-modified asphalt waterproofing coating, but the low-temperature performance was not discussed.

In recent years, the studies on polymer-modified asphalt waterproofing coatings have attracted wide attentions, and the methods for improving the performance of materials have been continuously advanced. Ullah [23] designed new intumescent flame retardant-modified asphalt to improve the flame retardant properties and increase the viscosity of asphalt, but they did not study the waterproofing properties in depth. To improve high-temperature resistance, Wang [24] presented a high-speed shearing method to modify emulsified asphalt with a nano-SiO₂- and water-based epoxy resin. However, the elongation at break of the material remained unresolved. Man [25] explored the effects of heavy calcium carbonate and granulated blast furnace slag powder of different fineness on the performance of modified asphalt waterproofing coatings. This study provided a method for improving the comprehensive properties of coating films, but the changes in coating properties under different temperature treatments were not mentioned. Zhang [26] modified a coating with different acrylic emulsions and emulsified latex. When the dosage of elastic emulsion 3030 was 25wt% and that of PVC was 20%, the coating performance improved significantly. However, the adhesive strength of the material requires further improvement.

With the rapid development of the construction industry, people have increasing requirements for waterproofing coatings, significantly promoting the development of polymer-modified asphalt waterproofing coatings. Polymermodified asphalt waterproofing coatings refer to waterproofing coatings made by emulsifying asphalt through emulsifiers, stabilizers, and other additives with water as the dispersion medium. With the increasing demand, improving bond strength, high- and low-temperature resistance, and durability has become an urgent challenge for waterproofing coatings. The goal is to enhance the adhesion of waterproofing coatings and their performance under high and low temperatures. Chen [27] discussed the effects of the types and addition amounts of raw materials, such as emulsified asphalt and modified latex, on the properties of emulsified asphalt waterproofing coatings. The results showed that emulsified asphalt significantly influenced highand low-temperature performance, while modified latex greatly affected heat resistance and low-temperature performance. The mechanical properties of materials require further investigation.

The above studies mainly focused on the modification and analysis of the aging resistance and some physical properties of waterproofing coatings. The mechanical properties of materials and their application to different waterproofing projects require further improvement. Meanwhile, few studies exist on the bond strength and elongation at break of polymer-modified emulsified asphalt, especially on the physical and mechanical properties of waterproofing coatings under different temperature treatments. In this study, the adhesive strength, elongation at break, low-temperature flexibility, and impermeability of polymer-modified emulsified asphalt coatings under different temperature treatments were investigated. A bond strength model of waterproofing coatings was established, and their comprehensive properties were analyzed. This study provides a basis for the optimization and testing of waterproofing coatings.

The remainder of this study is organized as follows. Section 3 presents the determination of the initial proportion of polymer-modified asphalt waterproofing coatings by examining the physical and mechanical properties of a threefactor four-level orthogonal test scheme. Section 4 discusses the effect of silica and defoamer on the bond strength and elongation at break of waterproofing materials, identifying the appropriate mixing amount of silica and defoamer for the optimal performance of waterproofing materials. The last section summarizes the whole paper and presents relevant research conclusions.

3. Methodology

3.1 Test Scheme

Orthogonal test scheme: The initial proportion of the coating was determined through a three-factor four-level orthogonal test (Table 1), with the mass ratio of acrylic emulsion to emulsified asphalt, the aliquots of filler added, and the aliquots of dispersant added as the three factors for the orthogonal test. The impermeability, elongation at break, and bond strength at each proportion were investigated. The proportions of other components such as defoamer, associative thickener, and Dow fungicide were fixed as a percentage of the total mass.

Silica modification test scheme: The formulation of Group 11 with relatively good performance from the orthogonal test was selected, and silica contents of 0%, 0.2%, 0.3%, 0.4%, and 0.5% were used to study the effect of silica on the bond strength and elongation at break of the waterproofing material.

Defoamer modification test scheme: For the formulation of Group 11 determined by silica modification, defoamer contents of 0%, 0.15, 0.3%, 0.45%, and 0.6% were used to study the effect on the physical and mechanical properties of the coating.

Table 1	. Orthogonal	Test	Scheme

Formula No.	A: Proportion of Acrylic Emulsion to Emulsified Asphalt	B: Filler (Aliquots)	C: Ammonium Salt Dispersant (Aliquots)
1	1	20	0.3
2	1	25	0.35
3	1	30	0.2
4	1	35	0.25
5	1.5	20	0.25
6	1.5	25	0.2
7	1.5	30	0.35
8	1.5	35	0.3
9	2	20	0.2
10	2	25	0.25
11	2	30	0.3

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12	2	35	0.35
13	2.5	20	0.35
14	2.5	25	0.3
15	2.5	30	0.25
16	2.5	35	0.2

3.2 Test Materials and Instruments

The components adopted in this study included anionic acrylic emulsion, anionic emulsified asphalt, defoamer, dispersant, thickener, fungicide, and deionized water. Solid components comprised 800-mesh heavy calcium carbonate, 1250-mesh talc powder, and silica.

The main test instruments were coating film frames, sheet-punching machines, dumbbell-shaped cutters, thickness gauges, mixers, low-temperature freezers, digital universal testing machines, impermeability testing instruments, and electric blast drying ovens.

3.3 Test Method for Elongation at Break

The investigation of the elongation at break was conducted in accordance with the Chinese construction industry JC/T408-2005 Emulsion standard (Water Asphalt Waterproof Coating). The test was performed under standard conditions (temperature: 23 °C, relative humidity: 50%). The thickener was diluted with water at 1:1 ratio and stirred evenly, and 0.5 aliquots were set aside; the fungicide was diluted with water at 2:1 ratio and stirred evenly, and 0.3 aliquots were set aside; heavy calcium carbonate and talc powder were mixed at a mass ratio of 4:1, stirred evenly, and set aside; the acrylic emulsion, deionized water, aliquot defoamer, and aliquot dispersant were mixed and stirred at a high speed for 5 min, and the slurry was prepared for use. For uniform mixing, the measured powder was slowly added and stirred at a high speed for 10 min; the measured emulsified asphalt was added and stirred at a low speed for 10 min; the measured thickener and fungicide were added sequentially and stirred at a low speed for 10 min, completing the preparation; the adjusted sample was applied to the film frame in 3-5 coats with 8-24 h intervals, resulting in a final film thickness of 1.5 mm. The cured specimens were cut into a dumbbell shape (Fig. 1) by using a cutter and a sheet-punching machine, their thickness was measured with a thickness gauge, parallel lines with a spacing of 25 mm were drawn on the specimen, and the specimen width was 6 mm. The specimens were fixed on the tensile testing machine (Fig. 2) for testing, recording the maximum tensile force and the distance between the marks at the point of breakage.

$$E = \frac{(L_1 - 25)}{25} \times 100\%$$
(1)

Where E is the elongation at break; L_1 is the distance between the marks at the point of breakage, in mm. The arithmetic average of the tensile strength and elongation at break of five specimens was taken as the test result.

3.4 Impermeability Test Method

The impermeability test was based on the Chinese Test Methods for Building Waterproof Coatings (JC/T408-2005). Three specimens of 150 mm×150 mm×1.5 mm were cut from the film cured, described in Section 3.3 (Fig. 3), for backup. The air in the impermeability testing instrument was removed. The specimen was placed on the permeability plate of the testing machine, as shown in Fig. 4, covered with a metal mesh and a seven-hole disc, and clamped tightly. The

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machine was started, and pressure was slowly applied. A water pressure of 0.3 MPa was maintained for 30 min, and the occurrence of water permeability on the non-water-facing side was observed. If no seepage occurred, the specimen was considered to pass.



Fig. 1. Dumbbell-shaped Specimen



Fig. 2. Tensile Testing Machine



Fig. 3. Impermeable Test Specimen



Fig. 4. Simplified Diagram of Specimen Installation

3.5 Low-temperature Flexibility Test Method

Three 100 mm×25 mm rectangular specimens (Fig. 5) were cured and prepared as required, and the test was conducted. The specimens and the round bar were placed into a low-temperature freezer adjusted to the specified temperature (Fig. 6) and kept for 1 h, then the specimens were bent around the round bar by 180° within 3 s. After bending, the three specimens were immediately removed, and the surface was observed for any cracks or breakages. If no cracks or breakages occurred, the specimen was considered to pass.



Fig. 5. Low-temperature Specimen



Fig. 6. Low-temperature Freezer

3.6 Bond Strength Test Method

After curing, the upper tensile fixture was bonded to the coating surface of the specimen with a high-strength adhesive, as shown in Fig. 7 Any excess adhesive was scraped off, and the specimen was cured horizontally for 24 h under standard test conditions. The specimen was positioned, with the upper tensile fixture attached on the testing machine, as shown in Fig. 8, ensuring that the centerline of the specimen surface aligned with the center of the testing machine fixture. The specimen was stretched to failure at a speed of (5 ± 1) mm/min, and the maximum tensile force was recorded. The test temperature was (23 ± 2) °C.

$$\sigma = \frac{F}{1600} \tag{2}$$

Where σ is the bond strength, measured in megapascals (MPa); F is the maximum tensile load, measured in newtons (N).



Fig. 7. Bond Strength Specimen



Fig. 8. Bond Strength Testing Machine



Fig. 9. Schematic of Polymer and Asphalt Molecules



Fig. 10. Schematic of Polymer and Asphalt Molecules Forming a Film

Fig. 9 and 10 illustrate the complexation of acrylic emulsion and emulsified asphalt molecules on the substrate surface before and after drying. As shown in Fig. 9, the freshly applied coating contained a large amount of water, and the polymer molecules (red), filler particles (blue), and asphalt molecules (black) were in a relatively dispersed state. The molecules were relatively distant from one another, moving freely. As the temperature, humidity, and other factors changed, the water in the coating continuously evaporated, causing the polymer, filler, and asphalt molecules to gradually get close. As the water evaporated further, the molecules were drawn even closer by van der Waals forces, causing them to aggregate and strengthen the tightness of the film. During this period, the polymer molecules acted as a bridge, connecting the asphalt molecules. Finally, as demonstrated in Fig. 10, after a large amount of water had evaporated from the coating, the molecules shrank, and the dried polymer molecules (red), filler particles (blue), and dried asphalt molecules (black) produced surface tension. Under the combined action of other forces, the molecular chains of the polymer and asphalt began to diffuse and interpenetrate, gradually forming a tightly interconnected network that encapsulated the filler molecules and reducing the phenomenon of sedimentation in the coating. The encapsulated filler particles were inconsiderably exposed to the external environment, tremendously enhancing their stability. In this phase, the acrylic acid significantly embodied the asphalt.

4. Result Analysis and Discussion

4.1 Analysis of Orthogonal Test Results

The orthogonal test results (Table 2) were based on the test scheme in Section 3.1.

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Formula No.	Impermeability (MPa)	Elongation at Break (%)	Bond strength (MPa)
1	Failed	899	0.69
2	Failed	839	0.71
3	Passed	736	0.75
4	Failed	650	0.69
5	Failed	912	0.75
6	Failed	859	0.77
7	Passed	769	0.83
8	Failed	703	0.70
9	Passed	1080	0.85

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10	Passed	1024	0.89
11	Passed	1256	0.96
12	Passed	1061	0.87
13	Passed	1032	0.82
14	Passed	979	0.86
15	Passed	933	0.87
16	Failed	857	0.79

The range analysis of the orthogonal test results (Tables 3 and 4) showed that the primary and secondary factors affecting the elongation at break of the waterproofing coating were A (the ratio of acrylic emulsion to emulsified asphalt) > B (filler) > C (ammonium salt dispersant).

As shown in Tables 3 and 4, the ratio of acrylic emulsion to emulsified asphalt exerted the greatest effect on the physical and mechanical properties of the waterproofing coating. Because of the evaporation of water from the acrylic emulsion, as the water in the system evaporated, the latex particles aggregated and fused to modify. The gaps between particles decreased until they disappeared, resulting in a mechanical dry state and forming a dense structure that improved the flexibility of the waterproofing coating after drying when evaporation reached a certain degree. As the proportion of acrylic emulsion to emulsified asphalt increased, the comprehensive performance of the waterproofing film was enhanced. Meanwhile, long-chain polymer molecules were considerably entangled around the asphalt particles, tremendously increasing the cohesive force of the system. This phenomenon changed the reliance on secondary forces, such as mechanical adsorption and intermolecular forces, of the emulsified asphalt, enhancing coating performance. The various polar groups of highmolecular-weight polymers formed primary valent forces with relatively high bond energies, such as hydrogen and covalent bonds, on the matrix surface, which improved the coating performance.

K1	3135	3837			
K2	3243 3712		3774		
K3	4421	4421 3694 3532			
K4	3801	3271	3519		
$\overline{K_1}$	783.75	980.75	959.25		
$\overline{K_2}$	810.75	928	943.5		
$\overline{K_3}$	1105.25	923.5	883		
$\overline{K_4}$	950.25 817.75 879.75				
Range R	294.5	163	76.25		
Primary and Secondary Order		A>B>C			

	0 1	0	
K1	2.84	3.11	3.21
K2	3.05	3.23	3.23
К3	3.57	3.41	3.14
K4	3.34	3.05	3.2
$\overline{K_1}$	0.71	0.7775	0.8025
$\overline{K_2}$	0.7625	0.8075	0.8075
$\overline{K_3}$	0.8925	0.8525	0.785
$\overline{K_4}$	0.835	0.7625	0.8
Range R	0.125	0.015	0.0075
Primary and		A>B>C	
Secondary			
Order			

Tables 3 and 4 also indicated that the filler exerted a significant effect on the mechanical properties, second to the proportion of acrylic emulsion to emulsified asphalt. When the proportion of fillers increased, the bond strength and elongation at break first increased and then decreased. The filler supplemented the gaps between the emulsion particles, which could increase the bond strength of the coating within a certain range. However, when the critical volume content was exceeded, the emulsion reached a discontinuous phase, resulting in incomplete wetting of the filler. The filler became loosely distributed in the coating, leading to a decrease in coating performance. From Table 2, when the proportion of acrylic emulsion to emulsified asphalt was considerably low or the proportion of filler was excessively high, failures occurred in the impermeability test. The acrylic emulsion could crosslink with the emulsified asphalt to form a networked structure that could resist damage from external water pressure. However, when the proportion of acrylic emulsion to emulsified asphalt was extremely low, the number of crosslinking points formed was reduced, leading to the inability to prevent the penetration of water molecules. When the content of acrylic emulsion was considerably low, the asphalt microparticles in the emulsified asphalt were prone to aggregation and precipitation, causing a decline in the performance of the waterproofing coating. When the proportion of fillers was remarkably high, the continuous-phase structure formed by the acrylic emulsion and emulsified asphalt was destroyed, making the coating discontinuous with numerous pores, thereby reducing the density of the waterproofing coating.

Furthermore, Tables 3 and 4 showed that the effect of the dispersant on the bond strength and elongation at break of the waterproofing coating was less than that of the proportion of acrylic emulsion to emulsified asphalt and the content of filler. The dispersant could adsorb onto the surface of filler and emulsion particles; electrostatic repulsion could effectively prevent particle agglomeration, allowing the particles to disperse uniformly in the system without precipitation or layering. However, dispersants generally have some surface activity, which can reduce the surface tension of the waterproofing coating. As the surface tension decreased, foam generation became easy; the dispersant formed an adsorption layer on the surface of bubbles, which could enhance foam stability, making it less likely to break and leading to defects in the waterproofing coating film. Thus, the effect on the film's bond strength and elongation at break was insignificant.

Based on the comprehensive performance of the emulsified modified asphalt waterproofing material, Group 11 in the orthogonal test showed excellent results in physical and mechanical properties and low-temperature flexibility.

4.2 Effect of Silicon Dioxide on the Performance of Waterproofing Coating Materials

On the basis of the test method in Section 3.1, Group 11, which had superior physical and mechanical properties and impermeability in the orthogonal test, was selected to investigate the effect of different mixing amounts of silicon dioxide (0%, 0.2%, 0.3%, 0.4%, 0.5%) on bond strength, elongation at break, and low-temperature flexibility at different treatment temperatures.



Fig. 11. Bond Strength Results

Characteristic graphs of the variation in bond strength and elongation at break with the content of silicon dioxide in different processing methods were formed on the basis of the test results. As shown in Fig. 11, the bond strength of the dry mortar substrate before and after high- and low-temperature treatment was in the range of 1.05-1.25 MPa and 0.81-1.05 MPa, respectively; without treatment, the bond strength varied between 0.96 and 1.18 MPa. All three properties showed a trend of first increasing and then decreasing with the addition of silicon dioxide. When the amount of silicon dioxide added was below 0.3%, the coating's bond strength increased with the increase in silicon dioxide content. The reason was that the volume density of fumed SiO2 powder was extremely low, with a large specific surface area, and its quantum size effect and three-dimensional structure could increase adhesion when used as a filler. When the silicon dioxide content exceeded 0.3%, the coating's bond strength began to decrease, which was due to the uneven dispersion in the acrylic emulsion with the increase in silicon dioxide, thus affecting the coating performance. The bond strength increased and decreased at high and low temperatures, respectively, for the reasons explained in Section 4.3.



Fig. 12. Elongation at Break Results

Fig. 12 exhibits the effect of silicon dioxide on the elongation at break during different temperature treatments. As shown in Figure 9, the elongation at break after high- and low-temperature treatment was in the range of 1011%–1163% and 1263%–1413%, respectively; without treatment, the elongation at break varied between 1105% and 1256%. With the increase in silicon dioxide content, the elongation at break of the coating showed a decreasing trend, given that

silicon dioxide, as a rigid particle, increased the hardness of the coating. Moreover, as the amount of silicon dioxide increased, the cohesive force of the film also improved, leading to stress concentration in the film during uniform tensile breakage process, thus reducing the film's elongation at break. The elongation at break decreased and increased at high and low temperatures, respectively, for the reasons explained in Section 4.3.



Both properties showed a trend of first increasing and then decreasing with the change in the mass ratio of silicon dioxide. The low-temperature flexibility of samples after high-temperature treatment was lower, to varying degrees, than that before thermal aging. When the mass ratio of silicon dioxide was below 0.3%, the addition of silicon dioxide showed a promoting trend, and the low-temperature flexibility of samples before and after high-temperature treatment was below -16 °C and -13 °C, respectively. The low-temperature flexibility decreased with the increase in silicon dioxide content because the nano-SiO2 particles distributed in the gaps of the polymer chains had high fluidity, promoting the uniform dispersion of nano-SiO₂ in the system and thus improving the stability of the system. When the mass ratio of silicon dioxide exceeded 0.3%, the viscosity of the coating increased, and the rigidity gradually enhanced after film formation, leading to reduced flexibility. As shown in Fig. 13, the low-temperature flexibility decreased after high-temperature treatment. During the thermal aging process, the matrix asphalt in the coating reacted with oxygen, forming unstable oxides that led to the destruction of the internal structure, resulting in brittleness.

4.3 Effect of Defoamer on the Performance of Waterproofing Coating Materials

Based on the test method in Section 3.1, the number of bubbles in the film was significantly reduced with the increasing amount of mineral oil defoamer. Specimens with different mixing amounts of mineral oil defoamer were cut into specimens of the specified size for impermeability test (Table 5). As the proportion of defoamer increased, the surface bubbles of the waterproofing coating were significantly reduced after drying. When the defoamer accounted for 0.3% of the components, no obvious bubbles occurred on the film surface. The mineral oil defoamer had a relatively low tension and was incompatible with water on the foam surface, leading to the destruction of the integrity of the liquid film, hindering and breaking its recovery and

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flow, reducing surface tension, and ultimately causing the foam to burst, thus preventing foam generation and achieving defoaming and bubble suppression. As shown in Table 5, without a defoamer, the coating had a porous internal structure, which, under the action of water pressure, would create channels for water permeability, leading to the water permeability of the specimen.

 Table 5. Impermeability Test Results

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Mass Ratio of Defoamer (%)	0	0.15	0.3	0.45	0.6
Test Results	Failed	Failed	Passed	Passed	Passed

As illustrated in Fig. 14, the bond strength after highand low-temperature treatment was in the range of 0.64-1.36 MPa and 0.41-1.15 MPa, respectively; without treatment, the bond strength varied between 0.56 and 1.29 MPa. All three properties showed an increasing trend with the increase in mineral oil defoamer content. As the defoamer amount increased, the number of bubbles in the film gradually decreased, thereby improving the overall density and uniformity of the coating. Meanwhile, the reduction in bubbles increased the contact area between the film and the substrate, enhancing the bond strength. Fig. 14 demonstrates that the bond strength increased and decreased after highand low-temperature treatment, respectively. At low temperatures, the intermolecular forces weakened, and phenomena such as cracks would likely occur, leading to a decrease in the bond strength between the coating and the substrate. After high-temperature treatment, the adhesion of the coating to the substrate surface improved with the temperature rise, promoting tight binding between the coating and the substrate surface molecules. Furthermore, high temperatures helped the coating's moisture and solvent to evaporate, reducing internal defects, increasing the overall density of the coating, and thus improving the bond strength.



Fig. 14. Bond Strength Results

From Fig. 15, the elongation at break after high- and low-temperature treatment was within the range of 479%–1099% and 752%–1339%, respectively; without treatment, the bond strength varied between 590% and 1180%. All three properties showed a trend of first increasing and then decreasing with the increase in mineral oil defoamer content. When the defoamer content was less than 0.3%, the elongation at break increased rapidly. The increase in defoamer effectively controlled the voids caused by internal bubbles in the coating, making the coating highly uniform

and dense, thus increasing the elongation at break of the coating to 1180%. When the defoamer content was higher than 0.3%, the elongation at break of the coating did not increase but decreased instead. The extreme amount of defoamer led to excessive active components being introduced, destroying the originally stable structure and resulting in increased rigidity of the coating and decreased elongation at break. Fig. 15 illustrates that the overall elongation at break after high- and low-temperature treatment decreased and increased, respectively. After lowtemperature treatment, the loose intermolecular bonding prevented excessive brittleness, maintaining a certain degree of looseness, which improved the elongation at break to some extent. After high-temperature treatment, the coating underwent excessive crosslinking reactions with the rise in temperature. The molecular chains became too tightly connected, restricting relatively large deformation under tensile stress and thus reducing the elongation at break.



Fig. 15. Elongation at Break Results

5. Conclusions

To improve the performance of polymer-modified emulsified asphalt waterproofing coatings, address the issues of low bond strength and elongation at break, and assess the waterproofing performance of building engineering waterproofing coatings, this study explored the effects of the proportion of polymer-modified emulsified asphalt waterproofing coating, silica, and defoamer on the performance of waterproofing materials via orthogonal and single-factor tests. The following conclusions were drawn:

(1) When the proportion of acrylic acid to emulsified asphalt was 2:1, the filler proportion was 30%, and the dispersant proportion was 0.3%, the prepared waterproofing coating passed the impermeability test under 0.3 MPa water pressure for 30 min. The bond strength was 0.96 MPa, and the elongation at break was 1256%, with stable physical and mechanical properties.

(2) When the amount of silica was increased, the bond strength and low-temperature flexibility initially increased and then decreased, while the elongation at break gradually decreased. When the silica content was 0.3%, the bond strength reached 1.18 MPa, the elongation at break was 1180%, and the low-temperature flexibility reached -16 °C. After high- and low-temperature treatments, the bond strength was 1.25 and 1.05 MPa, respectively; the elongation at break was 1099% and 1339%, respectively; and the low-

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temperature flexibility remained at -13 °C after both treatments. On the basis of the overall performance of the material, the silica content of 0.3% was determined as the optimal value.

(3) With increasing mineral oil defoamer content, the bond strength of the waterproofing coating showed a positive correlation with the defoamer content, reaching a maximum of 1.29 MPa. After high- and low-temperature treatments, the bond strength remained at 1.36 and 1.15 MPa, respectively. The elongation at break initially increased sharply and then slightly decreased. The impermeability performance reached 0.3 MPa, with no water permeability observed for 30 min.

In this study, experimental data test and theoretical research were combined, and a high-performance polymermodified asphalt waterproofing material with acrylic emulsion and emulsified asphalt composite was proposed. This study provided a reference for the application of polymer-modified asphalt waterproofing materials. In consideration of the lack of actual data from on-site engineering and the influence of the construction process and on-site construction environment, actual engineering test of the polymer-modified emulsified asphalt waterproofing material will be carried out in the future research. Moreover, the construction process will be optimized to improve the comprehensive performance of the polymer-modified emulsified asphalt waterproofing material.

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