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Research on the properties of asphalt-based polymer sealing materials and their application in pavement crack repair

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Research on the properties of asphalt-based polymer sealing materials and their application in pavement crack repair

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Abstract: If cracks in asphalt concrete pavement are not repaired in time, they can easily lead to damage to the entire road structure. Heated asphalt-based polymer sealing materials (asphalt-based polymer sealants and asphalt-based polymer mastics) are commonly used sealing materials, but there is still a lack of research on the composition control and performance of oxidized petroleum asphalt-based sealing materials. This paper investigated the effects of different grades of oxidized petroleum road asphalt, thermoplastic elastomer content, plasticizer content, and different types and amounts of mineral fillers on the performance of heated asphalt-based polymer sealing materials. At the same time, the pull-out test was employed to analyze the influence law of the surface temperature of the asphalt concrete in the crack area on the adhesion strength between the asphalt-based polymer sealing material and the crack area of the asphalt concrete. The results showed that when the content of plasticizer and Butonal NS 198 cationic latex remained constant, reducing SBS content from 8 % to 5 % caused the softening point to decrease by 7 °C and the elastic recovery rate to drop by 3 %, while slightly improving penetration depth and ductility of the material; when the plasticizer concentration was ≥ 15 %, both the brittleness temperature and low-temperature flexibility of the asphalt-based polymer sealing material were below -30°C; adding 15% mineral filler can increase the softening point by 4–8 °C and enhance the rutting resistance factor (G*/sin δ)and the low-temperature creep stiffness, with kaolin showing a superior effect. The surface temperature of asphalt concrete in the crack area significantly affects the adhesion strength. When specimens were preheated to 80 °C, adhesion strength increased by 1.36 to 1.77 times compared to when heated to 10 °C. This sealing material and its corresponding construction process had been applied to crack repair on national highways. Monitoring results showed that the sealed areas remained intact for 2.5 to 3 years of road operation, indicating excellent sealing, durability, and waterproofing performance. This technology can provide technical support for asphalt pavement crack repair.

Keywords: asphalt-based polymer sealing materials, cracks, thermoplastic elastomer, plasticizer, adhesion strength.

1. Introduction

Asphalt concrete is widely used in high-grade highways(motorways, class I highways, and class II highways) and urban roads due to its numerous advantages, including rapid construction speed, ease of repair and maintenance, as well as excellent skid resistance and wear resistance [1-3]. However, as traffic volume increases and road pavements undergo prolonged operation, asphalt

pavements often develop various problems. Cracks are a common type of damage in asphalt concrete pavements. Asphalt concrete pavements are highly susceptible to cracking under traffic loads in low-temperature environments or areas with significant daily temperature fluctuations [4-5]. Based on the causes of crack formation, cracks can be classified into temperature cracks, fatigue cracks, and reflective cracks [6]. Cracks in asphalt concrete pavements allow water to infiltrate and accumulate within the road structure, leading to premature deterioration [7-9]. Therefore, sealing the cracks in the early stages of their formation and before the autumn rainfall can prevent rainwater from entering the road structure through the pavement cracks, thus extending its service life.

Materials used for sealing cracks in asphalt concrete pavements are primarily divided into two categories: cold-applied and hot-applied materials. Among them, hot-applied asphalt-based sealing materials have been widely used in road maintenance due to their excellent crack-sealing performance and low cost [10-13]. Since the performance of asphalt-based polymer sealing materials primarily depends on the properties of the matrix asphalt component, enhancing their durability has become a major research focus. Currently, the main methods for improving the durability of asphalt-based sealing materials include polymer modification of the asphalt, incorporation of mineral or fiber fillers into the asphalt matrix, and addition of plasticizers to asphalt-based composites [14].

By incorporating various polymer additives to modify the asphalt binder, the heat resistance, low-temperature resistance, elasticity, water stability and aging resistance of the asphalt can be improved [15]. At present, the most widely used polymer materials include atactic polypropylene (APP), styrene-butadiene-styrene (SBS), ethylene-propylene rubbers, butyl rubbers, polyethylenes, copolymers of ethylene with propylene, ethylene vinyl acetate (EVA), ethylene methacrylate (EMA), ethylene butyl acrylate (EBA), divinyl styrene thermoplastic elastomer (DST), latexes (SKS-30, SKD-1, SKEP), polyisobutylene, polystyrene [19-21]. In the early 1960s, atactic polypropylene (APP) began to be used to enhance the heat resistance of petroleum asphalt [28]. However, compared with styrene-butadiene-styrene (SBS)-modified asphalt materials developed later, APP-modified asphalt materials exhibit lower deformation capacity and elasticity.Thermoplastic elastomer polymers (including SBS) combine the high strength of thermoplastic polymers with the elasticity of rubber [22]. Furthermore, the addition of polyethylene or ethylene-propylene rubber to asphalt increases the brittle temperature of the composite material compared to SBS polymer modification [23].

Adding finely dispersed powdered mineral fillers to asphalt can enhance its heat resistance. Studies have shown [24] that adding 20 % finely dispersed mineral filler increases the softening point of asphalt by 5 ℃, while adding 35 – 40% increases it by 7 – 8℃. Compared to asphalt without mineral fillers, asphalt containing finely dispersed mineral fillers exhibits a higher brittle temperature, higher heat resistance, and greater strength. Furthermore,the addition of mineral fillers reduces the shrinkage and creep, improves the physical and mechanical properties of asphalt composites, and lowers material costs by increasing the material volume. However, asphalt binders containing mineral fillers have lower deformation and bonding capabilities,as well as a higher water absorption rate. Mineral fillers used in the preparation of asphalt-based polymer sealants should possess chemical inertness, high strength, and be insoluble in water and non-hygroscopic. At present, the fine dispersed mineral fillers commonly used in asphalt-based polymer mastic mainly include: limestone, dolomite, brick, andesite mineral powders, kaolin, talc, talc-magnesite, chalk, ground sand, fly ash and cement. Common fiber fillers include asbestos, slag wool, basalt fiber, or heat-resistant polymer fibers [25-28]. To enhance the deformation capability of asphalt-based polymer sealants at low temperatures, plasticizers are typically added to their composition [29-31]. The substances that can be used as plasticizers include industrial oil, shale oil, dibutyl phthalate, styrene distillation bottoms, fuel oil, vacuum gas oil, tar and low-viscosity bitumen.

In summary, the main components for preparing heat-resistant asphalt-based polymer sealants are petroleum asphalt, polymer additives, and plasticizers. For asphalt-based polymer mastic, finely dispersed mineral fillers are also included. However, there is a lack of systematic research on the

component proportions, synthesis methods, aging resistance, cold resistance, and adhesion strength with asphalt concrete pavement crack areas of oxidized petroleum asphalt-based sealing materials. Therefore, this paper investigates the effects of the content and grade of oxidized petroleum bitumen, thermoplastic elastomer, plasticizer, and various types of mineral fillers on the penetration, softening point, ductility, elasticity, low-temperature flexibility, and rheological property of heated asphalt-based polymer sealants. A pull-off test was used to determine the effect of different test temperatures and the temperature of the asphalt concrete surface when coated with asphalt-based polymer sealant on the adhesion strength between the asphalt-based polymer sealant and the asphalt concrete surface.

2. Materials and Preparation Methods

2.1 Materials

2.2.1 Bitumen

To investigate the effects of various component compositions on sealant performance, this study employed oxidized road petroleum bitumen designated as BND 50/70 and BND 70/100 as matrix materials. It was modified by adding plasticizers, thermoplastic elastomer (SBS) and Butonal NS 198 cationic latex. The basic properties of oxidized road petroleum bitumen for BND 50/70 and BND 70/100 are shown in Table 1.

Table 1 Basic properties of oxidized road petroleum bitumen

Technical indicators	BND 50/70	BND70/100
Penetration (25 ℃), 0.1mm	65	96
Softening point, ℃	50	45
Ductility (25 ℃)，cm	58	＞100
Brittleness temperature, ℃	-19	-22
Adhesion to the glass surface, %	32	28
Flash point, °C	242	235
Weight change after heating, %.	0.4	0.5
Residual penetration, %	80	78
Change in softening point after heating, ℃	3.5	4

2.1.2 Thermoplastic elastomer and cationic Latex

As components of the sealing material, thermoplastic elastomer “Kraton D-1101” and cationic latex “Butonal NS 198” provide elasticity to the sealant and enhance its heat resistance. Thermoplastic elastomer Kraton D-1101 is produced by Shell Company. It is a linear block copolymer of styrene and butadiene, with a styrene content of 31%. Its main properties are shown in Table 2. The main properties of the cationic latex “Butonal NS 198” are shown in Table 3.

Table 2. Main properties of Kraton D-1101.

Parameters	Value
Styrene content, %	31
Volatile components, %	0.3
Extractable components, %	1
Solution viscosity, Pa·s	4
Antioxidant content, %	> 0,14
Flowability index, 200 ℃/5 kg, g/10 min.	< 1
Bulk density, t/m^3	0.3
Shore A hardness, 30 sec.	72
Tensile strength, MPa	33
Modulus of elasticity 300 %, MPa	2.9
Tensile elongation, %.	880

Table 3. Main properties of Butonal NS 198 cationic latex.

Appearance	Chemical composition	Solids content, %.	Density, g/cm^3	pH
Water dispersion of white color	Styrene-butadiene-styrene dispersion	64	0.95	4.5

2.1.3 Plasticizers

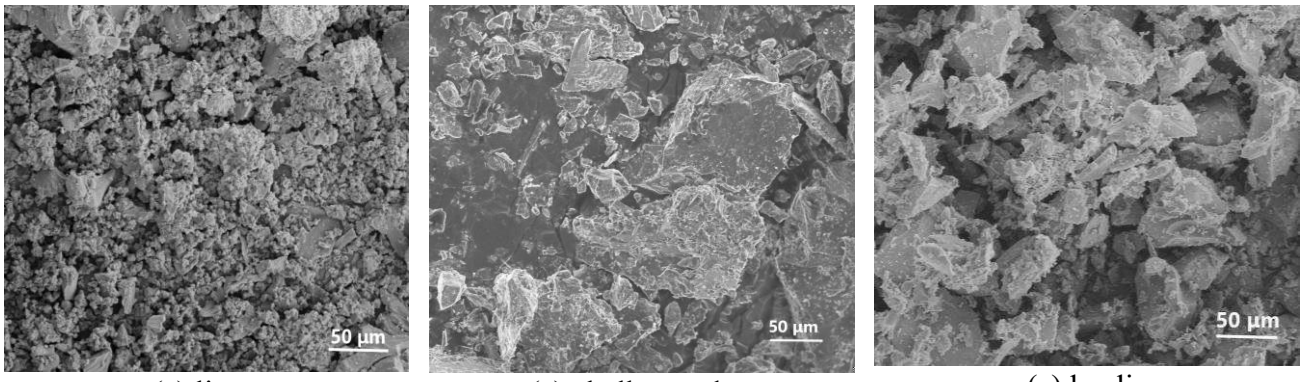
To ensure that the sealing material exhibits excellent deformation capability (low-temperature flexibility) at low temperatures, petroleum plasticizers were added to its composition. The main characteristics of the plasticizers are shown in Table 4.

Table 4 Technical properties of plasticizer.

Parameters	Value
Kinematic viscosity at 100 °C, mm^2/s	20.5
Viscosity index	80
Cokeability, %	0.29
Open-cup flash point, °C	275
Solidification, °C	-29

2.1.4 Mineral fillers

To enhance the heat resistance of sealing materials, 3 mineral fillers (lime, chalk powder, and kaolin) were added to the asphalt-based polymer sealant to prepare asphalt-based polymer mastic. The chemical composition of the mineral fillers determines the chemical properties of the fillers, and these chemical properties play a crucial role in the adhesion performance of the adhesive [36]. Kaolin is a typical clay mineral with the chemical formula $Al_2Si_2O_5(OH)_4$, chalk powder is composed of $CaCO_3$, while lime is mainly CaO or $Ca(OH)_2$. These mineral fillers are mostly neutral or alkaline materials. Their scanning electron microscope (SEM) images and particle size distributions are respectively shown in Fig.1 and Fig. 2.



(a) lime (a) chalk powder (c) kaolin

Figure 1. SEM images of mineral fillers

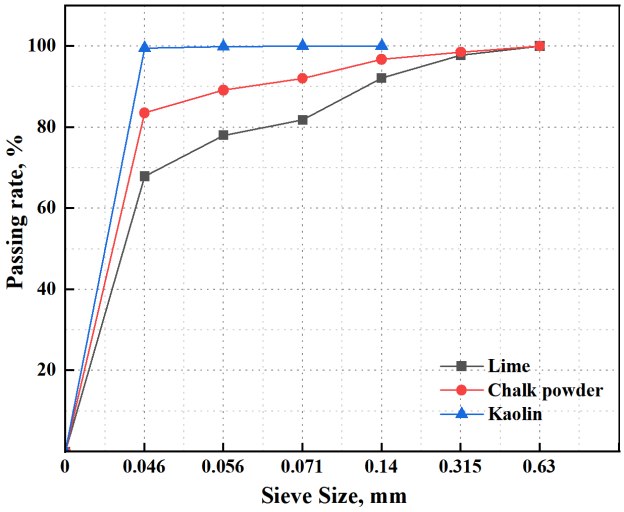


Figure 2. Particle size distribution of mineral fillers.

2.2. Test methods

2.2.1. Basic performance test

The three key indicators of bitumen (penetration depth, softening point and ductility, as shown in Fig. 3(a), (b) and (c)) are the crucial parameters for evaluating the technical performance and road application quality of petroleum bitumen. The penetration reflects the viscosity and hardness of asphalt. The ductility characterizes the plastic deformation capacity of asphalt. The softening point measures the thermal stability and temperature sensitivity of asphalt. Their testing methods were carried out in accordance with the specifications outlined in Table 7.

2.2.2 Low-temperature flexibility test

Low-temperature flexibility refers to the property of sealing materials samples where no cracks or fractures occur on their surface during the bending test around a rod at low temperatures. According to specification DSTU B V.2.7-116, apply a 2 mm thick layer of sealing material onto an aluminum foil strip measuring 100×20×2 mm. After the sample has cooled to the ambient temperature, let it stand at a temperature not exceeding 25°C for at least 1 hour. During the flexibility test, the prepared samples and 2cm metal rod were placed in a freezer and maintained at a constant temperature of -20°C for 1 hour. Then, the samples were taken out of the freezer one by one and placed on the 2cm diameter metal rod. The contact length between the sample and the metal rod should be approximately 0.25 times the length of the sample, as shown in Fig. 3(d). Bend the free end of the sample around the metal rod. Observe whether any cracks or fractures occur during the bending process. If no cracks or fractures are detected, the sealing material is considered to have passed the test. For the next set of samples placed in the freezer, the temperature is lowered by 5°C and maintained for 1 hour. Similar tests were also conducted on these samples. For the subsequent batches of samples, the temperature of the freezer was lowered by 5 °C each time until at least two samples cracked.

2.2.3 Rheological propertie tests

The addition of different types and contents of mineral fillers may affect the high-temperature rheological properties of asphalt-based polymer mastic. In this study, temperature sweep tests were conducted on various types of asphalt-based polymer mastic with different types and contents using a dynamic shear rheometer, as shown in Fig. 3 (d). The test results are used to reflect the rheological behavior of asphalt-based polymer mastic under high temperatures. The test temperature range is 64 to 76°C, with a temperature gradient of 6°C and an angular frequency of 10 rad/s. The shear modulus

(G*) and phase angle (δ) were tested, and the variation pattern of the rutting factor (G*/sin δ) was analyzed. The low-temperature rheological properties of asphalt mortar were investigated through bending beam rheological tests conducted at -12℃, -18℃ and -24℃, as shown in Fig. 3 (e).



(a) Softening point test



(b) Penetration depth test



(c) Ductility test



(c)Low-temperature flexibility test



(d) Dynamic shear rheometer



(e) Bending beam rheometer

Figure 3. Performance testing of asphalt-based polymer sealing materials

2.2.4 Adhesion strength between sealing material and asphalt concrete surface

This paper used the uniform separation method (pull-off test) to determine the adhesion strength between the sealing material and the asphalt concrete surface. The uniform separation method can simultaneously measure the force required to separate the adhesive from the substrate within the entire contact area. In this case, the force was applied perpendicularly to the separation surface, and the adhesion strength was characterized by the force related to the contact area. The adhesion strength between different sealing materials and the asphalt concrete surface was measured using an ONIX-1.AP device.

Fig. 5 showed the process of determining the adhesion strength of different sealing materials to the substrate. The sealing material was applied to a prepared asphalt concrete surface at 180 °C. Then a rectangular metal plate was fixed onto the surface of the sealing materials. Before contacting the heat-sealing material, clean the surface of the metal plate with sandpaper and degrease it with acetone. Then, heat the plate to a temperature 20 ℃ higher than the softening point of the sealing material. A constant thickness of sealing material between the surface of the metal stamp and the asphalt concrete specimen of 1.5 ± 0.2 mm was provided by placing pads of the specified thickness on each side of the stamp.

Cool the specimen coated with sealing material and metal pressure plate to room temperature. Trimmed away any excess sealing material around the metal plate so that the area of the asphalt-based

polymer sealant or asphalt-based polymer mastic corresponded to the area of the metal plate. Before testing, place the prepared specimens in an oven at the specified test temperature for 90 ± 5 min. After the specimen was kept at a constant temperature, it was removed from the oven and fixed onto the ONYX-1.AP device within 15-20 s, and then tested until the metal plate detached.

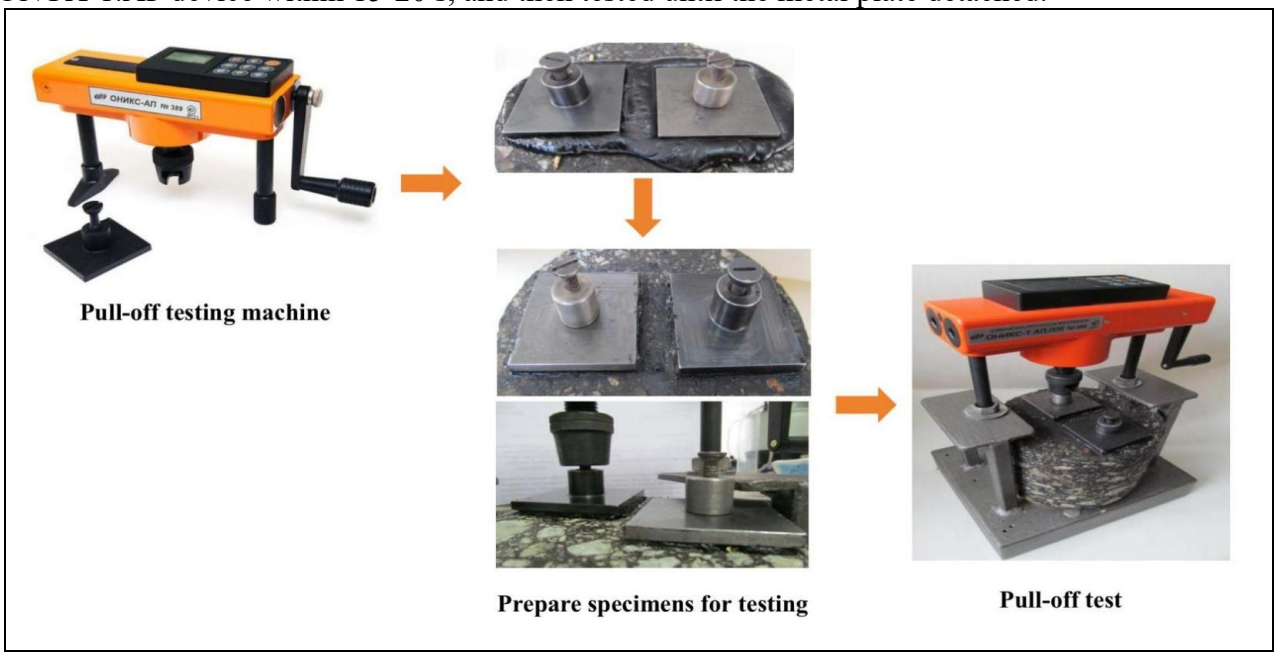


Figure 5. The specific process of the pull- off test.

Under uniform separation conditions, the adhesion strength between the sealing material and the substrate was determined by the ratio of the maximum separation force to the contact area of the metal plate, according to the following formula:

$$\sigma = \frac{P}{S} \cdot 10^{-6} \quad (1)$$

P-Maximum separation force, N;
S- Area of the metal plate, m².

3. Sealant mixing ratio design and preparation process

Asphalt-based polymer sealants were prepared using oxidized bitumen BND 50/70 and BND 70/100. To investigate the effect of component content on their properties, 4 formulations with different proportions were employed, as shown in Tables 5 and 6. The formulation for preparing asphalt-based polymer sealants based on BND 50/70 bitumen (Types A, B, C, D) was designed to investigate the effects of different contents of plasticizers and SBS polymer on their properties.

When preparing polymer sealant using BND 70/100 bitumen, formulations Type E and Type H adopted different contents of bitumen and plasticizers, while maintaining the content of SBS polymer and Butonal NS 198 cationic latex unchanged. The contents of each component in these two formulations were different, resulting in variations in the content of low-molecular-weight components (plasticizers) in the BND 70/100 bitumen dispersion medium. Therefore, this study aims to investigate how the content of plasticizers in dispersed media affects the cold resistance performance of sealing materials.

Table 5. Formulations for polymer sealants prepared based on BND 50/70 bitumen.

Name	Plasticizer, %	Cationic latex	BND 50/70	SBS

		Butonal NS 198, %	oxidized petroleum bitumen, %	polymer, %
Type A	20	5	60	15
Type B	20	5	65	10
Type C	15	3.75	75	6.25
Type D	10	5	75	10

Table 6. Formulations for asphalt-based polymer sealants prepared based on BND 70/100 bitumen.

Name	Plasticizer, %	Cationic latex Butonal NS 198, %	BND 70/100 oxidized petroleum bitumen, %	SBS polymer, %
Type E	20	5	65	10
Type F	15	5	72	8
Type G	15	5	75	5
Type H	10	5	75	10

The difference between asphalt-based polymer sealant and asphalt-based polymer mastic lies in the fact that the asphalt-based polymer mastic contains fillers. To research the effects of different types and contents of mineral fillers on the performance of asphalt-based polymer mastics, 5 %, 10 %, 15 %, and 20 % of lime, chalk powder, and kaolin were added separately to an asphalt-based polymer mastic (70 % BND 70/100 oxidized petroleum road bitumen + 17 % plasticizer + 8 % SBS polymer + 5 % Butonal NS 198 cationic latex). The preparation process of asphalt-based polymer sealant and asphalt-based polymer mastic is shown in Fig.6. The performance requirements of the prepared asphalt-based sealing material should comply with the requirements listed in Table 7.

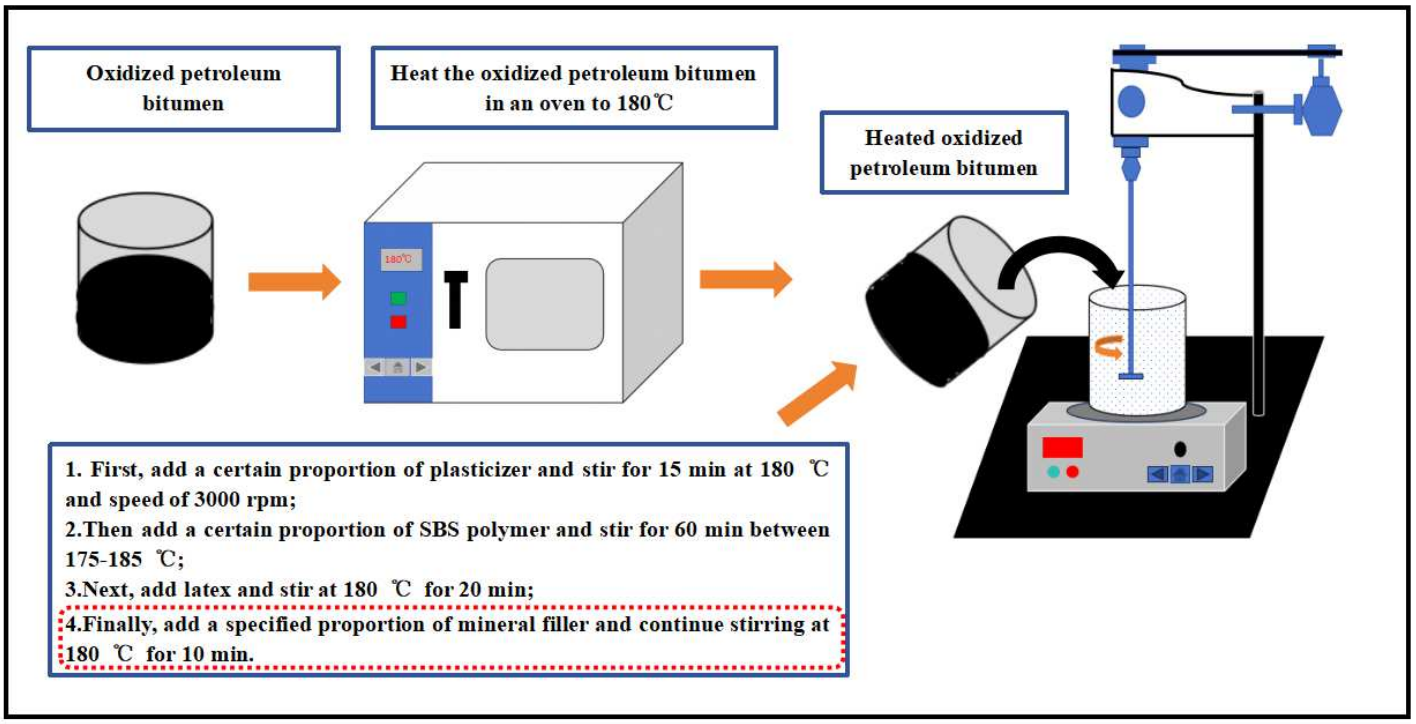


Figure 6. Preparation process of asphalt-based polymer sealant and asphalt-based polymer mastic.

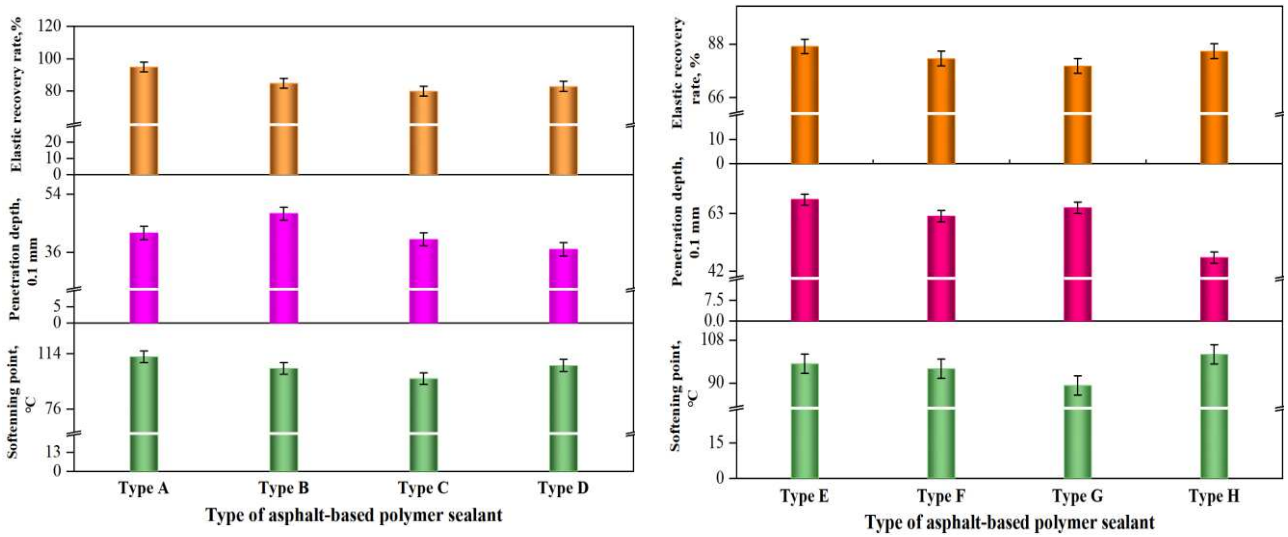
Table 7. Performance requirements for asphalt-based sealing materials

Name of index	Requirements for indicator values	Testing method
Penetration depth，0.1mm	55 - 80	DSTU EN1426 [32]
Softening point, °C, not lower than	90	DSTU EN1427 [33]
Brittleness temperature, °C, not higher than	-35	DSTU EN12593 [34]
The elastic recovery rate at 25 °C, %, not lower than	80	DSTU B V.2.7-135 [35]
Low-temperature flexibility, °C, not higher than	-30	DSTU B V.2.7-116 [36]

4. Results and Discussion

4.1. The influence of different proportions of components on the performance of asphalt-based polymer sealants

The experimental results on the influence of different proportions of components on the performance of asphalt-based polymer sealants prepared from BND 50/70 and BND 70/100 oxidized bitumen are shown in Fig.7 and Table 8.



(a) (b)

Figure 7. Main performance of asphalt-based polymer sealants: (a) with BND 50/70 as the base material (b) with BND 70/100 as the base material.

Table 8. Low temperature performance of asphalt-based polymer sealants.

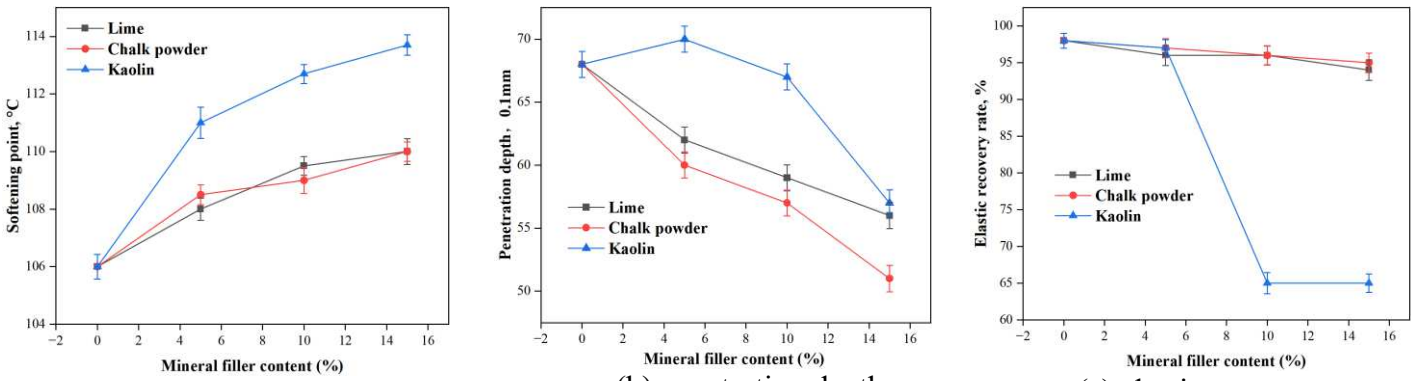
Parameter	BND50/70				BND 70/100			
	Type A	Type B	Type C	Type D	Type E	Type F	Type G	Type H
Brittle temperature, °C	＜-30	＜-30	＜-30	＜-30	＜-30	＜-30	＜-30	＜-30
Low-temperature flexibility, °C	＜-30	＜-30	＜-30	-25	＜-30	＜-30	＜-30	-29

As can be seen from Fig. 7, the performance research results of preparing asphalt-based polymer sealants using Formulas Type F and Type G show that, under the condition where the concentrations of plasticizers and Butonal NS198 cationic latex are the same, when the content of SBS polymer decreases from 8% to 5 %, the softening point will decrease by 7 ℃, the elastic recovery rate will decrease by 3 %, and the penetration depth and ductility at 25 ℃ will slightly increase. Asphalt-based polymer sealants prepared from BND 50/70 and BND 70/100 asphalt, with the same SBS polymer content, showed that the BND 50/70 bitumen had slightly higher heat resistance (measured by softening point). Depending on the plasticizer content, the softening point was 4 to 6 °C higher.

As shown in Table 8, in asphalt-based polymer sealants prepared based on BND50/70 bitumen, when the plasticizer concentration reached 15 % or more, the brittle temperature and low-temperature flexibility were below -30 °C. Reducing the plasticizer content in asphalt-based polymer sealants to 10 % increased their flexibility temperature to -25 °C. A similar phenomenon was observed in asphalt-based polymer sealants prepared using BND 70/100 bitumen. When the plasticizer content was reduced to 10 %, the flexibility temperature increased to -29 °C. In asphalt-based polymer sealants prepared from BND 70/100 bitumen (with the same SBS polymer content), when the content of plasticizer was halved, both the brittle temperature and flexibility temperature increased to above -30 ℃.

4.2. The influence of different types and contents of mineral fillers on the performance of asphalt-based polymer mastic

The results of investigating the influence of different types and contents of mineral fillers on the performance of asphalt-based polymer mastic prepared using BND 70/100 bitumen (70 % BND 70/100 oxidized petroleum road bitumen + 17 % plasticizer + 8 % SBS polymer + 5 % Butonal NS 198 cationic latex) are shown in Fig. 8.



(a) softening point (b) penetration depth (c) elastic recovery rate

Figure 8. The influence of different types and contents of mineral fillers on performance of asphalt-based polymer mastic.

As can be seen from Fig. 8, the addition of fillers to asphalt-based polymer sealants changed their performance. Furthermore, with increasing content of mineral fillers in the asphalt-based polymer sealant, the softening point increased, while their penetration depth, ductility, and elastic recovery rate decreased. When asphalt-based polymer sealants contained 15% mineral fillers, their softening point increased by 4 – 8 °C. Based on the three mineral fillers studied, it can be seen that kaolin was more effective in increasing the softening point of asphalt-based polymer sealants. Obviously, this was largely related to the high dispersibility of the mineral fillers (the residue of mineral filler lime on a 0.071 mm sieve was 18 %, chalk powder was 8 %, and kaolin was 0 %).

The rutting resistance factor (G*/sin δ) can represent the high-temperature resistance ability of asphalt -based polymer sealing material to deformation. The larger the value, the stronger the resistance to deformation. Fig. 9 showed the temperature dependence of rutting resistance factor

(G*/sin δ) for asphalt-based polymer mastics containing various types and contents of mineral fillers, as evaluated through temperature sweep tests.

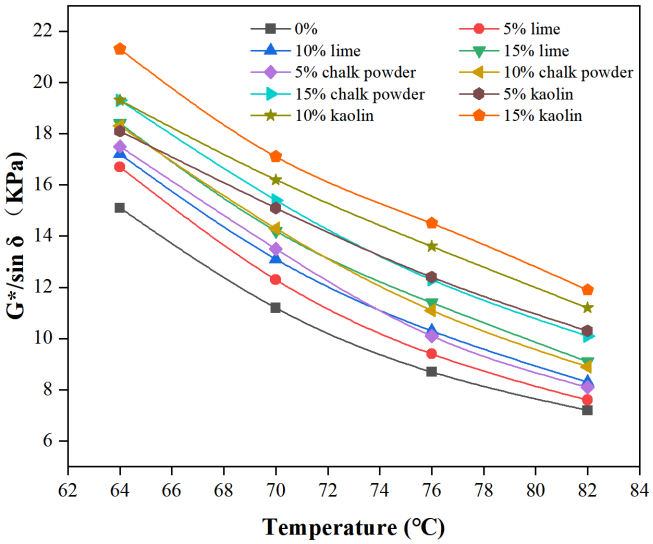
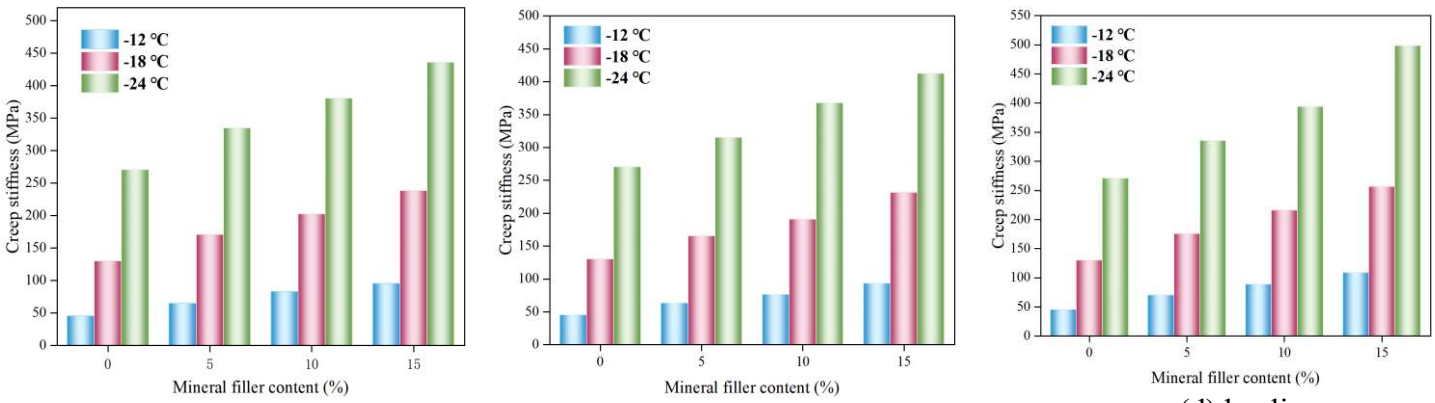


Figure 9. Rutting resistance coefficients of asphalt-based polymer mastics with different mineral filler types and contents

As shown in Fig. 9, the rutting factor (G*/sin δ) of the asphalt-based polymer mastic exhibited a gradual downward trend as the scanning temperature increased. At the same test temperature, the incorporation of mineral fillers significantly enhanced the rutting resistance of asphalt-based polymer mastic, and the rutting resistance factor progressively increased with the increasing filler content. Comparing the three types of fillers, kaolin demonstrated the optimal reinforcing effect, followed by chalk powder and lime. When the kaolin content was 15%, the rutting resistance factors of the asphalt-based polymer mastic at 64 ℃, 70 ℃, 76 ℃, and 82℃ increased by 41%, 52.6%, 66.7%, and 65.3% respectively. This was attributed to the fine particle size and large specific surface area of kaolin, which facilitate more extensive interfacial contact with the asphalt phase, thereby promoting adsorption and the formation of a greater quantity of structured asphalt. Consequently, this effectively enhanced the high-temperature rheological properties and resistance to permanent deformation of the asphalt-based polymer mastic.



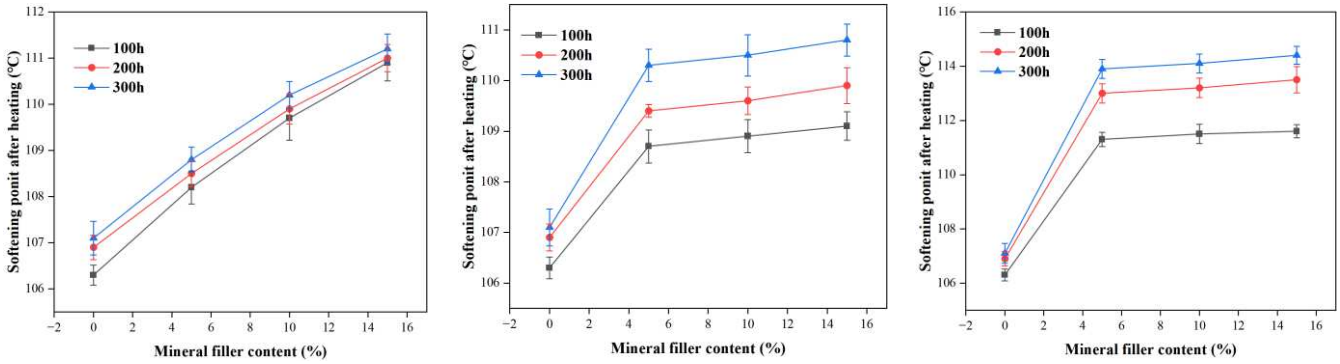
(a) lime (b) chalk powder (d) kaolin

Figure 10. Creep stiffness of asphalt-based polymer mastics with different mineral filler types and contents

Fig. 10 shows the creep stiffness of asphalt-based polymer mortars with different mineral filler types and contents at -12℃, -18℃ and -24℃. Under the same temperature conditions, the creep stiffness of asphalt-based polymer mortar increases with the increase of mineral filler content. This is because the rheological properties of asphalt-based polymer mastic are primarily determined by

the intrinsic properties of the asphalt itself, and its internal structural system undergoes significant changes as the content of mineral fillers increases. When the content of mineral fillers is low, free asphalt dominates in the mastic system, and the content of structural asphalt is relatively small. At this time, the rheological properties of asphalt-based polymer mastic are mainly determined by the asphalt itself. As the content of mineral fillers gradually increases, the proportion of structural asphalt steadily rises, and the overall structural system of the mastic undergoes a corresponding transformation. Consequently, its performance is also significantly influenced by the mineral fillers. Under the condition of the same mineral filler content, the influence of lime and chalk powder on the creep stiffness of asphalt-based polymer mortar is similar, while kaolin has a more significant effect on enhancing the creep stiffness. Kaolin possesses a larger specific surface area and greater surface activity. In asphalt-based polymer mastics, it facilitates more thorough adsorption of asphalt components, forming a continuous and stable structural asphalt film that enhances the overall structural strength of the mastic system as well as the inter-particle binding forces. This significantly improves the resistance of material to deformation at low temperatures, thereby resulting in a more pronounced enhancement of its low-temperature creep stiffness. Lime and chalk powder have a smaller specific surface area and relatively weaker physical adsorption and interfacial bonding with asphalt. Their effect on enhancing the structure of the mastic system is limited, and their underlying mechanisms of action are similar. Therefore, the difference in the impact on low-temperature creep stiffness is not significant, and the improvement effect is weaker than that of kaolin.

Asphalt-based polymer sealants were affected by high summer temperatures, which could cause their basic performance to deteriorate due to aging. Therefore, the effect of high temperature on them main performance changes of asphalt-based polymer sealants was simulated by heating 2 mm-thick samples in a ventilated heating oven at 65 °C. The changes in softening point of asphalt-based polymer sealants with different filler contents after heating were shown in Fig. 11.



(a) lime (b) chalk powder (c) kaolin

Figure 11. Effect of different types and content of mineral fillers on the performance of asphalt-based polymer sealants after heating.

As can be seen from Fig. 11, the softening point of asphalt-based polymer sealants with different fillers increased with increasing filler content after heating for 300 h. When the filler content was low, the absolute increase in the softening point of the asphalt-based polymer sealant was relatively small. This indicated that asphalt-based polymer sealants with mineral filler contents not exceeding 5% could meet the long-term service requirements for pavement repair.

4.3. The influence of sealing temperature conditions on the adhesion strength between sealing materials and asphalt concrete surfaces

To determine the adhesion strength between the asphalt-based polymer sealant and the asphalt concrete surface, cylindrical specimens of type A fine-graded asphalt concrete were used. To study the effects of different filler types and contents on the adhesion strength between asphalt-based polymer mastic and asphalt concrete surfaces, prismatic specimens of type B fine-graded asphalt

concrete were used. The asphalt-based polymer sealant was applied to the surface of the asphalt concrete specimen at a temperature of 180 ℃. To study the effect of asphalt concrete specimen surface temperature on the adhesion strength of asphalt-based polymer sealants during application, asphalt concrete specimens were heated in a ventilated heating oven to specific temperatures ranging from 10 to 80 ℃. When applying asphalt-based polymer sealant, the surface temperatures of the asphalt concrete specimens were 10 ℃, 20 ℃, 30 ℃, 40 ℃, 50 ℃, 60 ℃, 70 ℃, and 80 ℃. Pull-off tests were conducted on coated asphalt concrete specimens at temperatures of -20 °C, -15 °C, -10 °C, -5 °C, 0 °C, 5 °C, 10 °C, 15 °C, and 20 °C to determine the adhesion strength between the sealing material and the asphalt concrete surface.

The results of the adhesion strength between the asphalt-based polymer sealants and the asphalt concrete surface were shown in Fig. 12. The influence of test temperature on the adhesion strength between asphalt-based polymer sealants and asphalt concrete surfaces was shown in Fig. 13.

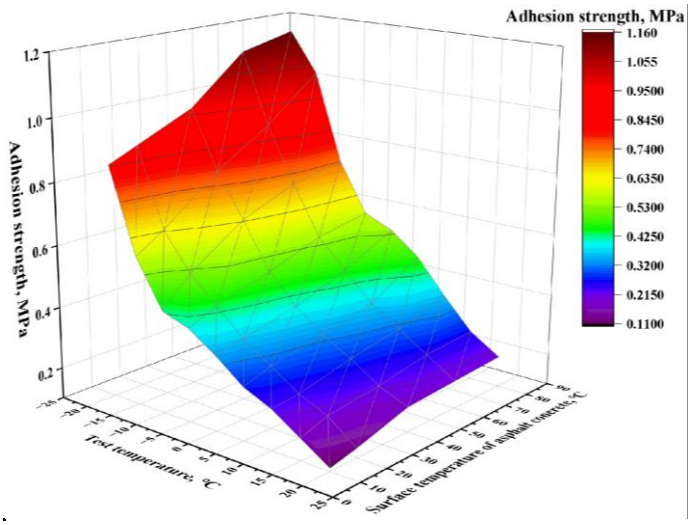


Figure 12. Relationship between adhesion strength of asphalt-based polymer sealant and test temperature.

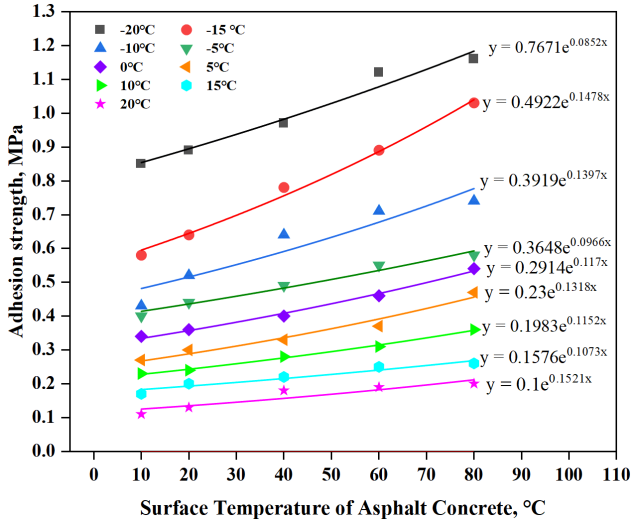


Figure 13. Relationship between adhesion strength of asphalt-based polymer sealant and surface temperature of asphalt concrete.

As can be seen from Fig. 12, the adhesion strength between the asphalt-based polymer sealant and the asphalt concrete surface was very sensitive to the test temperature and the temperature of the asphalt concrete surface. The adhesion strength between asphalt-based polymer sealant and asphalt concrete surfaces decreased as the test temperature increased. At the same time, the higher the temperature of the asphalt concrete surface, the greater the adhesion strength between the asphalt-based polymer sealant and the asphalt concrete surface. At test temperatures of -20 ℃, 0 ℃, and 20 ℃, the adhesion strength between asphalt concrete specimens preheated to 80 ℃ and 10 ℃ and the asphalt-based polymer sealant was tested. The test results showed that asphalt concrete specimens preheated to 80 ℃ exhibited 1.77 times, 1.56 times, and 1.36 times higher values compared to those preheated to 10 ℃. This indicated that when crack sealing was performed on the surface of asphalt concrete substrates at lower temperatures, a large area of weak interface formed between the sealant and the substrate.

When the test temperature decreased from 20 ℃ to 0 ℃, the adhesion strength between the asphalt concrete surface and the asphalt-based polymer sealant increased by 2.70 times at an asphalt concrete surface temperature of 80 ℃. When the test temperature decreased from 0 ℃ to -20 ℃, the adhesion strength between the asphalt concrete surface and the asphalt-based polymer sealant increased by 2.15 times at the same temperature. When the test temperature decreased from 20 ℃ to 0 ℃, the adhesion strength between the asphalt concrete surface and the asphalt-based polymer sealant increased by 3.06 times at an asphalt concrete surface temperature of 10 ℃. When the test temperature decreased from 0 °C to -20 °C, the adhesion strength between the asphalt concrete surface and the asphalt-based polymer sealant increased by 2.47 times. Furthermore, the absolute value of the adhesion strength between asphalt concrete and asphalt-based polymer sealant was significantly lower when the asphalt concrete surface temperature was 10 °C compared to when the asphalt concrete surface temperature was 80 °C. Therefore, the temperature sensitivity of the adhesion strength between asphalt concrete surfaces and asphalt-based polymer sealants depended both on the temperature range during testing and on the surface temperature of the asphalt concrete when sealing cracks. Analysis of the relationship shown in Fig. 13 indicated that under low-temperature testing conditions, the adhesion strength between asphalt-based polymer sealants and asphalt concrete surfaces exhibited a more significant increase compared to high-temperature conditions.

The test results for the adhesion strength between asphalt concrete and asphalt-based polymer sealants at different filler types and contents were shown in Fig 14.

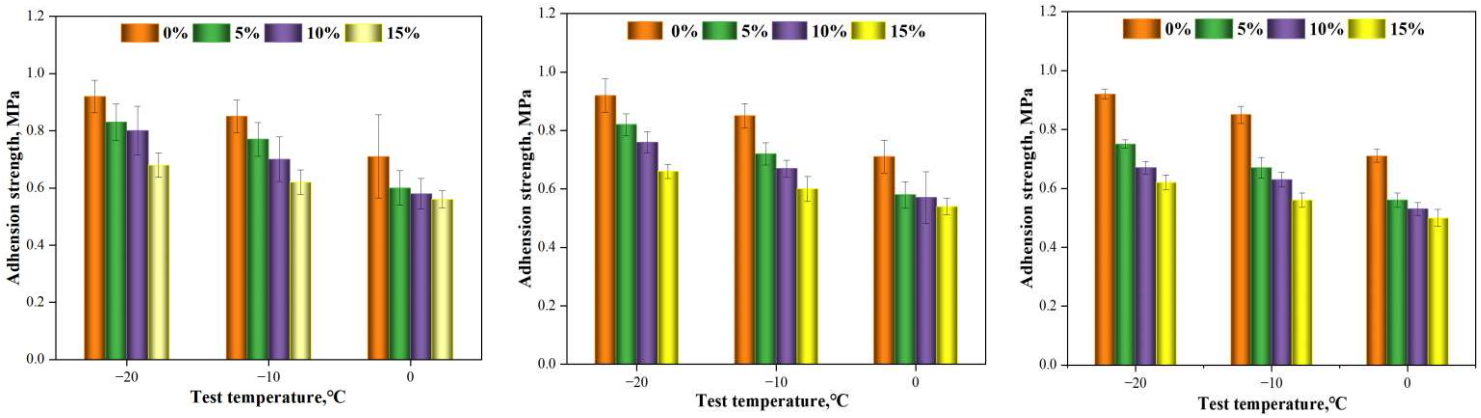


Figure 14. Temperature dependence of the adhesion strength between asphalt-based polymer sealant with different types of mineral fillers and asphalt concrete surface: (a) Lime (b) Chalk powder (c) Kaolin.

As shown in Fig. 14, as the content of mineral filler in the asphalt-based polymer sealant increased, its bond strength to the asphalt concrete surface decreased. Evidently, this was due to the increased viscosity of asphalt-based polymer mastic at construction temperatures compared to

asphalt-based polymer sealants, resulting in reduced flowability and wetting properties on asphalt concrete surfaces. This resulted in the formation of a weak boundary layer at the interface between the asphalt-based polymer mastic and the asphalt concrete surface, thereby reducing the adhesion strength between the asphalt-based polymer mastic and the asphalt concrete surface. The adhesion strength values of asphalt-based polymer mastic with different types of fillers increase as the test temperature decreased.

The effect of different types of mineral fillers on the adhesion strength between asphalt concrete and asphalt-based polymer mastic was ranked in the following order: lime, chalk powder, kaolin. This result was consistent with the dispersion degree of the mineral filler. The mineral filler lime had the lowest proportion of particles smaller than 0.046 mm (67.9 %), chalk powder had a moderate proportion (83.5 %), and kaolinite had the highest proportion of particles smaller than 0.046 mm (99.5 %). As the dispersion degree of mineral fillers increased, their specific surface area and adsorption capacity also increased. Consequently, mineral fillers with the largest specific surface area adsorbed a significant amount of low-molecular-weight components from the asphalt-based polymer mastic, thereby reducing its flowability and wetting properties on asphalt concrete surfaces [37]. Obviously, this will affect the formation of the weak boundary layer and reduce the adhesion strength between the asphalt-based polymer mastic and the asphalt concrete surface.

5. Application case studies of research results

This section introduces the performance of the hot-applied asphalt-based polymer sealing material produced by the "Kredmash" plant using the “DS-1631” type mixer and the "Hofmann HK-1000-1" mixing boiler, as well as the sealing process of cracks on the important national highway M-03 "Kiev - Kharkiv - Dovzhansky" using this product.

5.1. Properties of asphalt-based polymer sealing material produced under industrial conditions

Fig. 15 showd the production equipment for asphalt-based polymer sealing materials and the packaging process for asphalt-based polymer sealing materials. Properties of the asphalt-based polymer sealing materials produced under industrial conditions are shown in Table 9.

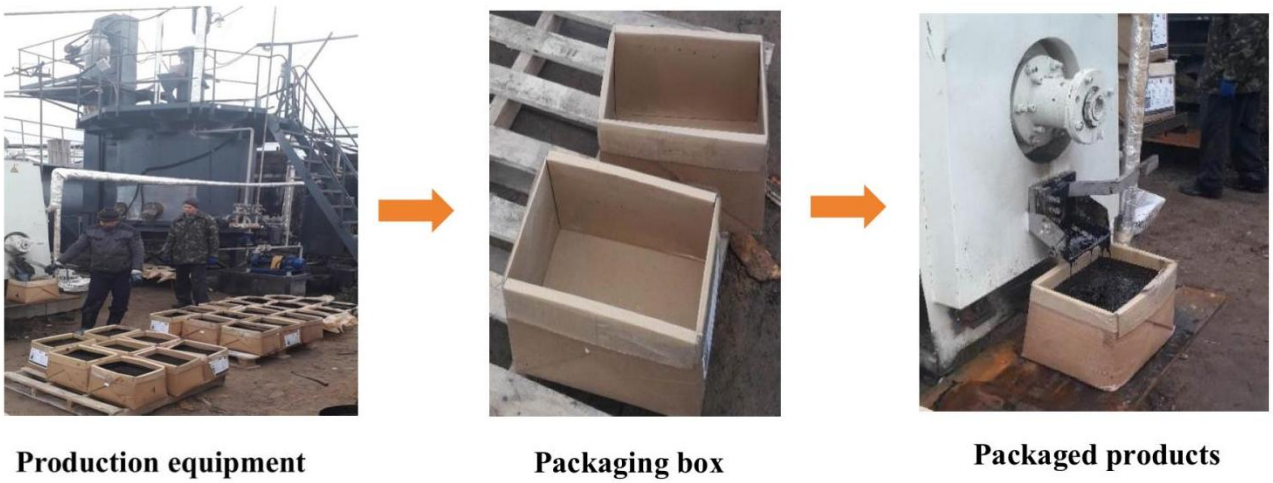


Figure 15. Production equipment for asphalt-based polymer sealing materials and the packaging process.

Table 9. Properties of asphalt-based polymer sealing materials produced under industrial conditions.

Properties	Penetration depth，0.1mm	Softening point, ℃	Elastic recovery rate, %	Brittle temperature, ℃	Low-temperature flexibility, ℃

Asphalt-based polymer sealant	66	96	99	-40	-30
Asphalt-based polymer mastic	59	98	99	-40	-30

5.2. Application of asphalt-based sealing material

The asphalt-based polymer sealing material prepared in this study was used to repair the pavement cracks on the section of National Important Highway M-03 from 0 + 395 km to 0 + 646 km, and from 0 + 000 km to 14 + 100 km. The specific operation process is shown in Fig. 16. Monitoring results of the crack sealing area showed that no damage occurred in the crack sealing area during the 2.5-3 years of road operation.



Figure 16. Process for sealing cracks in asphalt concrete pavements using asphalt-based polymer sealing materials

6. Conclusions

This paper studies the preparation of asphalt-based polymer sealants with different component compositions, the influence of different types and contents of mineral fillers on the performance of asphalt-based polymer mastic, and the effect of different sealing temperatures on the adhesion strength between asphalt-based polymer sealing materials and asphalt concrete. The following conclusions were drawn:

(1) Oxidized petroleum bitumen is suitable as a base material for preparing asphalt-based polymer sealing materials. Adding the same amount of plasticizer, SBS polymer, and cationic latex to both BND 50/70 and BND 70/100 oxidized petroleum bitumen, showed that the bitumen grade had little effect on the heat resistance of the polymer sealant. The Type D and Type H asphalt-based polymer sealants prepared based on BND 50/70 and BND 70/100, when the content of plasticizers, SBS polymer and cationic latex is the same, the heat resistance of the Type D is only slightly higher by 4 ℃ than that of Type H.

(2) To reduce the brittleness temperature and low-temperature flexibility of asphalt-based polymer sealants, the plasticizer content must be increased. To enhance their heat resistance, the content of SBS polymer and cationic latex must be increased, and mineral fillers must be added. For the asphalt-based polymer sealants prepared based on BND50/70, when the plasticizer content reached 15% or more, their brittleness temperature and low-temperature flexibility were lower than -30 ℃. When the plasticizer content in the asphalt-based polymer sealants was reduced to 10 %, their low-temperature flexibility could be increased to -25 ℃. A similar effect was also observed in the asphalt-based polymer sealants prepared based on BND 70/100 asphalt. When the plasticizer content was reduced to 10 %, their low-temperature flexibility increased to -29 ℃.

(3) As the content of mineral filler increases, the softening point of the asphalt-based polymer mastic increases, but its penetration, ductility, and elastic recovery rate decrease. When the asphalt-based polymer sealant contains 15 % mineral fillers, its softening point will increase by 4-8 ℃. When the filler content is low, the increase in the softening point of the asphalt-based polymer mastic is relatively small. Through the analysis of these three types of mineral fillers, it can be observed that kaolinite (softening point has increased by 8 ℃) is more effective at increasing the softening point of asphalt-based polymer mastic. Furthermore, as the content of mineral fillers increases, the rutting resistance factor of the asphalt-based polymer mastic continuously improves. In particular, kaolin proves most effective in enhancing the rutting resistance factor (G*/sin δ) of the asphalt-based polymer mastic. The rutting resistance factor (G*/sin δ) at 64℃, 70℃ and 76℃ increased by 33.6%, 43.0% and 64.4% respectively. Under the same filling content conditions, kaolin has a more significant effect on enhancing the creep stiffness compared to lime and chalk powder.

(4) The adhesion strength between asphalt-based polymer sealing material and asphalt concrete surface increases systematically with decreasing test temperature. Furthermore, the surface temperature of the asphalt concrete significantly affects the adhesion strength between the asphalt-based polymer sealing material and the asphalt concrete. The adhesion strength between the asphalt polymer sealing material and the asphalt concrete sample, when preheated to 80 ℃, was 1.77 times higher than that when preheated to 10℃. Therefore, preheating the cracked areas of the asphalt concrete pavement before sealing the cracks helps to create a stronger adhesive layer.

In future research, we will focus on two aspects of asphalt-based polymer sealing materials: wettability and storage stability. Through systematic research, we will clarify the mechanism of action, optimize the preparation scheme, and improve the evaluation system to promote the development of asphalt-based polymer sealing materials towards high performance, greenness, and long-lasting performance, providing more reliable technical support and theoretical basis for engineering applications.

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