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Recovery Efficiency of the Damaged Porous Asphalt Mixture with Emulsion-based Surface Treatment: Material Optimization and Performance Verification

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Abstract

Porous asphalt (PA) road surfaces usually have short service lives due to quick raveling. Recent field trials in Europe have shown that spraying surface-treatment (ST) asphalt emulsion is a potential method to address this problem. However, the recovery efficiency of ST emulsion in PA mixture is currently unknown, limiting the wide application of this preventive maintenance technique in practice. Therefore, this study aims to investigate the key factors affecting the recovery efficiency of ST emulsion when it is applied to damaged PA. The Cantabro abrasion tests were first conducted on damaged PA specimens with and without ST emulsions to evaluate the recovery performances of different ST scenarios. The functional properties, including noise-absorption, permeability, and skid-resistance, under the optimized ST application scenario were then characterized for verification purposes. The testing results showed that the abrasion loss of the damaged PA mixture under ST emulsion was significantly reduced after 3 days of curing. Both the application rate and solid content of ST emulsion are critical factors affecting the raveling resistance recovery of the damaged PA mixture. However, the addition of the bio-based or petrol-based rejuvenator has a negligible impact on the performance recovery of the damaged PA mixtures after 14 days of curing, indicating the diffusion of the ST emulsion (if any) may require a long time in this scenario. Besides, the application of the ST emulsion may have a slight side-effect on the functional performance of PA in the short term, necessitating functional performance verification for the ST emulsion design.

Keywords: Porous asphalt, Emulsion-based surface treatment, Preventive maintenance, Raveling resistance, Functional performance

1 Introduction

Porous asphalt (PA) refers to the open-graded asphalt mixture with a large air void content which is usually no less than 15%. It may include both the asphalt mixture used in the US for open-graded friction course (OGFC) and the asphalt mixture used in many other countries for the PA wearing courses. Due to its porous structure and large air void content, PA pavement provides various attractive functions, such as decreasing tire-road noise, reducing water splashing and hydroplaning on rainy days, improving pavement surface friction, and alleviating urban heat island effects [1, 2]. However, under the combined traffic and environmental effects, PA mixture usually has a shorter service life compared with conventional dense-graded or gap-graded asphalt mixture due to its quick raveling, which refers to the dislodgement of aggregate particles occurring at the pavement surface [3], because the large content of interconnected air voids in PA mixture makes it easier for oxygen and water to enter the mixtures, which leads to rapid aging of asphalt binder and loss of bonding between asphalt binder and aggregate [4, 5].

To address the raveling problem of PA, various practical experiences have been accumulated in many regions and countries, which can be divided into three categories based on the material sources and their roles in the PA mixture. Some researchers found that fibers [6] and different anti-stripping additives [7, 8] could be added to PA mixture to improve the cohesive strength of binder and the adhesive strength of asphalt binder to aggregate surface. Besides, some high viscosity asphalt binders have been widely adopted instead of conventional modified asphalt binders in many regions[9, 10]. In Hong Kong, both the virgin and polymer modified asphalt binders have been used to build PA road surfaces, and the PA with polymer modified binder was found more cost-effective because of its better durability [11]. The Japanese experience showed that PA with conventional polymer modified binder containing 5% styrene-butadiene-styrene (SBS) cannot provide sufficient durability. Instead, a highly modified bitumen containing 9% SBS with very high viscosity at 60 ºC was developed and found to be able to significantly extend the service life of PA wearing course. This special high-viscosity polymer modified asphalt has been used in force for PA wearing courses in Japan since 1998 [12]. The Netherlands, which has PA wearing courses on more than 90% of its main highway network, also has long-term experience with PA. But contradictory to the experience in Hong Kong and many other regions, the Netherlands experience has shown that polymer modified binder has an insignificant effect on the service life extension of PA wearing courses [13]. It was reported that polymer modified binder was only useful to obtain a higher binder content in PA which led to a better behavior in the field, but the same improvement could be obtained with virgin binder and drainage inhibitor [14]. Nowadays, some new binder materials, such as resins, have been applied to the pavement field and exhibited excellent mechanical performance. German researchers found that polyurethane (PU) is a good binder for permeable pavement owing to its excellent strength and good durability [15, 16]. Epoxy resin was also applied for permeable roads to withstand heavy traffic loads and maintain pavement functional properties [17-19]. However, all the above improvements mainly focused on the enhancement of cohesive and adhesive strength via material design and optimization during the pavement construction period. Although those experiences can prolong the service lives of PA pavements to some extent, raveling is still one of the common distresses which limits the service lives of PA wearing courses. Therefore, the development of a feasible preventive maintenance technology to alleviate the ravelling of PA after the road construction phase remains an important problem to be addressed.

Recently, spraying surface treatment (ST) asphalt emulsion has been investigated as a preventive maintenance method for PA wearing courses [20, 21]. This method is very similar to the fog seal, a preventive maintenance method for conventional asphalt pavements. In both methods, asphalt emulsions will be applied for the purpose of repairing micro-cracks and softening/rejuvenating aged asphalt binders. However, the fog seal method is expected to seal the conventional pavement surface, thus preventing the air and water from penetrating [22], while the ST emulsion sprayed to PA wearing course is expected to penetrate the voids of the PA, but without clogging them and affecting the functional performance of PA.

Compared with the relatively mature application of fog seal for conventional asphalt pavement, the study and application of the ST emulsion based preventive maintenance method for PA wearing courses are still at the early stage. The Netherlands Ministry of Infrastructure and Environment carried out a preventive maintenance study on PA wearing courses in a project entitled “Prolonging the service life of porous asphalt pavement" in 2010 [23]. This project was conducted to investigate the feasibility of preventive maintenance of PA wearing courses by spraying ST emulsions. Before the ST emulsion was applied to PA wearing courses, two trial sections, which have been in service for five years with no obvious diseases, were selected in this study [14]. The outcome of this project concluded that spraying ST emulsions can improve the raveling resistance of PA without clogging the voids. They claimed that ST emulsions could add new asphalt binder, fill cracks and rejuvenate the aged asphalt binder via diffusion [24, 25]. Besides, Xu et al. used the single-sided Cantabro test to investigate the ravelling recovery efficiency of four different emulsions [26]. They found that the one containing rejuvenator material showed the best improvement on the ravelling resistance of PA. However, except for some successful field trials and limited laboratory material performance testing, the fundamental working mechanism of ST emulsion in PA has not been systematically studied. To fill this gap, this study aims to investigate the key factors affecting the recovery efficiency of the damaged PA in laboratory using the ST emulsion. To achieve this objective, damaged PA specimens were first prepared through aging followed by multiple cycles of freeze-thaw (F-T) conditioning. Then, the effects of various material design factors of ST emulsion on the raveling resistance recovery of PA were investigated. Finally, the functional properties of the damaged PA subjected to the optimized ST were tested for verification purpose.

2 Experimental Program

2.1 Materials and specimen preparation

One commonly used PA mixture with a nominal maximum aggregate size of 13 mm (PA-13) was selected in this study. A polymer modified asphalt binder, which fulfilled the Superpave specification requirement for PG76-16, was used in the mixture. The coarse and fine aggregates for PA-13 were both granite and the content for the added hydrated lime was 1.5% by the weight of aggregate. The optimum asphalt content was 3.9% by the weight of mixture and the target air void content was 23% (± 0.5%). The aggregate gradation of PA-13 is shown in Fig. 1.

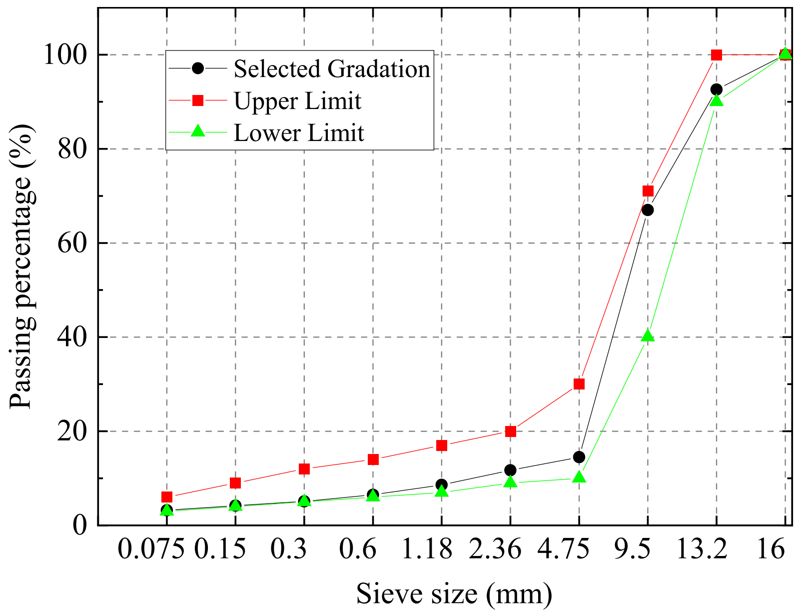


Fig. 1 Aggregate gradation of PA mixture

A cationic slow-setting (CSS-1) type asphalt emulsion with a solid content of 60% was selected as the ST emulsion. It mainly consists of the virgin asphalt binder, diluted water, stabilizer and emulsifier. Some basic properties of the asphalt emulsion are shown in Table 1. Two petrol-based rejuvenators and three bio-based rejuvenators were selected in this study, which were designated as P1, P2, B1, B2, and B3. The rejuvenators were added to asphalt emulsion with the expectation to further enhance the recovering or rejuvenating effects. Table 2 presents the basic information of the rejuvenators. The dosage of each rejuvenator is in terms of the weight of residual binder of the asphalt emulsion. Table 3 shows 16 ST conditions considered in this study.

Table 1 Basic properties of asphalt emulsion

	Evaporated residue				Storage stability	
	Residue content (%)	Penetration (25 ºC, 0.1 mm)	Softening point (ºC)	Ductility (5 ºC, cm)	1 day (%)	5 days (%)
Asphalt emulsion	60	64	50	67.2	0.3	2.1

Table 2 Basic information of rejuvenators

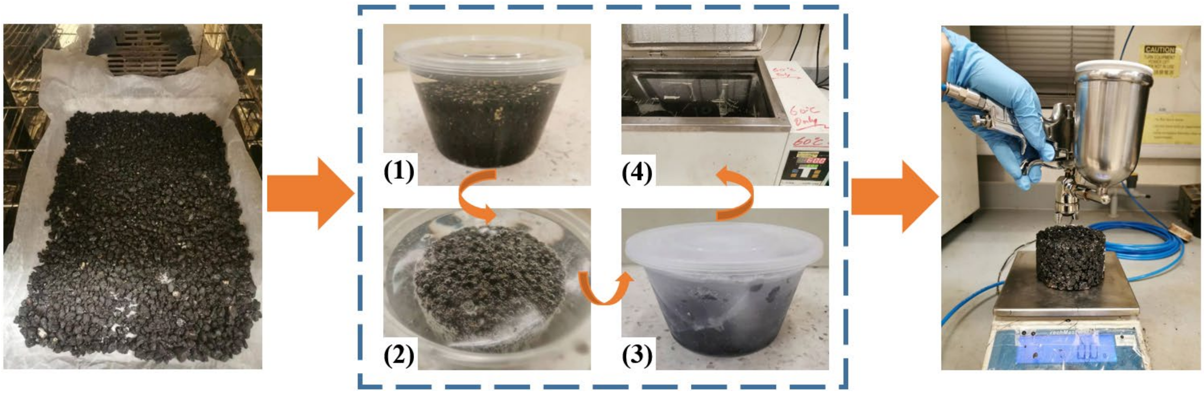
No.	Rejuvenator type	Dosage (%)	Viscosity at 135 ºC (mPa·s)	Petroleum or organic	Refined or waste	Molecular structure	Polarity
P1	Extract oil	5	98.4	Petroleum	Refined	Aromatic ring	High
P2	Aromatic oil	7	6.3	Petroleum	Refined	Aromatic ring	High
B1	Tall oil 1	2.5	4.1	Organic	Waste	Ring and strand	Mild
B2	Tall oil 2	2.5	3.8	Organic	Refined	Ring and strand	Mild
B3	Waste cooking oil	5	3.6	Organic	Waste	Strand	Slight

Table 3 Summary of ST conditions

Variables	Conditions
Solid content (%)	40, 50, 60
Application rate (kg/m^2)	0.4, 0.6, 0.8, 1.0
Curing duration (days)	0, 3, 7, 14
Rejuvenator type	P1, P2, B1, B2, B3

2.2 PA specimen preconditioning

To evaluate the treatment effects of emulsions, all PA specimens were subjected to aging and freezing-thawing (F-T) conditioning to create micro-damages inside the mixture. It is worth noting that the main purpose of aging and environmental conditioning is to create micro-damages, instead of completely simulating the field damage. As shown in Fig. 2(a), all specimens tested in this study were subjected to the long-term aging (LTA) before the compaction. Based on the previous study of Wisconsin Highway Research Program (WHRP) 17-04 [27], the LTA condition is an oven aging of loose mixtures at 135 ºC for 8 h, which has been confirmed that the aging degree of asphalt binder in the mixture processed by this method could well represent the asphalt binder after the standard pressure aging vessel (PAV) test for 20 h [28]. Then, all tested mixtures were fabricated using the Superpave gyratory compactor (SGC). The SGC specimens with a diameter of 150 mm were used for the skid-resistance test, while the SGC specimens with a diameter of 100 mm were used for all other tests.



(a) (b) (c)

Fig. 2 Specimen preconditioning: (a) long-term aging; (b) freezing and thawing; (c) spraying ST emulsion to the specimen's surface.

Fig. 2(b) illustrates the F-T procedure, which was implemented after the aged specimens were compacted. First, each specimen was placed into a plastic container filled with water and they were saturated under a vacuum of 87.8 kPa for 10 min. Subsequently, the plastic containers containing the specimens were placed in a freezer at a temperature of -18 ± 3 ºC for 16 h. Finally, all specimens were put into a water bath at 60 ºC for 24 h.

To determine the appropriate number of the F-T cycles, the indirect tensile strength modulus (ITSM) test was conducted as it's a non-destructive testing method. As shown in Fig. 3, the ITSM values of the aged specimens first rapidly decreased and then remained stable after three F-T cycles, indicating that some micro-cracks occurred inside mixtures leading to a nearly 20 % reduction of the ITSM. Similar variation trends about the effect of freeze-thaw (F-T) cycle number on mechanical properties of PA mixture were also found in other studies [29-31]. Under the freezing condition, water in a specimen was frozen and the volume swelled, leading to some micro-cracks in the asphalt mortar area, which interferes with the transmission of force and deformation between coarse aggregates. Those micro-cracks might further extend and even connect with other micro-cracks to form small cracks or voids with the increase of F-T cycles. However, after three cycles of F-T conditioning, the internal pore structure of PA mixture has been adjusted accordingly to resist F-T conditioning. Its internal pore structure is less and less sensitive to F-T treatment. Therefore, three cycles of F-T tests were adopted in the following study.

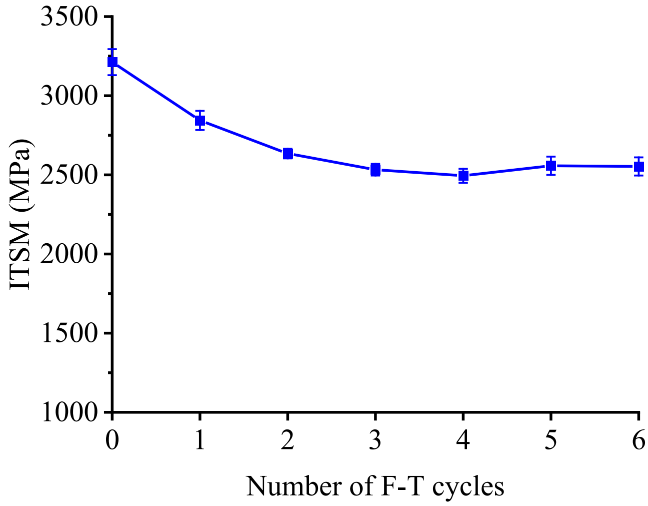


Fig. 3 The variation of the ITSM under different F-T cycles

After the aged and damaged PA specimens were prepared, ST emulsion was applied to them. Two methods had been commonly used to apply ST emulsion to PA specimens in the lab, i.e., directly dipping specimens into asphalt emulsion, and brushing emulsion onto the specimens with a brush.

However, these methods cannot accurately control the application of the ST emulsion and may easily cause inhomogeneity problem. Moreover, these indoor methods are quite different from the field practice, where asphalt emulsions are usually sprayed under high pressure, and sometimes at a high temperature if necessary. Therefore, the spraying method by using a spray gun was adopted in this study as shown in Fig. 2(c). This method can precisely control the ventilation pressure, airflow volume, and the mass of the ST emulsion sprayed on the surface of the specimens.

2.3 Testing program

In this study, the Cantabro abrasion test was conducted as the main approach to evaluate the ravelling resistance recovery of PA mixture after the application of ST emulsion, considering various factors, such as the rejuvenator type, curing duration, application rate and solid content of asphalt emulsion. Then, statistical analysis was carried out to compare the significance of different factors. In addition, functional performance tests were conducted on the PA mixtures to characterize the noise absorptions, permeabilities and skid resistances before and after the application of ST emulsion. The flowchart of the test scheme is presented in Fig. 4.

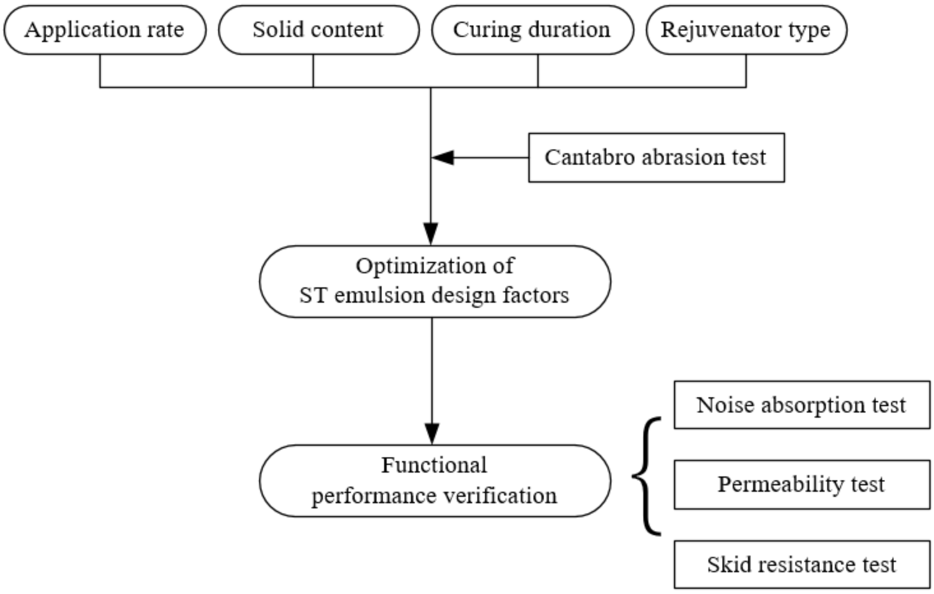


Fig. 4 Test scheme

2.3.1 Cantabro abrasion test

According to ASTM D7064, Cantabro abrasion test measures the raveling resistance of the PA specimen, which is carried out in the abrasion machine as shown in Fig. 5(a). Each time, one specimen is placed into the steel drum of the machine. The specimen will be picked up by a shelf plate and carried around until it is dropped to the opposite side of the drum. During this process, some aggregates may fall off depending on the adhesive and cohesive strength of PA mixtures. Fig. 5(b) shows the specimens after the Cantabro tests.

(a) (b)

Fig. 5 Cantabro abrasion test: (a) abrasion machine; (b) specimens after test.

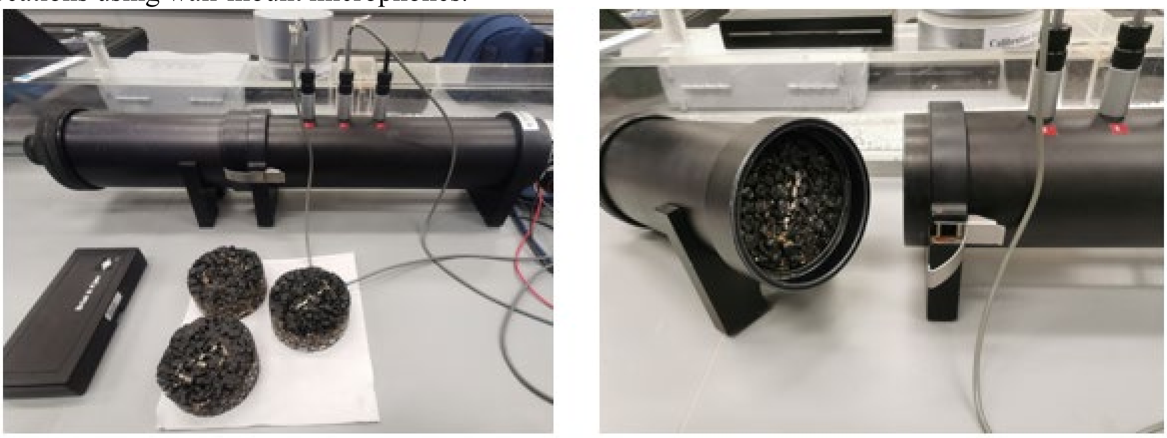
According to ASTM C131, the abrasion machine is operated for 300 revolutions with a speed of 30 to 33 rpm at 25 ºC. At least three replicates were prepared for each ST condition. The following formula was used for calculating the mass loss ratio (M_r):

$$M_r = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

where m_1 and m_2 represent the original and final mass of the tested specimen before and after the abrasion test, respectively, g.

2.3.2 Noise absorption test

The noise absorption of PA mixtures was measured by the impedance tube test in accordance with EN 10534-2. The difference in the noise-reduction ability of a PA specimen before and after the application of ST emulsion can be detected by this method. As Fig. 6(a) shows, the impedance tube shall be straight with a uniform cross-section and with smooth, rigid and non-porous walls in the test section. As shown in Fig. 6(b), the test specimen is mounted in the tube at one end, and plane waves are generated by a sound source at the other end. The acoustic pressure is measured at two fixed locations using wall-mount microphones.



(a) (b)

Fig. 6 Noise absorption test: (a) impedance tube; (b) PA specimen in the tube.

Considering that the diameter of the tube and the distance between the microphone positions have an obvious influence on the usable frequency range, the specimen with a diameter of 100 mm and a thickness of 40 mm was used in this test, which can detect the frequency range between 50 Hz and 1600 Hz. The complex acoustic transfer functions are used to calculate the reflection factor, r, and normal-incidence absorption coefficient, α, of the test material, using Eq. (2) and (3), respectively.

$$r = |r|e^{j\phi_r} = r_r + jr_i = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jkx} \quad (2)$$

$$\alpha = 1 - |r|^2 \tag{3}$$

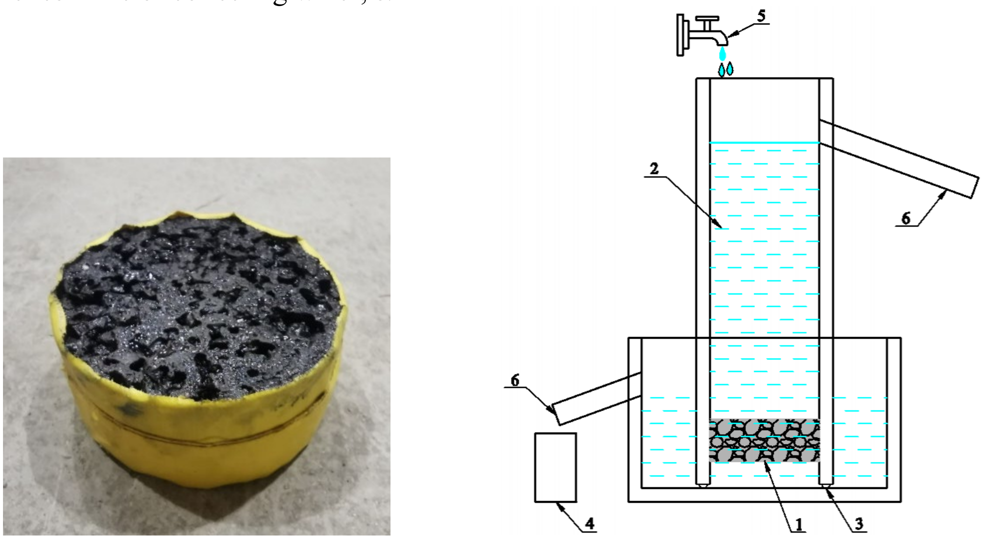
where α represents the noise abortion coefficient; r is the reflection factor, r_r and r_i are its real and imaginary components; $\emptyset_r$ is the phase angle of the normal incidence reflection factor; j is an imaginary unit; x represents the distance between the specimen and the further microphone location, mm; k is the wave number; H_{12} is a complex acoustic transfer function; and H_I and H_R are the transfer functions for the incident wave and reflected wave, respectively.

2.3.3 Permeability test

As Fig. 7(a) shows, the specimen used for the permeability test has a diameter of 100 mm and a thickness of 40 mm. Before this test, each specimen was wrapped by tapes to ensure that water only infiltrated vertically through the specimen. As Fig. 7(b) illustrates, a constant head permeameter was used to measure the hydraulic conductivity based on the Darcy's law [32]. The vertical permeability coefficient is calculated by Eq. (4).

$$K_V = \frac{4\times Q_V \times L}{h\times \pi\ D^2 \times t} \tag{4}$$

where K_V is the vertical permeability coefficient, mm/s; Q_V is the volume of water vertical flowing through the specimen during the test period, mm^3; L and D are the thickness and diameter of the specimen, respectively, mm; h is the actual height of water column and equals to 150 millimeters here; and t is the test time of collecting water, s.



(a) (b)

Fig. 7 Permeability test: (a) PA specimen wrapped with a tape; (b) permeameter, where 1 = specimen, 2 = water, 3 = mold, 4 = water collector, 5 = tap, and 6 = plastic tube.

2.3.4 Skid resistance test

According to ASTM E303, a British pendulum tester was used to measure the frictional properties of the PA surface before and after ST conditions. As shown in Fig. 8, a 75 mm rubber strip with a slider contact path length of 126 mm was provided by the tester for measuring the friction between the slider and the specimen surface. The skid resistance of the PA mixture is represented by the measured value of British pendulum number (BPN), with a lower value indicating a more slippery surface condition. At the beginning of each swing, adequate water is sprayed onto the test area, and the test is repeated four times for each specimen.

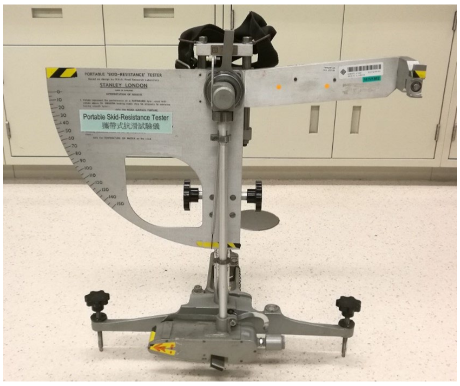


Fig. 8 British pendulum tester

3 Results and Discussion

3.1 Recovery efficiency of the damaged PA after emulsion-based ST

As aforementioned, raveling is one of the main distresses for PA pavement at the early stage. To evaluate the performance of emulsion-based ST on improving the raveling resistance of PA, the Cantabro tests were conducted, and the effects of different material design factors, such as the application rate, the solid content of ST emulsion, the curing duration, and the rejuvenator type, on the M_r index were analyzed.

3.1.1 Effect of the application rate of ST emulsion

Based on the actual construction experience [33], four different application rates of the ST emulsion ranging from 0.4 to 1.0 kg/m^2 were selected in this study. The solid content of the ST emulsion was 60%. After being treated with the ST emulsion and cured for 14 days, the PA specimens were used for the Cantabro abrasion test.

Fig. 9 presents the mass losses of the specimens with different ST emulsion application rates. It can be seen that the M_r values of all specimens treated with ST emulsions were lower than that of the untreated PA, which indicates that the application rate could significantly affect the recovery efficiency of the damaged PA mixture. In addition, M_r decreased rapidly from 28.7% to 17.4% when the application rate increased from 0.4 kg/m^2 to 0.6 kg/m^2. Then, the downtrend of M_r flattened out with the increase of the application rate within the range of 0.6 kg/m^2 to 1.0 kg/m^2. These results suggested that after ST emulsions penetrated into PA mixtures and flowed through connected voids, some ST emulsion coated on the surface of aged asphalt mortar and the newly added emulsion residues might fuse with aged asphalt binders. Meanwhile, some micro-cracks inside the specimens might be filled. All the above changes are helpful to improved cohesion of the binder and adhesion between the binder and aggregates. However, too much ST emulsion showed no additional recovery efficiency enhancement for the damaged mixtures. Because the redundant emulsion residue not only filled the air voids but also directly flowed out from the bottom of the specimen through the interconnected voids, leading to the waste. When the application rate increased from 0.6 kg/m^2 to 0.8 kg/m^2, some ST emulsions were found at the bottom of the specimens. Taking material cost into consideration, the application rate of 0.6 kg/m^2 was selected in the following tests.

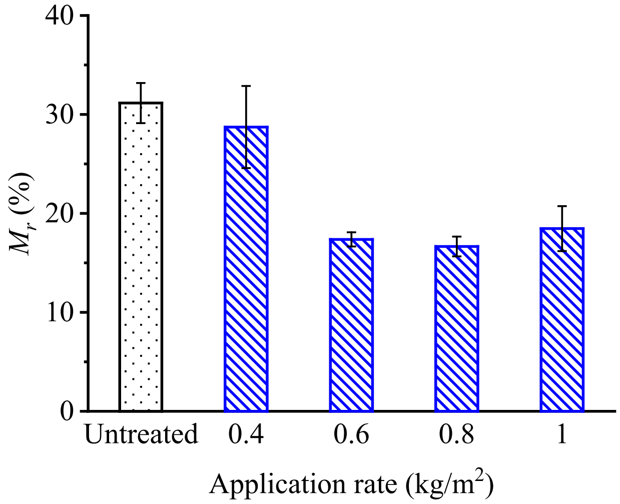


Fig. 9 M_r of PA mixtures with different application rates of the ST emulsion

3.1.2 Effect of the solid content of ST emulsion

The solid content of ST emulsion could affect its viscosity, which further influences the recovery efficiency of damaged PA mixtures. In the laboratory tests, three emulsion solid contents were selected, including 40%, 50% and 60%. The asphalt emulsion with a solid content of 60% was first prepared by the collide mill as the raw emulsion. The emulsions with lower solid contents were obtained by directly diluting the raw emulsion. To better reveal the effect of solid content, the application rate of ST emulsion with different solid contents was set to be same as 0.6 kg/m^2.

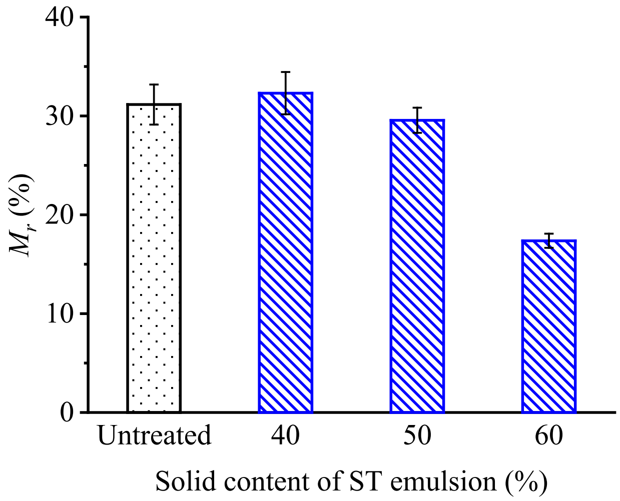


Fig. 10 M_r of PA mixtures with different solid contents of the ST emulsion

Fig. 10 shows that the PA mixture treated with the ST emulsion with a solid content of 60% had the lowest material loss. When the solid contents were diluted to 50% and 40%, the material losses sharply increased to around 30%, which are similar to that of the untreated specimens. It suggested that the solid content may significantly affect the recovery efficiency of the damaged mixtures. There are two possible reasons for this phenomenon. On one hand, under the same application rate of ST emulsion, the smaller the solid content, the fewer emulsion residues left inside a specimen after the water of emulsion evaporated. The effective fresh binders were too few to improve the ravelling resistance of damaged PA specimens. On the other hand, ST emulsions with smaller solid contents usually have relatively lower viscosities, which will make the emulsion quickly flow through a specimen, resulting in the draindown and waste of ST emulsion. Therefore, it is recommended to use the ST emulsion with a solid content of 60% in the following study.

3.1.3 Effect of curing duration

Fig. 11 shows the M_r of the specimens at different conditioning and ST stages. The application rate and solid content of the ST emulsion were 0.6 kg/m^2 and 60%, respectively. Compared with the unaged and no FT treated specimens, the M_r of the specimens subjected to the LTA and three cycles of FT conditioning gradually increased. However, after applying ST emulsion, the M_r decreased first sharply and then slowly as the curing duration increased. To balance the curing duration and recovery efficiency, it is recommended to maintain 14 days to get a better raveling resistance. It is worth noting that the 14-day curing period is for the emulsions inside mixture to cure and form strength, but for the emulsion stayed at the pavement surface, its moisture can be quickly evaporated to form the initial strength, which allows for traffic opening after several hours.

In addition, it is interesting to notice that the M_r of the ST specimens after 7 days' curing became lower than that of the LTA conditioned specimens, which indicates that the asphalt emulsion not only filled up the micro-cracks inside the mixtures, but also possibly diffused into the aged binder.

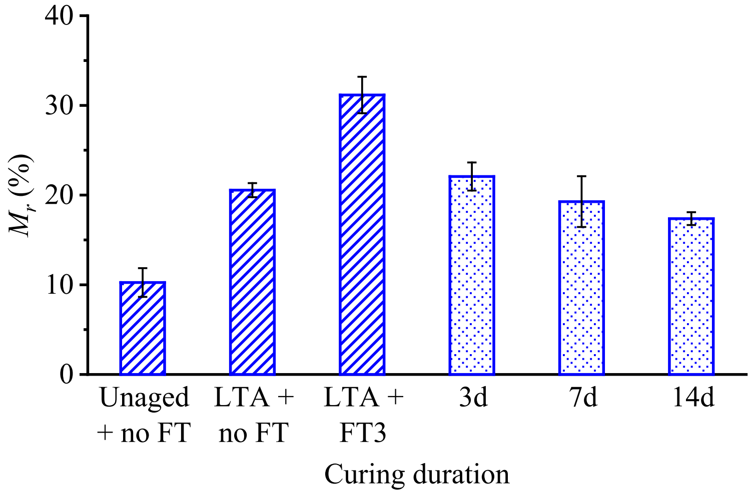


Fig. 11 M_r of PA mixtures with different curing durations

3.1.4 Effect of the rejuvenator type

Rejuvenator has been widely used in asphalt pavement recycling. Five types of rejuvenators were evaluated in this study. Each type of rejuvenator was mixed with asphalt emulsion in advance, and then the emulsion was applied to the damaged specimens, which were tested after 14 days' curing. The damaged specimens with the ST application rate of 0.6 kg/m^2 and solid content of 60% were set as the control group. Fig. 12 shows that most rejuvenators weakened the recovery efficiency of the ST emulsion except for one bio-based rejuvenator. One possible explanation is that those rejuvenators have slightly higher viscosities than the pure ST emulsion, leading to the non-uniform penetration effect. Another possible reason is that the diffusion effect of rejuvenators is very slow, which needs longer-term observation.

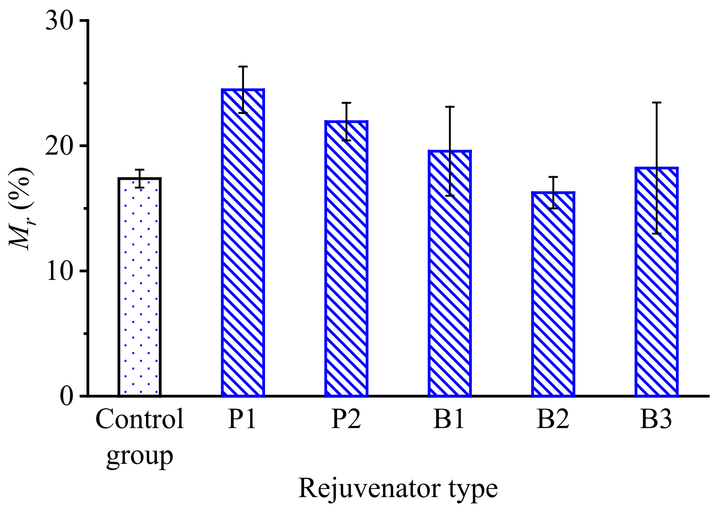


Fig. 12 M_r of PA mixtures with different rejuvenators

3.1.5 Significance analysis

To further analyze the effects of different ST emulsion design factors on the M_r index, a one-way analysis of variance (ANOVA) was carried out and the results are summarized in Table 4. It can be seen that only rejuvenator type has a significance value greater than the threshold of 0.05, indicating that rejuvenator type is not a significant factor. This result is consistent with the analysis based on Fig. 12. However, the other three factors all had significance values less than 0.05, which means that there is a statistically significant difference between the experimental groups. Moreover, the significance values of the application rate and solid content were all less than the threshold of 0.01, suggesting that the application rate and solid content had a significant effect on the M_r at the 99% confidence level. Therefore, it is critical to control these design factors of the ST emulsion in practice to achieve a better recovery efficiency for the PA mixture.

Table 4 The ANOVA results between different ST emulsion design factors on the M_r index

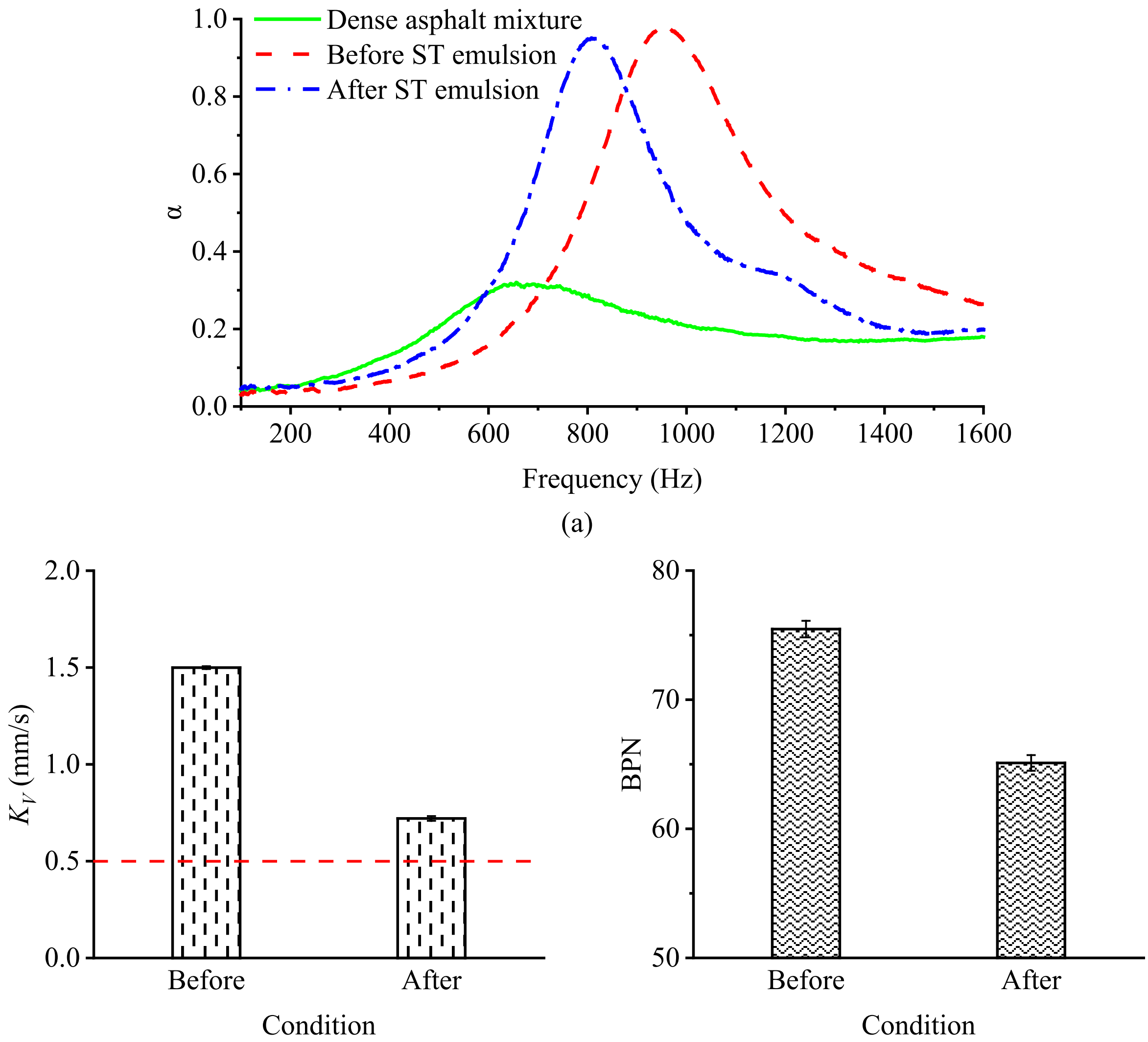
Factors	Source of difference	SS	df	MS	F	Sig.
Application rate	Between groups	288.649	3	96.216	16.618**	0.001
	Within groups	46.320	8	5.790	-	-
	Total	334.9692	11	-	-	-
Solid content	Between groups	377.509	2	188.754	86.939**	0.000
	Within groups	13.027	6	2.171	-	-
	Total	390.536	8	-	-	-
Curing duration	Between groups	33.012	2	16.506	7.382*	0.024
	Within groups	13.416	6	2.236	-	-
	Total	46.428	8	-	-	-
Rejuvenator type	Between groups	123.215	4	30.804	1.805	0.204
	Within groups	170.630	10	17.063	-	-
	Total	293.844	14	-	-	-

** means a high significance at the 99% confidence interval; * means a high significance at the 95% confidence interval.

Note: SS represents the sum of squares; df represents the degrees of freedom, F represents the F statistic, and Sig. represents the significance value.

3.2 Functional performance verification

Although it is expected that ST emulsion can help extend the service life of PA pavements in terms of its raveling resistance recovery, it is also very important to ensure that the ST emulsion will not compromise the functional performances of PA mixtures. Fig. 13 shows the test results of three functional performances, including noise absorption, permeability, and skid resistance. All tests were carried out before and after emulsion ST.



(a)

(b) (c)

Fig. 13 Functional performance: (a) noise absorption; (b) permeability; (c) skid resistance

Fig. 13(a) shows the noise absorption coefficients of the PA specimens in comparison to that of a conventional dense-graded asphalt mixture used in Hong Kong. After the damaged specimens were treated by ST emulsions, the noise absorption curve shifted horizontally to the left. However, the peak value of the noise absorption coefficient for the treated PA mixture is slightly lower than that of the untreated one. The absorption coefficients of the treated PA specimen were still within the range of 35-95% between 800 Hz to 1200 Hz, which is the sensitive frequency range for human auditory perception. In addition, even after the PA mixtures were treated with the ST emulsion, they still had much better noise absorption properties than the dense-graded asphalt mixtures. As Fig. 13(b) shows, the vertical permeability coefficients of the untreated and treated specimens obviously decreased from 1.50 mm/s to 0.72 mm/s, indicating that some pores, especially the connected pores, might have been clogged or partially clogged by the ST emulsions. However, according to EN 12697-19, the vertical permeability coefficient of the treated PA specimens can still meet the minimum requirement of 0.5 mm/s. The BPN values from the skid resistance tests are shown in Fig. 13(c). After the damaged specimens were treated by ST emulsions, the BPN values of the PA mixtures were also reduced from 75.5 to 65.1, but it can still meet the minimum requirement of 45 in accordance with the Chinese standard JTG 5142-2019. The previous studies indicated the BPN values can quickly recover after the roads are open to traffic for several months [34, 35]. Therefore, the ST emulsion may only negatively affect the functional performances of the PA mixtures in the short term, but the effect is considered overall acceptable.

4 Findings and Conclusions

This study investigated the recovery efficiency of the damaged PA mixture treated by ST emulsion. Several material design and treatment factors were considered, and the functional performances of the treated mixture specimens were evaluated. The following points summarize the major findings of this study:

1) Both application rate and solid content of the ST emulsion have significant effects on the raveling resistance recovery of the damaged PA mixtures. In practice, it is critical to control both factors to ensure the performance of this preventive maintenance method.
2) The recovery efficiency of the rejuvenator on the damaged PA mixtures was not obvious within 14 days of curing. But in the long term, it is still possible for the rejuvenator to soften the aged binder by diffusion, which needs further study.
3) The application of ST emulsion may have a slight side-effect on the functional performance in the short term, so verification is needed for the material design of the ST emulsion. This could help achieve a more balanced design between the mechanical performance recovery and the functional performance preservation.
4) For the CSS-1 emulsion and PA mixture evaluated in this study, the optimum application rate of 0.6 kg/m^2 and solid content of 60% were recommended, which could reduce the M_r from 31.2% to 17.4%. At the same time, the negative effect of the ST emulsion on the functional performance is limited. This confirms that the ST emulsion can serve as a promising preventive maintenance material for PA pavements.

It is worth noting that this study mainly focused on the short-term effect of the ST emulsion on the damaged PA in the laboratory. In the future, the long-term effects of the ST emulsion on the mechanical and functional performance will be further investigated, and field trials will be conducted based on the outcomes of the laboratory investigation.

Author contributions

The authors confirm contribution to the paper as follows: 1) study conception and design: Zhen Leng, Jiwang Jiang, Bin Yang; 2) data collection: Bin Yang, Zijian He; 3) analysis and interpretation of results: Jiwang Jiang, Bin Yang; and 4) draft manuscript preparation: Bin Yang, Jiwang Jiang, Zhen Leng, Danning Li. All authors reviewed the results and approved the final version of the manuscript.

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