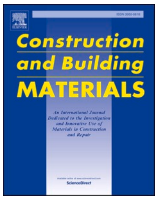
Construction and Building Materials 421 (2024) 135772

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat



Effect of synthesized warm mix additive and rejuvenator on performance of recycled warm asphalt mixtures

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ARTICLE INFO

Keywords:
Warm mix additive
Rejuvenator
RAP
SBS
FWD

ABSTRACT

In this study, a warm mix additive (composed of diamine and fatty acid amine) and a rejuvenator (consisting of styrene-butadiene-styrene and aromatic elements) were synthesized to facilitate the incorporation of 50% recycled asphalt pavement (RAP) in warm mix asphalt for the surface layer and 100% RAP in cold asphalt mixtures for the base layer. The effect of WMA and rejuvenator-modified asphalt binder was performed through rotation viscosity, dynamic shear rheometer, and bending beam rheometer. Simultaneously, the performances of RAP-modified asphalt mixtures were assessed using dynamic modulus, overlay test, and flow number test. Constructing two testbed roads provided a real-world evaluation of two surface mixtures and two base mixtures. The results indicated that modifying asphalt binder PG 64–22 with 2.0% warm mix additive (WMA) and 5.0% rejuvenator upgraded the performance grade to PG 76–22, significantly improving rutting resistance, and reducing 40% creep stiffness. The asphalt mixture with 50% RAP, modified with WMA and rejuvenator, demonstrated a better resistance to rutting and low-temperature cracking compared to the original mixture. Both surface and base mixtures met field application specifications, exhibiting excellent performance after a year of service, as confirmed by pavement condition surveys, and falling weight deflectometer tests, thus highlighting the potential for sustainable and high-performance recycled asphalt solutions in road construction.

1. Introduction

Asphalt, a remarkably versatile material with an extensive history of diverse applications, has been utilized across various cultures globally for centuries. The earliest recorded use of asphalt can be traced back to the inhabitants of the Euphrates River valley, historically known as Sumer, Accad, and later, Babylonia. Archaeological excavations at Teli-Asmar, situated northeast of Baghdad, revealed Sumerians employing asphalt in building construction between 3200 and 2900 B.C. [1]. Nowadays, in the face of rising global temperatures and reducing construction resources, particularly in the area of hot mix asphalt used in pavements, there's an urgent need for sustainable solutions [2–7]. Hot asphalt mixture, although providing outperforms performances of pavement, escalating material shortage and augmenting energy consumption during construction processes [8–12]. Warm mix asphalt technologies stand as a pivotal approach to mitigating CO_2 emissions. One of the key advantages of warm mix additive (WMA) is its ability to reduce mixing and compaction temperatures compared to conventional hot mix asphalt, which translates to decreased energy usage and emissions during the manufacturing process [13–15]. The lower production temperatures of WMA also contribute to improved working conditions for construction crews, reducing exposure to high temperatures and fumes on the job site. However, achieving these lower temperatures while maintaining the desired performance characteristics of the asphalt mixture often requires the use of additives [16–19]. These additives, such as organic or chemical compounds, are incorporated into the asphalt mix to facilitate workability at lower temperatures and maintain the required performance standards of the pavement [20–22]. Zhang et al. investigated styrene butadiene styrene (SBS) modified binder in warm mix asphalt. The research indicates that in SBS modified asphalt binder could reduce mixing and compaction temperature as well as improving rutting and fatigue resistance of the mixture [23]. Singh's research recommended using SBS 3% by weight of virgin binder could improve the Marshall stability and Marshall flow up to 23% [24]. In

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https://doi.org/10.1016/j.conbuildmat.2024.135772
Received 31 December 2023; Received in revised form 29 February 2024; Accepted 7 March 2024
Available online 12 March 2024
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general, the utilization of additives becomes important in warm asphalt mixtures to enable the effective reduction of mixing and compaction temperatures while preserving the pavement's structural integrity and performance properties.

Moreover, the current trend in asphalt mixtures leans towards the increased utilization of waste materials such as recycled asphalt pavement (RAP), waste glass, and steel slag [25–28]. Specifically, RAP-modified asphalt mixtures have gained popularity as an economical alternative to traditional asphalt mixtures. The inclusion of RAP not only decreases the reliance on conventional aggregates (e.g., coarse, and fine aggregates) but also maximizes the use of the existing asphalt binder in the RAP. Consequently, the adoption of RAP could provide economic advantages and contribute to minimizing environmental impact. This is primarily due to the reduction in landfill areas, leading to a decrease in both air and water pollution. [29,30]. However, the utilization of RAP in asphalt mixtures often necessitates the addition of specific a rejuvenating agent or a chemical additive to rejuvenate the aged binder present in RAP [31,32]. Over time, the binder in asphalt pavement ages and loses its original properties, leading to reduced performance in the recycled asphalt. Rejuvenators, which are typically rejuvenating agents or additives, are incorporated into the mix to restore the aged binder's essential properties. These additives work to soften the aged binder, improving its workability, viscosity, and overall performance. By rejuvenating the aged binder in recycled asphalt, these additives aim to enhance the durability, stiffness, and resistance to various distresses, thus optimizing the quality and lifespan of the resulting asphalt mixture [33]. Several studies have utilized waste materials such as cooking oil, vegetable oil, waste engine oil as rejuvenator [34,35]. The research from Fernandes et al. demonstrated that the modification of aged binder with engine oil, polymer (e.g., polyethylene, crumb rubber and styrene-butadiene-styrene), could restore the aged binder [36]. The rheological properties of asphalt binder modified with engine oil were investigated through dynamic shear rheometer (DSR) test. The findings indicated that modified binders could acquire high penetration and restore properties of binder in RAP. By using this modified binder in the production of stone matrix asphalt (SMA) mixtures, Fernandes found that those modified binder modified with waste materials revealed to be excellent solutions for road paving works due to their good mechanical and surface performance without affecting the environment or the human health. In addition, rejuvenator and cooking oil waste were also used in recycled asphalt mixture could improve the self-healing performance of asphalt pavement [37]. In Dinh's results, recycled asphalt mixture with 5.0% of waste cooling oil as rejuvenator could obtained the 90% strength recovery after 2–3 self-healing cycles.

In addition to its application in hot and warm asphalt mixtures for surface layers, RAP can also be incorporated into cold asphalt mixtures for the base layer in asphalt pavement. Several researchers have successfully developed cold asphalt mixtures utilizing 90–100% recycled asphalt for the base layer [38–40]. This approach aligns with sustainable practices, addressing the growing need for eco-friendly solutions in road construction. Cold mix asphalt, formulated with 100% RAP, provides a cost-effective and environmentally friendly alternative to conventional asphalt materials. The use of RAP in cold mix base layers reduces the demand for virgin materials, minimizes waste generation, and contributes to lower carbon emissions associated with traditional pavement construction. Yang et al. formulated a cold asphalt mixture comprising recycled asphalt, cement, and asphalt emulsion. Their study highlighted that the inclusion of aged asphalt and cement within the RAP significantly enhanced various characteristics of asphalt emulsion cold recycled mixes. The findings demonstrated improvements in the indirect tensile strength, high-temperature stability, moisture resistance, and fatigue performance of the cold recycled mixes due to the presence of aged asphalt and cement in the RAP blend [41]. To enhance the performance of cold recycled mix, Wang incorporated a recycling agent along with an acrylic copolymer emulsion. The study concluded that this method notably enhanced the overall engineering performance of the cold recycled asphalt mixture, surpassing the conventional approach [42]. Overall, various studies have addressed the utilization of RAP in asphalt mixtures. Nevertheless, there is an absence of a comprehensive assessment of the performance of RAP-modified asphalt mixtures in both laboratory and real-world conditions. Furthermore, the complete substitution of conventional aggregates in cold asphalt mixtures for base layers and the subsequent evaluation of their operational performance remains unexplored.

Therefore, this study aims to integrate recycled asphalt into warm mix asphalt formulations, aiming to reach a 50% weight ratio of total mixture. This involves the synthesis of warm mix additive and rejuvenator, strategically designed to increase the recycled asphalt content while concurrently reducing the mixing and compaction temperatures in the asphalt mix. The determination of the optimal proportions of warm mix additive and rejuvenator entailed several binder tests, including rotation viscosity, dynamic shear rheometer, and bending beam rheometer analyses. Two distinct surface layer asphalt mixtures were considered: one constituted a hot asphalt mixture comprising 30% recycled asphalt, while the other comprised warm asphalt containing 50% recycled asphalt. Additionally, for the base mixture, an innovative approach was adopted, aiming to incorporate 100% recycled asphalt using acrylic polymer emulsion with cement. A series of laboratory tests was conducted to assess the performance of these four mixtures, involving scrutiny under varied loading frequencies and temperatures through dynamic modulus tests. To evaluate resistance against rutting, dynamic testing using the 30 kN system was conducted via the flow number test. Moreover, an assessment of resistance to reflective cracking was carried out by overlay test. Subsequently, real-world conditions were simulated through the construction of two road sections. Surface mixtures were evaluated via air void, indirect tensile strength, and tensile strength ratio tests, while pavement analyzer techniques assessed surface conditions, focusing on crack rate and deformation. Evaluation of the base mixtures was executed by the level of compaction and conducting falling weight deflectometer (FWD) tests.

2. Materials and mixture preparation

2.1. Materials

2.1.1. Developed additives

2.1.1.1. Warm mix additive. The synthesis of a novel warm mix additive was formulated from diamine and fatty acid amine ($CH3(CH2)_nCOOH$). Various ratios of these compounds were evaluated to find the ideal proportion. Based on the melting point test, the increase in ratio of diamine and fatty acid amine lead to the lower melting point. Fig. 1 illustrates that the most effective ratio ranged between 1:3 and 1:6 for these components. Within this research, a ratio of 1:5 was explored, resulting in the warm mix additive possessing a melting point of 105℃.

2.1.1.2. Rejuvenator for warm mix recycled asphalt. Besides, a rejuvenator specifically designed for warm mix recycled asphalt was created. Utilizing an impregnation method, Styrene-Butadiene-Styrene (SBS) and aromatic components were incorporated. The liquid regeneration additive consisted of porous polymer SBS with an apparent density between 0.5 and 0.8 and a molecular weight ranging from 40,000 to 80,000 g/mol, blended with an aromatic constituent comprising 30% by weight. The ratio adopted for mixing was 70:30. The process involved

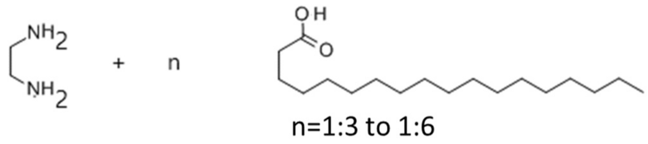

Fig. 1. Synthesis process of warm mix additive.

impregnating a low molecular weight porous polymer with the liquid regenerative additive, where the latter acted as two of the circulating mesophilic reformers. The preparation method followed these steps: The porous polymer was placed in a stirrer and agitated. The temperature of the mixture was raised to above 40℃ by stirring vigorously. Once the target temperature was attained, the liquid regenerative additive was added. Stirring continued until the porous polymer was thoroughly impregnated with the liquid regenerative additive. Completion of the impregnation process marked the end of stirring as shown in Fig. 2.

2.1.1.3. Acrylic polymer emulsion for base layer. Acrylic Polymer Emulsion (APE) was used to enhance the chemical bond between recycled asphalt pavement and cement. APE materials offer improved elasticity, weather resistance, and bonding strength. While relatively costly, they form robust connections with hydrophobic asphalt and use hydrophilic styrene to link asphalt and cement. Acrylic, known for its stability and outstanding water resistance under UV exposure, undergoes copolymerization to significantly enhance weather endurance. Typically used at 1–5% of the total weight, an anion system ensures ionic stability when mixed with the material.

2.1.2. Aggregates

To assess the impact of newly formulated additives on asphalt mixture performance, encompassing 13-mm surface and base mixtures, a total of four variations were examined. The first type represents a surface course control mixture, incorporating 30% recycled asphalt, utilizing 3.6% binder content, and 1.4% commercial rejuvenator by weight of the total mixture. Meanwhile, the second type constitutes a warm mix additive-modified mixture with 50% recycled asphalt, employing 0.5% developed WMA and 0.1% rejuvenator. Both types utilize the PG 64–22 asphalt binder. For the base layer, the third type comprises 100% recycled asphalt, cement, and acrylic polymer emulsion at 0.2%, with a cement content of 6.0%. Lastly, the fourth type stands as a base control mixture utilizing 2.7% emulsion asphalt. Detailed mixture compositions for the four types are presented in Table 1 and Table 2.

2.2. Mixture preparation

To prepare Type 1 and Type 2 mixtures, the aggregates underwent heating in an oven, with Type 1 being heated for four hours at 160 ℃ and Type 2 at 140 ℃. The virgin asphalt binder was melted in an oven for two hours, then mixed with the additive at 120 rotation per minute (RPM) for 2 minutes. After the binder-additive blending, the binder was conditioned at the desired mixing temperature for 30 minutes before being mixed with aggregates. Aggregates and binder were mixed at 120 RPM for 2–3 minutes. Subsequently, the Type 1 and Type 2 mixtures were preheated in the oven at 140 and 120 ℃, respectively, before compaction. Super Gyration Compactor (SGC) was utilized to compact the test samples, applying a pressure of 600 kPa and an inclination angle of 1.25 degrees as shown in Fig. 3.

The procedure for preparing the Type 3 mixture is depicted in Fig. 4. Initially, dry aggregates consisting of recycled asphalt and cement were mixed for 2 minutes before the addition of water. Meanwhile, an additive-water mixture was concurrently prepared using a ratio of 100% acrylic polymer emulsion and 50% water. This additive-water blend was then introduced into the aggregate mixture and continuously mixed for 2 minutes. Subsequently, the remaining 50% of the water was slowly incorporated into the mixture and blended for 1 minute. It's crucial to exercise caution while adding the remaining water to prevent any water bleeding from the mixture

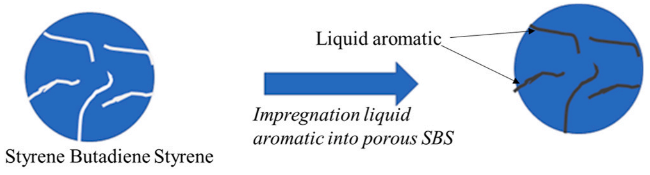

Fig. 2. Impregnation method for rejuvenator.

Table 1
Mixture proportions of surface layer (%).

Mixture	13 mm	RAP	Asphalt binder	WMA	Rejuvenator
Type 1	65.0	30.0	3.7	0.0	1.3
Type 2	47.0	50.0	2.3	0.2	0.5

Table 2
Mixture proportions of base layer (%).

Mixture	20 mm	RAP	Cement	APE	Asphalt emulsion	Water
Type 3	0.0	91.3	6.0	0.2	0.0	2.5
Type 4	16.1	75.0	3.0	0.0	2.7	3.2

The process for preparing the Type 4 mixture is depicted in Fig. 5. Firstly, dry aggregates, including both conventional and recycled aggregates, were mixed for 2 minutes before the addition of water-asphalt emulsion. Then, an additive water mixture was prepared using a ratio of 100% commercial asphalt emulsion and 50% water. Subsequently, the water-asphalt emulsion was added to the aggregate mixture and continuously mixed for 2 minutes. Finally, the remaining 50% of the water was gradually introduced into the mixture and blended for 1 minute.

3. Test methods

3.1. Performances of WMA and rejuvenator modified binder

The aim of this test is to identify the optimum content of the developed warm mix additive. The original asphalt binder, PG 64–22, was utilized and modified by incorporating the developed WMA and rejuvenator, as indicated in Table 3. The process of mixing the binder involved heating it in an oven at 150 ℃ for 2 hours. Subsequently, the developed WMA and rejuvenator were slowly added to the binder and stirred continuously for two minutes at 120 RPM. Following this, the modified binders underwent testing in various binder tests outlined in the subsequent sections.

3.1.1. Dynamic shear rheometer

Dynamic Shear Rheometer (DSR) serves to assess the viscous and elastic properties of asphalt binders within medium to high-temperature ranges. The DSR test followed the guidelines outlined in AASHTO T 315 [43]. The complex shear modulus (G*) indicates the overall resistance to repeated deformation when subjected to shear stress, while the phase angle (δ) represents the delay between the applied shear stress and the consequent shear strain. During the test, a small sample of asphalt binder is placed between two plates. Test temperatures exceeding 76°C utilize a sample 1 mm thick and 25 mm in diameter. During the test, the top plate oscillates in a sinusoidal waveform at a frequency of 10 rad/sec, while the equipment records the maximum applied stress, resulting maximum strain, and the time delay between them. Subsequently, specialized software automatically computes the complex modulus (G*) and phase angle (δ).

3.1.2. Beam bending rheometer

Bending Beam Rheometer (BBR) test assesses the low-temperature stiffness and relaxation characteristics of asphalt binders, which are indicative of their ability to resist cracking in low-temperature conditions. The BBR test following the guidelines specified in AASHTO T 313 [44]. A sample of asphalt binder was shaped into a beam measuring 6.25×12.5×127 mm. This beam was supported at two points 102 mm

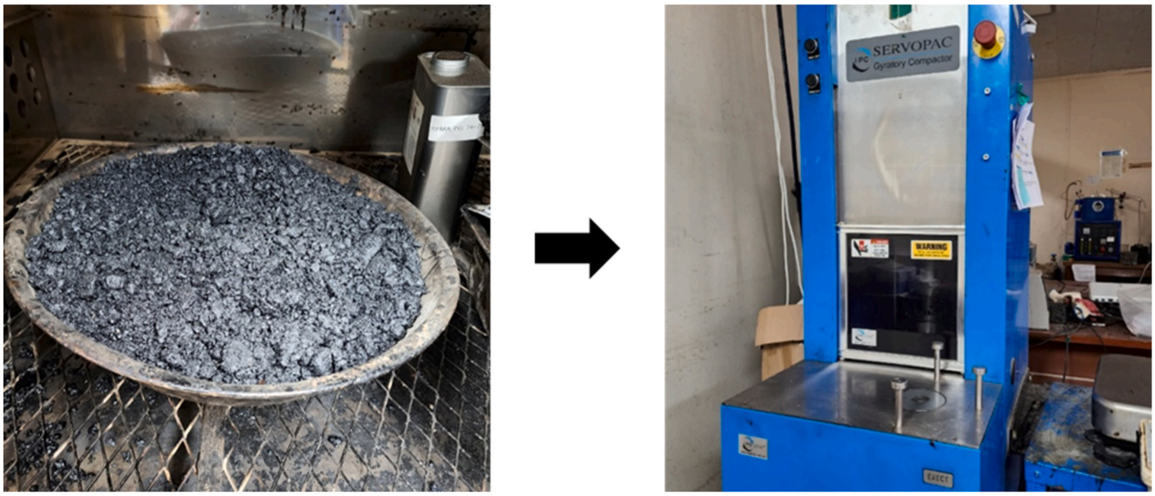

Fig. 3. Heating mixture at target compaction temperature and compaction sample.

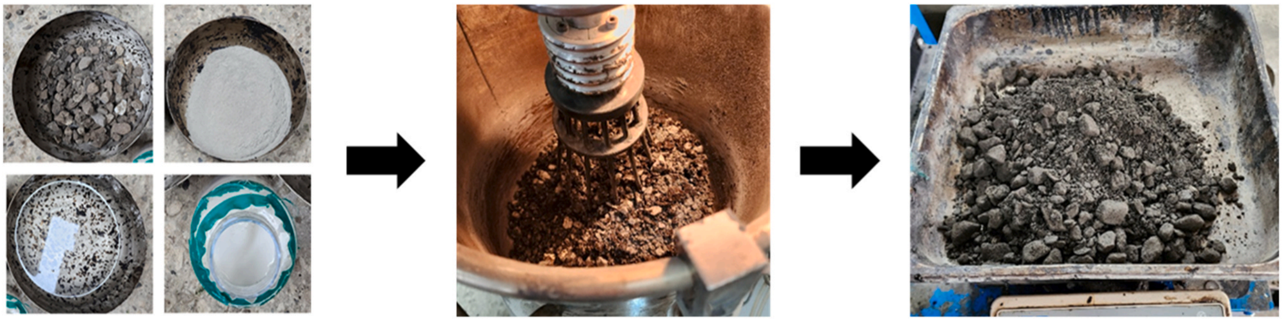

Fig. 4. Preparation process of Type 3 mixture.

Fig. 5. Preparation process of Type 4 mixture.

Table 3
WMA and rejuvenator-modified asphalt binder mixture.

Name	Original asphalt binder	Developed WMA	Rejuvenator
Mix A	100%	0.0%	0.0%
Mix B	94.5%	0.0%	5.5%
Mix C	93.0%	2.0%	5.0%
Mix D	93.5%	2.0%	4.5%

Note: Ratio of mix C was used in Type 2 mixture.

apart within a controlled temperature water bath. Subsequently, a load of 100 g, which was applied at the midpoint of the beam. The deflection of beam was measured at intervals of 8, 15, 30, 60, 120, and 240 seconds. The stiffness of the beam, often referred to as creep stiffness, was computed based on these specific time intervals.

3.2. Performances of asphalt mixtures

3.2.1. Dynamic modulus

Dynamic Modulus test is performed to analyze the response of asphalt mixtures to varying loading frequencies and temperatures. This study adopted the AASHTO T342 test standard for Dynamic Modulus assessment, utilizing the Dynamic Testing System 30 kN (DTS-30) for conducting the tests. Initially, the sample was compacted into a cylindrical shape with a diameter of 150 mm and a height of 170 mm, employing the Super Gyration Compactor. To ensure consistency, the initial air void of the sample was maintained at 10±1%. Subsequently, through coring and trimming processes, the sample's diameter was reduced to 100 mm and its height to 150 mm, achieving an air void of 7 ±1% [45]. For each mixture, a minimum of three samples were prepared to obtain an average value. Following preparation, the samples underwent a 48-hour conditioning period at room temperature to eliminate moisture. This test encompassed four different testing temperatures: −10 ℃, 4℃, and 21℃. At each temperature level, six frequencies (e.g., 25, 10, 5, 1, 0.5, and 0.1 Hz) were executed. During the testing process, the values for dynamic modulus and phase angle were recorded. These recorded data were instrumental in constructing the dynamic modulus master curve at referenced temperature of 21℃. By leveraging the Python programming language and the Optimize SciPy library [46]. The Standard logistic Sigmoid model was employed to construct the dynamic modulus master curve as displayed to Eq. (1). The temperature shift factor was based on Williams–Landel–Ferry (WLF) equation as shown in Eq. (2).

$$\log\left|E_f^*\right| = \delta + \frac{\alpha}{1 + e^{\beta+\gamma\times\log(f\times\alpha_T)}} \tag{1}$$

$$\log(\alpha_T) = \frac{-C_1(T - T_R)}{C_2 + (T - T_R)} \tag{2}$$

Where,E_f*, is dynamic modulus at frequency,f is loading frequency (Hz),δ, α, λ, β, γ is fitting parameters,α_T is time-temperature shift factor, C_1, C_2: two regression parameters.

3.2.2. *Overlay test*

Overlay Test (OT) is designed to evaluate the susceptibility of asphalt mixture to both reflective and fatigue cracking. In this study, the OT procedure adhered to the Tex-248-F standard [47]. The test specimen, measuring 150 mm in length, 76 mm in width, and 38 mm in height, can be obtained by trimming a laboratory-molded specimen. The laboratory-molded specimen should be compacted to a diameter of 150 and a height of 115 ± 5 mm. Additionally, the air voids in the trimmed laboratory-molded specimen should be within the range of 7±1%. After the cutting process, the samples underwent a 48-hour resting period to eliminate moisture. An environmental chamber maintained the specimen at a constant temperature. Prior to testing, the specimen is held at 25 °C for a minimum of one hour. Throughout the test, the testing temperature was controlled at 25±0.5 °C. One plate remained fixed, while the other moved horizontally until the specimen failed. Tensile load and displacement of the moving plate were recorded at 0.1-second intervals. It involved applying a cyclic saw-tooth load to the moving plate, maintaining a constant maximum opening displacement of 0.635 mm. Loading was consistently applied at a rate of 10 seconds per cycle until the peak load decreased by at least 93% compared to the peak load during the initial cycle. The test was terminated at 93% load drop or 1200 cycles.

3.2.3. *Flow number*

Flow Number (FN) test assesses the rutting performance of asphalt mixtures under high temperatures. The FN test was conducted following the AASHTO TP79 standard [48]. The sample dimensions were 150 mm in height and 100 mm in diameter. Initially, the samples were preconditioned in an incubator at 50 ℃ for 2 hours to attain the desired temperature. The test was carried out under conditions of unconfined pressure and 0.7 MPa compressive stress. The testing chamber was allowed to stabilize at the testing temperature of 50 ℃ for a minimum of one hour. Each loading cycle consisted of a 0.1-second load period followed by a 0.9-second rest period. The test was concluded either after 10,000 cycles or upon reaching a five percent permanent strain.

3.3. *Field application*

3.3.1. *Surface mixtures*

To assess the efficacy of the developed WMA and rejuvenator, a road section spanning 105 m was paved using two distinct mixtures-Type 1 and Type 2-each covering a 105-meter length, depicted in the Fig. 6. The experimental road is located in South Korea, Daegu, Dalseong-gun, Habin-myeon, Hasan-ri. A suitable quantity of 60 tons of asphalt mixture was utilized for paving, covering an area measuring 105 m in length, 3.6 m in width, and 0.07 m in thickness. In the paving process, as indicated in Fig. 6, the Type 1 mixture underwent mixing at the plant at a temperature of 170 ℃ and was compacted at 150 ℃. Conversely, the Type 2 mixture was mixed and compacted at lower temperatures, specifically at 140℃ and 120 ℃, respectively.

After compaction, multiple locations were chosen to collect samples for assessing the compaction level and evaluating the mixture's performance, including tensile strength ratio, indirect tensile strength, and air void content. Additionally, after one year of service, the pavement conditions were assessed using an automated vehicle which can evaluate pavement condition. These evaluations covered aspects such as crack rate and permanent deformation of the pavement as shown in Fig. 7.

3.3.2. *Base mixtures*

To evaluate the effectiveness of two distinct base layers, a 200-meter road was built incorporating these layers. The experimental road is located in South Korea, Gyeongsangbuk-do, Goryeong-gun, Seongsan-myeon, Gisan-ri. The first 100 m were paved with the type 3 mixture, while the subsequent 100 m used the type 4 mixture. The road surface was completed using the type 1 mixture. As illustrated in the figure below, the testbed was built with a 10 cm base layer and a 5 cm surface layer. Following the preparation of the subbase layer, the base mixture was compacted to achieve the desired height of 10 cm. Subsequently, a thin layer of RSC4 coating was applied to the surface of the base layer before compacting the surface layer. The type 1 mixture was produced at the asphalt plant and transported to the construction site, where the compaction temperature was maintained at 150 ℃, as depicted in Fig. 10. The construction process is detailed in Fig. 8.

Several locations within the testbed were drilled to examine the compaction effects, visually demonstrated in the figure below. Subsequently, the extracted core samples were transported to the laboratory for density determination. Utilizing the vacuum method, the core specimen's density was assessed without water contacting the specimen. This method involves compressing the core specimen under a vacuum and measuring the weight of water within the device. Due to the inclusion of cement in this developed product, standard density measurement methods for asphalt cores could not be applied due to water absorption. Hence, the vacuum method was employed to accurately measure the density. Moreover, the bearing capacity of the two base layers was assessed using the FWD. Non-destructive pavement deflection testing, commonly conducted via FWD, finds widespread application in pavement evaluation, design, and maintenance programs. This technique employs an impact load to analyze the pavement and ground characteristics by measuring the maximum vertical deformation resulting from the load generated through the free fall of an applied load onto the pavement surface.

4. Results and discussions

4.1. *Performances of WMA modified asphalt binder*

4.1.1. *DSR*

Fig. 9 illustrates the dynamic shear rheometer results for four modified asphalt binders with different additives. Generally, the addition of WMA and rejuvenator could decrease the viscosity and increase rutting resistance factor (G*/sinδ). The Mix C, incorporating 2.0% warm mix additive and 5.0% rejuvenator, displayed the highest G*/sinδ value at 7.35 kPa, which approximately three times higher compared to original binder (e.g., 2.29 kPa). A higher G*/sinδ indicated that the addition of WMA and rejuvenator could improve resistance to rutting in the modified binder. Despite the test temperature being 76℃, three

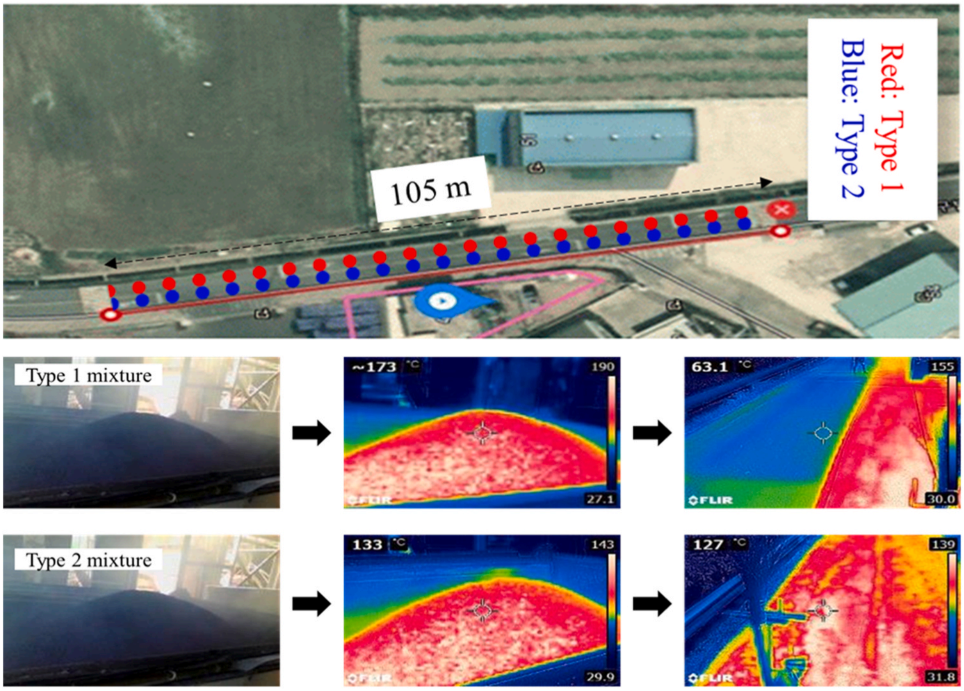

Fig. 6. Field application of type 1 and type 2 mixture.

Fig. 7. Cored sample and PMS test.

modified asphalt binders met the specification of greater than 2.2 kPa, indicating potential enhancements in rutting resistance or an increase in binder grade from 64℃ to 76℃ due to the addition of WMA and rejuvenator. Meanwhile, the viscosity at 135℃ increased with the addition of warm mix additive and rejuvenator. Mix B exhibited the highest viscosity at 1.71 Pa.s compared to Mix C and Mix D, which recorded viscosities of 1.18 Pa.s and 1.05 Pa.s, respectively. In contrast, the viscosity of unmodified binder (Mix A) was 0.44 at 135℃. While higher viscosity might offer improved rutting resistance, it could potentially impact the mixing process negatively. Therefore, it can be concluded that the inclusion of 2.0% warm mix additive and 5.5% rejuvenator was not recommended due to resulting high viscosity levels.

4.1.2. BBR

Fig. 10 showcases the creep stiffness and m-value of four asphalt binders. The BBR test was conducted at −12℃, following the RFTO and PAV procedures for the binders. Overall, the creep stiffness of all four binders met the specifications, demonstrating values lower than 300 MPa. Mix C exhibited the lowest value at 150.8 MPa compared to Mix A, which was 249.0 MPa. The addition of 2.0% rejuvenator significantly reduced the creep stiffness by approximately 15%, evident in Mix B and Mix C. Lower values in creep stiffness indicate superior resistance to low temperatures or fatigue cracking. This can be explained by a lower creep stiffness value indicated decrease in thermal stresses, implying a reduced risk of thermal cracking. However, the m-value of mix D measured at 0.277 did not meet the specification of higher than 0.3, causing the Mix D mixture to fall short of meeting the PG 76–22 specification. As a result, the Mix C, containing 2.0% WMA and 5.0% rejuvenator, emerged as the recommended choice for utilization in further warm mix asphalt mixture experiments.

4.2. Asphalt mixture performance tests

4.2.1. Dynamic modulus

Fig. 11 shows the dynamic modulus master curves for surface and base mixtures, respectively. Generally, an increase in test frequencies resulted in higher dynamic modulus values. Especially, the Type 2 mixture displayed a lower dynamic modulus than the Type 1 mixture at higher frequencies, which correspond to lower temperatures. This lower dynamic modulus indicated a better resistance to low-temperature cracking. Conversely, at lower frequencies corresponding to higher temperatures, the Type 2 mixture exhibited higher dynamic modulus values, which enhanced resistance to rutting compared to the Type 1 mixture. As illustrated in Fig. 12, the developed warm mix additive plays a crucial role in forming hydrophilic connections between Si-O/Si-OH on the aggregate surface and the -NH- groups presented in the warm

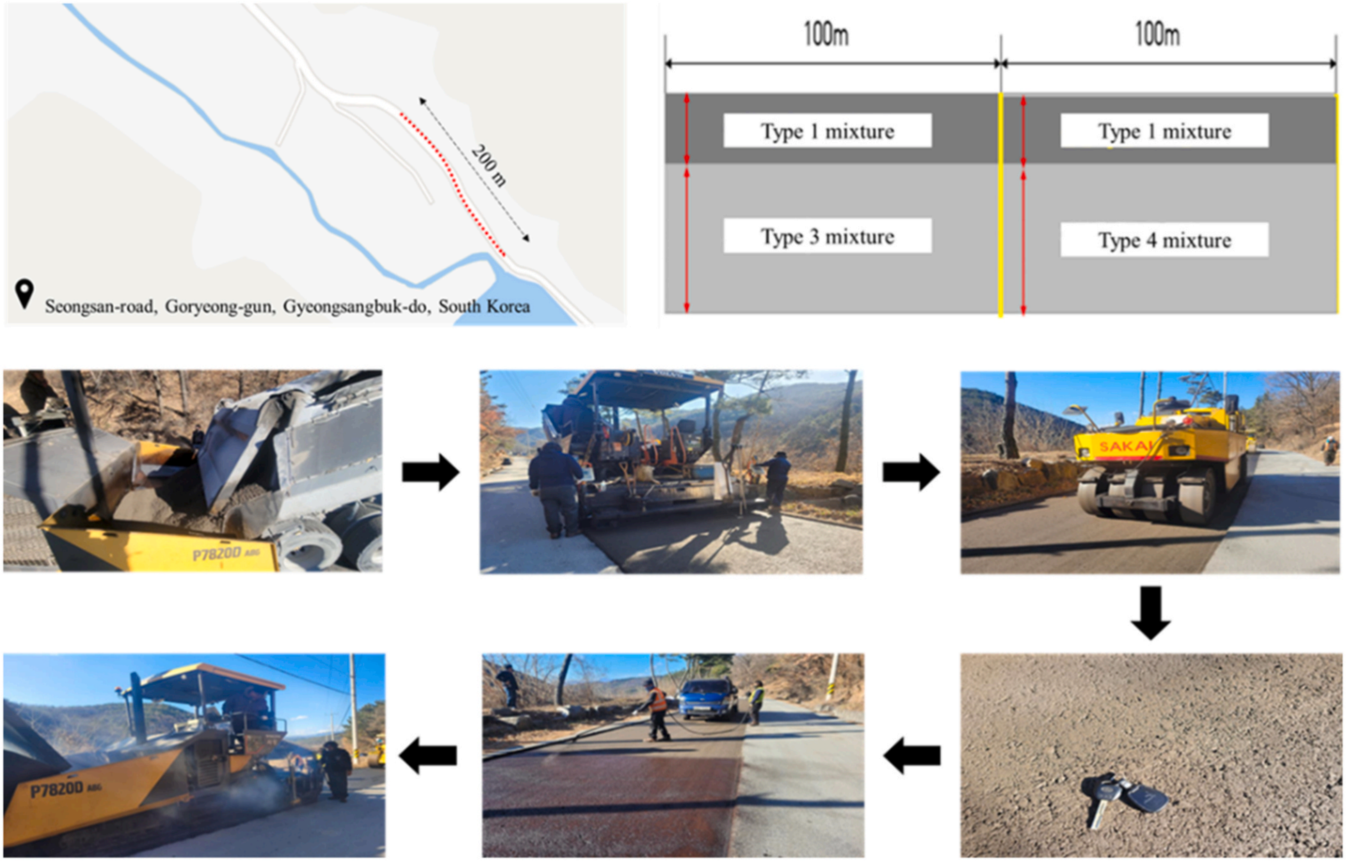

Fig. 8. Field construction process for base mixtures.

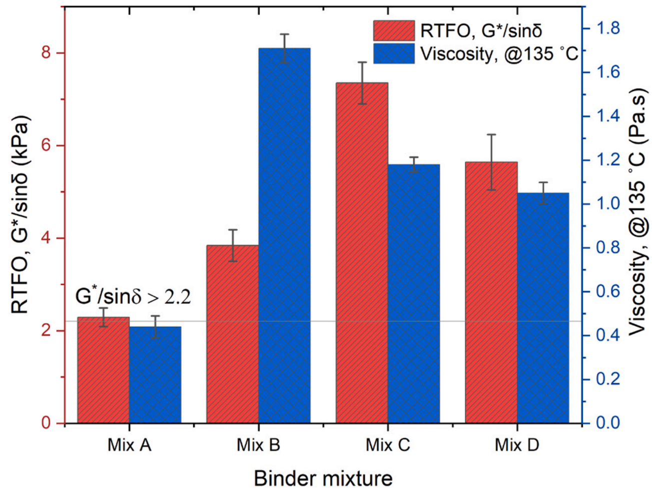

Fig. 9. G*/sinδ values after RFTO.

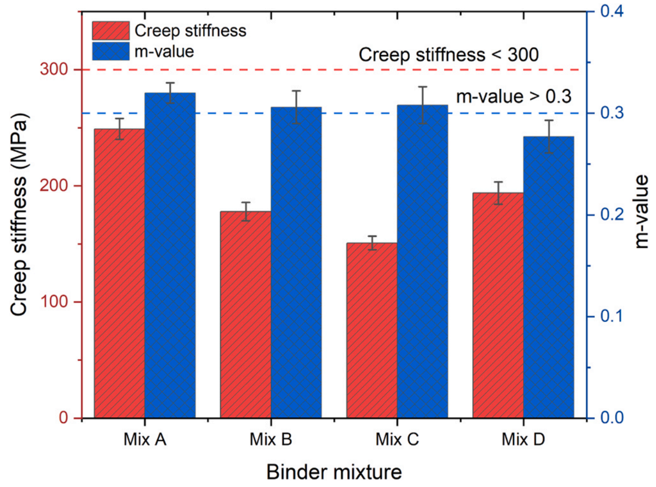

Fig. 10. Creep stiffness and m-value at −12 °C.

mix additive. This interaction enhances the internal cohesion between the aggregate and asphalt binder, leading to increased strength within the Type 2 asphalt mixture. In simpler terms, the warm mix additive facilitates stronger bonds between the aggregate and binder, ultimately enhancing the overall performance of the asphalt mixture. Additionally, Fig. 11 also presents the dynamic modulus of the two base mixtures—Type 3 and Type 4. Similarly, an increase in frequency correlated with heightened dynamic modulus values for both mixtures. Type 3 mixtures, incorporating APE and cement, displayed a higher dynamic modulus compared to Type 4 mixtures utilizing asphalt emulsion. The increase in dynamic modulus of Type 3 could be attributed to APE, enhancing the bond between recycled asphalt and cement. Furthermore, the use of acrylic emulsion potentially reduced water content, subsequently decreasing air voids after cement hydration process.

4.2.2. *Overlay test*

Fig. 13 displays the OT test results for four asphalt mixtures. Generally, Type 1 and Type 2 mixtures exhibited higher OT cycle numbers in comparison to Type 3 and Type 4 mixtures. Especially, Type 2 mixture demonstrated the highest OT cycles, reaching 806 cycles and 404 cycles at load drops of 87% and 85%, respectively. A higher number of OT cycles indicated a better resistance to reflective cracking. The

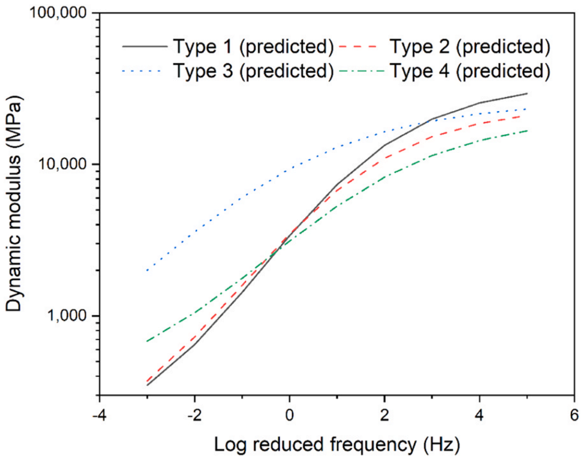

Fig. 11. Dynamic modulus master curve at 21℃.

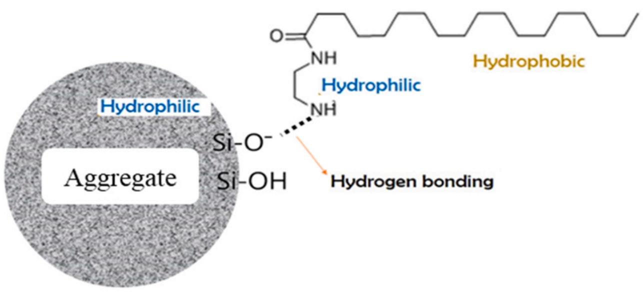

Fig. 12. Internal link between aggregate and warm mix additive.

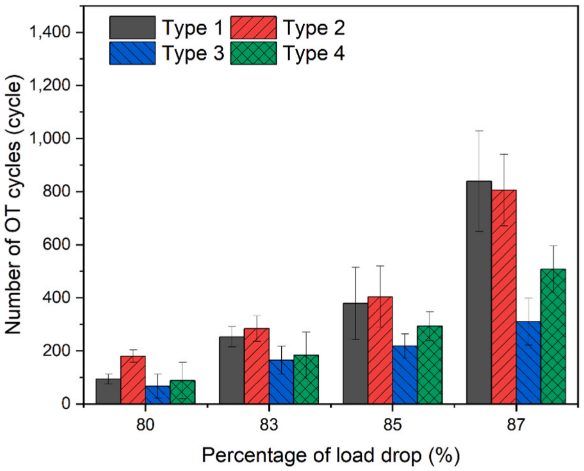

Fig. 13. Number of OT cycles.

increased OT cycles in Type 2 mixture, attributed to the addition of warm mix additive and rejuvenator, potentially reduced the creep stiffness of the modified asphalt binder, enhancing resistance to cracking. Despite Type 2 mixture incorporating up to 50% recycled material, it outperformed the Type 1 mixture containing 30% recycled material, indicating the promising results of incorporating warm mix additive and rejuvenator. In contrast, Type 3 and Type 4 mixtures exhibited lower OT cycle numbers compared to Type 1 and Type 2 mixtures, reaching 310 and 508 cycles at load drops of 87%, respectively. Specifically, Type 3 mixture showed the lowest values, recording 218 and 310 cycles at 85% and 87%, respectively. This lower number of OT cycles could be attributed to the cement component in the asphalt base mixture, which tended to induce a brittle behavior in the mixture compared to the asphalt emulsion utilized in Type 4 mixture. Overall, the addition of WMA and rejuvenator could increase the resistance to resistance to reflective cracking when incorporated with 50% of RAP.

4.2.3. Flow number test

Fig. 14 illustrates the relationship between flow number cycles and permanent deformation across four asphalt mixtures. Generally, an increase in flow number cycles correlated with increased deformation. Notably, Type 1 mixture exhibited the highest deformation at 2.73 mm after 10,000 cycles, while Type 2 mixture showcased a lower deformation of 1.95 mm. The diminished permanent deformation in Type 2 mixture may be attributed to the incorporation of warm mix additive (WMA) and rejuvenator, as previously discussed. The asphalt binder comprising WMA and rejuvenator showcased higher G*/sinδ at 76℃, contributing to enhanced resistance to deformation in the asphalt mixture. Despite Type 2 mixture containing 50% recycled asphalt compared to the 30% in Type 1 mixture, the incorporation of WMA and rejuvenator in Type 2 yielded promising results in resisting rutting. Moreover, Type 3 and Type 4 mixtures demonstrated lower permanent deformation compared to Type 1 and Type 2 mixtures. Specifically, Type 3 mixture displayed the lowest permanent deformation at 0.65 mm after 10,000 cycles, while Type 4 mixture recorded 1.52 mm. The reduced permanent deformation in Type 3 mixture might be attributed to its cement composition and modified acrylic polymer emulsion, contributing to better resistance against aggregate sliding and a tendency increased brittleness over time.

4.3. Field application

4.3.1. Surface mixtures

The outcomes obtained from the cored samples collected during the field application of surface mixtures (Type 1 and Type 2) are outlined in Table 4. Overall, both mixtures met the specifications concerning designed air void, saturation, indirect tensile strength, and tensile strength ratio. Especially, the indirect tensile strength and tensile strength ratio of the Type 2 mixture slightly higher those of the Type 1 mixture, indicating enhanced moisture resistance. Moreover, results obtained from the pavement analyzer revealed a 0.0% observed crack rate after one year of service in the field test. As shown in Table 5, the permanent deformation measured 2.1 mm and 2.3 mm corresponding to Type 1 and Type 2 mixtures, respectively. It should be noted that Type 2 contained 50% recycled asphalt while Type 1 mixture contained 30% recycled asphalt. However, the field application results for both mixtures did not significantly differ. Hence, the incorporation of the

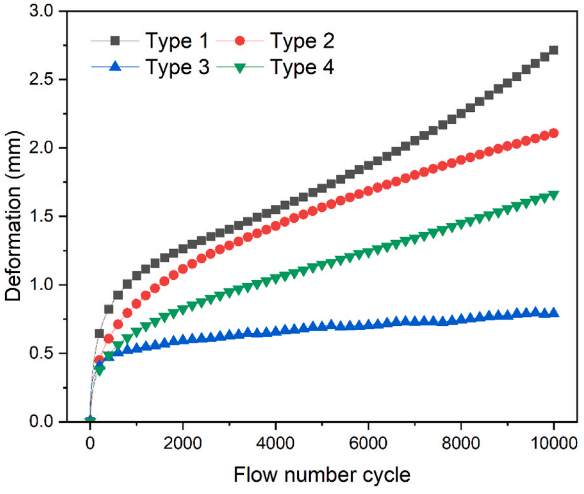

Fig. 14. Flow number results.

Table 4
Test results of cored samples from field application.

Test specifications	Type 1 mixture	Type 2 mixture
Air void (4÷6%)	4.2	4.1
Degree of saturation (60÷80%)	73	74
Indirect tensile strength (≥0.8 MPa)	1.44	1.45
Tensile strength ratio (≥0.8)	0.86	0.89

Table 5
Test results base on pavement condition survey.

Mixture	Length (m)	Crack rate (%)	Deformation (mm)
Type 1	105	0.0	2.1
Type 2	105	0.0	2.3

developed warm mix additive and rejuvenator not only increased the utilization of recycled asphalt content up to 50% in the mixture but also provided the excellent performance of the asphalt mixture.

4.3.2. Base mixtures

The average density of three specimens collected at the test site measured at 2.274 g/cm^3. Additionally, three specimens for indoor density measurement, produced and tested in the laboratory on the same day, showed an average density of 2.026 g/cm^3. The average firmness, derived from the density of indoor-manufactured test specimens and field-collected cores, was measured at 112%. Generally, both base mixtures exhibited a better field compaction, indicating favorable working properties. The average compressive strength of cored samples was 8.4 MPa, which satisfied the standard specifications for asphalt pavement in road construction. This outcome reflects commendable on-site construction and quality control practices. Moreover, the FWD results for both base mixtures are illustrated in Fig. 15. Typically, the deflection of the asphalt base decreased as the distance increased from the center of the falling weight meter. At the bottom of the deflectometer (D0), deflections were recorded at 290μm and 319μm for Type 3 and Type 4 mixtures, respectively. Especially, Type 3 mixture displayed lower deflection than Type 4, possibly due to the cement composition and acrylic polymer emulsion, resulting in a more brittle and hardened structure. However, as the distance increased from the center load, minimal difference was observed between Type 3 and Type 4 mixtures. It can be concluded that the incorporation of APE in Type 3 mixture (100% RAP) produced similar performances compared to Type 4 mixture with asphalt emulsion.

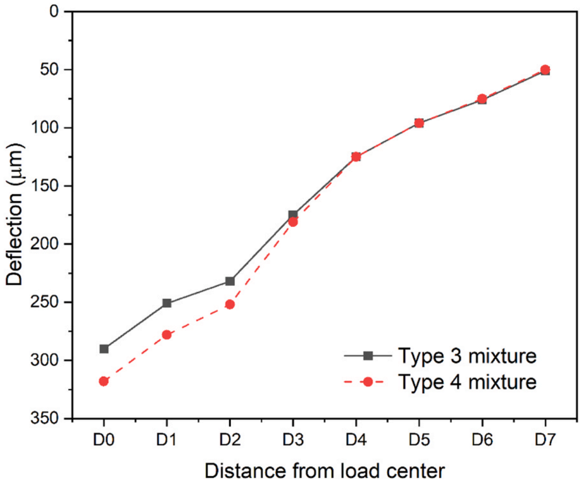

Fig. 15. FWD of type 3 and type 4 base mixtures.

5. Conclusions

The primary objective of this research is to develop a warm mix additive and rejuvenator aiming to enhance the utilization of recycled asphalt in warm mix additives, extending up to 50%. The warm mix additive was formulated using diamine and fatty acid amine, while the rejuvenator was composed of Styrene-Butadiene-Styrene (SBS) and aromatic elements. The study encompassed four distinct mixtures, comprising two surface mixtures and two base mixtures, which underwent comprehensive laboratory tests and field applications. The optimization of WMA and rejuvenator for the warm mix additive was determined through the DSR test and the BBR test assessments using modified asphalt binder. Moreover, the performance evaluation of the four asphalt mixtures was conducted through dynamic modulus tests, flow number tests, and overlay tests. Lastly, two road sections were constructed to assess the performance of the two surface mixtures and two base mixtures throughout their service life. From these investigations, several pivotal conclusions were drawn.

- Warm mix additive (1:5 diamine and fatty acid amine) with a 105°C-melting point has the potential to lower mixing and compaction temperatures in recycled warm mix asphalt. A rejuvenator (SBS and aromatic components, 70:30) could increase RAP content up to 50% of total mixture.
- Binder tests showed that modifying PG 64–22 asphalt binder with 2.0% WMA and 5.0% rejuvenator upgraded it to PG 76–22, resulting in a three-time improvement in resistance to rutting and a 40% reduction in susceptibility to low-temperature cracking.
- Type 2 mixture (50% recycled asphalt, WMA, and rejuvenator) outperformed a 30% RAP hot asphalt mixture in dynamic modulus, flow number, and reflective cracking tests.
- Both surface mixtures (type 1 and type 2) met field application specifications concerning air void, tensile strength ratio, and indirect tensile strength. After one year of service, pavement condition survey results showed a 0% crack rate and 2.2 mm deformation.
- Two base mixtures demonstrated good workability with a compaction level up to 112% in field applications. Type 3 base mixture, incorporating cement and acrylic polymer emulsion, displayed lower deflection than type 4 mixtures with asphalt emulsion in Falling Weight Deflectometer test.

Overall, this study introduced a newly developed warm mix additive rejuvenator aimed at maximizing the use of recycled asphalt up to 50% while lowering mixing and compaction temperatures to 140°C and 120°C, respectively. Additionally, the integration of acrylic polymer emulsion with cement could the full utilization of 100% recycled asphalt in base mixtures. Although the initial field test during the first year of service shows promising results, it is crucial to consider the performance and life cycle cost analysis over an extended period to ascertain its durability and effectiveness.

CRediT authorship contribution statement

Yu-Seung Choi: Writing – original draft, Formal analysis, Data curation. **Tam Minh Phan:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Dae-Wook Park:** Writing – review & editing, Supervision, Conceptualization. **Sang-Hyeok Youn:** Writing – original draft, Methodology, Data curation.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1F1A1063979), and this work also was partially supported by Yoonsung Development Co., Ltd.

References

[1] J. Davis, ttp://asphaltmagazine.com/early-uses-of-asphalt/, Mag. Asph. Inst. (n. d.).

[2] J. Gao, Y. Yao, J. Yang, L. Song, J. Xu, L. He, W. Tao, Migration behavior of reclaimed asphalt pavement mastic during hot mixing, J. Clean. Prod. 376 (2022) 134123, https://doi.org/10.1016/j.jclepro.2022.134123.

[3] I.N.A. Thanaya, I.M.A. Ariawan, I.D.G.R. Yudistira, I.M. Widiyarta, Properties of recycled hot asphalt mixture added with mastic asphalt component, IOP Conf. Ser. Earth Environ. Sci. 1065 (2022) 12038, https://doi.org/10.1088/1755-1315/1065/1/012038.

[4] N. Shatarat, A.A. Alhaq, H. Katkhuda, M.A. Jaber, Investigation of axial compressive behavior of reinforced concrete columns using recycled coarse aggregate and recycled asphalt pavement aggregate, Constr. Build. Mater. 217 (2019) 384–393, https://doi.org/10.1016/j.conbuildmat.2019.05.085.

[5] F. Kaseer, A.E. Martin, E. Arámbula-Mercado, Use of recycling agents in asphalt mixtures with high recycled materials contents in the United States: a literature review, Constr. Build. Mater. 211 (2019) 974–987, https://doi.org/10.1016/j.conbuildmat.2019.03.286.

[6] I. Rodríguez-Fernández, P. Lastra-González, I. Indacoechea-Vega, D. Castro-Fresno, Recyclability potential of asphalt mixes containing reclaimed asphalt pavement and industrial by-products, Constr. Build. Mater. 195 (2019) 148–155, https://doi.org/10.1016/j.conbuildmat.2018.11.069.

[7] S.-H. Lee, A.B. Tam, J. Kim, D.-W. Park, Evaluation of rejuvenators based on the healing and mechanistic performance of recycled asphalt mixture, Constr. Build. Mater. 220 (2019) 628–636, https://doi.org/10.1016/j.conbuildmat.2019.05.150.

[8] D. Khan, R. Khan, M.T. Khan, M. Alam, T. Hassan, Performance of hot-mix asphalt using polymer-modified bitumen and marble dust as a filler, J. Traffic Transp. Eng. 10 (2023) 385–398, https://doi.org/10.1016/j.jtte.2022.12.002. English Ed.

[9] Y. Kim, J. Lee, C. Baek, S. Yang, S. Kwon, Y. Suh, Performance evaluation of warm- and hot-mix asphalt mixtures based on laboratory and accelerated pavement tests, Adv. Mater. Sci. Eng. 2012 (2012) 901658, https://doi.org/10.1155/2012/901658.

[10] S.B. AL-Ghurabi, B.H. Al-Humeidawi, Evaluation of performance of hot mix asphalt contained various sizes of Reclaim asphalt pavement and polymer modified Bitumen, Mater. Today Proc. 80 (2023) 2905–2910, https://doi.org/10.1016/j.matpr.2021.07.063.

[11] T. Wang, W. Jiang, J. Xiao, D. Guo, D. Yuan, W. Wu, W. Wang, Study on the blending behavior of asphalt binder in mixing process of hot recycling, Case Stud. Constr. Mater. 17 (2022) e01477, https://doi.org/10.1016/j.cscm.2022.e01477.

[12] W. Rafiq, M. Bin Napiah, M. Hartadi Sutanto, W. Salah Alaloul, Z. Nadia Binti Zabri, M. Imran Khan, M. Ali Musarat, Investigation on Hamburg wheel-tracking device stripping performance properties of recycled hot-mix asphalt mixtures, Materials 13 (2020), https://doi.org/10.3390/ma13214704.

[13] M. Alinezhad, A. Sahaf, Investigation of the fatigue characteristics of warm stone matrix asphalt (WSMA) containing electric arc furnace (EAF) steel slag as coarse aggregate and Sasobit as warm mix additive, Case Stud. Constr. Mater. 11 (2019) e00265, https://doi.org/10.1016/j.cscm.2019.e00265.

[14] M.R. Keymanesh, S. Amani, A.T. Omran, M.M. Karimi, Evaluation of the impact of long-term aging on fracture properties of warm mix asphalt (WMA) with high RAP contents, Constr. Build. Mater. 400 (2023) 132671, https://doi.org/10.1016/j.conbuildmat.2023.132671.

[15] H. Ji, B. Li, A. Li, Z. Li, J. Han, Z. Liu, Adhesion mechanism of warm-mixed recycled SBS Modified Asphalt Binder: Surface free energy, microstructure and chemical compositions, Case Stud. Constr. Mater. 19 (2023) e02426, https://doi.org/10.1016/j.cscm.2023.e02426.

[16] V. Kumar, E. Coleri, Effects of finer gradation, temperature, warm mix additives, and compaction methods on density and performance of asphalt mixtures, Constr. Build. Mater. 394 (2023) 132226, https://doi.org/10.1016/j.conbuildmat.2023.132226.

[17] T.M. Phan, T.H.M. Le, D.-W. Park, Evaluation of cracking resistance of healed warm mix asphalt based on air-void and binder content, Road. Mater. Pavement Des. 23 (2022) 47–61, https://doi.org/10.1080/14680629.2020.1829010.

[18] A. Milad, A.M. Babalghaith, A.M. Al-Sabaeei, A. Dulaimi, A. Ali, S.S. Reddy, M. Bilema, N.I.M. Yusoff, A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: towards a sustainable asphalt pavement, Int. J. Environ. Res. Public Health 19 (2022), https://doi.org/10.3390/ijerph192214863.

[19] S. Spadoni, L.P. Ingrassia, E. Mariani, F. Cardone, F. Canestrari, Long-term performance assessment of a warm recycled motorway pavement, Case Stud. Constr. Mater. 17 (2022) e01451, https://doi.org/10.1016/j.cscm.2022.e01451.

[20] Y. Zhao, M. Chen, S. Wu, Y. Zhu, X. Zhou, C. Yang, Z. Zhao, J. Zhang, D. Chen, Feasibility assessment of palmitamide derived from waste edible oil as a warm mix asphalt additive, Constr. Build. Mater. 401 (2023) 132972, https://doi.org/10.1016/j.conbuildmat.2023.132972.

[21] T.M. de Sousa, O. de Medeiros Melo Neto, A. Elísio de Figueiredo Lopes Lucena, E. R. Nóbrega, Enhancing workability and sustainability of asphalt mixtures: investigating the performance of beeswax as a novel additive for warm mix asphalt, Constr. Build. Mater. 405 (2023) 133306, https://doi.org/10.1016/j.conbuildmat.2023.133306.

[22] H. Köse, O.N. Çelik, D. Arslan, A novel approach to warm mix asphalt additive production from polypropylene waste plastic via pyrolysis, Constr. Build. Mater. 411 (2024) 134151, https://doi.org/10.1016/j.conbuildmat.2023.134151.

[23] S. Zhang, D. Wang, F. Guo, Y. Deng, F. Feng, Q. Wu, Z. Chen, Y. Li, Properties investigation of the SBS modified asphalt with a compound warm mix asphalt (WMA) fashion using the chemical additive and foaming procedure, J. Clean. Prod. 319 (2021) 128789, https://doi.org/10.1016/j.jclepro.2021.128789.

[24] B. Singh, N. Saboo, P. Kumar, Effect of polymer and warm mix modification on asphalt mixture properties, IOP Conf. Ser. Mater. Sci. Eng. 1075 (2021) 12015, https://doi.org/10.1088/1757-899X/1075/1/012015.

[25] N. Barazi Jomoor, M. Fakhri, M.R. Keymanesh, Determining the optimum amount of recycled asphalt pavement (RAP) in warm stone matrix asphalt using dynamic creep test, Constr. Build. Mater. 228 (2019) 116736, https://doi.org/10.1016/j.conbuildmat.2019.116736.

[26] M. Pasetto, A. Baliello, G. Giacomello, E. Pasquini, The use of steel slags in asphalt pavements: a state-of-the-art review, Sustainability 15 (2023), https://doi.org/10.3390/su15118817.

[27] G. Dondi, F. Mazzotta, C. Lantieri, F. Cuppi, V. Vignali, C. Sangiovanni, Use of steel slag as an alternative to aggregate and filler in road pavements, Materials 14 (2021), https://doi.org/10.3390/ma14020345.

[28] T.M. Phan, D.-W. Park, T.H.M. Le, Crack healing performance of hot mix asphalt containing steel slag by microwaves heating, Constr. Build. Mater. 180 (2018) 503–511, https://doi.org/10.1016/j.conbuildmat.2018.05.278.

[29] J. Ma, H.M.C. Nawarathna, S.A.M. Hesp, On the sustainable use of recycled plastics in flexible asphalt pavements, J. Clean. Prod. 359 (2022) 132081, https://doi.org/10.1016/j.jclepro.2022.132081.

[30] A. Abdalla, A.F. Faheem, E. Walters, Life cycle assessment of eco-friendly asphalt pavement involving multi-recycled materials: a comparative study, J. Clean. Prod. 362 (2022) 132471, https://doi.org/10.1016/j.jclepro.2022.132471.

[31] I. Holleran, D.J. Wilson, E. Masad, G. Holleran, E. Alrashydah, Effect of bio-rejuvenator on recycled porous asphalt mixes, Road. Mater. Pavement Des. 24 (2023) 340–366, https://doi.org/10.1080/14680629.2021.2017331.

[32] W.S. Mogawer, A. Booshehrian, S. Vahidi, A.J. Austerman, Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures, Road. Mater. Pavement Des. 14 (2013) 193–213, https://doi.org/10.1080/14680629.2013.812836.

[33] N. Tran, A. Taylor, P. Turner, C. Holmes, L. Porot, Effect of rejuvenator on performance characteristics of high RAP mixture, Road. Mater. Pavement Des. 18 (2017) 183–208, https://doi.org/10.1080/14680629.2016.1266757.

[34] S.K. Pradhan, U.C. Sahoo, Evaluation of recycled asphalt mixtures rejuvenated with Madhuca longifolia (Mahua) oil, Int. J. Pavement Res. Technol. 14 (2021) 43–53, https://doi.org/10.1007/s42947-020-0279-6.

[35] G. Gurunath, K. Chethan, G. Bharath, K.K. K, Effectiveness of different categories of rejuvenators in recycled asphalt mixtures, J. Transp. Eng. Part B Pavements 147 (2021) 4021006, https://doi.org/10.1061/JPEODX.0000255.

[36] S.R.M. Fernandes, H.M.R.D. Silva, J.R.M. Oliveira, Developing enhanced modified bitumens with waste engine oil products combined with polymers, Constr. Build. Mater. 160 (2018) 714–724, https://doi.org/10.1016/j.conbuildmat.2017.11.112.

[37] B.H. Dinh, D.-W. Park, T.H.M. Le, Effect of rejuvenators on the crack healing performance of recycled asphalt pavement by induction heating, Constr. Build. Mater. 164 (2018) 246–254, https://doi.org/10.1016/j.conbuildmat.2017.12.193.

[38] M.A. Al-Jumaili, O.D. Issmael, Cold asphalt mixtures with high reclaimed pavement material percentages response to local traffic loading and environmental conditions, IOP Conf. Ser. Mater. Sci. Eng. 433 (2018) 12013, https://doi.org/10.1088/1757-899X/433/1/012013.

[39] W.U. Filho, L.M. Gutiérrez Klinsky, R. Motta, L.L. Bariani Bernucci, Cold recycled asphalt mixture using 100% RAP with emulsified asphalt-recycling agent as a new pavement base course, Adv. Mater. Sci. Eng. 2020 (2020) 5863458, https://doi.org/10.1155/2020/5863458.

[40] H. Zhao, J. Su, S. Ma, C. Su, X. Wang, Z. Li, J. Wei, S. Cui, Study on cold recycled asphalt mixtures with emulsified/foamed asphalt in the laboratory and on-site, Coatings 12 (2022), https://doi.org/10.3390/coatings12071009.

[41] J. Yan, H. Zhu, Z. Zhang, L. Gao, S. Charmot, The theoretical analysis of the RAP aged asphalt influence on the performance of asphalt emulsion cold recycled mixes, Constr. Build. Mater. 71 (2014) 444–450, https://doi.org/10.1016/j.conbuildmat.2014.09.002.

[42] Y. Wang, Z. Leng, X. Li, C. Hu, Cold recycling of reclaimed asphalt pavement towards improved engineering performance, J. Clean. Prod. 171 (2018) 1031–1038, https://doi.org/10.1016/j.jclepro.2017.10.132.

[43] AASHTO-T315-10, Determining the Rheological Properties of Asfhalt Binder Using a Dynamic Shear Rheometer (DSR), (2010).

[44] AASHTO-T-313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), (2022).

[45] AASHTO-T342-11, Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures, (2019).

[46] Python, Python, (2022). ⟨https://www.python.org/⟩.
[47] Tex-248-F, Test Procedure for Overlay Test, (2019).
[48] AASHTO-TP79, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT), (2015).