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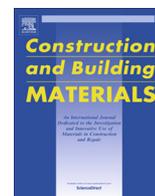
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Use of epoxy asphalt as surfacing and tack coat material for roadway pavements

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HIGHLIGHTS

- Epoxy asphalt mixes have higher tensile strength than conventional asphalt mixes.
- The four-point bending tests indicate that a high modulus material, as the epoxy asphalt, can effectively reduce deflections of specimen beams and improve their fatigue resistance.
- Epoxy-type tack coat improves significantly the bonding strength between two asphaltic layers.
- Two-layer monolithic pavements with epoxy asphalt could mitigate bonding defects of surfacing layers of enhanced strength, modulus and fatigue resistance.

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ABSTRACT

This work presents an experimental program developed to evaluate the effect of epoxy-asphalt binder, used as replacement of bitumen, on the durability and fatigue life of an asphalt concrete mix. The use of epoxy-type binder as tack coat has been explored as well and thus experiments have been conducted to quantify the effect of epoxy tack coat on the interface strength of two-layer asphalt samples. Results indicated that the epoxy asphalt mixes had higher tensile strength than control mixes, and the increase of strength was noticed with increasing proportionally the amount of epoxy in bitumen. Additionally, the four-point bending tests indicate that a high modulus material, as the epoxy modified asphalt, can effectively reduce deflections of specimen beams and improve the fatigue resistance of mixes designed for surfacing roadway applications. On the basis of interlayer tests, the use of epoxy asphalt binder as tack coat improved the bonding strength between the two layers offering monolithic performance characteristics on high modulus roadway pavements. Overall, the current study concludes that a two-layer monolithic pavement system with epoxy asphalt could mitigate bonding defects, such as debonding, slippage and fatigue cracking propagated from bottom to top, of a surfacing (top) pavement layer of enhanced strength, modulus and fatigue resistance.

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1. Introduction

Transportation generates more greenhouse gas emissions than any other sector [1]. Critical challenges, such as transition to zero carbon emissions for the transport infrastructure construction or free of maintenance transport networks, leads policy makers to explore the most cost-effective technologies to address these challenges. For the road infrastructure, long-life road pavements of enhanced durability can reduce the major repair needs justifying their high initial costs. Highly styrene-butadiene-styrene polymer

modified asphalt binders, cement or epoxy-based binders could be solutions toward replacing the conventional asphalt binders and to produce durable and long-lasting surfacing pavement layers. Among them, the epoxy-based binders have been proven as binding systems of low fracture [2–5] and aging sensitivity [6,7], and, apart from high demanding airfields [8] and bridges [9,10], they have been implemented successfully as surfacing materials on roadway pavements [11,12].

Nevertheless, the structural performance of pavements depends not only on the mechanical characteristics of individual pavement layers but also on the interlayer bonding strength between them [13,14]. Therefore, sufficient interlayer bonding of epoxy asphalt pavements will be critical to provide structural monolithic

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behaviour. The interlayer shear strength depends on temperature, wetness and cleanliness of the surface, and type and texture of pavement surface [15]. Poor bonding could lead to various distresses (e.g., debonding, slippage and fatigue cracking) decreasing thus the lifetime of epoxy asphalt pavements.

To improve the interlayer bonding pavement characteristics, tack coats are applied by selecting the appropriate coat type under certain application rates and methods. Tack coat is a light application of asphalt-based emulsion or asphalt binder which is used to create a strong bonding between the surface being paved and the overlying course to ensure adequate bonding strength [16]. Tack coats of pure asphalt binders typically show higher bonding strength than of emulsified binders. However, due to the fact that emulsified binders offer ease of handling, reduced personnel safety and energy consumption, they are widely used as tack coats [17]. Additionally, different pavement surfaces require different application rates to achieve proper interface bonding strength [18–20]. Thus, one of the main challenges related to the application of tack coat binders is the choice of the optimum quantity of additives to be applied at the interface, to achieve an adequate level of interlayer bonding. Excessive tack coat may promote shear slippage at the interface. In contrast, insufficient tack coat may cause tensile stresses concentrated at the bottom of the surface layer, leading to significant increase of tensile strains, and generation of cracks [21–23]. The knowledge of development of bonding properties over time is of great importance especially when interlayer bonding requirements are not met.

Table 1
Aggregate gradation used in the study.

Sieve Size (mm)	min. (% m/m)	max. (% m/m)	Percentage Passing (% m/m)
11.2	98	100	100
8	86.5	99.5	93
5.6	46.1	60.1	52
4			31
2	16.9	28.9	23
0.5	11.1	19.1	8.2
0.063	6.2	11.2	6.7
Binder content (% m/m): 6.7			

Table 2
Properties of epoxy asphalt binder used in the study.

Property	Value
<i>Epoxy-based component (Part A)</i> ¹	
Viscosity at 25 °C (cP)	11,000–15,000
Specific gravity at 23 °C	1.16
Boiling point (°C)	>260
<i>Asphalt-based component (Part B)</i> ²	
Viscosity at 100 °C (cP)	140
Specific gravity at 25 °C	0.99
Boiling point (°C)	288
Flash point, Cleveland open cup (°C)	232

¹ Bisphenol-A-epichlorohydrin epoxy resin.

² Mix of petroleum asphalt, heavy naphthenic distillate and extract.

Table 3
Physical properties of studied mixes designed for surfacing applications.

Property	Specification	ESMA-0 ¹	ESMA-20 ²	ESMA-40 ²
Target density (kg/m ³)		2304	2310	2310
Mix density (kg/m ³)	NEN-EN 12697-5	2449	2435	2435
Air voids content (%)	NEN-EN 12697-8	5.9	5.1	5.3

Production temperature range: 140–180 °C¹ and 125–145 °C².

As a continuation of an effort to implement the epoxy asphalt as paving material for roadways [12], this work presents an experimental program developed to evaluate the effect of epoxy modification on the durability and fatigue life of asphalt concrete. Laboratory studies have been conducted as well to quantify the interface shear strength of two-layer epoxy asphalt concrete samples for different tack coats (i.e., emulsion- and epoxy-type binders).

2. Performance of epoxy asphalt concrete

Epoxy asphalt has been widely applied as surfacing pavement material in New Zealand developing open-graded porous materials of enhanced durability and long-life characteristics [5,6,11]. In general, epoxy-modified asphaltic materials have shown high strength, fatigue resistance and resistance to oxidative aging. In the Netherlands, few successful trial roads have been constructed with implementing the epoxy asphalt as pavement surfacing material [12]. In this section, emphasis was given on assessing the effect of epoxy modification on the strength, modulus and fatigue resistance characteristics of asphalt concrete mixes.

2.1. Materials and specimen preparation

The gradation of asphalt concrete (i.e., stone mastic asphalt, SMA) of 8-mm nominal maximum aggregate size (SMA-NL 8B, RAW-2015) is given in Table 1. This asphalt type is designed with 5% air voids and 6.7% mass binder content. With the objective to lower the cost of designed epoxy asphalt (EA) mix, the effect of diluting the epoxy binder with neat bitumen (70/100 pengrade) was studied. 20 and 40% wt. of bitumen was substituted by a commercially available two-component EA binder. The EA binder supplied by ChemCo Systems Ltd (California, the United States) was

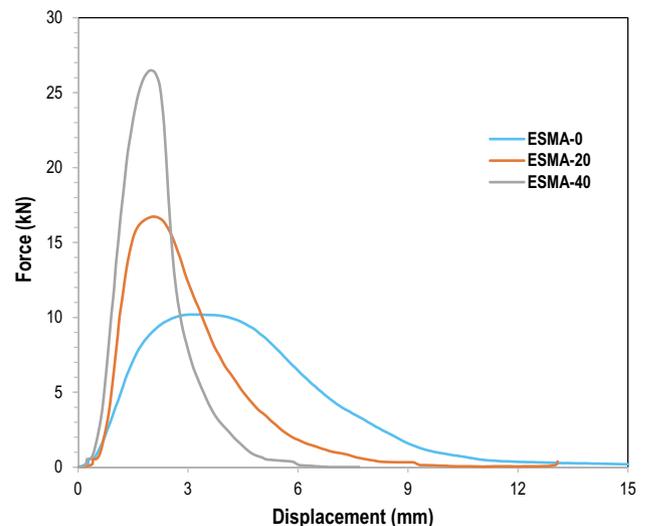


Fig. 1. Representative indirect tensile force versus displacement curves of studied materials at 15 °C.

formulated by blending Part A with Part B with weight ratio of 25:75, under certain energy conditions (i.e., temperature and pressure). The basic properties of individual parts of EA binder used in this study are shown in Table 2.

The two parts react together through an irreversible polymerization process formulating a rubber-like elastomeric polymer named EA binder. By mixing the two parts of EA together, the poly-

merization process starts, and the viscosity of binder increases over time up to gel point [24–26]. After gelation, the EA binder begins to build-up its modulus [25]. According to the supplier, the typical lab curing process of this polymeric binder is at 121 °C for 4–5 h or 130 °C for 3 h in oven. Depending on the ambient conditions, it usually takes approximately 60–90 days to be fully cured in the field.

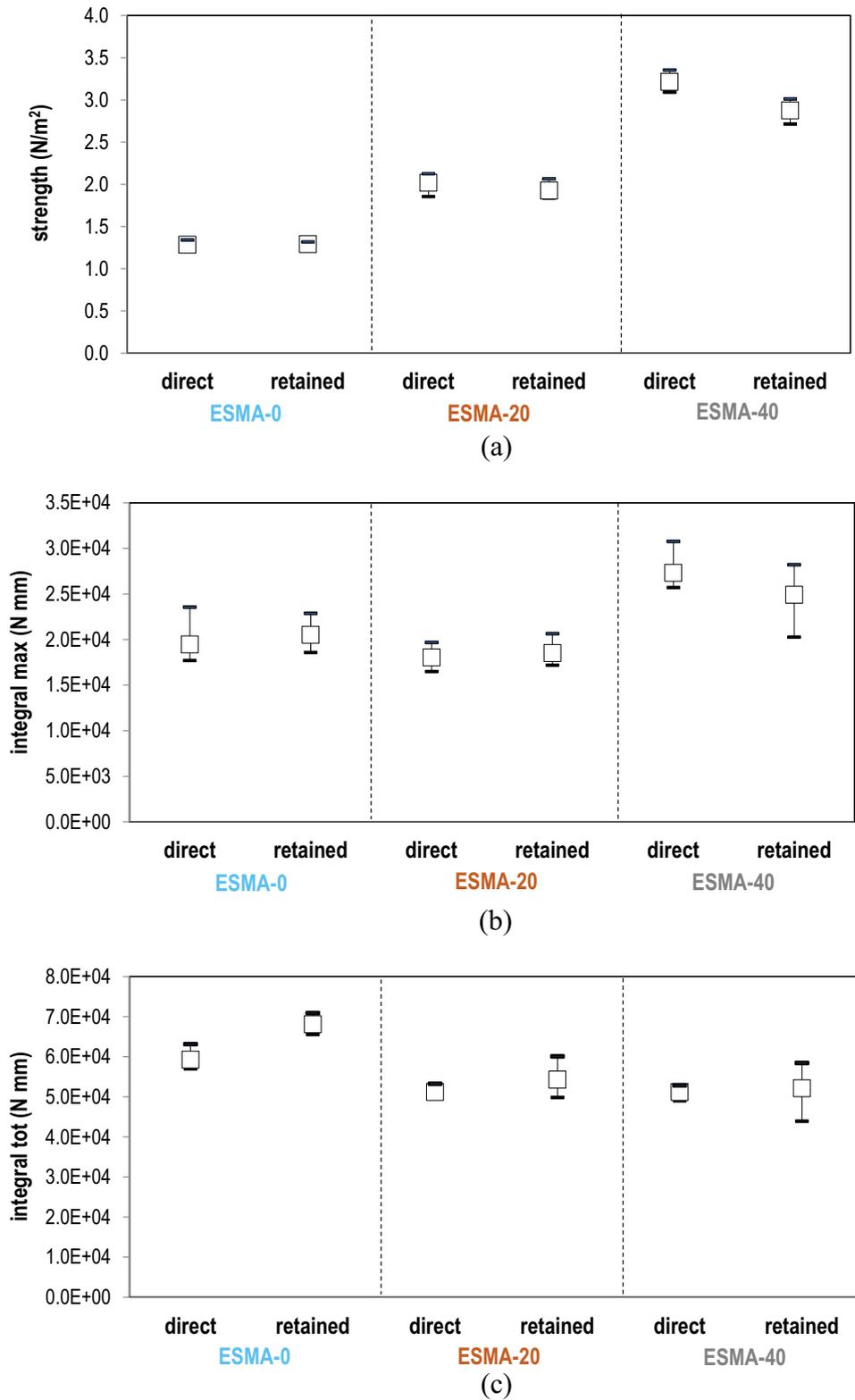


Fig. 2. Indirect tensile test results; (a) tensile strength and (c) elastic energy and (c) fracture energy of studied materials at 15 °C.

As in [7], Part A and B were oven-heated separately for 1 h to 85 and 110 °C, respectively. Afterwards, they were mixed together and the new binder diluted in the already pre-heated (at 120 °C) neat bitumen, on the basis of the supplier's recommendations. As mentioned earlier, two diluted versions of EA concrete were studied, named ESMA-20 and ESMA-40. In other words, two epoxy-modified binders were formed with weight ratio of 20:80 and 40:60 of EA binder and bitumen, respectively, and mixed together with mineral particles at 135 °C, producing loose mixes. Immediately after mixing, slabs of loose mixes were rolling wheel compacted within a 500-mm by 500-mm steel mold. According to the Dutch standards (RAW-2015), the target density of control asphalt (ESMA-0) and epoxy-modified asphalt (ESMA-20 and ESMA-40) samples was 2304 and 2310 kg/m³, respectively. Amount of loose mix based on a 5% target air-void content was compacted to a pre-determined volume so the target air-void content to be achieved. Compacted slabs were cooled down to 20 °C and oven-cured at 85 °C for a week. After sampling four-point bending beams and cylindrical specimens for further investigation, specimens were conditioned at 12 °C for two weeks. The determined values of mix density (NEN-EN 12697-5 method A) and air voids content (NEN-EN 12697-8) of studied materials are given in Table 3. All mixes were evaluated by

- indirect tensile (IT) tests in accordance to NEN-EN 12697-12 to assess the water sensitivity,
- four-point bending (4PB) tests in accordance to NEN-EN 12697-26 method B and NEN-EN 12697-24 method D to assess the effect of epoxy modification on stiffness and fatigue resistance, respectively.

2.2. Indirect tensile tests

Cylindrical specimen of 100-mm diameter and 49.5-mm height were cored from the one-layer slabs to perform the IT tests. Tests were conducted at 15 °C assuming a Poisson's ratio of 0.35, and a representative graph of the response of the three studied materials during IT testing is shown in Fig. 1. The results presented herein were the mean of four replicates.

The influence of epoxy modification on IT strength of studied mixes is shown in Fig. 2, in which the impact of moisture on the strength of specimen is demonstrated as well. Especially, without moisture conditioning, the mean indirect tensile strength of unmodified SMA (i.e., ESMA-0) was 1.283 N/m², almost 60% and 40% of the strength of ESMA-20 (2.017 N/m²) and ESMA-40 (3215 N/m²), respectively (see Fig. 2(a)). Thus, the increase of epoxy proportion is asphalt resulted to increase of material strength, with the ESMA-40 mix to have the highest capacity to withstand the applied forces. By comparing the retained strength after moisture conditioning, the unmodified (control) mix (i.e., ESMA-0) has demonstrated the lowest sensitivity to moisture, as it retained 100% of its original strength after conditioning. ESMA-20 and ESMA-40 had 95% and 85% of water sensitivity. Possibly due to the incomplete curing of EA binder, epoxy asphalt mixes consist of a binder, which needs longer conditioning time periods prior to be fully cured, and therefore the mixes are not ready to be tested.

The maximum dissipated energy of studied materials, or elastic energy up until reaching the maximum force, and the total dissipated energy are shown in Fig. 2(b) and (c), respectively. The control mix (i.e., ESMA-0) demonstrated a slightly higher value of maximum dissipated energy (19,446 N mm) than of ESMA-20 (18,029 N mm) but significantly lower than of ESMA-40 (27,315 N mm) (see Fig. 2(b)). The incorporation of epoxy in asphalt to 40% of mass of bitumen resulted in an increase in elastic energy, or maximum dissipated energy. In similar fashion, the total

dissipated energy to ultimate failure has marginally decreased with the addition of EA binder in this system (see Fig. 2(c)). Furthermore, the epoxy asphalt mixes have shown almost the same retained maximum and total dissipated energy compared with that of mixes without moisture damage. Overall, the ESMA-40 mix is the material of the highest strength and elastic energy, reflecting the impact of epoxy modification on developing surfacing pavement materials of enhanced capacity to withstand forces against fracture failure.

2.3. Four-point bending stiffness and fatigue tests

The stiffness and fatigue life lab measurements of 4PB specimens were performed at 10 °C assuming a Poisson's ratio of 0.35 as well. Flexural stiffness and phase angle of 4PB specimens were measured at one strain level, with 10 different loading frequencies; 0.1, 0.2, 0.5, 1, 2, 5, 8, 10, 20 and 30 Hz. 16 replicates were tested for each material.

The mean values of measured stiffness and phase angle of studied materials are shown in Fig. 3. Particularly, the proportional substitution of bitumen with the EA binder resulted to stiffer mixes with lower phase angle, or increased elasticity, as shown in Fig. 3.

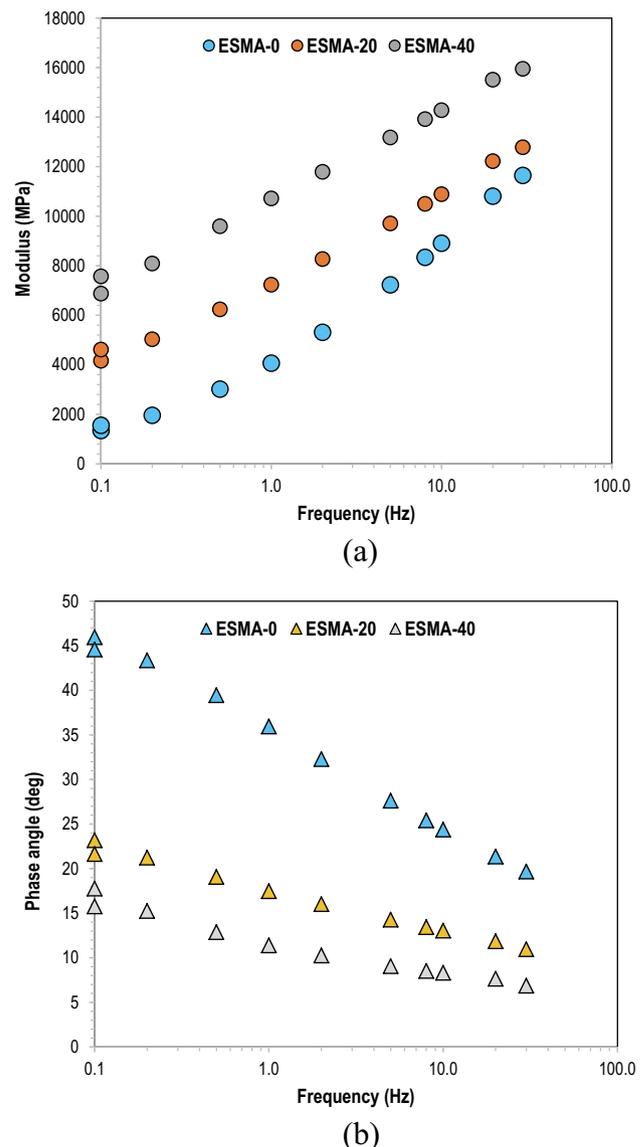


Fig. 3. Master curves of (a) modulus and (b) phase angle of studied materials 10 °C.

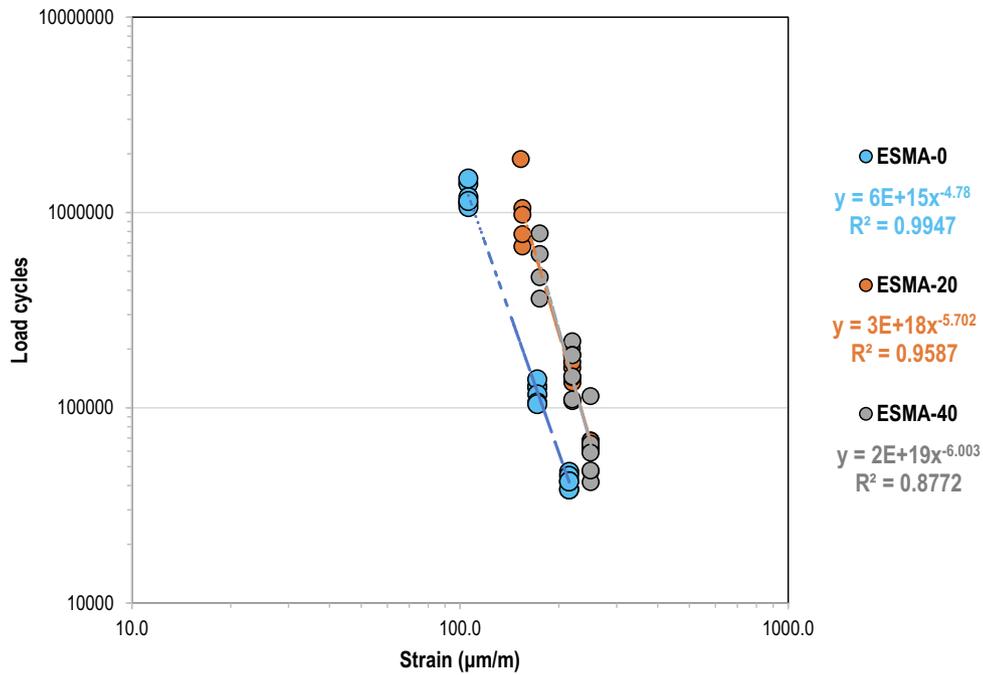


Fig. 4. The relationship between applied strain and fatigue life of studied materials 10 °C.

Table 4
Mechanical properties of studied mixes designed for surfacing applications.

Property	Specification	ESMA-0	ESMA-20	ESMA-40
<i>IT tests</i>				
IT strength (N/m ²)	NEN-EN	1283	2017	3215
Water sensitivity (%)	12697-12	100	95	89
<i>4PB tests</i>				
Stiffness (MPa)	NEN-EN 12697-26B	8334	10,494	13,914
Fatigue resistance (µm/m)	NEN-EN 12697-24	110.6	156	159

Table 5
Test factors for lab-prepared samples.

Variable	Content
Bottom layer material	AC
Top layer material	ESMA-20
Tack coat material	EA binder, emu-A, emu-B
Residual application rate (kg/m ²)	0 (tackless), 0.30 (for emulsion coat), 0.45 & 0.60 (for epoxy coat)
Wetness condition	Dry
Cleanliness conditions	Clean
Test temperature (°C)	20
Test displacement rate (mm/min)	50

According to NEN-EN 12697-26 method B, the stiffness of 4PB specimens were determined as 8334, 10,494 and 13,914 MPa for the ESMA-0, ESMA-20 and ESMA-40 mixes, respectively.

For the 4PB fatigue tests, the 50% reduction of the initial modulus was considered as fatigue life criteria. In other words, the fatigue test terminates when the flexural stiffness reaches half of its initial value. Three strain level were applied in 4PB beam specimens.

Fig. 4 demonstrates the fatigue life at the three different strain levels of the three different studied materials designed for surfacing applications. Both ESMA-20 and ESMA-40 have significantly

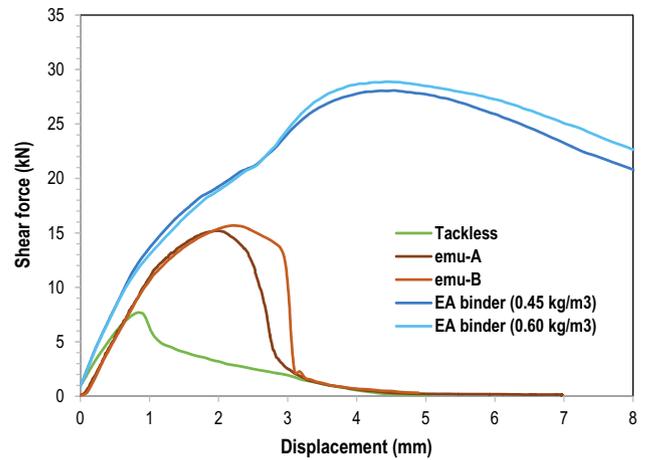


Fig. 5. Representative shear force versus displacement curves of studied two-layer systems at 20 °C.

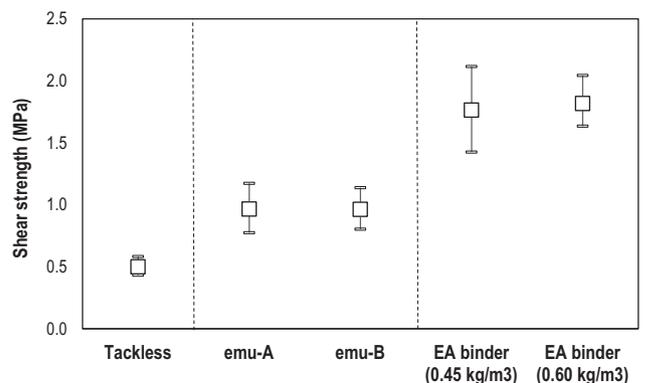


Fig. 6. Effect of different tack coats on the interlayer bonding strength between ESMA-20 and AC 20 °C.

higher fatigue resistance than the control mix. According to NEN-EN 12697-24, the 4PB fatigue resistance of ESMA-0, ESMA-20 and ESMA-40 was 110.6, 156 and 159, respectively. As expected, the increase of epoxy modification level in asphalt leads to materials of high resistance to failure under cyclic loading, an observation which coincides with the fracture performance of epoxy-modified asphalt mixes under monotonic loading.

Overall, the increase of epoxy modification in asphalt leads to elastic materials of high modulus and strength and enhanced fatigue life (see Table 4).

3. Performance of epoxy asphalt tack coat

Epoxy asphalt can be employed also to enhance interlayer bonding strength, when is applied or sprayed with a minimum

residual application rate of 0.45 L/m² [28], or 0.68 L/m² [27]. On steel decks, the epoxy-type tack coat serves as waterproofing as well, but an anti-corrosive treatment (e.g., zinc-rich epoxy primer) is needed prior to its application.

As in epoxy asphalt surfacing layers, important aspect on using epoxy-type tack coat is the curing time period. During curing, chemical bonds are generated between tack coat and contacting layers and once these bonds are formed, it is very difficult to be broken even at high temperature. However, incomplete curing may occur when the construction temperature is too low. Another aspect that should be considered through the curing process of epoxy-type tack coats is to avoid moisture or humid environments. Usually, moisture changes the site of bond rupture resulting to possibly incomplete curing of EA during construction and thus jeopardizes the build-up of mechanical properties (e.g., strength, modulus) [29,30]. The construction conditions for EA materials

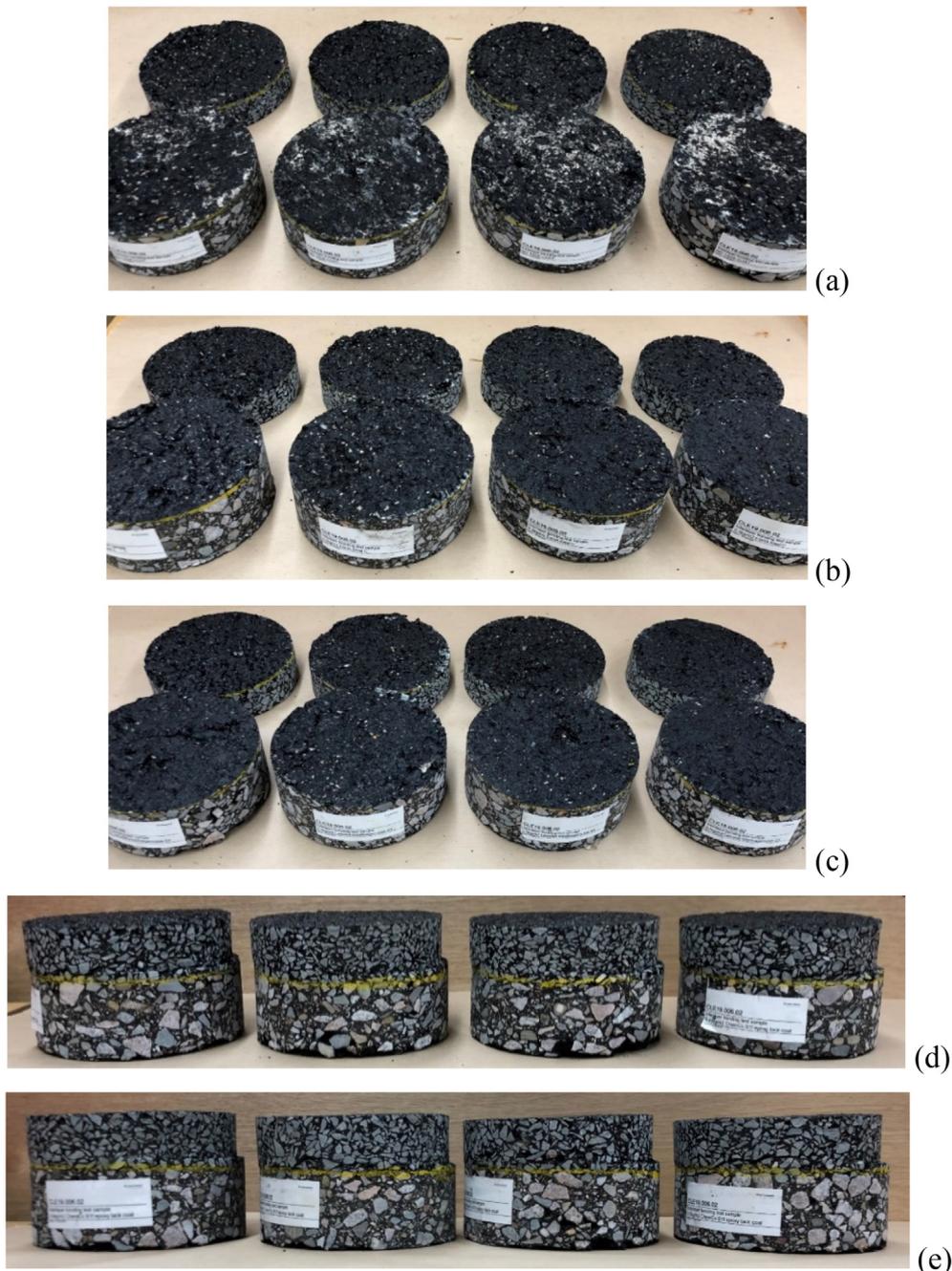


Fig. 7. Tested samples; (a) tackless, (b) emu-A, (c) emu-B, and EA binder applied with (d) 0.45 kg/m² and (e) 0.60 kg/m² residual rate.

are extremely stringent, the presence of any unexpected factors will result in premature pavement defects, mainly cracking.

Within this framework, the interface shear strength of an epoxy asphalt concrete with a typical asphalt concrete as substrate was studied. The objective of the testing program was to quantify the interface bonding generated by using emulsion- and epoxy-type tack coats.

3.1. Materials and specimen preparation

ESMA-20 was selected as the top layer material and produced with the same way discussed in an earlier section. A hot-mix asphalt concrete with 65% RAP, named AC, were used as bottom layer material and on the top of it the tack coats applied. For the compaction of bottom layer, slab specimens were rolling wheel compacted similarly with the earlier section. 500-mm by 500-mm steel molds were used and layers of 55-mm and 35-mm height were fabricated for AC bottom and ESMA-20 top materials, respectively. Without prior curing, the top ESMA-20 loose mix was applied and compacted on the top of an already compacted and tack coated bottom AC layer.

Two emulsion type asphalt tack coats were selected in this study; emu-A and emu-B. These emulsion tack coats were heated to 40 °C and brush applied on the top of AC with one residual rate of 0.3 kg/m², half an hour before laying the ESMA-20. A blow-dryer was used as well for the remaining unbroken emulsion.

In case of EA tack coat, Parts A and B was heated to 85 and 150 °C, respectively. A few minutes before applying the top ESMA-20, the two parts of EA tack coat were mixed at the mixing ratio A:B = 25:75, directly applied on the bottom layer and spread out evenly. It has been noticed that it was difficult to spread the binder evenly, mainly due to the high viscosity of the Part B of EA binder at elevated temperature and increase when cooling down. Therefore, two application residual rates were applied on AC bottom layer; 0.45 kg/m² and 0.6 kg/m². To determine the contribution of the various tack coats, a system without tack coat (tackless) was produced as well. All samples have been oven-conditioned at 100 °C for 5 h to accelerate the curing of tack coating and ESMA surfacing materials.

Table 5 shows the test factors of lab-prepared two-layer systems developed for this study. Eight replicate samples were prepared and tested for each condition. Overall, the lab-produced samples consisted of the top and bottom layers bonded with a tack coat at their interface. Two tests were performed to evaluate the contribution of different tack coats on interface bonding characteristics of two layers; interface shear tests. Samples of 150-mm and 50-mm diameter were cored out of two-layer slabs for shear and tensile testing, respectively. Details on testing methods and results are given in the next sub-section.

3.2. Interface shear test

Shear tests performed using a configuration originally developed by Leutner [31]. The Leutner shear test apparatus has been developed as a simple method to determine the interlayer bonding strength between two pavement courses. Before testing, the shear zone of the samples was marked to be able to put them in the right position between the shear rings. Samples were conditioned in an insulated climate chamber with dimensions 0.6 × 0.5 × 0.6 m. Tests were performed on two-layer cylindrical samples of 150-mm diameter and under a displacement rate of 50 mm/min at 20 °C in accordance to CEN/TC 227 WG2 N 879E. According to this norm, there was a gap of 5-mm between the shear rings. The average of two external LVDT's, with a range of ±10-mm, was used to

measure the shear velocity and the displacement between the shear rings. Five replicate samples were tested for each tack coat.

Fig. 5 shows the representative graphs of shear force versus displacement of the two-layer samples bonded with different tack coats. It is quite obvious the effect of EA tack coat on bonding the two layers for both application rate cases (i.e., 0.45 and 0.60 kg/m²). Layers bonded with the EA binder have demonstrated a significantly higher shear strength and a more ductile fracture comparing the behaviour of samples bonded with emulsified tack coats. According to Fig. 6, in where the average shear strength plotted versus displacement, the tackless samples showed the lowest average shear strength (0.50 MPa) with the minimum error bar, and the samples bonded with emulsified tack coat shown an improvement (emu-A: 0.97 MPa & emu-B: 0.96 MPa). Therefore, the shear bonding strength values of emulsion type tack coats are of the same order of magnitude, significantly higher than the tackless system with approximately 100% increase of strength. Moreover, the highest average shear bonding strength was obtained with using EA tack coat (EA_0.45 kg/m²: 1.76 MPa & EA_0.60 kg/m²: 1.82 MPa), which finally did not result interlayer fracture failure as shown in Fig. 7. It can be noticed that almost 200% higher shear bonding strength is obtained with the use of epoxy binder than the two-layer systems with emulsion-type tack coat. Definitely, the use of epoxy-type binder as tack coat show remarkable improvement on interlayer bonding for epoxy asphalt surfacing materials offering an excellent solution for developing long-lasting pavements.

4. Conclusions

In this study, epoxy asphalt has been used to enhance the durability of an asphalt concrete mix and to prove that the epoxy binder can improve the interlayer bonding capacity between two asphaltic layers. Special emphasis was given also on the material preparation and curing the epoxy asphalt materials under certain energy conditions in order to guarantee that the epoxy component was fully polymerized. The major findings of this study are as follows:

The laboratory results of durability and performance testing confirm that increase of the epoxy modification level in asphalt leads to stiffer and stronger materials of improved fatigue resistance. Especially, the IT tests results show that epoxy modified asphalt mixes have higher tensile strength than of control mixes, while increase of strength is noticed by increasing proportionally the amount of epoxy binder in bitumen (ESMA-0: 1283; ESMA-20: 2017 and ESMA-40: 3251 N/m²). Moreover, the 4PB tests indicate that high modulus materials (ESMA-0: 8334; ESMA-20: 10,494 and ESMA-40: 13,914 MPa) can effectively reduce deflections of specimen beams and enhance the fatigue resistance of asphalt mixes designed for surfacing applications for roadways (ESMA-0: 110.6; ESMA-20: 156 and ESMA-40: 159).

It is believed that the interlayer bonding capacity is among the most decisive parameters that determine the long-term performance of epoxy asphalt systems. Therefore, the effect of epoxy-type tack coat on interlayer bonding between an epoxy asphalt mix (ESMA-20) and an asphaltic substrate was investigated as well. Two different emulsion-type tack coats of the same application rate (0.3 kg/m²) and one epoxy binder with two application rates (0.45 and 0.6 kg/m²) have been shear tested in a Leutner configuration. The test results confirmed that the use of epoxy-type coat can improve significantly the interlayer bonding strength, offering monolithic performance characteristics on a high modulus surfacing system. The shear bonding strength with epoxy binder (≈1.82 MPa) was almost 2 and 3.5 times higher than of emulsion coated (≈0.95 MPa) and tackless (0.5 MPa) systems, respectively.

Although a single aggregate gradation, bitumen and epoxy binder were used here, the results revealed that a two-layer monolithic system with epoxy asphalt could mitigate potential bonding defects, such as debonding, slippage and fatigue cracking propagated from bottom to up, of a surfacing layer of high strength, modulus and fatigue resistance.

Author contribution statement

The authors confirm contribution to the paper as follows: study conception and design: PA, XL, AS; data collection: PA; analysis and interpretation of results: PA, XL, SE, AS; draft manuscript preparation: PA. All authors reviewed the results and approved the final version of the manuscript.

Conflict of interest

We state that there are no conflicts of interest regarding the publication of this manuscript.

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References

- [1] Environmental Protection Agency. 2017. Total U.S. Greenhouse Gas Emissions by Economic Sector.
- [2] J. Youtcheff et al., The evaluation of epoxy asphalt and epoxy asphalt mixtures, *Proceedings of the Canadian Technical Asphalt Association* 51, 2006.
- [3] I. Widyatmoko et al., Curing characteristics and the performance of epoxy asphalts, *Proceedings of the Canadian Technical Asphalt Association* 51, 2006.
- [4] S. Luo et al., Performance evaluation of epoxy modified open-graded porous asphalt concrete, *Constr Build. Mater.* 79 (2015) 97–102.
- [5] J.P. Wu et al., Long-term durability of epoxy-modified open-graded porous asphalt wearing course, *Int. J. Pavement Eng.* 20 (8) (2019) 902–927.
- [6] P. Herrington, D. Alabaster, Epoxy modified open-graded porous asphalt, *Road Mater. Pavement Design* 9 (3) (2008) 481–498.
- [7] P. Apostolidis et al., Evaluation of epoxy modification in bitumen, *Constr. Build. Mater.* 208 (2019) 361–368.
- [8] W.C. Simpson et al., Epoxy asphalt concrete for airfield pavements, *J. Air Transp. Div., Proc. Am. Soc. Civil Eng.* 86 (1960) 57–71.
- [9] W. Huang et al., Epoxy asphalt concrete paving on the deck of long-span steel bridges, *Chin. Sci. Bull.* 48 (2003) 2391–2394.
- [10] Q. Lu, J. Bors, Alternate uses of epoxy asphalt on bridge decks and roadways, *Constr. Build. Mater.* 78 (2015) 18–25.
- [11] Long-Life Surfacing for Roads: Field Test Results. 2017. International Transport Forum, Research Reports, OECD, Paris, France.
- [12] A. Zegard et al., Long-lasting surfacing pavements using epoxy asphalt: Province of North Holland case study, *Proceeding of Transportation Research Board 98th Annual Meeting, Washington D.C., USA, 2019.*
- [13] J. Uzan et al., Investigation of adhesion properties between asphaltic concrete layers, *J. Assoc. Asphalt Paving Technol.* 47 (1978) 495–521.
- [14] S.A. Romanoschi, Characterization of Pavement Layer Interfaces PhD dissertation, Louisiana State University, Baton Rouge, 1999.
- [15] R. West et al., Evaluation of Bond Strength Between Pavement Layers. National Center for Asphalt Technology. Report 05–08, Auburn University, Auburn, Ala, 2005.
- [16] F. Canestrari, E. Santagata, Temperature effects on the shear behaviour of tack coat emulsions used in flexible pavements, *Int. J. Pavement Eng.* 6 (1) (2005) 39–46.
- [17] L.N. Mohammad et al., Worldwide state of practice on the use of tack coats: a survey, *J. Assoc. Asphalt Paving Technol.* 77 (2008) 1–26.
- [18] G. Sholar et al., Preliminary investigation of a test method to evaluate bond strength of bituminous tack coats, *J. Assoc. Asphalt Paving Technol.* 73 (2004) 771–801.
- [19] L. Tashman et al., Evaluation of the Influence of Tack Coat Construction Factors on the Bond Strength between Pavement Layers. Report WCAT 06–002, Washington Center for Asphalt Technology, Washington State University, Pullman, 2006.
- [20] L.N. Mohammad, J. Button, Optimization of Tack Coat for HMA Placement. NCHRP Project 9–40. Phase I Report, Louisiana Transportation Research Center, Baton Rouge, 2005.
- [21] L.N. Mohammad et al., Influence of asphalt tack coat materials on interface shear strength, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 1789, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 56–65.
- [22] Z. Leng et al., Interface bonding between hot-mix asphalt and various portland cement surfaces: laboratory assessment, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2057, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 46–53.
- [23] Z. Leng et al., Interface bonding between hot-mix asphalt and various portland cement concrete surfaces: assessment of accelerated pavement testing and measurement of interface strain, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2127, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 20–28.
- [24] P. Apostolidis et al., Chemo-rheological study of hardening of epoxy modified bituminous binders with the finite element method, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2672(28), Transportation Research Board of the National Academies, Washington, D. C., 2018, pp. 190–199.
- [25] P. Apostolidis et al., Kinetic viscoelasticity of crosslinking epoxy asphalt, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2673(3), Transportation Research Board of the National Academies, Washington, D.C., 2019, pp. 551–560.
- [26] P. Apostolidis et al., Characterization of epoxy asphalt binders by differential scanning calorimetry, *Constr. Build. Mater.* (2020).
- [27] ChemCo Systems, Inc. 2015. Paving Contractor Information: Application of Epoxy Asphalt Bond (Tack) Coat. Technical Report.
- [28] C. Chen et al., Performance characteristics of epoxy asphalt paving material for thin orthotropic steel plate, *Int. J. Pavement Eng.* (2018), <https://doi.org/10.1080/10298436.2018.1481961>.
- [29] E. Bocci, F. Canestrari, Experimental evaluation of shear resistance of improved steel-asphalt interfaces, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2370, TRB, Washington, D.C., 2013, pp. 145–150.
- [30] X. Jia et al., Investigation of tack coat failure in orthotropic steel bridge deck overlay: survey, analysis, and evaluation, in: *Transportation Research Record: Journal of the Transportation Research Board*, No. 2444, TRB, Washington, D.C., 2014, pp. 28–37.
- [31] R. Leutner, Untersuchung des Schichtenverbundes Beim Bituminösen Oberbau (Investigation of the Adhesion of Bituminous Pavements), *Bitumen* 3 (1979) 84–91.