Long-Life Pavements with Epoxy Asphalt

Panos Apostolidis, Ruxin Jing, Xueyan Liu, Sandra Erkens, Tom Scarpas
TU Delft

Paul Waarts, Jur Hoefakker
Province of Noord Holland

Remco Hermsen
Province of Gelderland

Robbert Naus
Dura Vermeer

Abstract: Many governments have devoted significant resources to deploying high-quality highway networks, which subsequently demand adequate maintenance. Nowadays, most national road budgets are spent on maintaining existing highways as the need for repair is more frequent. Regular repair operations imply increased maintenance costs for the highway authorities. The initial cost of pavements is often surpassed by the maintenance and reconstruction costs, leading to high life cycle costs.

Flexible pavements of enhanced longevity would be expected to withstand the continuously increasing traffic intensities, loadings, and varying environmental conditions, reducing major maintenance needs. Considering the adoption of long-term contracts by highway authorities, long-life pavements have started to attract the interest of contractors worldwide. For developing long-life pavements, polymer modified asphalt materials have been employed in the past. Among others, pavement materials with epoxy asphalt have improved the cracking resistance of surfacing layers in orthotropic steel deck bridges, justifying their high initial costs. It has also been proven that epoxy asphalt is an aging resistant material with enhanced fatigue resistance. The use of these materials was also proposed for roadway pavements, but limited field data are available. Thus, there is currently an urgent need to link the promising laboratory results with the material performance in the field.

In this context, an extended experimental program has been conducted at TU Delft to validate the benefits of pavements containing epoxy asphalt and to assess their recyclability potential in enabling the wider acceptance of the epoxy asphalt technology. Trial roads were constructed in cooperation with Dura Vermeer, and the effects of epoxy asphalt on the performance of a material normally applied in Dutch highways have been evaluated. The laboratory results of the fresh, aged, and recycled materials were also presented, showing that the epoxy modified asphalt materials exhibit a similar recycling attribute to standard asphalt pavements.

Keywords: Epoxy Asphalt, Flexible Pavement, Pavement Monitoring, Recycling, Sustainability

INTRODUCTION

Many governments have devoted significant resources to deploying high-quality highway networks, which subsequently demand adequate maintenance. Nowadays, most national road budgets are spent on maintaining existing highways as the need for repair is more frequent. Regular repair operations imply increased maintenance costs for the highway authorities and inconvenience for users due to the temporary disruption of normal traffic flows. Thus, the initial construction cost of pavement is often surpassed by the maintenance and reconstruction costs, leading to high life cycle costs.

Flexible pavements of enhanced longevity would be expected to withstand the continuously increasing traffic intensities, loadings, and varying environmental conditions, reducing major maintenance needs. Considering the adoption of long-term contracts by highway authorities, long-life pavements have started to attract the interest of contractors worldwide. For developing long-life pavements, polymer modified asphalt materials have been employed in the past. Among others, pavement materials with epoxy asphalt have improved the cracking resistance of surfacing layers in orthotropic steel deck bridges, justifying their high initial costs. It has also been proven that epoxy asphalt is an aging resistant material with enhanced fatigue resistance (Youtcheff et al., 2006; Widyatmoko et al., 2006; Herrington and Alabaster 2008; Herrington et al., 2010; Widyatmoko & Elliot 2014; Lu & Bors 2015; Qian & Lu 2015; Luo et al., 2015; Wu et al., 2017; Apostolidis et al., 2019 & 2020a). The use of these materials was also proposed for roadway pavements (International Transport Forum 2017; Zegard et al., 2019; Apostolidis et al., 2020b) but limited field data are available. Thus, there is currently an urgent need to link the promising laboratory results with the material performance in the field.

In this context, an extended experimental program conducted in collaboration with Provincie Noord Holland and Provincie Gelderland has been conducted at TU Delft to validate the benefits of pavements containing epoxy asphalt and to assess their recyclability potential in enabling the wider acceptance of the epoxy asphalt technology. Trial roads were constructed in cooperation with Dura Vermeer, and the effects of epoxy asphalt on the performance of a material normally applied in Dutch highways have been evaluated. The laboratory results of the new, aged, and recycled materials were also presented, showing that the epoxy modified asphalt materials exhibit a similar recycling attribute to an unmodified asphalt.

PERFORMANCE LABORATORY RESULTS

Pavement Materials

As mentioned, an asphalt concrete containing the epoxy-asphalt binder, named epoxAC, has been studied in the laboratory and later applied as surfacing pavement material in a test section by having the aggregate gradation of SMA-NL 8B (5% air voids and 6.7% mass binder content). To lower the cost of the designed epoxAC mix, the effect of diluting the epoxy binder with a neat asphalt binder (70/100 pengrade) was studied. 20 % wt. of the binder was substituted by the epoxy binder. The target densities of reference asphalt and epoxy modified asphalt samples were 2304 and 2310 kg/m^3, respectively. The determined values of mix density (NEN-EN 12697-5 method A) and air voids content (NEN-EN 12697-8) of the studied materials are given in **Table 1**. Materials were evaluated by four-point bending (4PB) tests to assess the effect of epoxy modification on the mix stiffness and fatigue life.

Table 1 Physical properties of studied mixes designed for surfacing applications.

Property	Specification	reference[*1]	epoxAC[*2]
Target density [kg/m^3]		2304	2310
Mix density [kg/m^3]	NEN-EN 12697-5	2449	2435
Air voids content [%]	NEN-EN 12697-8	5.9	5.3

production temperature range : 140-180ºC [*1] and 125-145ºC [*2]

Laboratory Results

The 4PB specimens flexural stiffness tests were performed at 10 C, assuming a Poisson's ratio of 0.35. The flexural stiffness and phase angle of 4PB specimens were measured at one strain level (50 ± 0.5 μm/m), 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 modulus and phase angle of studied materials are shown in **Fig. 1**. The stiffness modulus at 8 Hz of 4PB specimens was determined as 8334 and 10494 MPa for the reference and epoxAC mixes, respectively. Therefore, the proportional substitution of asphalt binder with epoxy resulted in stiffer mixes with lower phase angle, indicating pavement materials with higher elasticity and capacity to resist traffic deformations in the field.

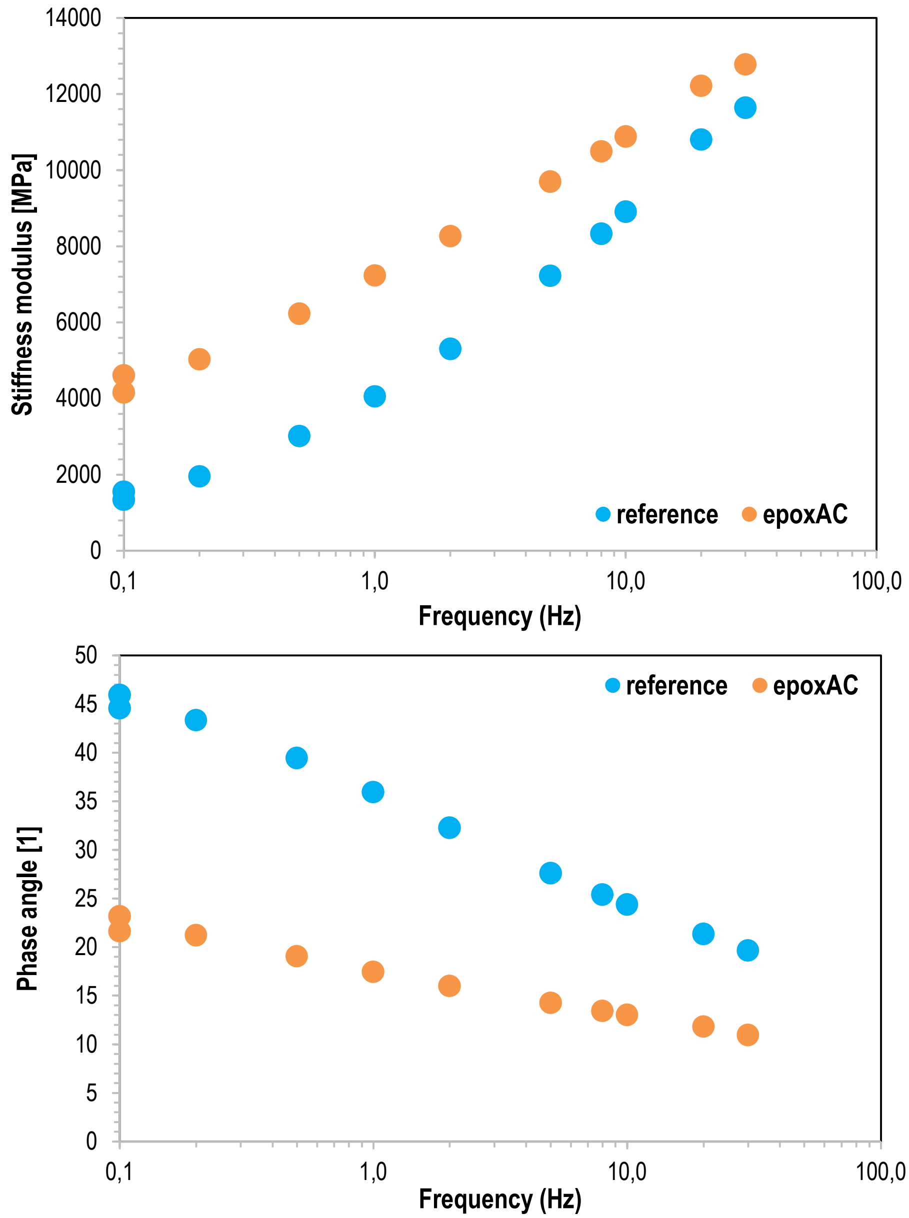


Fig. 1 Stiffness modulus (top) and phase angle (bottom) of the studied materials.

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 levels were applied in 4PB beam specimens. **Fig. 2** demonstrates the fatigue life at the three different strain levels of the studied materials designed for surfacing applications. The epoxAC mix has significantly higher fatigue resistance than the reference one.

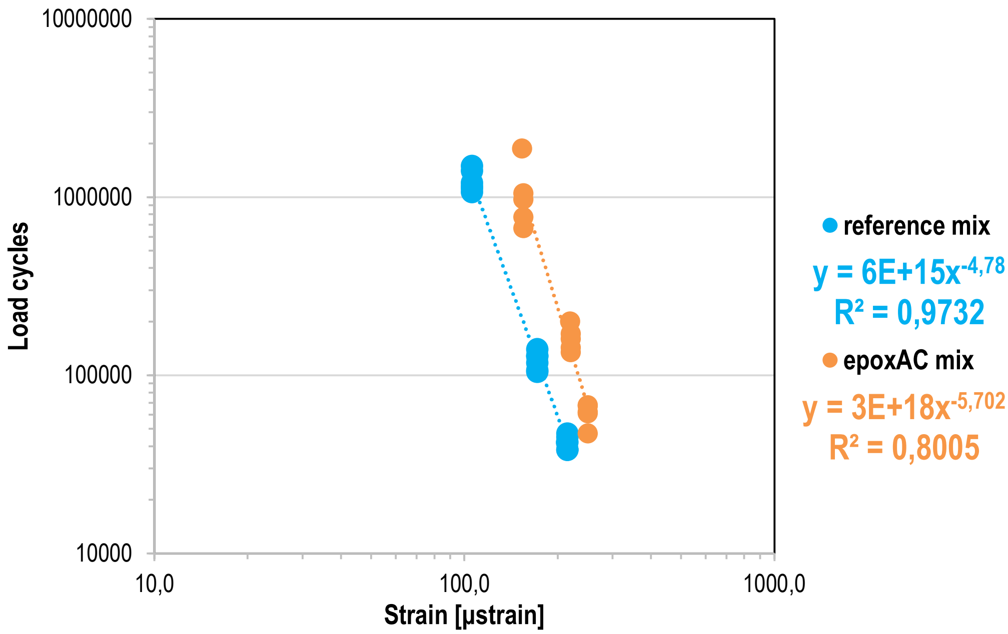


Fig. 2 The relationship between applied strain and fatigue life of studied materials (at 10ºC).

PERFORMANCE FIELD RESULTS

Instrumentation & Remote Monitoring System

After completing the experimental program in the laboratory, the reference and epoxAC layers of 30-mm thickness, constructed on the same old pavement structure, were regularly monitored to assess their actual structural capacity and understand their mechanical response comprehensively. The two test sections were constructed simultaneously and monitored under real traffic and environmental conditions.

The goal of instrumenting the field tests is to obtain continuous and precise measurements of the actual structural response of surface pavement layers by coupling the measurements provided by strain gauges and temperature sensors. The instrumentation array consisted of (a) strain gauges (H-shaped gauges, Dynatest) to measure the traffic loads resulting in surfacing deformation variation in tension and compression, and (b) temperature sensors in the top surfacing layer to measure the temperature variation. Two temperature sensors and four strain gauges were installed as (i) 2 temperature sensors at the bottom of the top layer, (ii) 1 longitudinal strain gauge at the bottom of the top layer, thus 2 longitudinal gauges in total, and (iii) 1 transverse strain gauge at the bottom of the top layer, thus 2 transverse gauges in total. It is thought that combining the measurement from the strain gauges could help to perform a thermo-mechanical study of the test sections over time and enable predictions of their fatigue life.

In general, the temperature variation is one of the main influential factors of the performance of flexible pavements as the stiffness modulus of asphalt materials alters with the temperature changes. A flexible pavement shows viscoelastic behavior at high temperatures, while it behaves as an elastic and brittle system at lower temperatures. Temperature variation also causes thermal volumetric changes (e.g., contraction). As the air temperature reduces, the restrained pavement contracts, inducing thermal stresses and strains within the structure. This attribute could accelerate failure mechanisms, such as low-temperature thermal cracking through the transverse direction. Therefore, the response of two test sections at decreased temperatures in the winter period was assessed in this study.

Strain gauges are typically used to measure the magnitude of horizontal strains, usually at the bottom of asphalt layers, as the tensile strains are mainly concentrated in this area. Note that the repeated traffic loading causes high tensile strains at the bottom of pavement layers, causing a reduction of the structural capacity of pavement. In this research, the horizontal strain gauges were placed at the bottom of the surfacing layers (**Fig. 3**) before paving, both in longitudinal (in the direction of traffic) and transverse (perpendicular to traffic) direction.

Fig. 3 Schematic of strain gauge (left) and its installation at the top of the bottom layer (right).

All sensors recorded measurements stored and sent via a specially designed data acquisition platform in TU Delft (see **Fig. 4**). The remote data acquisition platform was a compact and modular system that integrates a processor, data storage, a Wi-Fi communication module, and a small power receiver for localization and time synchronization. The system was protected by a weatherproof cabinet and via the 4G network to remotely transfer the recorded measurements in TU Delft.

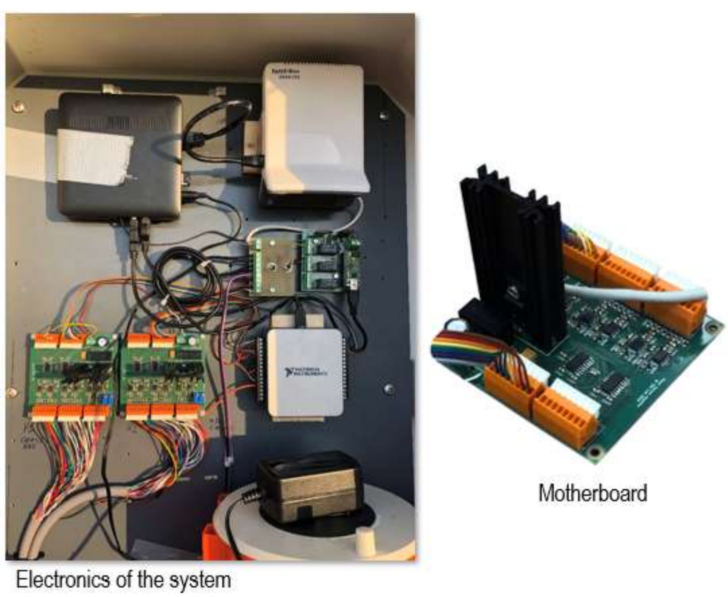


Fig. 4 Data acquisition system.

Field Results

Fig. 5 shows the strain readings at 22°C. Different cases of the truck pass are illustrated in **Fig. 5**, showing all similar responses. The 1st strain pulse represented the passing of a truck's axle (compression), whereas the following strain pulses represented a sequential axle (compression). The measured strains in longitudinal and transverse directions decreased under the passing axles, returning slowly to their original state after loading. The shape of strain signals in the longitudinal direction at the bottom of test sections was different than in the transverse direction illustrating a more pronounced strain. While the response in the transverse direction was always in compression, the longitudinal strain signals were composed of a compressive part followed by a tensile part, which agrees with earlier studies. All strain readings showed typical viscoelastic responses, which changed daily with changes in air temperature.

Field data, collected daily from 18/04/2021 to 05/12/2021, were plotted in **Fig. 6**. Especially the measured strain responses in the longitudinal and transverse directions at the bottom of the two trial sections are shown in this figure. The influence of seasonal temperatures on the measured strain responses is depicted. The strain response of sections increased because of increased temperatures in the summer period, but both test sections did not appear strong difference in their measured strain responses. In **Fig. 7**, the same strain data were also plotted against the bottom-depth pavement temperatures to enable the fatigue performance predictions discussed in the following sub-section.

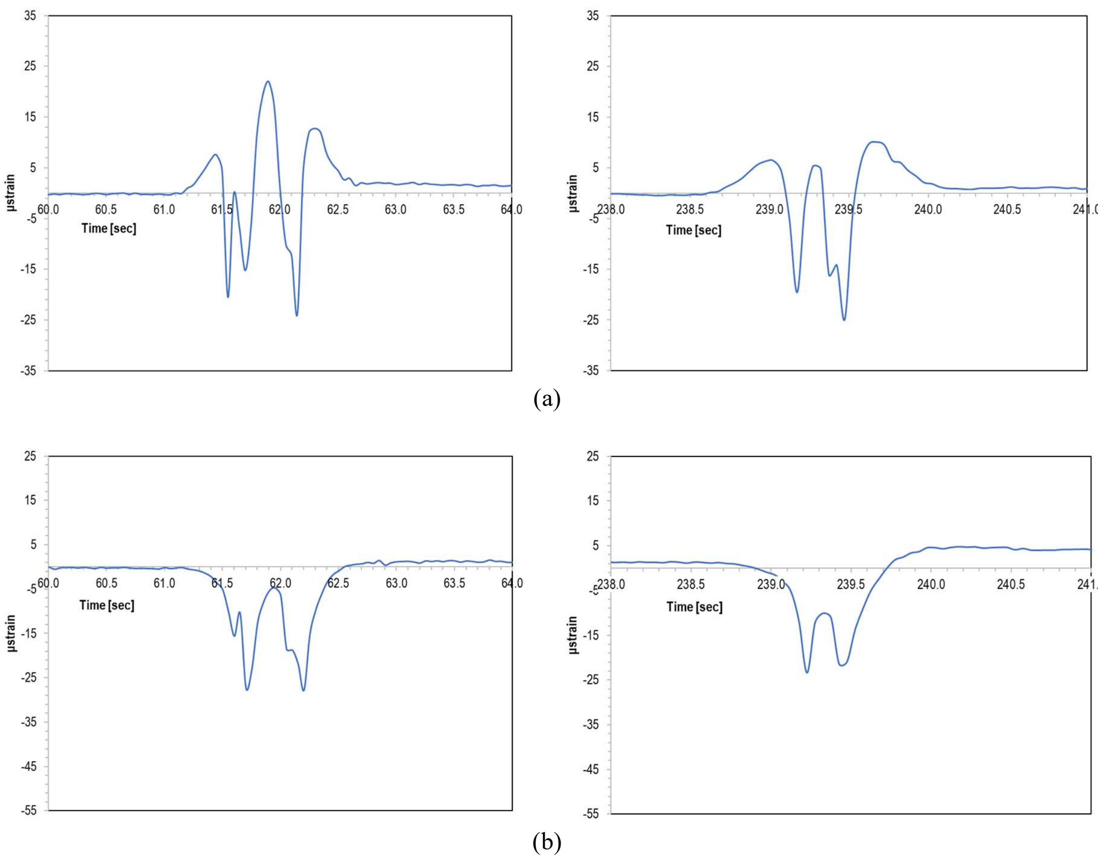
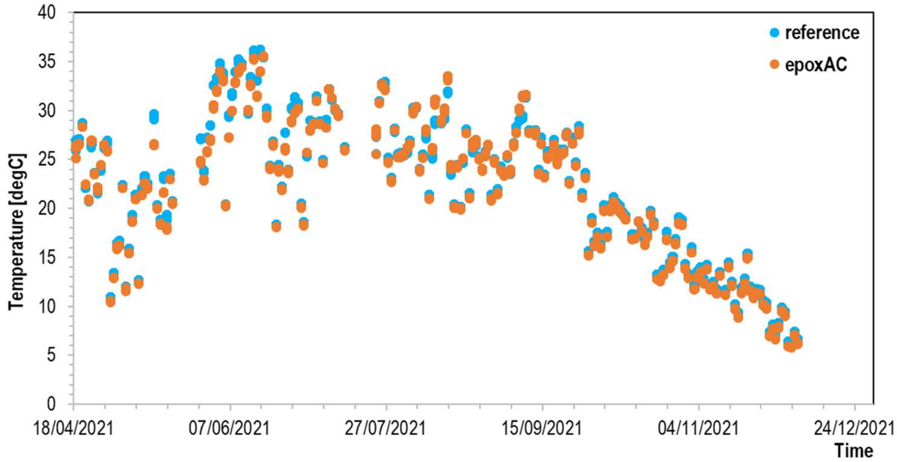


Fig. 5 Measured (a) longitudinal and (b) transverse strain events under traffic loading at 22°C.



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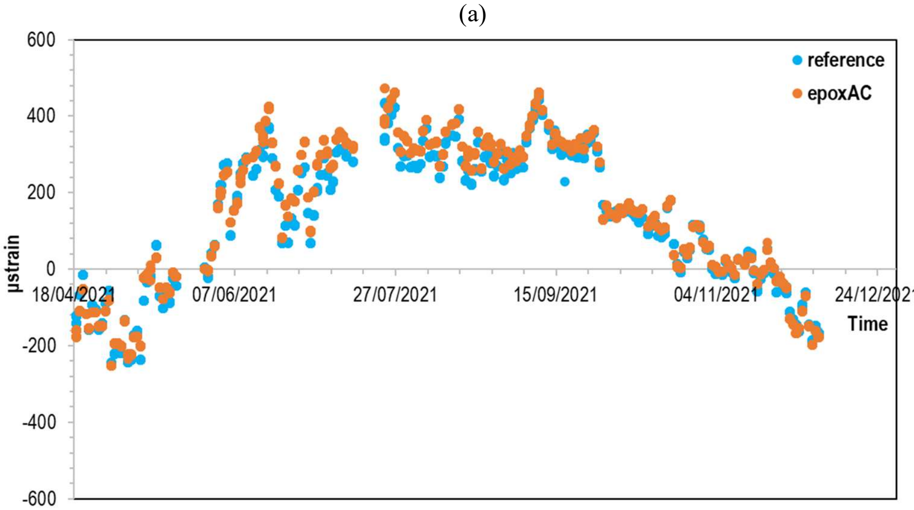

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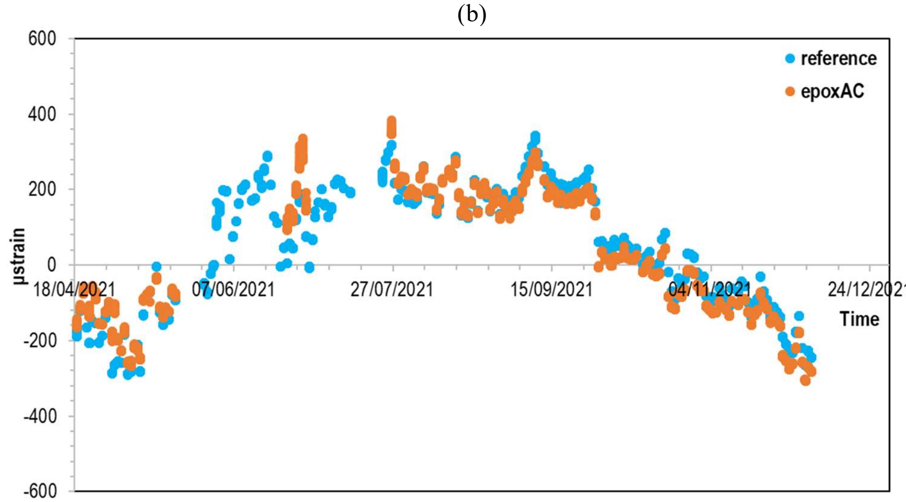
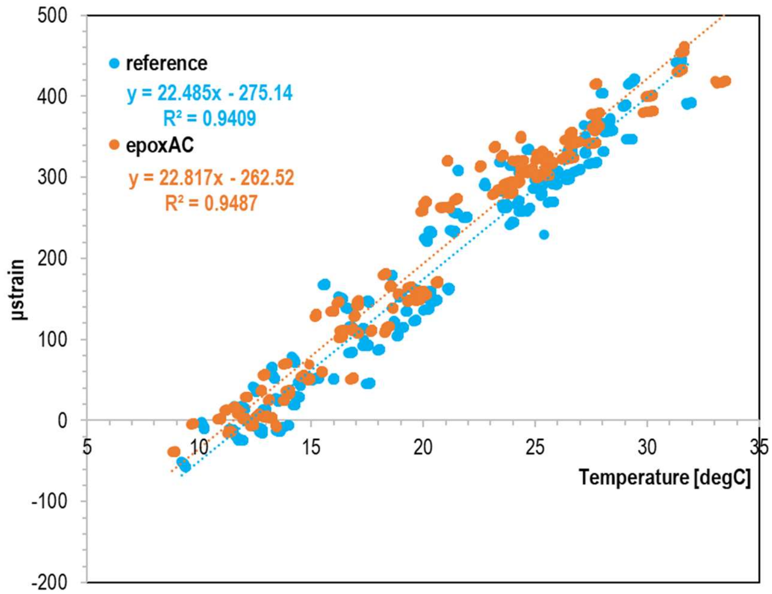


(c)

Fig. 6 Measured (a) temperature, (b) longitudinal and (c) transverse strains from 18/04/2021 to 05/12/2021.



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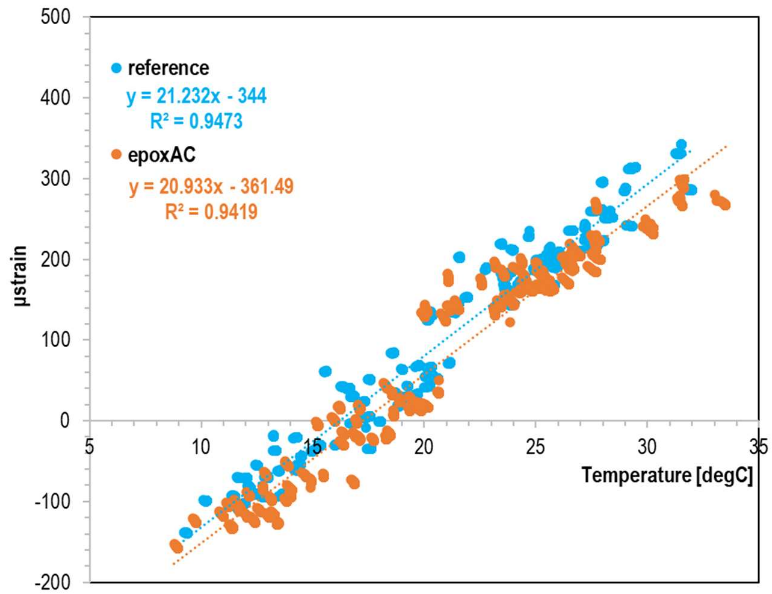


(b)

Fig. 7 Measured (a) longitudinal and (b) transverse strains versus temperature under traffic loading.

Life Prediction based on Laboratory and Field Results

Various mathematical relationships have been developed to assess the fatigue damage in asphalt pavement layers to predict the number of load repetitions to fatigue cracking. The commonly used mathematical relationship used for fatigue characterization is a generalized fatigue cracking model, which is expressed as follows

$$N_f = C \cdot k_1 \cdot \left(\frac{1}{\varepsilon_t}\right)^{k_2} \cdot \left(\frac{1}{E}\right)^{k_3} \tag{1}$$

where N_f is the repetitions until fatigue failure (bottom-up fatigue crack 25-50% of total lane area), ε_t is the tensile strain at the critical location, E is the initial stiffness modulus of material [MPa], C is a laboratory to field adjustment factor, and k_1, k_2, and k_3 are laboratory regression coefficients.

In this research, the Shell equation of fatigue cracking was employed, and this equation is defined as

$$N_f = 0.0685 \cdot \left(\frac{1}{\varepsilon_t}\right)^{5.671} \cdot \left(\frac{1}{E}\right)^{2.363} \tag{2}$$

The horizontal tensile strain measurements at the bottom of the test surface layers were also applied to compare their relative fatigue cracking performance. A specific time window with comparable pavement temperatures for the two test sections was selected from **Fig. 7b** (i.e., horizontal tensile strains in transverse direction versus the pavement temperature). In this temperature range, the reference test section demonstrated higher strains than epoxAC, and strains at a reference temperature of 20°C were interpolated from **Fig. 7b**. The horizontal tensile strain level employed for the reference and epoxAC section was 80 and 55 µstrain, respectively.

The laboratory results obtained a material modulus under dynamic loading of various frequency levels at the same reference temperature. The fatigue lifetimes of test sections at different frequencies were predicted, as shown in **Fig. 8**. For example, the predicted fatigue life of the epoxAC section was approximately 4.2 times greater than the fatigue life of the reference section when the 5 Hz dynamic loading frequency was employed (see **Table 2**). The improvement of fatigue life of asphalt with epoxy use has also been proven previously in the laboratory. Overall, the epoxy can enhance the fatigue performance of asphalt pavements considerably; nevertheless, further field data are needed to validate the theoretical findings based on the 1-year monitoring measurements and obtain a more accurate view of the longevity of test road sections.

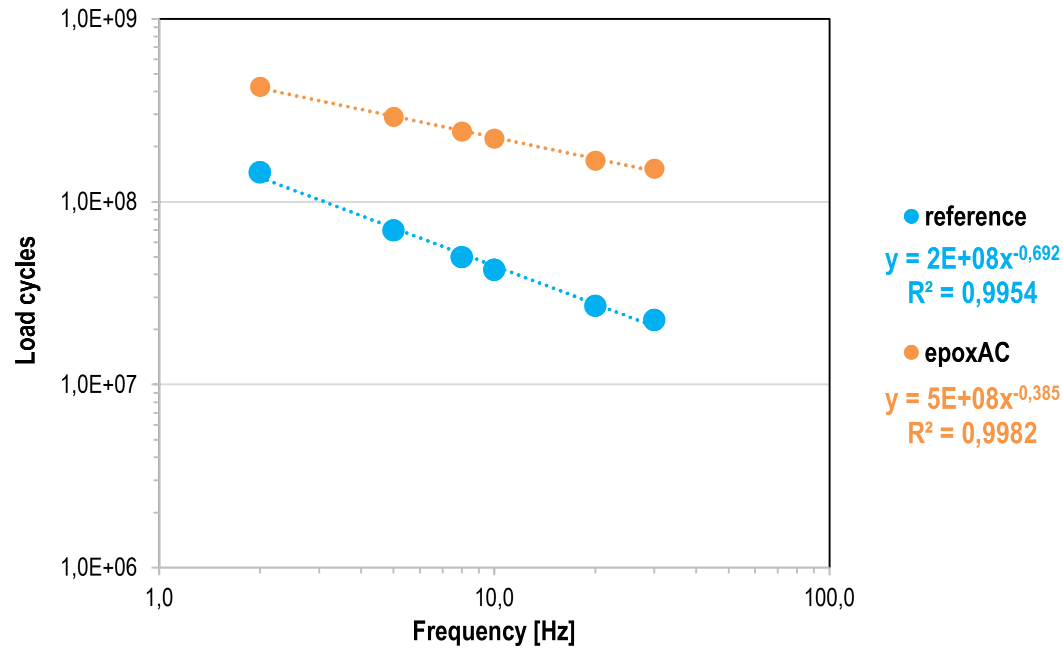


Fig. 8 Predicted fatigue life of test sections under different frequencies.

Table 2 Predicted fatigue life of test sections under different frequencies.

Frequency [Hz]	5.0	8.0	10.0	20.0	30.0
reference, $N_{f,ref}$	6.97E+07	4.98E+07	4.25E+07	2.69E+07	2.26E+07
epoxAC, $N_{f,epoxAC}$	2.91E+08	2.42E+08	2.22E+08	1.69E+08	1.52E+08
$N_{f,epoxAC}$ / $N_{f,ref}$	4.2	4.9	5.2	6.3	6.7

RECYCLABILITY LABORATORY RESULTS

Many of the polymer modified asphalt pavements in national highway networks have reached or are more and more reaching their end of life. Thus, highway agencies face a rapidly increasing source of reclaimed asphalt pavement (RAP) materials containing polymers. Even though the recycling of RAP in new asphalt pavements is a common practice, the re-usability of such materials containing residual polymers, particularly thermosetting, has not been comprehensively studied.

The potential of using the aged epoxy asphalt materials in new pavements plays a pivotal role in enabling the wider acceptance of this material technology, especially in countries with strict sustainability requirements. In this framework, this part of the research presents an experimental program conducted in the laboratory to assess the potential recyclability of epoxAC mixes. The new, aged, and recycled epoxAC mixes' performance characteristics were compared with those of standard asphalt mixes.

Pavement Materials, Preparation & Methods

The experimental program designed for the scope of recyclability of materials with epoxy asphalt includes one aggregate type (i.e., bestone), one gradation (i.e., PA 8G, RAW 2015), and three binder types. Fibers were added in all three mixes by 0,3% (by mass of aggregates) to increase the allowable amount of binder in the mixes and prevent the excessive drain-down of binders during construction. It should be pointed out that thick asphalt binder films around the mineral aggregates are desired to increase the stone-mastic adhesive bonding and aging resistance and avoid raveling. Thin binder films oxidize quickly, exacerbating the failure due to raveling. In this regard, the optimum binder content was 6,0% (by mass of aggregates) in all mixes.

Limestone (calcium carbonate) with a certain amount of hydrated lime (calcium hydroxide) was used for all mixes. Fillers with hydrated lime in limestone fillers (Wigro 50K) were added in reference and epoxAC mixes. Earlier studies have shown that fillers with hydrated lime have been quite effective in improving the durability and workability of pavement mixes. Hydrated lime in epoxy modified asphalt binders has also been proven effective in increasing the thermal cracking resistance of mastics over long-term aging (Jing et al., 2021). The pure limestone fillers could lead to mastics of the increased glass transition temperature, stiffness, and toughness. The hydrated lime in epoxy modified binders (weight ratio of 25:75 of epoxy and asphalt binder) can result in acidic species' neutralization, which assists in curing, causing a slower polymerization. This phenomenon could be beneficial as the curing window of epoxy modified mixes could be extended. Still, the neutralization of polymerization could be detrimental to formulate binders of desired properties, especially in the case of epoxy-rich systems.

Although all samples were conditioned and tested under the same conditions, the pre-heating and mixing temperatures differed. For the reference mixes, the standard 70/100 binder was oven preheating at 155°C for 4 hrs. The mineral particles were to be preheated at the same temperature overnight to ensure that they were being warm enough for mixing. The mixing of reference's components was performed at 155°C for at least 4 min, and immediately afterward, the loose mix was compacted.

The fabrication of epoxAC required some extra steps to simulate the actual field operations since these mixes are thermosetting. Especially, the epoxAC mixes were made with Parts A and B of epoxy binder heated separately for 4 hrs at 135°C and 85°C, respectively. The mineral particles were also held at 135°C overnight. Parts A and B and the 70/100 pen asphalt binder were blended at 135°C for 1 min before adding mineral particles. The mixing of all components was performed at 135°C for 4 min. The newly produced loose mix was held at 135°C for 2 hrs before compaction to simulate the transport and paving operations to ensure that the mix viscosity is acceptable for compaction. In this way, it was expected to minimize the variation in the density obtained from the laboratory and field compaction.

A rolling wheel compactor was used to compact slab specimens of 50-mm height in a 500-mm by 500-mm steel mold. In accordance with AASHTO R30, oven conditioning of specimens at 85°C for 120 hrs corresponds to 5- to 10-years field aging. Recent work suggested that reference mixes aged 85°C for 3- and 6-weeks in the laboratory have identical stiffness changes after 3- and 3.5-years field aging, respectively (Jing et al., 2020). In this study, the compacted specimens were subjected to oven aging for 12-weeks at 85°C to simulate longer than 3-years of field aging. After aging, the slabs (height of approximately 50-mm) were drilled to cylindrical specimens of 100-mm in diameter. All specimens were prepared with three replicates for each sample. The density [kg/m^3] and air void content [%] of mixes were measured according to NEN-EN 12697-5 and NEN-EN 12697-8, respectively, and the mean values are provided in **Table 3**.

Table 3 Physical properties of studied mixes after 1-week oven aging.

Property	Specification	reference[*1]	epoxAC[*2]
Mix density [kg/m^3]	NEN-EN 12697-5	1908	1885
Air voids content [%]	NEN-EN 12697-8	22,8	23,7
ITS [MPa]	NEN-EN 12697-23	0,82	1,05
ITSR [%]	NEN-EN 12697-12	0,81	0,89

production temperature: 155°C [*1]; 135°C [*2]

The aged specimens, which were preheated at 130°C for 1 hr, were broken into small pieces to produce the reclaimed asphalt (RA) materials. The RA materials from two mixes were sampled, and the binders were extracted from mixes using an automatic apparatus (EN 12697-1). During the extraction process, methylene chloride was used as a solvent. To separate asphalt binders out of solvent, a rotary evaporator was used according to EN 12697-3, and the physical and rheological properties of recovered binders were evaluated in a penetration tester and dynamic shear rheometer, respectively. The recovered binders were also analyzed using a Fourier Transform Infrared spectrometer. To restore the rheology of the aged binders to their original state, a certain amount (i.e., 25%) of a 160/220 pen grade asphalt binder was added to simulate one of the common hot recycling processes in asphalt plants.

Three recycling levels were evaluated (50, 75 and 100%wt of RA materials of both mixes). For this purpose, the soft binder was applied as recycling agent to the aged loose mixes, which were already preheated at 130°C for 1 hr. To keep the consistent mixing temperature, the virgin aggregates used to produce the recycled mixes were pre-heated at different temperatures related to the recycling level (i.e., 75% RA at 220°C and 50% RA at 180°C). Afterward, the wet mixes were placed in the oven at the same temperature for another 1 hr to ensure that the mixes are warmed uniformly. As for the fabrication of specimens for aging studies, the gyratory compaction was utilized with a height controlled, and the same open-graded gradation was used for all recycled mixes (PA 8G). Note that the soft binder was not applied to the mixes with 100% RA to demonstrate the potential to re-melt the epoxy modified asphalt mixes.

Asphalt durability is the preservation of the structural integrity of compacted mixes over their expected service-life when exposed to the effects of the environment, such as oxygen, temperature, water, and traffic loading. In this research, the effects of aging on three mixes were quantified by performing indirect tensile tests at 15°C (NEN-EN 12697-23) and determining the indirect tensile strength (ITS). All specimens were kept at 15°C for a minimum of a week before testing. Unless otherwise stated, the indirect tensile results presented were the mean values of three replicates. A representative graph of the overall responses of the reference and epoxAC mixes are shown in **Fig. 9**.

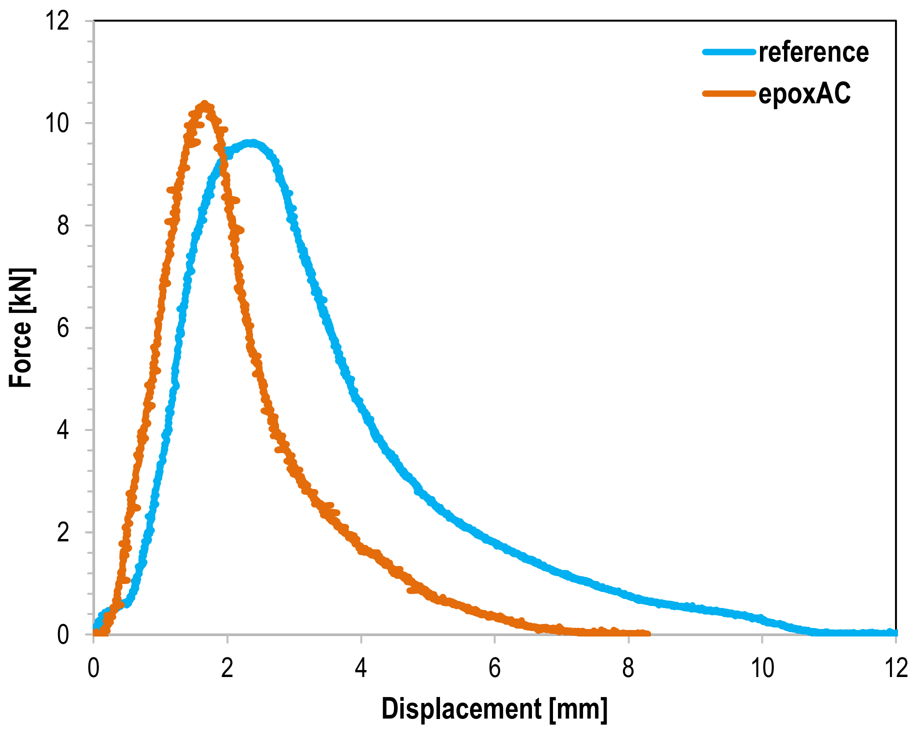
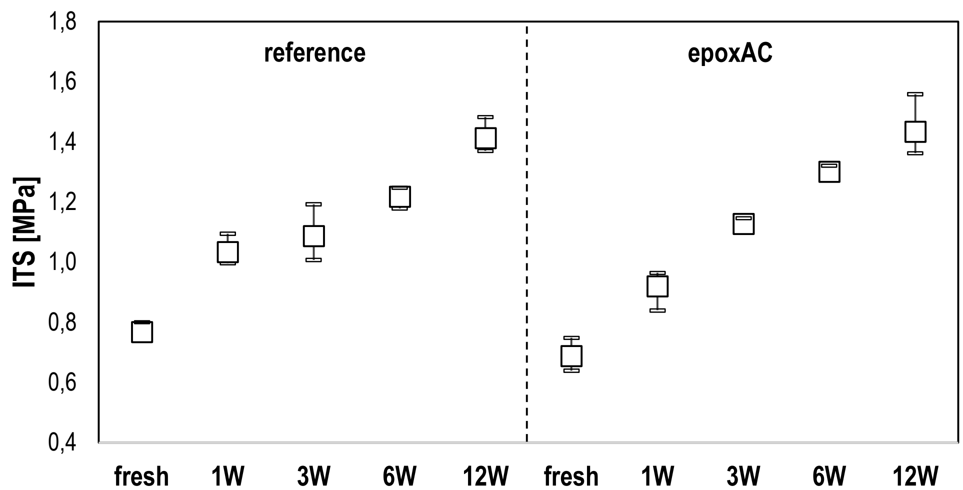


Fig. 9 Representative force versus displacement curves of studied mixes (after 6-weeks oven-aging).

The studied mixes could be prone to water damage if the stone-mastic bonds weaken in the presence of water. The water sensitivity of the three mixes was evaluated by indirect tensile strength ratio (ITSR) (NEN-EN 12697-12). Then, the ITS values were measured and compared with the ITS values of unconditioned specimens. The results of this procedure were the ratio of ITS values with and without water damage or the ITSR values. The ITSR values of mixes were also determined for all age conditioning periods (i.e., 1-, 3-, 6-, and 12-weeks at 85ºC). The minimum threshold ITSR value for accepting a mix is set at 80%. The same characterization program was followed for the recycled mixes.

Laboratory Results

Fig. 10a shows the ITS for two mixes over aging. The ITS values of epoxAC mixes were almost identical with reference after 12-weeks of aging, while these mixes have shown a similar increasing rate of ITS. The ITSR values of mixes are also shown in **Fig. 10b**, where these values of epoxAC show an increasing trend with the longer conditioning periods. After 12-weeks of aging, the ITSR values of reference and epoxAC were 86% and 92%, respectively, indicating that the addition of epoxy increases the resistance of asphalt materials against water damage. This observation is consistent with earlier studies on epoxy asphalt concrete mixes (Luo et al., 2015; Qian & Lu et al., 2015; Wu et al., 2017).



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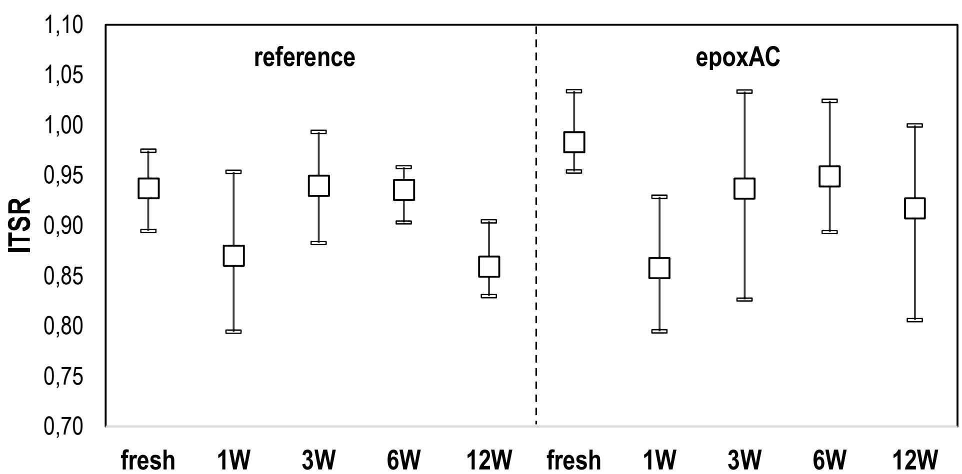
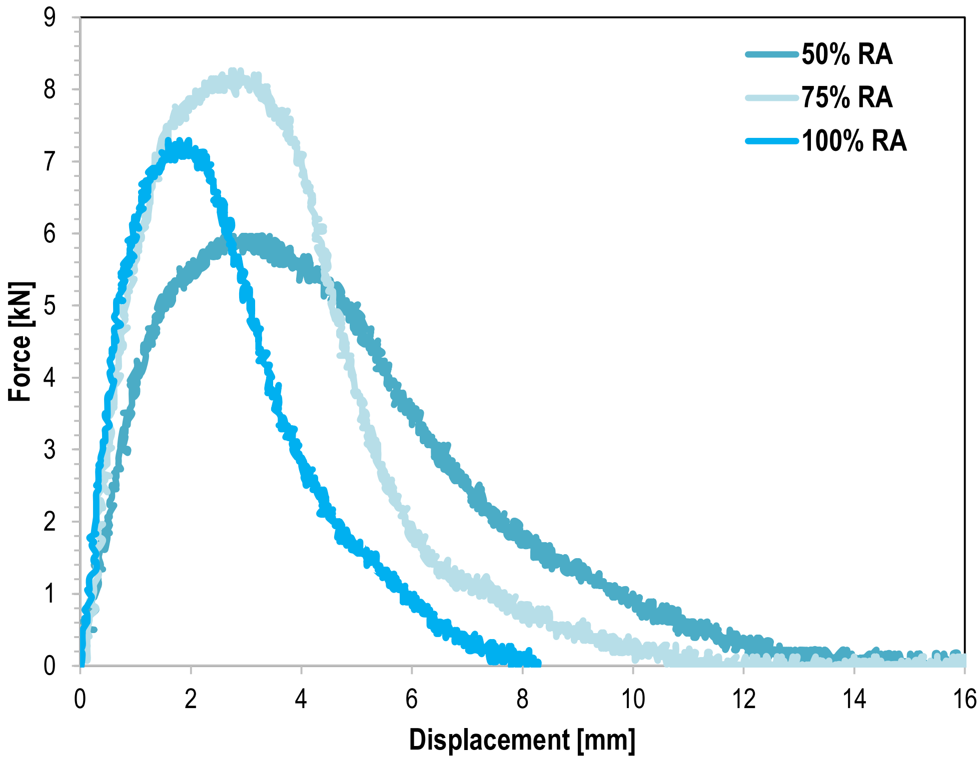


(b)

Fig. 10 Effect of aging on indirect (a) strength and (b) strength ratio test results of studied mixes.



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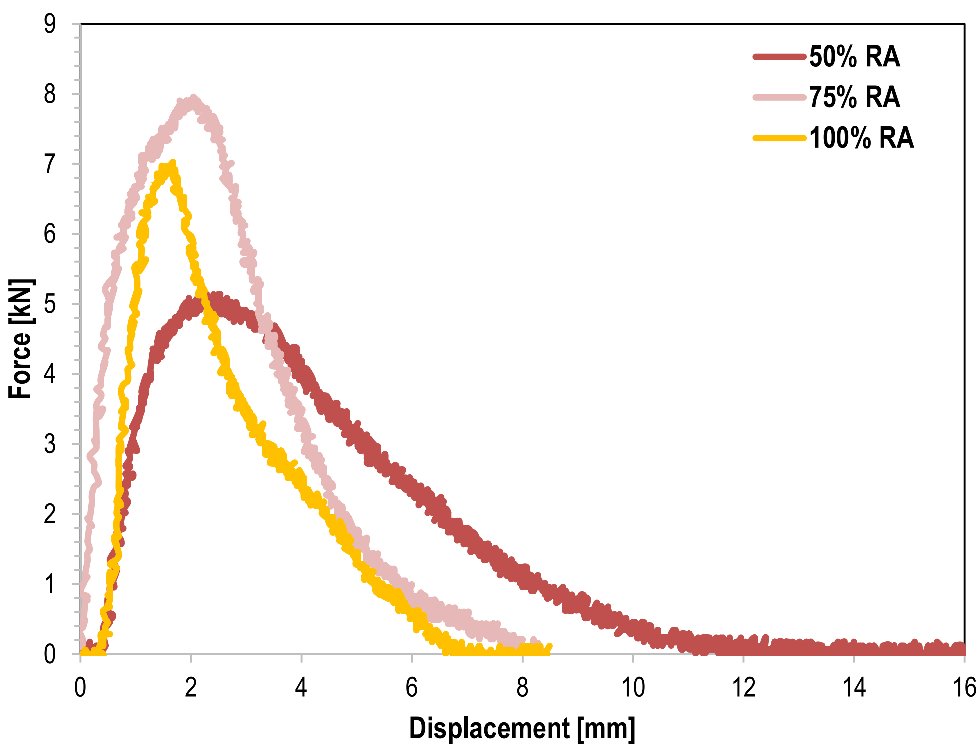
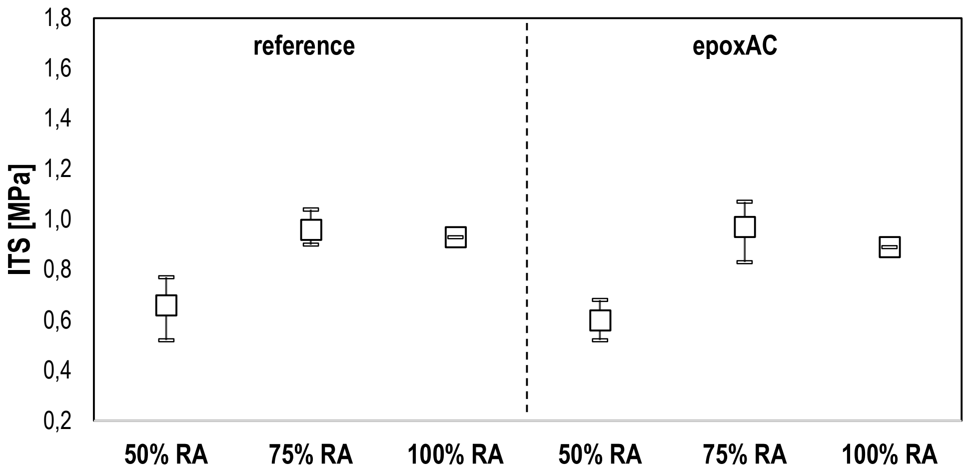


(b)

Fig. 11 Representative force versus displacement curves of recycled (a) reference and (b) epoxAC mixes.

The benefits of the epoxy part in bitumen are mainly apparent after long-term aging. Therefore, the 12-weeks of oven aging might not sufficiently reflect the positive influence of epoxy in bitumen. Longer time aging lengths in the oven would be recommended, which is also supported by (Wu et al., 2017). Nevertheless, in this contribution, the ultimate goal remains the re-usability of the epoxAC mixes. It is believed that the 12-weeks of oven aging is enough time to ensure that the materials are adequately hardened to perform recyclability analyses in the epoxAC mixes.

In this part of this study, the indirect tensile strength of recycled mixes in relation to the proportion of added recycled aggregates were evaluated. The representative graphs of the response of the recycled reference and epoxAC mixes with different amounts of RA material are shown in **Fig. 11**.



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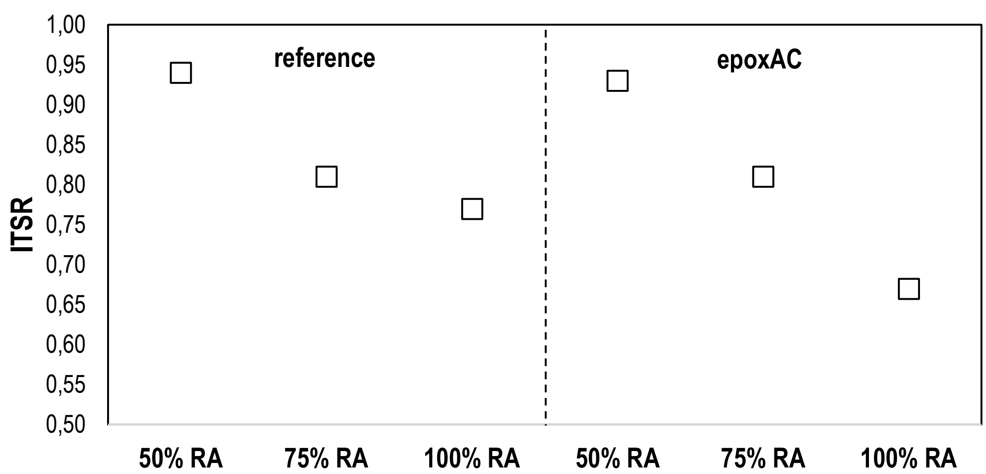

(b)

Fig. 12 Effect of recycled material on indirect (a) strength and (b) strength ratio test results of mixes.

Based on these graphs, it can be concluded that the epoxAC mixes developed with 100% RA can be re-melted and re-used without applying any recycling agent as it illustrates an identical mechanical response with the 100% recycled reference mixes. The ITS values of 100% recycled reference and epoxAC mixes were 0,93 and 0,89 MPa, respectively (see **Fig. 12**). Especially, the ITS values of both mixes containing 75% of recycled materials (i.e., 0,96 MPa for reference and 0,97 MPa for epoxAC) was higher than those of the 50% (i.e., 0,66 MPa for reference and 0,60 MPa for epoxAC) of recycled materials, mainly due to the softening effect of added binder (see **Fig. 12a**). Mixes containing recycled epoxAC materials exhibited sufficient ITS values without remarkable strength differences with mixes produced by replacing new aggregates with recycled reference materials.

Finally, it was observed in **Fig. 12b** that the ITSR values of both recycled mixes were almost identical. The ITSR values are greater than 80% in reference and epoxAC mixes containing 50% and 75% of RA materials, fulfilling the requirement prescribed by the specification. Water resistance issues were noticed in 100% recycled mixes, but it should be considered that no soft binder or other recycling agent was utilized to develop them. No remarkable differences in the ITS and ITSR values were observed when the new aggregates in mixes were replaced with recycled materials with epoxy. Overall, the aged epoxy modified asphalt materials have shown a similar 'rejuvenation' attribute with a conventional asphalt. Thus, this type of modified asphalt can be re-utilized through the standard asphalt recycling processes.

CONCLUSIONS

This study presents the first-year performance results of monitoring two instrumented test sections constructed in 2020. The test sections, featuring reference and epoxAC, were subjected to thermal- and traffic-induced deformations, and the main findings are as follows:

- The measured strain responses alter significantly with the temperature changes, and the strain readings of both studied materials show typical viscoelastic responses.
- At the traffic-free phase and decreased temperatures, the thermal-induced compressive strains were higher at the bottom of the reference section. At the same time, the thermal contraction was more pronounced in the measurements provided by the transverse strain gauges. This attribute suggests that the reference section is more prone to low-temperature transverse deformations than epoxAC.
- The strain response of both sections increased from compression to tension because of increased temperatures in the summer period. The strain measurements of epoxAC indicate that this material behaves fundamentally similar to the reference section in its first year of service.
- The epoxAC test section demonstrates lower horizontal tensile strains in the transverse direction at the bottom of the surface layer than the strains of the control section during the measuring period. Based on the field measurements and earlier laboratory data, a fatigue cracking model was employed to estimate the fatigue life of studied sections, and the fatigue life of epoxAC was approximately 4 times greater than the fatigue life of the reference test section at 20ºC.

Furthermore, another objective of this study was to evaluate the durability characteristics of new, aged, and recycled epoxy modified asphalt mixtures. These newly developed materials also compared with the standard asphalt, and the main findings are summarized as follows:

- The epoxAC mixes have shown the highest resistance against water damage dictating that the stone-mastic adhesion strength is improved with the use of an epoxy binder.
- A soft binder was applied as a recycling agent to mixes containing various amounts of recycled materials, and the mechanical properties of new mixes were assessed. The strength of both reference and epoxAC mixes containing 75% of recycled materials was higher than those with 50% of recycled materials mainly because of the softening effect of the applied binder. No remarkable differences in the water susceptibility were also observed when the new aggregates in mixes were replaced with recycled materials, with the mixes with 50% and 75% of recycled materials to fulfil the water resistance requirements.

- The epoxAC mixes developed with 100% recycled epoxy material exhibited similar durability characteristics with reference mixes containing 100% recycled asphalt materials without applying any recycling agent. This response dictates that the aged material containing the epoxy diluted asphalt binder can be re-melted and re-used to produce new pavements.

More field measurements are suggested over time to track the evolution of material properties and elucidate the long-term benefits of epoxy in asphalt. Evidence from the in-field performance of epoxy modified asphalt is also needed for validation purposes, even though the laboratory results have illustrated the potential benefits of epoxy modified asphalt for flexible pavement materials.

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