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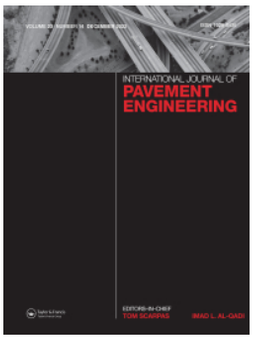

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Effect of mineral fillers on epoxy-modified open-graded porous asphalt durability

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ABSTRACT

Epoxy-asphalt (EA) attracted the attention of road authorities in many countries as a solution for open-graded porous surface layers with enhanced durability and longevity. This research presents an experimental programme to assess the durability of epoxy-modified open-graded porous asphalt (EMOGPA) mixes, emphasising the effects of the reactivity of two mineral fillers on mixes containing various EA proportions. Results indicate that the EMOGPA mixes have shown a high sensitivity to the conditioning time before compaction (aka. preconditioning). The materials produced exclusively by EA are the most sensitive to preconditioning, reducing their water and ravelling resistance with increased preconditioning time lengths. The number of gyrations has also been proven as an efficient quantity of the compaction effort required to reach the target mix properties. Moreover, the proportional increase of EA in mixes led to substantially improved durability. Hydrated lime in epoxy-modified asphalt mixes also affected their mechanical response. The indirect tensile strength and toughness of EA mixes were higher than other mixes, while mixes with limestones were stronger and tougher than those with hydrated lime. This attribute reflects the positive contribution of apolar fillers to strengthen and toughen the EA mixes.

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KEYWORDS
Open-graded porous asphalt; epoxy asphalt; filler; durability; longevity; sustainability

Introduction

Open-graded porous asphalt (OGPA) mixes are increasingly placed as thin layers at the surface of asphalt pavements to benefit the travelling public regarding the safety and the environment (Kandhal and Mallick 1999, Huber 2000, Alvarez *et al.* 2006, National Academies of Sciences, Engineering and Medicine 2009, 2018). The OGPA mixes contain a high percentage of air voids, most often consisting of narrowly graded crushed aggregates with a relatively large nominal maximum aggregate size (NMAS) and without a significant amount of fines. As the strength of the OGPA mixes is highly dependent on aggregate-on-aggregate contact and the durability of the mastic part, these mixes can be found with low NMAS levels (e.g. 6- or 8-mm) as well. Moreover, water travels easily through the interconnected air voids of OGPA layers and drains laterally toward their edge, minimising in this way the risk of hydroplaning and wet skidding (National Academies of Sciences, Engineering and Medicine 2018). The high water permeability for subsurface drainage of these mixes is also associated with improved wet weather visibility and the visibility of pavement markings at night. These conditions result in the enhancement of riding safety and comfort of the drivers (National Academies of Sciences, Engineering and Medicine 2018). The reduced tire wear and pavement noise also belong among the main benefits of OGPA mixes, with the use of OGPA mixes being related to noise reduction generated by passing vehicles by 3.0–6.0 dB and 5.5–10.5 dB comparing dense-graded asphalt concrete and cement concrete mixes, respectively (Huber 2000).

Despite the aforementioned benefits, potential shortcomings related to material durability could limit the broader use of OGPA mixes as surface pavement materials. The durability issues of OGPA mixes are evidenced by ravelling, which consists of the loss of aggregates at the pavement surface occurring when the binder ages. The ravelling defect evolves rapidly once it begins, leading to riding comfort deterioration, increased traffic noise, and significantly shorter service life (Wang *et al.* 2014, Hernandez-Saenz *et al.* 2016, Gu *et al.* 2018). Several additives and chemical modifiers have been used to improve the cohesive and adhesive properties and the ability of binders to age slower. Although fibers and modifiers have proved to be effective in enhancing the durability of OGPA mixes, the improvements resulting from using these materials are often limited. Novel modification approaches should be developed to formulate binders of aging resistance and cohesive/adhesive strength and produce mixes of improved durability.

Epoxy-asphalt (EA) attracted the attention of road authorities in many countries as a solution for OGPA surface layers with enhanced durability and longevity. The EA binder is a two-part thermosetting binder consisting of an epoxy resin and a specially formulated asphalt binder operating as a hardener. Once the two parts are mixed, polymerisation (curing) reactions happen over time, leading to a binder of rubbery

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characteristics. The EA has been found to have high strength, stiffness, toughness, and aging resistance (Youtcheff *et al.* 2006, Widyatmoko and Elliott 2014, Apostolidis *et al.* 2019, Apostolidis 2022). This binder has also been diluted with standard petroleum-based asphalt binders to lower the initial cost and offer economically feasible and durable OGPA mixes. The epoxy-diluted asphalt binders are alternatively named epoxy-modified asphalt binders.

Epoxy-modified open-graded porous asphalt (EMOGPA) mixes were first introduced on roadways in New Zealand under an Organisation for Economic Co-operation and Development (OECD) programme (International Transport Forum 2017). Particularly, in 2001, a research programme on the Economic Evaluation of Long-Life Pavements was initiated by the OECD with the main target of improving pavement longevity. According to the programme output, epoxy-modified asphalt has been indicated as the only existing material that could lead to long-life pavements. The improved mechanical properties of epoxy-modified asphalt mixes observed in New Zealand (Herrington and Alabaster 2008, Wu *et al.* 2019) have also been proved by studies internationally (Luo *et al.* 2015, Qian and Lu 2015, Yin *et al.* 2021, Jing *et al.* 2023, Li *et al.* 2022, 2023).

A primary concern that might affect the implementation of epoxy-modified asphalt pavement mixes is the construction issues associated with uncontrolled irreversible curing, which the contractors could face. As observed recently, the reactivity of minerals employed to develop such pavement mixes is critical (Apostolidis *et al.* 2020, Jing *et al.* 2021). The curing rate in epoxy-modified asphalt binders is also influenced by the chemistry of the base binders (Apostolidis *et al.* 2023, Dongre *et al.* 2023). In practice, on the one hand, the relatively slow curing of these mixes could cause their segregation after compaction due to the low binder viscosity, lower than that of standard asphalt binders at the onset of compaction. On the other hand, these mixes could be fully cured before paving, making the mix compaction impossible if the production and transport temperatures are too high. Thus, controlling the production chain and the composition of epoxy-modified asphalt mixes is crucial to ensure the development of durable and long-life pavements (Apostolidis 2022).

This research presents an experimental programme conducted in the laboratory to assess the durability of EMOGPA mixes, emphasising the effects of the reactivity of mineral fillers on the final mixes containing various EA proportions. The mineral fillers are variable in chemistry, and reactive fillers like limestone with calcium hydroxide (hydrated lime) perform differently in asphalt binders. For the epoxy-modified asphalt binders, earlier works showed that the limestone fillers with calcium hydroxide effectively increase the thermal cracking resistance of materials after aging but also, they cause a slower curing (Apostolidis *et al.* 2020, Jing *et al.* 2021). This phenomenon could be beneficial as the curing window of these mixes could be extended, but the neutralisation of curing agents like the acidic compounds in EA could be detrimental to formulating binders of desired properties. To facilitate this research, two mineral fillers (i.e. limestone with hydrated lime and limestone without hydrated lime) are selected to be used with the epoxy-modified asphalt binders and formulate the studied mixes. The changes in durability induced by curing and aging were evaluated as a function of the filler type and time by conducting indirect tensile strength and Cantabro tests.

Materials and methods

Materials

The experimental programme designed for the scope of this research includes: one aggregate type, one aggregate gradation and two filler types. The aggregate gradation of OGPA mixes (PA 8G, normally used in the Province of Gelderland, the Netherlands) with a nominal maximum aggregate size (NMAS) of 8-mm is given in Table 1. Fibers (i.e. pelletised blend of 20% by weight cellulose fibers and 80% by weight of Fischer–Tropsch wax) were added in all mixes by 0.3% (by mass of aggregates) to increase the allowable amount of binder in the mixes and prevent the excessive binder drain-down during construction. Note that thick binder films around aggregates are desired to increase the aggregate-mastic bonding and aging resistance and subsequently avoid ravelling (Herrington *et al.* 2005). Thin binder films oxidise quickly, exacerbating the failure due to ravelling. In this regard, the optimum binder content in all mixes was 6.0% (by aggregate mass).

A 70/100 pengraded asphalt binder commonly applied in the Netherlands for mixes was used to produce the studied open-graded porous mixes. The EA binder consists of Part A (i.e. Bisphenol A diglycidyl ether, commonly abbreviated BADGE or DGEBA) and Part B (i.e. a mix of a 70 pengrade petroleum binder with heavy naphthenic distillates and extracts). Further information about EA can be found elsewhere (Apostolidis 2022).

First, Part A and B were oven-heated for 1 h to 85°C and 110°C, respectively, and mixed manually at a weight ratio of 25:75 for 20 s to produce the EA binder. Immediately afterward, to formulate the epoxy-modified asphalt binder, a 70/100 pen binder preheated to 130°C was mixed further for 60 s with the EA binder. According to the experience in New Zealand, the Netherlands and the United States of America, an asphalt-epoxy ratio of 75:25 (% by weight, or wt.) can balance sufficiently between cost and performance as the original price of EA is high. In this research, EA replaced the standard 70/100 pen binder with a percentage of 50% and 100% (by mass of binder) to fabricate the EMOGPA mixes. Details about the minerals used to produce the mastic part of EMOGPA mixes are given in the next sub-section.

As a continuation of the work conducted at the binder level (Apostolidis *et al.* 2020, Jing *et al.* 2021), two mineral fillers

Table 1. Aggregate gradation of PA 8G.

Sieve size [mm]	min. [% m/m]	max. [% m/m]	Percentage passing [% m/m]
11.2	98.0	100.0	100.0
8.0	81.6	95.6	90.0
5.6	33.7	51.7	45.0
2.0	5.0	19.0	14.0
0.5	2.8	12.8	10.0
0.063	3.0	9.0	7.6

Norwegian Bestone: 84.9%; crushed sand: 3.2%.

Table 2. Basic properties of mineral fillers.

		NRF[a]	RF[b]
Grain distribution (sieve)			
0.063-mm	[% m/m]	85	80
0.125-mm	[% m/m]	95	93
2.000-mm	[% m/m]	100	100
Mass loss, 110°C	[% m/m]	0.4	0.3
Solubility, H_2O	[% m/m]	1.7	5.8
Density	[Mg/m^3]	2.8	2.7
Voids	[% v/v]	38.0	40.0
$Ca(OH)_2$	[% m/m]	0.0	5.7

[a]Limestone without calcium hydroxide.
[b]Limestone with calcium hydroxide.

were employed: (a) limestone fillers with hydrated lime (or reactive filler, abbreviated here RF) and (b) limestone fillers without hydrated lime (or non-reactive filler, abbreviated NRF). The basic properties of these fillers are provided in Table 2. The amount of calcium hydroxide in RF was 5.7% m/m. The composition of the mastic component of the studied mixes is given in Table 3.

Specimen fabrication

Although all samples were conditioned and tested under the same conditions, the pre-heating and mixing temperatures differed. For the control mixes (i.e. EA0), the standard 70/100 binder was oven preheated at 155°C for 1 h. The mineral particles were to be preheated at the same temperature overnight to ensure they were warm enough for mixing. The mixing of components of the control mix was performed at 155°C for at least 4 min. As mentioned, these mixes were made with Parts A and B of the EA binder heated individually for 1 h at 130°C and 85°C, respectively. The mineral particles were held at 130°C overnight. Parts A and B and the 70/100 pen binder were blended at 130°C for 1 min before adding mineral particles. The mixing of components was performed at 130°C for 4 min.

The material conditioning and testing programme are divided into: (a) phase I: short-term oven preconditioning and (b) phase II: long-term oven conditioning. Note that the term preconditioning time corresponds to the time length between the asphalt mixing and compaction at a certain temperature. Explanations of the (pre)conditioning periods selected for phase I and II is discussed below.

Phase I: short-term oven preconditioning

The in-field strength gain predominantly occurs in several days and is initially dependent upon processing variables and, later, substrate temperatures. The typical lab curing process of the EA binder is at 120°C for 4–5 h or 130°C for 3 h in the oven (Apostolidis 2022).

In this research, after mixing, all loose mixes were compacted after (i) 2 h and (iii) 4 h of oven-conditioning at 130°C. In other words, the newly produced loose mixes were held at 130°C for 2 and 4 h before compaction to simulate the mix transport and paving operations to ensure that the material viscosity is acceptable for compaction. Zero-hour loose mixes were compacted immediately after mixing, and this case was used as a reference. For the mixing, a Hobart pan mixer and a spiral dough hook were employed according to EN 12697-35.

Laboratory compaction was performed using a Superpave gyratory compactor (angle: 0.82 and shear stress: 1000 kPa) to generate cylindrical samples of 100-mm diameter and 50-mm thickness. The number of gyrations was recorded during compaction to quantify the compaction effort required to reach a predetermined volume so that the target height (i.e. 50-mm) and air void content (i.e. 22% volume) of open-graded porous mixes.

Table 3. Mastic composition of studied mixes.

Mix	Binder	Filler
EA0-NRF	AB[a] (100%) & EA[b] (0%)	NRF
EA0-RF	AB[a] (100%) & EA[b] (0%)	RF
EA50-NRF	AB[a] (50%) & EA[b] (50%)	NRF
EA50-RF	AB[a] (50%) & EA[b] (50%)	RF
EA100-NRF	AB[a] (0%) & EA[b] (100%)	NRF
EA100-RF	AB[a] (0%) & EA[b] (100%)	RF

[a]70/100 pen asphalt binder.
[b]Epoxy-asphalt binder.

Phase II: long-term oven conditioning

In accordance with AASHTO R30, oven conditioning of samples at 85°C for 120 h corresponds to 5- to 10-years field aging. Considering that the EA can effectively extend the service life of OGPA, the compacted samples (no short-term oven conditioning before compaction) were subjected to oven conditioning for 168 and 1008 h at 85°C. Note that the periphery of all samples was covered with a tape to enable aging from top to bottom, and avoid any thermal-induced deformation. All samples were prepared with three replicates for each mix.

Characterisation methods

Asphalt durability is defined as the preservation of the structural integrity of compacted mixes over their expected service life when exposed to the effects of the environment and traffic loading.

In this research, the effect of fillers, compaction preconditioning, and long-term aging on mixes were quantified phenomenologically by performing indirect tensile tests at 15°C, determining the indirect tensile strength [MPa] (NEN-EN 12697-23). The dissipated work [N/mm] which is defined as the total area of the force-displacement curve was determined by the indirect tensile tests as well. Also, the mixes could be prone to water damage if the stone-mastic bonds weaken in the presence of water. Hence, the effect of water on the mechanical response of studied mixes was also evaluated (NEN-EN 12697-12). All compacted samples were submerged at 15°C for a minimum of 4 h before testing. Unless otherwise stated, the indirect tensile results (i.e. tensile strength, dissipated work) presented were the mean values of three replicates. A representative graph of the overall responses of mixes is shown in Figure 1.

The durability of developed mixes was also assessed by performing Cantabro tests. Some agencies proposed low temperatures in abrasion machine for better differentiation between materials or a moisture-conditioning period (e.g. samples submerged for 24 h at 60°C in a water bath) prior to testing

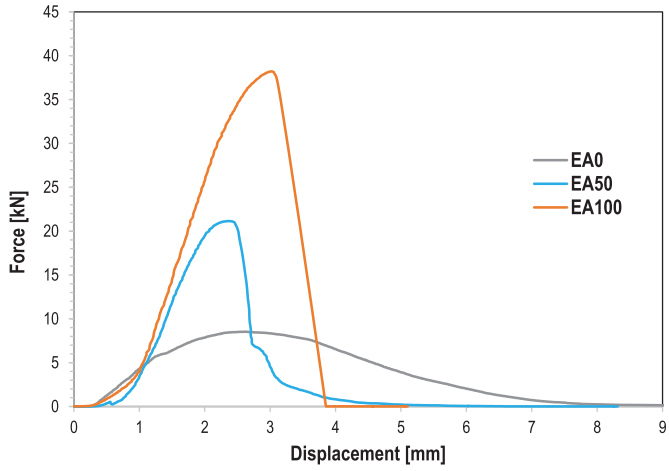

Figure 1. Representative force-displacement plots of studied mixes (after 1008 h of oven conditioning).

(National Academies of Sciences, Engineering and Medicine 2009, 2018). Despite these practices, by following NEN-EN 12697-17, samples were placed inside the Los Angeles abrasion machine and rotated freely at a rate of 30 revolutions per min for 300 revolutions at 15°C. The Cantabro mass loss was calculated as the ratio between the loss weight after testing and the initial weight of the sample. Three replicates were considered per case mix.

Results and discussion

Phase I: short-term oven preconditioning before compaction

Figure 2 demonstrates the number of gyrations to reach the target height of samples. It is noticed that there was no significant difference in the gyrations among the different mixes when compaction occurred immediately after mixing (i.e. 0 h of short-term oven preconditioning). However, the number of gyrations increased with the EA amount in the mixes, and the loose mixes with EA became almost unworkable after 4 h of oven preconditioning. Mixes developed purely with EA (i.e. 100% EA with NRF abbreviated EA100-NRF; 100% EA with RF abbreviated EA100-RF) could not be compacted as indicated in Figure 2, with more than 200 gyrations, and still, the target height was not reached. The boxes represent the mean values while the solid lines the standard deviation.

In addition to the compaction effort results in Figures 2 and 3 shows the indirect tensile test results of these compacted samples with the various filler and binder compositions. As depicted in Figure 3(a), the strength values of the compacted EA50 mixes reduced with the increase of oven preconditioning time before compaction, despite the attribute observed in mixes without EA, which has shown a slight increase of strength with the oven preconditioning.

To be specific, the EA0 mixes containing NRF have shown an increase of strength from 0.47 to 0.64 MPa from 0 to 4 h, while the same mixes with RF had increased from 0.52 to 0.63 MPa (see Figure 3(a)). Also, for the same time, the strength values of the EA50 mixes with and without hydrated lime were decreased from 0.79 to 0.60 MPa and from 0.99 to 0.55 MPa, respectively. A different trend was observed for EA100, which exhibited the highest sensitivity to preconditioning time comparing the other case materials. Particularly, the EMOGPA materials with 100% wt. EA showed an increase of strength from 0 to 2 h, and then the strength decreased (for the period 0-4 h with 2 h step: EA100-NRF: from 0.12 to 1.94 and 0.16 MPa; EA100-RF: from 0.21 to 0.88 and 0.36 MPa). The latter response indicates that the EA100 mixes were compactable for the first two hours after mixing. Still, longer preconditioning periods could be detrimental to producing the target mixes during the curing process. Note that the curing of these materials occurs in two steps: first, the epoxy ring opening, and second, the crosslinking of low molecular weight polymers producing long chains of repeating units. Once fully cured, the re-melting possibilities of these materials are minimal. The changes in the dissipated work values of these materials followed a similar trend with the indirect tensile strength, as shown in Figure 3(b).

As discussed above, it was impossible to compact the 4 h preconditioned loose EA100 mixes, which was the reason for showing the lowest strength and dissipated work values and, subsequently, the highest Cantabro mass loss. The changes in Cantabro mass loss were demonstrated in Figure 4, where the values followed the inverse trend with the indirect tensile test results in all case materials. With the increase of oven preconditioning periods, the increase of EA amount in OGPA mixes led to less workable loose materials, unable to reach

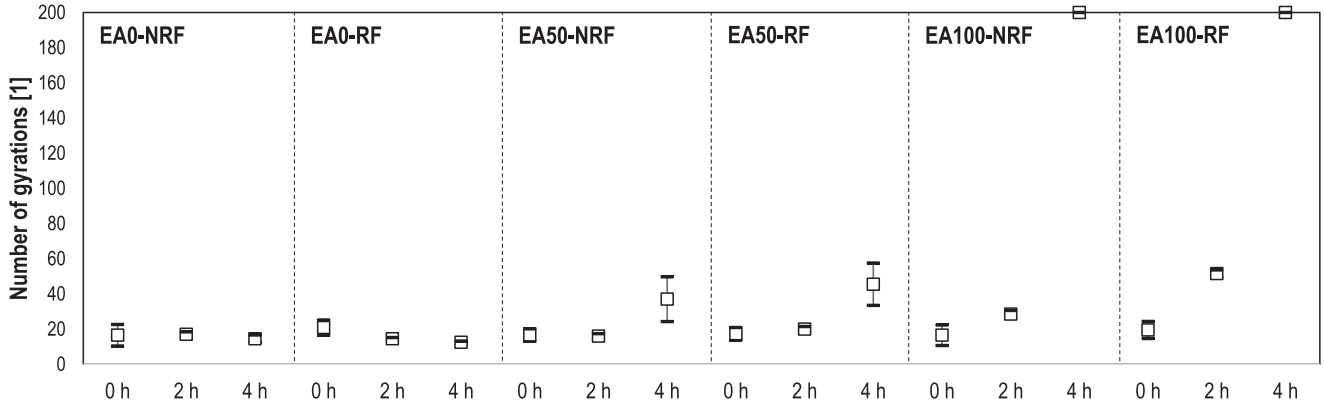

Figure 2. The number of gyrations of materials compacted after 0, 2, and 4 h of oven conditioning at 130°C.

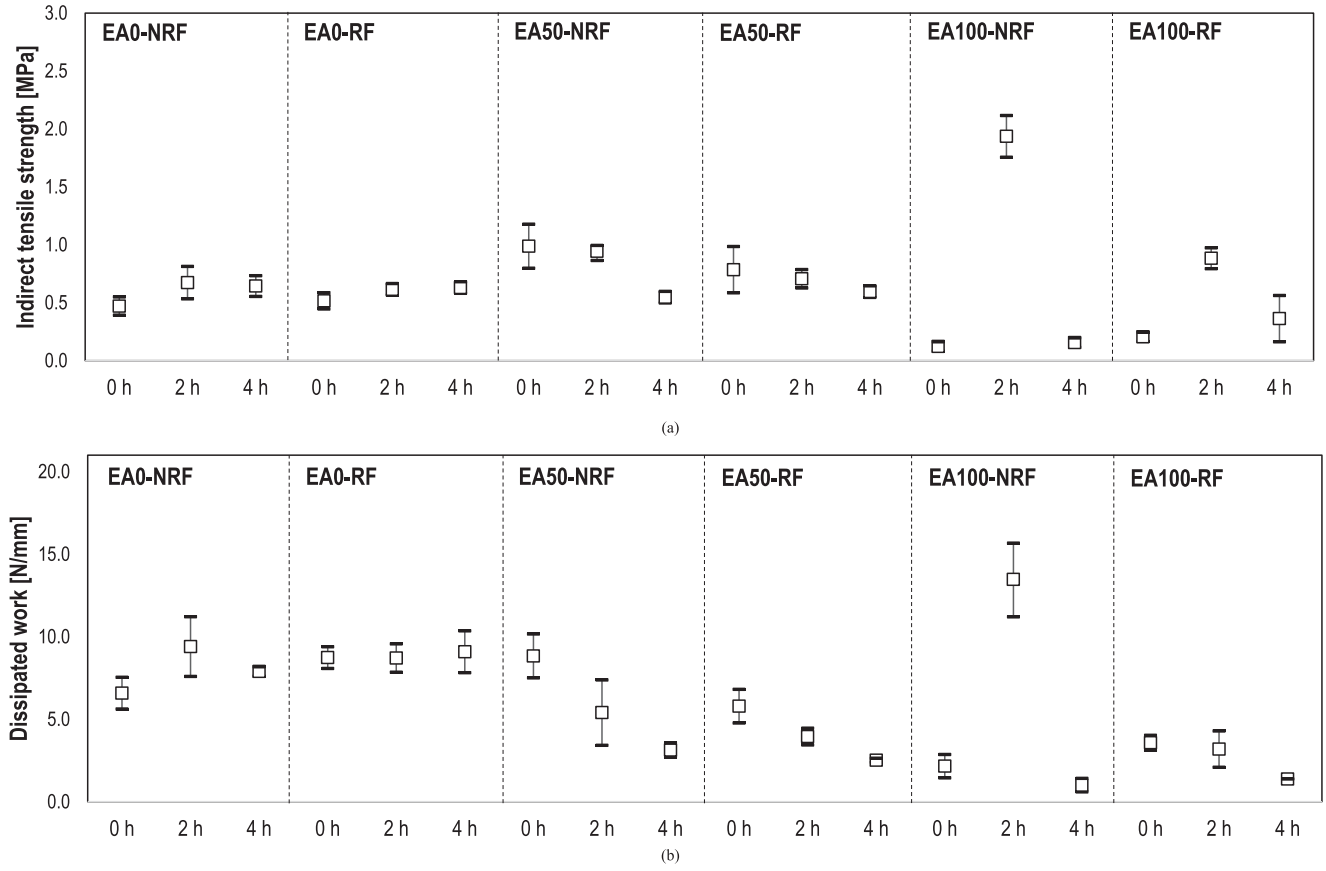

Figure 3. Change of (a) tensile strength and (b) dissipated work of mixes compacted after 0, 2, and 4 h of oven conditioning at 130°C.

the target mechanical properties. As preconditioning time increase, Cantabro mass loss of EMOGPA increases. No significant difference in the Cantabro mass loss values was observed for the control mixes (i.e. OGPA mixes without EA). It is important to note that it is apparent from both indirect tensile and Cantabro mass loss results that the preconditioning periods at high temperatures, which were selected to simulate the manufacturing procedures of the actual epoxy-modified asphalt pavement materials, play a dominant role in the development of mechanical properties and also the durability characteristics of these materials. Hence, special attention is highly recommended in the production, transportation, paving, and compaction operations of these thermosetting pavement materials, as also discussed extensively in (Apostolidis 2022).

Figure 5 presented the indirect tensile test results of the compacted mixes after water conditioning. The 4 h preconditioned EA100 mixes containing hydrated lime (i.e. EA100-RF) exhibited lower strength and dissipated work values than the mixes with the same binder and pure limestone fillers (i.e. EA100-NRF). This observation on the effect of fillers is also valid for the strength values of the compacted mixes with lower EA amounts. The EA50 mixes containing hydrated lime showed lower strength values than the EA50-NRF mixes. Interestingly, the presence of hydrated lime also contributed to the workability of loose mixes. Still, its effects

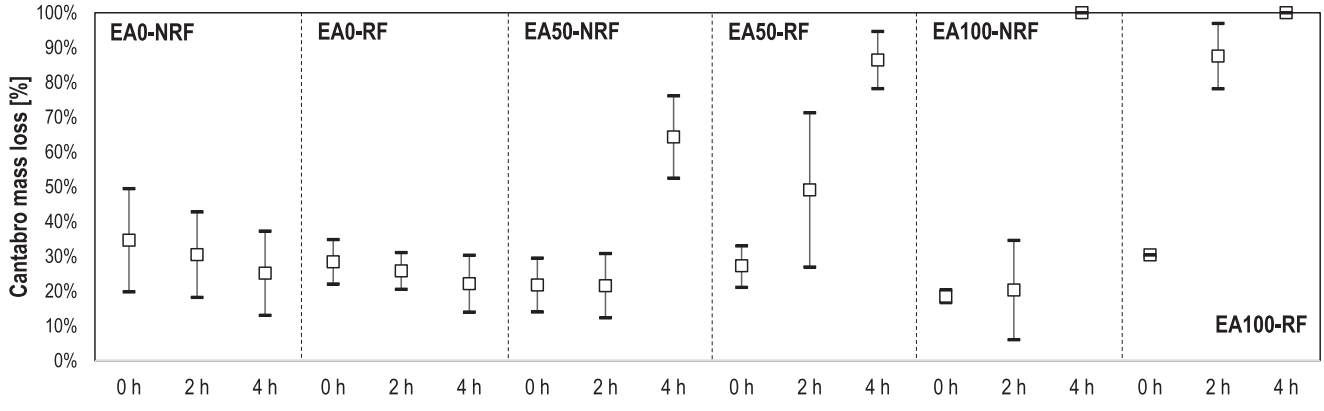

Figure 4. Change of Cantabro mass loss of mixes compacted after 0, 2, and 4 h of oven conditioning at 130°C.

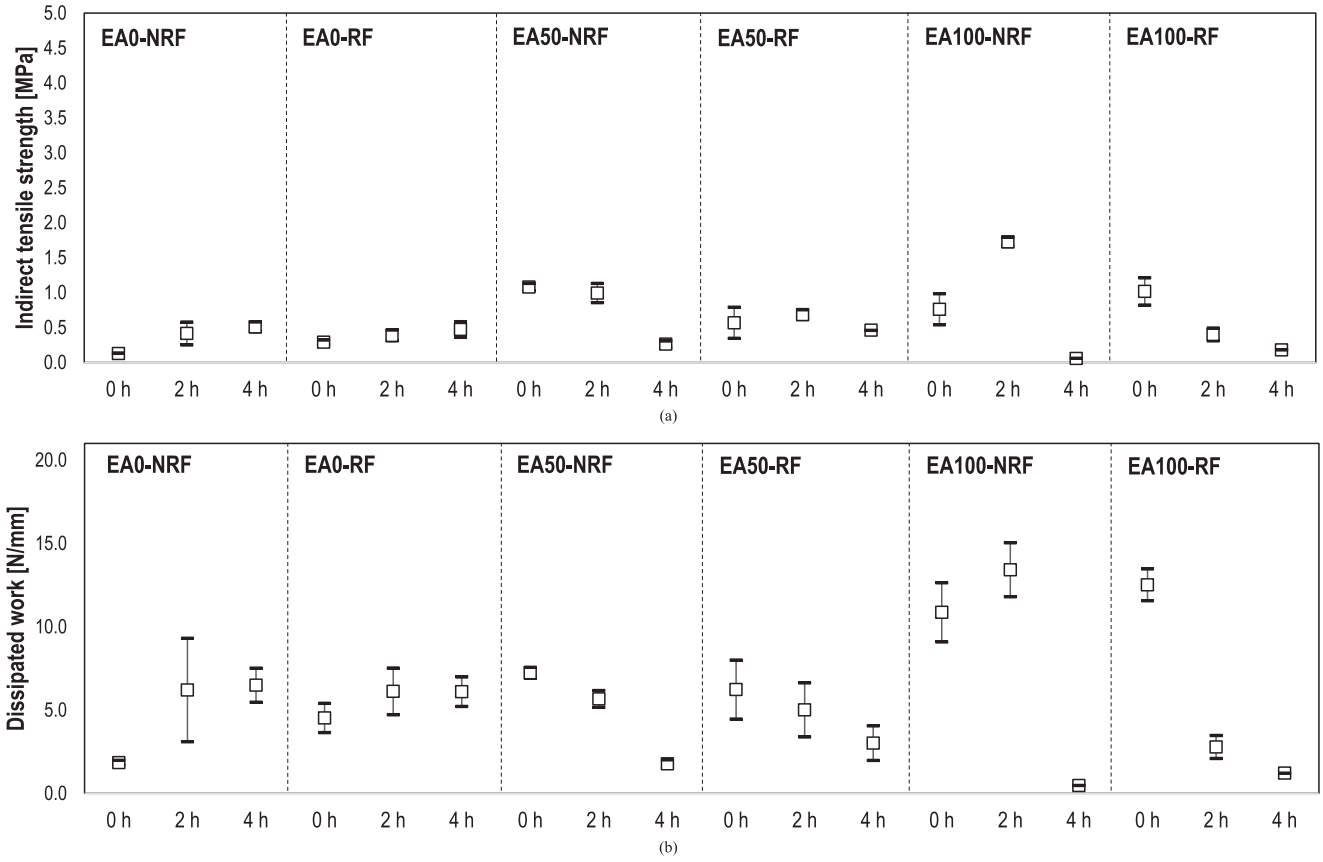

Figure 5. Change of (a) tensile strength and (b) dissipated work of short-term aged materials due to water conditioning.

were more apparent in indirect tensile test results of the samples after water conditioning. In the next section, the impact of EA amount (i.e. 0, 50, and 100% wt.) and filler type (i.e. NRF and RF) on the mechanical response of compacted mixes are discussed.

Phase II: long-term oven conditioning after compaction

The influence of long-term oven conditioning on the tensile strength and dissipated work of the studied mixes was evaluated by indirect tensile tests. Figure 6 shows the strength and dissipated work results of all mixes over 0, 168 and 1008 h of oven conditioning.

First, the proportional increase of EA in the OGPA mixes led to substantially improved mechanical properties. Both strength and dissipated work values of the EA100 mixes were higher than all the other cases after 168 and 1008 h in the oven, while EA100 with pure limestone fillers (i.e. EA100-NRF: 168 h: 3.4 MPa & 18.5 N/mm; 1008 h: 3.7 MPa & 17.4 N/mm) showed greater values comparing the mixes containing hydrated lime (i.e. EA100-RF: 168 h: 3.4 MPa & 12.8 N/mm; 1008 h: 2.9 MPa & 10.3 N/mm) (see Figure 6(a, b)). While the high tensile strength dictates a strong material, the increased dissipated work values reflect the high potential toughness. After 1008 h of oven conditioning, the dissipated work of EA100-NRF also showed the highest values with a slower reduction rate comparing the EA100-RF mixes reflecting thus the positive contribution of pure limestones to strengthen and toughen the epoxy-modified asphalt mixes. The reason for having materials of lower strength and toughness with the addition of hydrated lime might be associated with potential reactions between the calcium hydroxides and acid compounds in Part B of EA, leading to a reduction in crosslink density in the newly producing mastic. This attribute was also noticed phenomenologically elsewhere (Apostolidis *et al.* 2020, Jing *et al.* 2021).

The increasing rate of strength values of EA50 was similar between mixes with and without hydrated lime, although the dissipated work changes have demonstrated a different attribute. It seems that the dissipated work of EA50-RF was increased with the increase of oven conditioning time (see Figure 6(b)) simultaneously with the rise of strength (see Figure 6(a)). Nevertheless, the EA50-NRF mixes (2.3 MPa) demonstrated higher strength values than the EA50-RF mixes (2.1 MPa) after 1008 h of oven conditioning. Still, the dissipated work of these epoxy-modified asphalt mixes containing pure limestone decreased by following the same trend as the control mixes (i.e. EA0-NRF and EA0-RF). For toughening purposes, the presence of calcium hydroxide in limestones seems beneficial for the case of 50% wt. of EA, confirming an earlier study from the same laboratory when the same fillers were incorporated in mastic mixes of 25% wt. of EA (Apostolidis *et al.* 2020, Jing *et al.* 2021).

Figure 7 shows the Cantabro mass loss results indicating the low ravelling propensity of aged epoxy-modified asphalt mixes. The mixes developed with EA have demonstrated

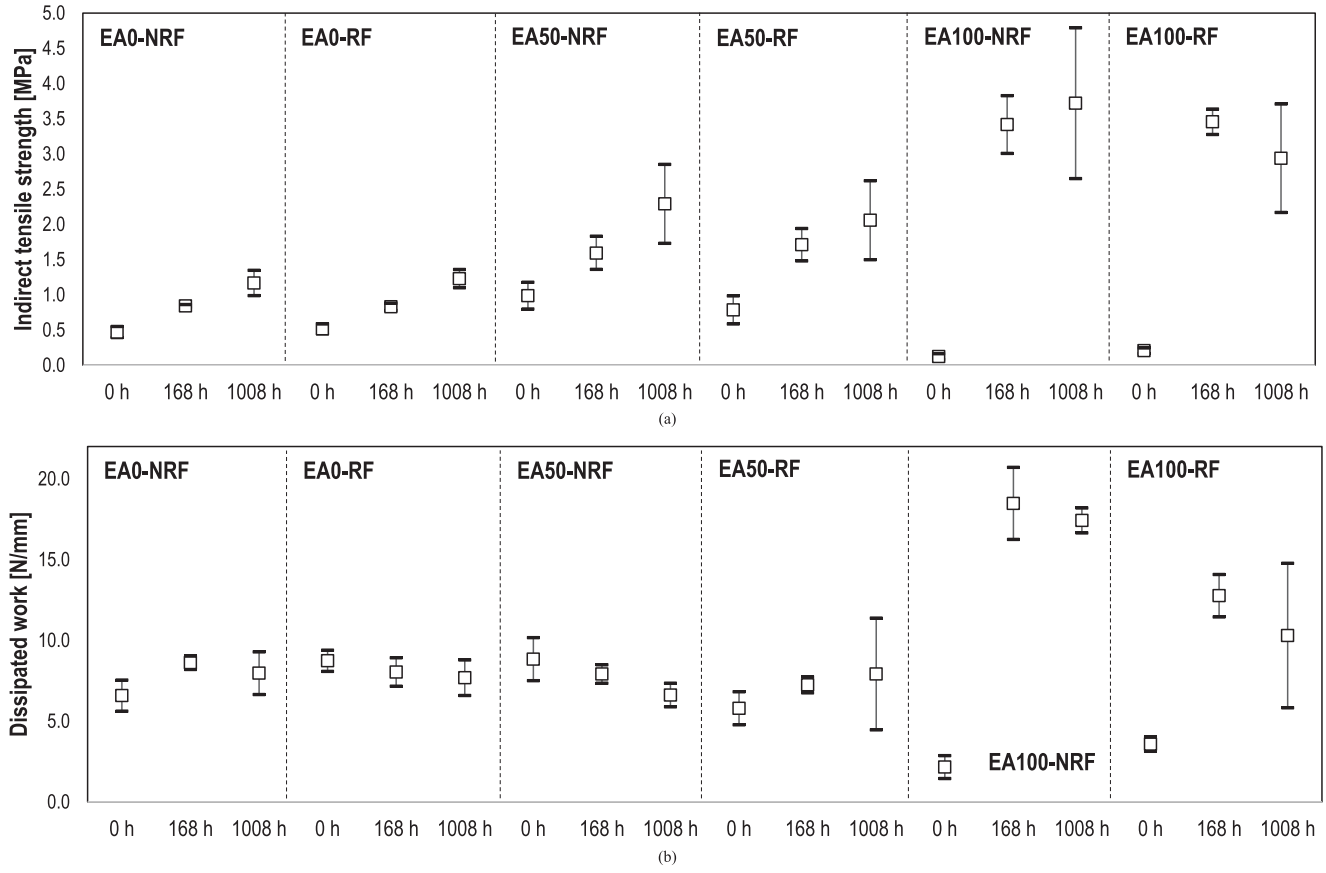

Figure 6. Change of (a) tensile strength and (b) dissipated work of compacted mixes during long-term oven conditioning

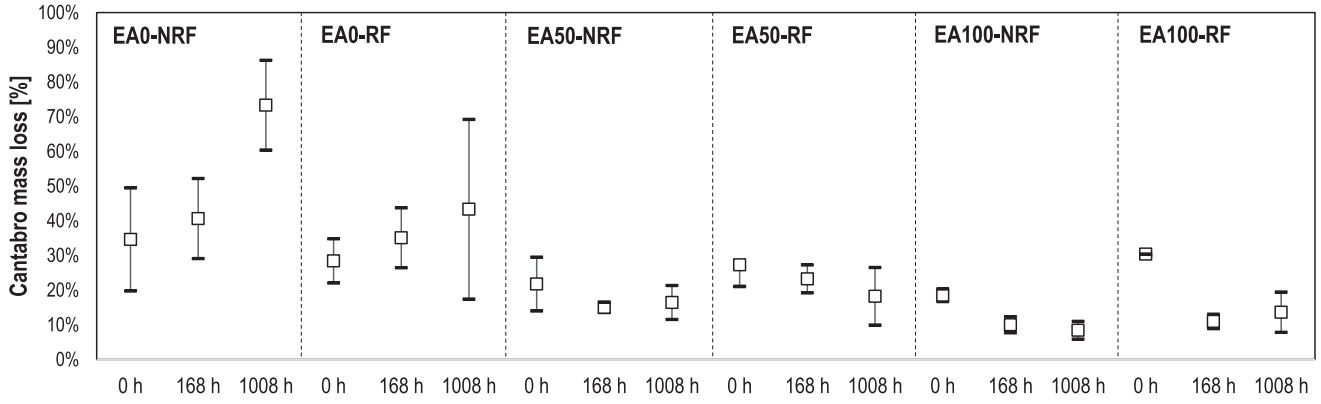

Figure 7. Change of Cantabro mass loss of compacted mixes during long-term oven conditioning.

remarkable resistance to losing their mass during the Cantabro tests. The mass loss of control mixes was high, especially after 1008 h of oven conditioning (i.e. EA0-NRF: 75 ± 15%; EA0-RF: 45 ± 25%). As expected, the 1008 h oven conditioned EA0 mixes with hydrated lime also showed improved ravelling resistance comparing the same control mixes with limestone. On the contrary, after 1008 h of oven conditioning, the OGPA mixes with EA had their lowest mass loss when the pure limestone fillers were employed (i.e. EA50-NRF: 15 ± 5%; EA50-RF: 15 ± 10%; EA100-NRF: 10 ± 5%; EA100-RF: 15 ± 5%), indicating the importance of materials selection to generate the goal chemical compositional characteristics and mechanical properties.

All samples were water conditioned and evaluated in accordance with NEN-EN 12697-12. The test results are depicted in Figure 8. The trends observed in this figure are close to the mechanical responses of dry mixes shown in Figure 6, with the main important difference being the filler type role in EA100 mixes (i.e. EA100-NRF and EA100-RF). The 1008 h of oven conditioning of samples and then their placing in a water bath sufficiently reflect the positive influence of pure limestone fillers on the EA mixes on strengthening (see Figure 8(a)) and toughening (see Figure 8(b)). The aged

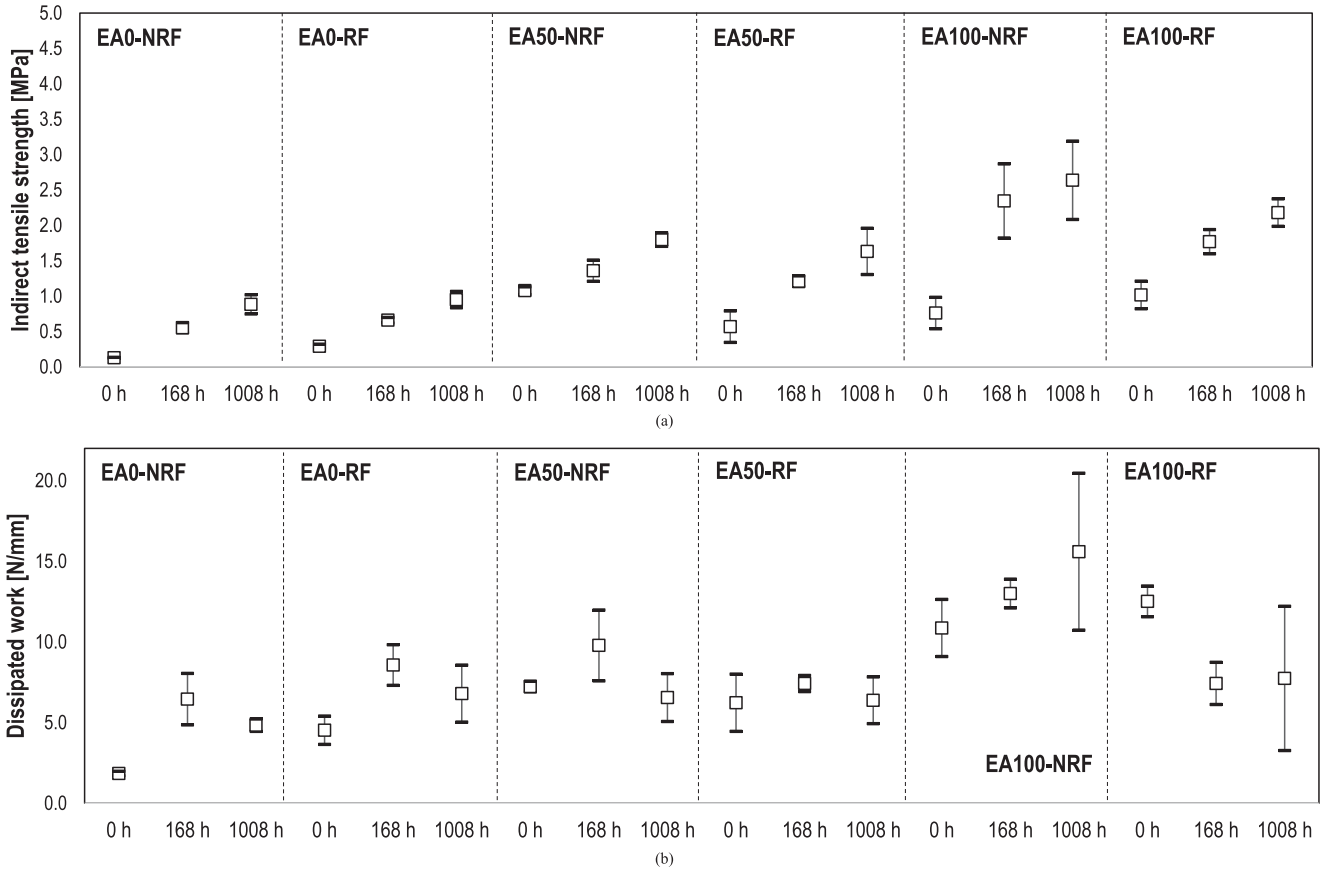

Figure 8. Change of (a) tensile strength and (b) dissipated work of long-term aged materials due to water conditioning.

EA100-RF mixes have shown lower strength values than the EA100-NRF mixes. The dissipated work of EA100 mixes with hydrated lime was also reduced with the increase of oven conditioning time lengths despite the inverse trend, which was noticed in EA100-NRF. Although hydrated lime is recommended for asphalt pavement mixes with small EA amounts, apolar fillers should be used in epoxy-rich mixes to ensure sufficient polymerisation and crosslinking of all components to generate the desired materials.

Conclusions

This research investigated the effects of filler type on the durability of EMOGPA mixes. These mixes were subjected to short- and long-term oven conditions and their changes in strength, toughness and ravelling resistances were evaluated by conducting indirect tensile strength and Cantabro tests. Based on the experimental results, the main findings are as follows:

- Longer preconditioning (from mixing to compaction) time lengths were detrimental to producing the target EMOGPA mixes. With the increased preconditioning time, the tensile strength, toughness, and ravelling resistance characteristics of EMOGPA mixes were reduced. The extent of reduction varied with the EA proportion in OGPA mixes. Especially, the EA100 mixes were the most sensitive to preconditioning time, and they became almost unworkable after 4 h. This attribute indicated the compactability of the EA100 mixes is minimal once these materials are fully cured. Note that the presence of hydrated lime in mineral fillers also contributed to the workability of loose mixes, with its effects being more apparent after water conditioning.
- The proportional increase of EA in the OGPA mixes led to substantially improved mechanical properties (i.e. strength and toughness) and ravelling resistance. Both strength and toughness of mixes containing only EA were higher than all the other mixes, while those with pure limestone were stronger and tougher than those with hydrated lime. This attribute reflects the positive contribution of apolar fillers to strengthen and toughen the EA100 mixes and the water and ravelling resistance. Moreover, the increasing rate of the strength of EA50 was similar between mixes with and without hydrated lime, although the dissipated work changes have demonstrated a different trend. The presence of hydrated lime seems beneficial for the EA50 mixes for toughening purposes.

Low temperature cracking tests were not included in this experimental programme. It is planned to evaluate the thermal cracking propensity of the herein studied mixes at temperature conditions representing cold climatic environments and compare their response with other polymer-modified asphalt materials.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data Availability Statement:

All data, models, and code generated or used during the study appear in the submitted article.

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References

Alvarez, A.E., *et al*., 2006. *Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses. FHWA/TX-06/0-5262-1*. TX: Texas Transportation Institute, Texas A&M University.
Apostolidis, P., *et al*., 2019. Evaluation of Epoxy Modification in Bitumen. *Construction and Building Materials*, 208, 361–368.
Apostolidis, P., *et al*., 2020. Evaluation of Epoxy Modification in Asphalt Mastic. *Materials & Structures*, 53 (120).
Apostolidis, P., 2022. *Chemo-Mechanics of Epoxy-Asphalt*. Delft University of Technology.
Apostolidis, P., *et al*., 2023. Study of Phase Behavior of Epoxy Asphalt Binders using Differential Scanning Calorimetry. *Construction and Building Materials*, 369, 130566.
Dongre, A., *et al*., 2023. Exploration of Curing Characteristics of Epoxy-Modified Asphalt. *Transportation Research Record*.
Gu, F., *et al*., 2018. Evaluation of the Benefits of Open Graded Friction Course: Case Study. *Construction and Building Materials*, 189, 131–143.
Hernandez-Saenz, M.A., *et al*., 2016. Mix Design, Performance and Maintenance of Permeable Friction Courses (PFC) in the United States: State of the Art. *Construction and Building Materials*, 111, 358–367.
Herrington, P., and Alabaster, D., 2008. Epoxy Modified Open-Graded Porous Asphalt. *Road Materials and Pavement Design*, 9 (3), 481–498.
Herrington, P., Reilly, S., and Cook, S., 2005. Porous Asphalt Durability Test. Transfund New Zealand Research Report No. 265.
Huber, G., 2000. *Performance survey on open-graded friction course mixes. synthesis of highway practice 284, transportation research board*. Washington, D.C.: National Research Council.
International Transport Forum, 2017. *Long-Life Surfacings for Roads: Field Test Results*. OECD.
Jing, R., *et al*., 2021. Effect of mineral fillers on oxidative aging of epoxy bitumen. *Journal of Materials in Civil Engineering*, 33 (12), 04021360.
Jing, R., *et al*., 2023. First-year field performance of epoxy-modified asphalt. *Transportation Research Record*, 2677(3), 1110–1122.
Kandhal, P.S., and Mallick, R.B., 1999. *Design of new-generation open-graded friction courses*. Alabama: National Center of Asphalt Technology (NCAT) Report No. 99-93.
Li, X., *et al*., 2022. Fatigue properties of aged porous asphalt mixtures with an epoxy asphalt binder. *Journal of Materials in Civil Engineering*, 34 (3), 04021488.
Li, X., *et al*., 2023. Multi-index evaluation for anticracking performance of epoxy porous asphalt mixtures based on overlay test. *Journal of Materials in Civil Engineering*, 34 (12), 04022336.
Luo, S., Lu, Q., and Qian, Z., 2015. Performance evaluation of epoxy modified open-graded porous asphalt concrete. *Construction and Building Materials*, 76, 97–102.
National Academies of Sciences, Engineering and Medicine, 2009. *Construction and maintenance practices for permeable friction courses*. Washington, D.C.: The National Academies Press.
National Academies of Sciences, Engineering, and Medicine, 2018. *Performance-based Mix design for porous friction courses*. Washington, D.C.: The National Academies Press.
Qian, Z., and Lu, Q., 2015. Design and laboratory evaluation of small particle porous epoxy asphalt surface mixture for roadway pavements. *Construction and Building Materials*, 77, 110–116.
Wang, Y., Leng, Z., and Wang, G., 2014. Structural contribution of open-graded friction course mixes in mechanistic-empirical pavement design. *International Journal of Pavement Engineering*, 15 (8), 731–741.
Widyatmoko, I., and Elliott, R.C., 2014. Strength characteristics and durability of epoxy asphalts. *Proceedings of the Institution of Civil Engineers*, 1300029.
Wu, J.P., Herrington, P.R., and Alabaster, D., 2019. Long-Term durability of epoxy-modified open-graded porous asphalt wearing course. *International Journal of Pavement Engineering*, 20 (8), 920–927.
Yin, F., *et al*., 2021. *Design and performance of open-graded friction course (OGFC) mixtures containing epoxy asphalt*. National Center for Asphalt Technology, Auburn University.
Youtcheff, J., *et al*., 2006. The evaluation of epoxy asphalt and epoxy asphalt mixtures. *Proceedings of the Canadian Technical Asphalt Association*, 51, 351–368.