Document Version
Final published version

Citation (APA)
Apostolidis, P., Naus, R., Liu, X., Hermsen, R., Erkens, S., & Scarpas, T. (2025). Evaluation of Plant-Produced Epoxy-Modified Open-Graded Porous Asphalt Mixture. *Journal of Materials in Civil Engineering*, *37*(4), Article 05025002. https://doi.org/10.1061/JMCEE7.MTENG-19091

Evaluation of Plant-Produced Epoxy-Modified Open-Graded Porous Asphalt Mixture

Panos Apostolidis[1]; Robbert Naus[2]; Xueyan Liu[3]; Remco Hermsen[4];
Sandra Erkens[5]; and Tom Scarpas[6]

Abstract: Pavement materials that could enhance the mechanical properties of open-graded porous asphalt mixtures in long-term service periods could offer a solution to produce long-life pavements, causing a reduction of interventions' needs, as well as the associated disruptions to road users and user costs. One option to improve the longevity of open-graded porous mixtures is with the use of epoxy asphalt that, despite its high initial cost, offers enhanced longevity that might offset any future user and intervention costs. This study aimed to evaluate the durability of plant-produced epoxy-modified open-graded porous asphalt mixtures. A batch production plant was employed to produce loose mixtures, which were used to pave a test road in the Province of Gelderland, the Netherlands, and compact specimens in the laboratory. Control mixtures with a non-epoxy-modified asphalt binder were also produced in the same plant. The durability of laboratory- and field-compacted mixtures was evaluated by conducting indirect tensile tests before and after oven conditioning. Results illustrated that the epoxy-modified asphalt demonstrated the highest strength and stiffness values, while the strength was reduced after conditioning in a water bath with the retained strength within the allowable specification limits. This attribute was confirmed from drill cores obtained from the test road after one year in service. Also, the materials compacted in the field had slightly higher strength and stiffness values than the laboratory-produced mixtures. Although the results provided have illustrated the improvement of durability of open-graded porous asphalt with implementing epoxy modification, further evidence from the test road over the years is needed for validation. **DOI: 10.1061/JMCEE7.MTENG-19091.** *© 2025 American Society of Civil Engineers.*

Author keywords: Open-graded porous asphalt; Epoxy asphalt; Pavement; Durability; Longevity; Sustainability.

Introduction

Open-graded porous asphalt (OGPA) mixtures have a high air void content, which allows water to drain by offering benefits such as reduced hydroplaning, splash and spray, noise generated by the tire-pavement interaction, and improved visibility and friction during rainy events (Kandhal and Mallick 1999; Huber 2000; NASEM 2009, 2018). Nevertheless, despite these benefits, it has been seen that pavement surfaces with OGPA mixtures have experienced premature raveling defects. The raveling, which is the loss of aggregates from the pavement surface, is a defect mainly associated with material damage due to the insufficient adhesion between binder and aggregates or loss of cohesion of the binder under mechanical loading and weather conditions. As a consequence of raveling, the average service life of OGPA mixtures is shorter (i.e., 6–12 years) compared to the life of dense-graded mixtures (i.e., 12–18 years), leading to frequent maintenance and rehabilitation interventions. Road activities associated with pavement interventions might lead to significant travel delays and congestion.

Within this context, the major international research efforts focus on improving OGPA mixtures' longevity, causing a reduction of interventions' needs, as well as the associated disruptions to road users and user costs. Pavement materials that could enhance the mechanical properties of OGPA mixtures in long-term service periods could offer a solution to produce long-life pavements, especially in countries like the Netherlands, where approximately 95% of the highway network is surfaced with OGPA mixtures. One option to improve the durability of OGPA mixtures is with the use of premium materials that, despite their high initial cost, the enhanced longevity might offset any future user and intervention costs.

Epoxy asphalt is a premium binder differing from conventional asphalt materials. This binder is a two-part thermosetting system (i.e., it will not melt once cured) of rubbery characteristics originally developed by Shell in the 1960s, and first used as a high-performance surfacing to orthotropic bridge decks (Huang et al. 2003; Lu and Bors 2015). The concept of using this binder in OGPA to develop epoxy-modified open-graded porous asphalt (EMOGPA) mixtures was introduced on roadways under an Organisation for Economic Co-operation and Development (OECD) program (ITF 2017), and since then, comprehensive research has being

---

[1] Researcher, Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft Univ. of Technology, Stevinweg 1, Delft 2628 CN, Netherlands (corresponding author). ORCID: https://orcid.org/0000-0001-5635-4391. Email: p.apostolidis@tudelft.nl

[2] Innovation Manager, Dura Vermeer Infra Participaties BV, Eemnes 3755 LD, Netherlands. Email: r.naus@duravermeer.nl

[3] Associate Professor, Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft Univ. of Technology, Stevinweg 1, Delft 2628 CN, Netherlands. Email: x.liu@tudelft.nl

[4] Pavement Asset Specialist, Provincie Gelderland, Arnhem 6800 GX, Netherlands. Email: r.hermsen@gelderland.nl

[5] Professor, Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft Univ. of Technology, Stevinweg 1, Delft 2628 CN, Netherlands. Email: S.M.J.G.Erkens@tudelft.nl

[6] Professor, Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft Univ. of Technology, Stevinweg 1, Delft 2628 CN, Netherlands; Professor, Dept. of Civil Infrastructure and Environmental Engineering, Khalifa Univ. of Science and Technology, Abu Dhabi, United Arab Emirates. Email: A.Scarpas@tudelft.nl; athanasios.skarpas@ku.ac.ae

Note. This manuscript was submitted on March 30, 2024; approved on August 9, 2024; published online on January 25, 2025. Discussion period open until June 25, 2025; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561.

J. Mater. Civ. Eng., 2025, 37(4): 05025002

conducted in New Zealand (Herrington and Alabaster 2008; Wu et al. 2019), the United States of America (Youtcheff et al. 2006; Yin et al. 2021; Moraes et al. 2023; Dongré et al. 2023), and elsewhere (Widyatmoko and Elliott 2014; Luo et al. 2015; Qian and Lu 2015; Dinnen et al. 2020). In New Zealand, an integrated technical specification on open-graded porous asphalt mixtures with epoxy asphalt has also been published (NZTA 2023). In the Netherlands, pavement mixtures containing epoxy asphalt have been proven to have high strength and stiffness from the micro to macro level (Apostolidis 2022). Evidence regarding the durability and sustainability of EMOGPA materials (Zegard et al. 2019; Jing et al. 2021, 2022, 2023a, b) led to the construction of several test sections in motorways and provincial roads. However, the use of epoxy asphalt binders for surfacing applications is still unregulated in the Netherlands.

Objectives

This study presents an experimental program conducted in a laboratory to assess the durability of drill cores of EMOGPA mixtures from a test road located in the Province of Gelderland, the Netherlands (N837). Loose mixes produced in an asphalt production plant were also obtained to compact EMOGPA mixtures in the laboratory and compare their durability characteristics with those compacted in the field. Drill cores were also sampled from the test road after one year in service as part of a monitoring program to prove the durability benefits of epoxy asphalt. All plant-produced materials were evaluated by performing indirect tensile strength tests before and after oven conditioning to simulate field aging.

Materials and Methods

Materials

The experimental program designed for the scope of this research included one aggregate type and gradation. The sandstone aggregate gradation of OGPA mixtures (PA 8G, normally used in the Province of Gelderland, the Netherlands) had a nominal maximum aggregate size (NMAS) of 8 mm (Table 1) (Jing et al. 2023b). Fibers (i.e., pelletized 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 mixtures and prevent the excessive binder drain-down during construction.

A 70/100 pengraded asphalt binder (Aqualt 70/100 EM supplied by TotalEnergies) was used to produce the EMOGPA mixtures. The epoxy asphalt (EA) binder consists of two parts: part A, which includes epichlorohydrin–bisphenol A (DGEBA), and part B (Table 2). The part B consists of a 70-pen petroleum asphalt binder with heavy naphthenic distillates and crosslinkers derived from nonfood oleochemical sources and are the materials to cure the epoxy part–part A. The EA binder is prepared by mixing part A and part B at a weight ratio of 20:80. Further information about EA can be found in Apostolidis (2022). The EA binder was added to the 70/100 pen binder by 20% (by mass of binder) to fabricate the EMOGPA, named here epoxAC. According to the experience in New Zealand and the Netherlands, it has been concluded that this EA-asphalt ratio can successfully balance cost and performance as the original price of the neat EA is high. A proprietary polymer-modified asphalt binder was also used to fabricate the control OGPA (reference) as recommended by the agency that implements this binder for the single-layer wearing courses. Limestone fillers with hydrated lime were used in reference and epoxAC mixtures.

Table 1. Aggregate gradation of PA8G mixtures

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
Binder content (% m/m)	5.4	6.6	6.0

Note: Bestone 4/8: 84.91%; crushed sand: 3.21%; fiber: 0.30%.

Table 2. Properties of the EA parts

Properties	Value
Part A	
Density at 25°C (g/cm^3)	1.16
Viscosity at 25°C (cP)	11,000–15,000
Boiling point (°C)	>260
Part B, type BX	
Density at 25°C (g/cm^3)	1.00
Melting point/freezing point (°C)	100–150
Initial boiling point (°C)	371.1
Flash point, Cleveland open cup (°C)	>232

Plant Production

A twin axle batch plant was utilized by Dura Vermeer to produce the OGPA mixtures studied in this research. The plant is located in Eemnes, the Netherlands, and is approximately 50 minutes' driving distance from the provincial road selected for implementing the epoxy-modified asphalt. For the use of EA in the plant, an in-line temperature system and a mass flow-control automated distribution unit were installed to fully control the heating conditions of two EA parts (Zegard et al. 2019). Parts A and B, preheated at 75°C and 120°C, respectively, were pumped in the asphalt binder weighing vessel, and the base 70/100 pengraded binder and injection pump achieved the premixing of the EA parts. Afterward, the dried aggregates were added at 120°C, and the produced mixtures were discharged to trucks for transport to the test road. Isolated Live Bottom Belt Asphalt trucks were used for the mixture transport to prevent temperature segregation of the mix entering the paver. The handling conditions in delivering trucks for the construction of the mixtures were decided by the contractor in accordance with Dutch construction standards. The compaction was done by three-wheel static rollers followed by tandem steel wheel vibratory rollers under sunny and dry weather conditions (Fig. 1).

Plant-produced mixtures were sampled immediately after compaction and a year in service and their properties were evaluated according to the test methods mentioned later in the document.

Laboratory Specimens Fabrication

All loose plant-produced mixtures were obtained from the contractor in buckets and were reheated in the same manner to fabricate specimens in the laboratory. The research group of TU Delft obtained loose mixtures, which were produced in the production plant, for laboratory compaction and testing. The first step was to preheat the reference and epoxAC loose mixtures at 180°C and 130°C for 1 h, respectively, before compaction in a gyratory compactor to ensure they were workable enough. Then, the compacted


(a) (b) (c)

Fig. 1. (a and b) View of paving operations; and (c) compacted test section at N837, Province of Gelderland, the Netherlands.

mixtures were stored at 12°C for 1 week, which is a common practice in the laboratory, and afterward tested to assess their mechanical properties. To evaluate the effect of aging on the mechanical properties of these mixtures, oven conditioning was applied for 6 weeks at 85°C. The same oven-conditioning and testing program was implemented for the drill core materials received from the test roads after compaction.

Laboratory compaction was performed using a Superpave gyratory compactor (angle: 0.82 and shear stress: 1,000 kPa) to generate cylindrical samples of 100 mm diameter and 50 mm thickness. The number of gyrations was recorded during compaction to quantify the effort required to reach a predetermined volume for the target height (i.e., 50 mm) and air void content (i.e., 22% volume) of porous asphalt mixtures. The density (kg/m^3) and air void content (%) of mixtures were measured according to NEN-EN 12697-5 (Nederlandse Norm 2019a) and NEN-EN 12697-8 (Nederlandse Norm 2019b), respectively, and the mean values are provided in Table 3.

Laboratory Test Methods

Fig. 2 shows the flowchart of the experimental program performed in this study.

The mechanical properties and durability characteristics of both types of mixtures prepared in the laboratory by plant-produced loose mixtures and obtained drill cores from test roads (immediately after compaction and a year in service) were determined by performing indirect tensile tests (ITTs) [NEN-EN 12697-23 (Nederlandse Norm 2017)] at 15°C with a displacement rate of 50 mm/min, assuming a Poisson's ratio of 0.35. In this way, the indirect tensile strength (ITS), measured in MPa, was determined, while the effect of water on the same material properties was evaluated following NEN-EN 12697-12 (Nederlandse Norm 2018a). The samples were placed in a water bath at 40°C for 72 h. Before the ITT of water-conditioned samples, they were submerged at 15°C for a minimum of 4 h before testing. Unless otherwise stated, the indirect tensile results presented were the mean values of three replicates.

Indirect tensile stiffness modulus measurements [NEN-EN 12697-26 (Nederlandse Norm 2018b)] were also performed by employing a procedure of five frequencies (i.e., 10.0, 5.0, 2.0, 1.0, 0.5 Hz) and three temperatures (i.e., 0°C, 10°C, and 20°C) to evaluate the stiffening effect due to the long-term oven conditioning. The data at all temperatures and frequencies were consolidated to the 20°C reference temperature by employing the Witczak model, with the presented master curves to be the average of three replicates.

Table 3. Physical properties of mixtures

Mixtures	Mix density[a] (kg/m^3)	Air voids content[b] (%)
Reference-lab	1,929 ± 19	21.89 ± 0.77
Reference-field	1,998 ± 17	19.10 ± 0.71
EpoxAC-lab	1,925 ± 22	22.05 ± 0.90
EpoxAC-field	1,976 ± 16	20.00 ± 0.63

[a] Measured according to NEN-EN 12697-5.
[b] Measured according to NEN-EN 12697-8.

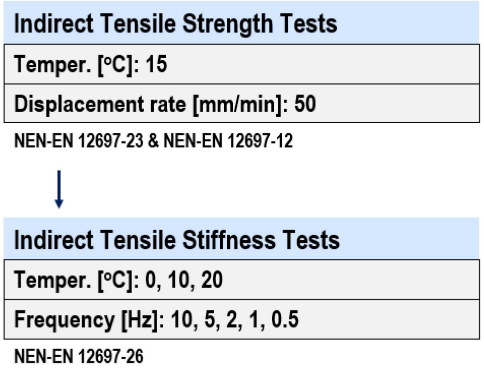

Fig. 2. Flowchart of the experimental program performed in this research.

Results and Discussion

Fig. 3 shows the ITT results of studied mixtures (i.e., representative force-displacement plots), both field- and laboratory-compacted OGPA mixtures, while Table 4 depicts the average ITS values of these materials before and after oven conditioning, with and without water conditioning. The strength values of the compacted epoxAC mixtures increased with the increase in oven conditioning time. The same attribute was observed in the reference mixtures, which showed an increase of strength with the oven preconditioning, but with lower values than epoxAC for both compaction cases. To be specific, epoxAC compacted in the laboratory has shown an increase of strength from 0.70 to 1.56 MPa from 0 to 6 weeks at 85°C, while the field-compacted mixtures containing EA had increased from 0.79 to 1.77 MPa for the same period (Table 4). The strength values of the reference mixtures compacted in the laboratory and field were also increased from 0.62 to 1.09 MPa and from 0.85 to 1.25 MPa, respectively. The results showed slightly higher strength values for the mixtures compacted in the field, which might be linked to the fact that the laboratory-compacted specimens were cooled down during their delivery to the laboratory and then had to be reheated for gyratory compaction.

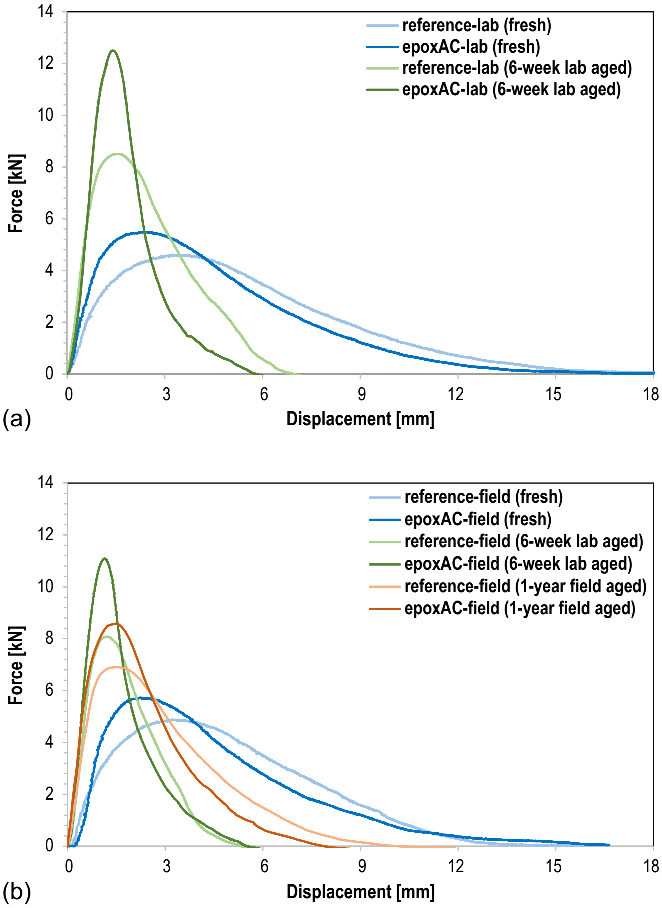

Fig. 3. Change in strength due to oven conditioning for 6 weeks at 85°C and field aging (representative force-displacement plots at 15°C): (a) laboratory-compacted specimens; and (b) field-compacted specimens.

The aforementioned response indicates that the OGPA mixtures containing 20% wt. EA are materials with high strength values in general, and thus are of sufficiently high capacity to withstand mechanical forces to failure. The epoxy-modified asphalt mixtures of the same EA dosage, based on the mechanical testing, can be remelted and reused to produce new pavement materials; see the tests results of mixtures produced in the laboratory (Jing et al. 2022, 2023b). The recyclability attributes of epoxy-modified asphalt mixtures observed in the Netherlands were also confirmed elsewhere (Alamri and Liu 2022).

The studied mixtures exhibited lower strength values after conditioning in a water bath than those without water conditioning. A reduction of tensile strength values was noticed for all mixtures before and after water conditioning, but within the allowable retained strength limits, or <80% indirect tensile strength ratio (ITSR) (Table 4). The ITSR values of field-compacted mixtures were higher compared to those compacted in the laboratory, after oven conditioning (i.e., epoxAC-lab: 85%; epoxAC-field: 91%; reference-lab: 90%; reference-field: 90%), as also seen for the indirect tensile strength (ITS) values without water conditioning and explained as a phenomenon associated to the thermal history differences between mixtures. Both laboratory- and field-compacted mixes were of the same plant-produced loose mixtures.

It worth mentioning that the drill cores of mixtures sampled from the test roads after a year in service indicated the same mechanical response. The one-year field-aged mixtures with EA (i.e., epoxAC) showed higher strength (1.35 MPa) compared to the control OGPA mixture (1.18 MPa). These strength values were higher than the same materials before any conditioning but lower than the materials conditioned in the oven for 6 weeks at 85°C. In both cases, with and without EA, a reduction in ITSR (%) values was evident (i.e., reference-field: 89%; epoxAC-field: 82%), which remained within the allowable limit according to NEN-EN 12697-23.

From the indirect tension test results, the postcracking energy of studied mixtures was calculated in an effort to provide insights into the influence of epoxy asphalt on the capacity of material to absorb energy until rupturing. The postcracking energy parameter corresponds to the area from the moment that the material reaches the peak force until the complete failure divided by the product of height and diameter of specimen. This parameter is determined

Table 4. Change of mixtures strength due to oven conditioning and field aging

	Fresh		1-year field aged		6-week lab aged	
Mixtures	Dry ITS[a] (MPa)	ITSR[b] (%)	Dry ITS[a] (MPa)	ITSR[b] (%)	Dry ITS[a] (MPa)	ITSR[b] (%)
Reference-lab	0.62 ± 0.04	102 ± 2	—	—	1.09 ± 0.07	90 ± 1
Reference-field	0.85 ± 0.07	98 ± 1	1.18 ± 0.05	89 ± 3	1.25 ± 0.11	90 ± 4
EpoxAC-lab	0.70 ± 0.02	101 ± 3	—	—	1.56 ± 0.14	85 ± 1
EpoxAC-field	0.79 ± 0.05	91 ± 1	1.38 ± 0.05	82 ± 1	1.77 ± 0.01	91 ± 6

Note: ITS = indirect tensile strength; and ITSR = indirect tensile strength ratio.
[a] Measured according to NEN-EN 12697-23.
[b] Measured according to NEN-EN 12697-12.

Table 5. Change of mixtures postcracking energy due to oven conditioning and field aging

Mixtures	Fresh		1-year field aged		6-week lab aged	
	Dry postcrack energy (N/mm)	Postcrack energy ratio (%)	Dry postcrack energy (N/mm)	Postcrack energy ratio (%)	Dry postcrack energy (N/mm)	Postcrack energy ratio (%)
Reference-lab	4.81 ± 0.30	104.2	—	—	3.64 ± 0.45	107.1
Reference-field	4.76 ± 0.48	112.4	5.12 ± 0.85	85.2	3.55 ± 0.61	112.7
EpoxAC-lab	4.70 ± 0.44	104.5	—	—	2.99 ± 0.47	92
EpoxAC-field	5.85 ± 0.05	90.1	5.36 ± 1.02	94.8	3.07 ± 0.00	152.1

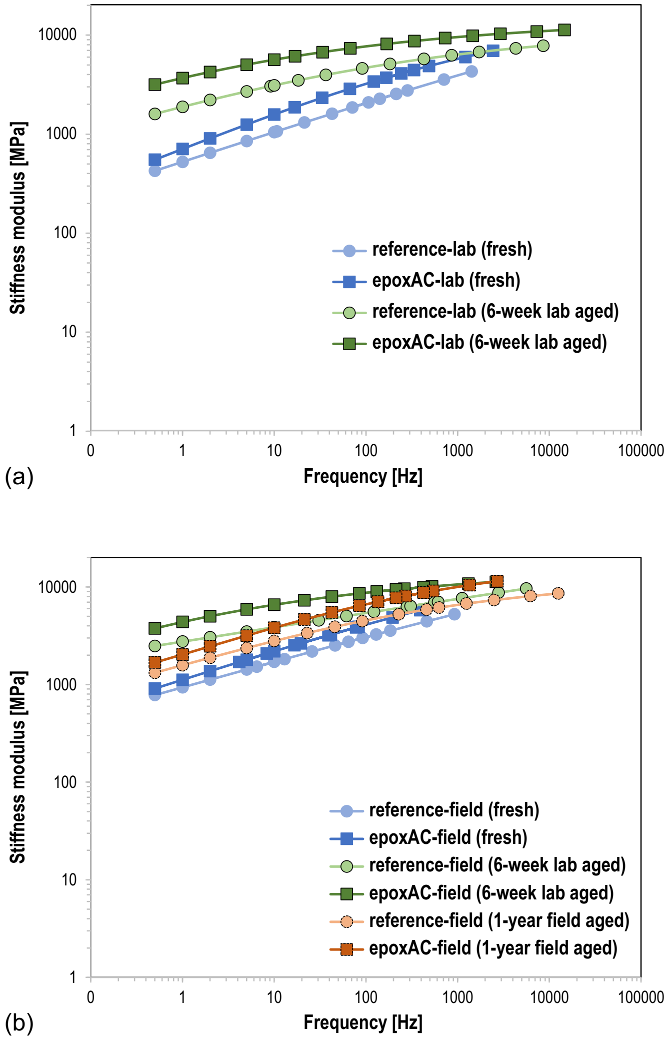

Fig. 4. Change in stiffness modulus due to oven conditioning and field aging: (a) laboratory-compacted specimens; and (b) field-compacted specimens.

using the force-displacement curves, as those presented in Fig. 3, and values of case materials are given in Table 5.

After one year in service, mixtures with EA, or epoxAC, appear to be the most tough materials, both of the highest strength (1.38 MPa, in Table 4) and postcrack energy parameter (5.36 N/mm, in Table 5). The control OGPA mixtures, which were field aged under the same conditions, showed a lower strength (1.18 MPa) and postcrack energy (5.12 N/mm). The trend of the energy in the postcrack performance area was different when the same plant-produced mixtures were aged in the laboratory for 6 weeks at 85°C. Especially, the control mixtures, both compacted in the field and in the laboratory, exhibited higher postcrack energy values (reference-field: 3.55 N/mm; reference-lab: 3.64 N/mm) than the materials with EA (epoxAC-field: 3.07 N/mm; epoxAC-lab: 2.99 N/mm). Moreover, the ratio of energy after water conditioning was calculated and indicated high values in mixtures with EA, such as 94.8% and 152.1% for epoxAC-field after one year in service and six weeks oven conditioning, respectively.

Finally, the stiffness modulus master curves of the two studied mixtures before and after oven conditioning are presented in Fig. 4. Both the reference and epoxAC showed an increase in stiffness modulus at all test frequencies with oven conditioning, with epoxAC demonstrating the highest stiffness values. The frequency dependency of the stiffness of epoxAC mixtures was reduced after 6 weeks in the oven, indicating the response of an elastic material of high stiffness. Again, the materials compacted in the field had slightly higher stiffness values than the laboratory-produced mixtures.

Summary

The main objective of this study was to assess the durability of plant-produced epoxy-modified open-graded porous asphalt mixtures. The loose mixtures from the asphalt plant were used to pave a test road and produce test specimens in the laboratory. Then, the durability of laboratory- and field-compacted mixtures was evaluated by conducting indirect tensile strength and stiffness tests before and after oven conditioning to simulate aging. Indirect tension results of the field materials after one year in service are also presented in this study. The main findings were as follows:

- Both the reference and epoxy-modified open-graded porous asphalt mixtures showed an increase in indirect tensile strength and stiffness modulus with oven conditioning, with the epoxy-modified asphalt demonstrating the highest strength and stiffness values. The same attribute was observed from the test roads after a year in service, showing slightly lower values compared to laboratory-aged mixtures.
- After conditioning in a water bath, the studied mixtures demonstrated lower strength values, compared to the materials without water conditioning. The reduction of strength values of materials resulted after water conditioning but were within the allowable specification limits.
- The materials compacted in the field had slightly higher strength and stiffness values than the laboratory-produced mixtures. Note that both laboratory- and field-compacted mixtures were of the same plant-produced loose materials.

Even though the laboratory results provided here have illustrated the improvement of the mechanical response of open-graded porous asphalt mixtures using epoxy asphalt, further evidence from the continuous collection and testing materials from the test roads is needed for validation.

Data Availability Statement

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

Acknowledgments

Financial support from the Province of Gelderland and Province of Noord Holland for the Epoxy-modified Asphalt Concrete project is gratefully acknowledged.

References

Alamri, M., and Q. Liu. 2022. "Investigation on the inclusion of reclaimed diluted epoxy asphalt pavement materials into hot mix asphalt." *Constr. Build. Mater.* 361 (Dec): 129710. https://doi.org/10.1016/j.conbuildmat.2022.129710.

Apostolidis, P. 2022. "Chemo-mechanics of epoxy-asphalt." Ph.D. thesis, Delft Univ. of Technology. https://repository.tudelft.nl/record/uuid:ec7eedb6-97a1-43a0-b7d9-46e78d0cd046.

Dinnen, J., J. Farrington, and D. Widyatmoko. 2020. "Experience with the use of epoxy-modified bituminous binders in surface courses in England." *Asphalt Prof.* 82 (Feb): 14–21.

Dongré, R., A. Andriescu, M. Elwardany, D. J. Mensching, and J. Youtcheff. 2023. "Exploration of curing characteristics of epoxy-modified asphalt." Accessed February 16, 2023. https://journals.sagepub.com/doi/abs/10.1177/03611981221150445.

Herrington, P., and D. Alabaster. 2008. "Epoxy modified open-graded porous asphalt." *Road Mater. Pavement Des.* 9 (3): 481–498. https://doi.org/10.1080/14680629.2008.9690129.

Huang, W., Z. Qian, and J. Yang. 2003. "Epoxy asphalt concrete paving on the deck of long-span steel bridges." *Chin. Sci. Bull.* 48 (21): 2391–2394. https://doi.org/10.1360/02ww0123.

Huber, G. 2000. *Performance survey on open-graded friction course mixes*. Synthesis of Highway Practice 284. Washington, DC: Transportation Research Board, National Research Council.

ITF (International Transport Forum). 2017. *Long-life surfacings for roads: Field test results*. Paris: Organisation for Economic Co-operation and Development.

Jing, R., P. Apostolidis, X. Liu, S. Erkens, and T. Scarpas. 2021. "Effect of mineral fillers on oxidative aging of epoxy bitumen." *J. Mater. Civ. Eng.* 33 (12): 04021360. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004003.

Jing, R., P. Apostolidis, X. Liu, S. Erkens, and T. Scarpas. 2023a. "First-year field performance of epoxy-modified asphalt." *Transp. Res. Rec.* 2677 (3): 1110–1122. https://doi.org/10.1177/03611981221121271.

Jing, R., P. Apostolidis, X. Liu, R. Naus, S. Erkens, and A. Scarpas. 2022. "Effect of recycling agents in rheological properties of epoxy bitumen." *Road Mater. Pavement Des.* 23 (11): 2592–2606. https://doi.org/10.1080/14680629.2021.1986122.

Jing, R., P. Apostolidis, X. Liu, R. Naus, S. Erkens, and T. Scarpas. 2023b. "Recyclability of epoxy-modified open-graded porous asphalt." In *Proc., 3rd Int. Conf. on Advances in Materials and Pavement Performance Prediction*. Delft, Netherlands: Delft Univ. of Technology.

Kandhal, P. S., and R. B. Mallick. 1999. *Design of new-generation open-graded friction courses*. Rep. No. 99-93. Auburn, AL: National Center of Asphalt Technology.

Lu, Q., and J. Bors. 2015. "Alternate uses of epoxy asphalt on bridge decks and roadways." *Constr. Build. Mater.* 78 (Mar): 18–25. https://doi.org/10.1016/j.conbuildmat.2014.12.125.

Luo, S., Q. Lu, and Z. Qian. 2015. "Performance evaluation of epoxy modified open-graded porous asphalt concrete." *Constr. Build. Mater.* 76 (Feb): 97–102. https://doi.org/10.1016/j.conbuildmat.2014.11.057.

Moraes, R., A. Anand, and F. Yin. 2023. "Laboratory approach for the selection of compatible epoxy-modified asphalt binders." *Transp. Res. Rec.* 2677 (10): 676–687. https://doi.org/10.1177/03611981231163829.

NASEM (National Academies of Sciences, Engineering and Medicine). 2009. *Construction and maintenance practices for permeable friction courses*. Washington, DC: National Academies Press.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2018. *Performance-based mix design for porous friction courses*. Washington, DC: National Academies Press.

Nederlandse Norm. 2017. *Bituminous mixtures—Test methods—Part 23: Determination of the indirect tensile strength of bituminous specimens*. NEN-EN 12697-23. Brussels, Belgium: European Committee for Standardization.

Nederlandse Norm. 2018a. *Bituminous mixtures—Test methods—Part 12: Determination of the water sensitivity of bituminous specimens*. NEN-EN 12697-12. Brussels, Belgium: European Committee for Standardization.

Nederlandse Norm. 2018b. *Bituminous mixtures—Test methods—Part 26: Stiffness*. NEN-EN 12697-26. Brussels, Belgium: European Committee for Standardization.

Nederlandse Norm. 2019a. *Bituminous mixtures—Test methods—Part 5: Determination of the maximum density*. NEN-EN 12697-5. Brussels, Belgium: European Committee for Standardization.

Nederlandse Norm. 2019b. *Bituminous mixtures—Test methods—Part 8: Determination of void characteristics of bituminous specimens*. NEN-EN 12697-8. Brussels, Belgium: European Committee for Standardization.

NZTA (New Zealand Transport Agency—Waka Kotahi). 2023. *Specification for open-graded porous asphalt*. NZTA P11:2023. Auckland, New Zealand: NZTA.

Qian, Z., and Q. Lu. 2015. "Design and laboratory evaluation of small particle porous epoxy asphalt surface mixture for roadway pavements." *Constr. Build. Mater.* 77 (Feb): 110–116. https://doi.org/10.1016/j.conbuildmat.2014.12.056.

Widyatmoko, I., and R. C. Elliott. 2014. "Strength characteristics and durability of epoxy asphalts." *Proc. Inst. Civ. Eng. Constr. Mater* 167 (5): 241–250. https://doi.org/10.1680/coma.13.00029.

Wu, J. P., P. R. Herrington, and D. Alabaster. 2019. "Long-term durability of epoxy-modified open-graded porous asphalt wearing course." *Int. J. Pavement Eng.* 20 (8): 920–927. https://doi.org/10.1080/10298436.2017.1366764.

Yin, F., A. Anand, R. Moraes, N. Tran, R. West, and F. Gu. 2021. *Design and performance of open-graded friction course (OGFC) mixtures containing epoxy asphalt*. Auburn, AL: National Center for Asphalt Technology, Auburn Univ.

Youtcheff, J., N. Gibson, A. Shenoy, and G. Al-Khateeb. 2006. "The evaluation of epoxy asphalt and epoxy asphalt mixtures." In Vol. 51 of *Proc., Canadian Technical Asphalt Association*, 351–368. Laval, QC, Canada: Polyscience Publications.

Zegard, A., L. Smal, R. Naus, P. Apostolidis, X. Liu, M. F. C. van de Ven, S. Erkens, and A. Scarpas. 2019. "Long-lasting surfacing pavements using epoxy asphalt: Province of North Holland case study." In *Proc., Transportation Research Board 98th Annual Meeting*. Washington, DC: Transportation Research Board.