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Life cycle assessment of epoxy-modified asphalt pavement

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ABSTRACT: This research aims to evaluate the potential environmental impact of epoxy-modified asphalt used as a pavement material for roadways in the Netherlands and identify what determines the environmental performance of the epoxy asphalt technology through life cycle assessment. Results indicated that the incorporation of epoxy binder in asphalt could lead to significantly lower environmental impact than the unmodified asphalt. Such benefits are attributed by the minimal maintenance interventions of a pavement with epoxy and their remarkably higher service life over the analysis period. Finally, although the initial price of epoxy-modified asphalt production and construction was substantially higher than of standard asphalt mixtures, the overall score of epoxy-modified asphalt pavement in all weight scenarios was lower than that of the reference structures reflecting the sustainability benefits of using this technology for roadway pavements.

1 INTRODUCTION

In recent years, increasing environmental awareness has encouraged research in the environmental impacts of various products for pavement structures. Products such as asphalt-rubber (Hicks & Epps 2000), recycled polyethylene-modified asphalt (Rangelov et al. 2021), and epoxy-modified asphalt (Herrington 2010) are some examples toward sustainable flexible pavements. Notably, epoxy-modified asphalt has attracted the attention of road authorities in many countries as a feasible solution for developing long-life pavements. Economic analyses funded by an Organisation for Economic Co-operation and Development (OECD) project have indicated the benefits of epoxy-modified porous asphalt concrete performance and the potential for reducing costs by diluting a commercially available epoxy binder with a standard binder (OECD 2017). According to another study performed by the same agency, the epoxy-modified porous asphalt mixes show a potential lifetime of 30 years compared with the average life of 7,5 years of standard open-graded porous asphalt mixes (Alabaster et al., 2017). The resurfacing budget can be reduced to 1/6 of its current level when 25% epoxy binder is diluted in a standard binder (assuming a 40-years life period), also providing high noise reduction benefits. All these figures imply that epoxy-modified asphalt as long-life surfacing material is a sound investment that could be applied in other regions globally.

This research aims to assess the environmental impact of epoxy-modified asphalt used as a pavement material for roadways in the Netherlands and identify what determines the environmental performance of this technology through life cycle assessment. Typically, the environmental performance of a pavement material or structure is multifaceted and context-sensitive, and the various trade-offs of performance from different perspectives are common. This research also discusses an environmental assessment approach for innovative pavement materials considering their merits and trade-offs and, ultimately, their life-cycle performance.

2 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a methodology to quantify and evaluate the environmental impact of products and processes by accounting for relevant input and output parameters of a system and the conversion and interpretation of output parameters into potential environmental impacts. All the life-cycle stages are encompassed in LCA, from the material acquisition through production, construction, maintenance, use, and disposal. The goal and scope definition described the product regarding the boundaries and selection of a function unit. The latter gives the comparison basis between the alternative products.

Although it is well known that the incorporation of epoxy in asphalt leads to the formulation of epoxy-modified asphalt, which can enhance the performance of asphalt pavement (Youtcheff et al., 2006; Widyatmoko & Elliott 2014; Lu & Bors 2015; Apostolidis et al., 2020), the high cost of epoxy binders has prohibited their regular use in pavements. A flexible pavement made with epoxy-modified asphalt concrete (epoxAC) optimized in (Apostolidis et al., 2019; 2020 & 2022) was the product case of this research (see Figure 1). This product was assessed and compared with a standard pavement material commonly used for roads in the Netherlands (Zegard et al., 2019).

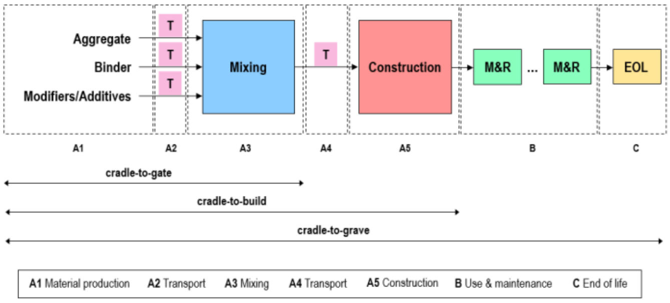

Figure 1. One lane mile of pavement product.

To contextualize the results, a declared unit of 1 ton of a pavement mix is presented over the material production. As no extra modifications are needed over the delivery and construction phase of epoxAC compared to a standard mix (OECD 2017), emphasis was given on the material production phase. Thus, the life-cycle phases beyond the material production, which are included as a functional unit of one lane-mile of pavement structure, were considered equal environmental impacts between standard asphalt (reference) and epoxAC. Specifically,

- the cradle-to-gate analysis includes a functional unit (i.e., performance) of 1 ton of a pavement mix produced in the asphalt plant. For this part of the analysis, which consists of extraction, transportation, and mixing of all individual components of pavement material (i.e., A1-A3 in Figure 1), reference and epoxAC mixes had the same binder content of 6,7% of the weight of mineral particles (Apostolidis et al., 2020). The mixing temperatures and duration of epoxy-modified asphalt with minerals were the same as a warm asphalt mix. In this research, the reference mix was modeled as a warm mix asphalt; thus, it was assumed that there was no difference in the total mixing energy consumed to produce both mixes.
- the cradle-to-built analysis includes a functional unit of one lane-mile of a pavement constructed with different mixes. Here, pavements should be evaluated by comparable performance beyond the construction phase. A critical aspect of this part is to vary the thickness of pavements to obtain equal performance in terms of environmental impacts compared to other alternative solutions. In this research, the thickness of the surface pavement layer was considered the same for both reference and epoxAC mixes (35-mm) (Zegard et al., 2019). The material hauling and placement processes were included in the construction phase (i.e., A4 & A5 in Figure 1).
- the cradle-to-grave analysis includes all life-cycle phases for a functional unit of one lane-mile of a pavement. For the cradle-to-grave scope, the performance of pavements should be assessed by accounting through different intervals between maintenance and rehabilitation (M&R) actions to restore pavement serviceability (i.e., B in Figure 1). The M&R actions were milling and repaving of the top surface pavement layer with a new mix with the same mix design used in the initial construction phase. A critical aspect of this part is to alter the timing between M&R actions to reach equal annualized environmental impacts to the alternatives. A schematic of cradle-to-grave analysis is demonstrated in Figure 2, with materials production and pavement construction happening at the time zero, followed by subsequent M&R actions of certain time intervals, and finally with end-of-life (EOL) actions, which include the removal of the total pavement thickness when the pavement reaches its terminal serviceability (i.e., C in Figure 1). Here, epoxAC was considered as a M&R free product (see Figure 2-bottom) due to its enhanced aging resistance and mechanical performance characteristics. As both reference and epoxAC materials have shown similar recyclability characteristics (Jing et al., 2021), they were treated the same in terms of EOL actions.

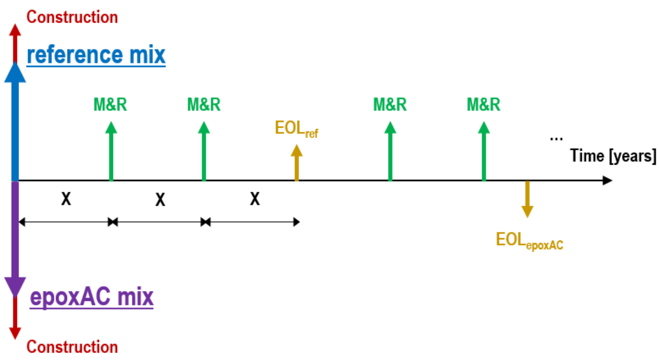

Figure 2. Schematic of cradle-to-grave analysis framework. Parameter X represents the baseline time intervals between the subsequent M&R interventions.

3 LIFE CYCLE COST ANALYSIS

A simplified life cycle cost analysis (LCCA) was conducted, considering the service life and agency costs of epoxAC to determine its overall economic feasibility. Particularly,

- The laboratory fatigue performance of epoxAC is discussed in (Apostolidis et al., 2020). By selecting a tensile strain of 200 μstrain, the fatigue life of epoxAC is almost 230.000 load repetitions comparing the 60.000 load repetitions of reference. Hence, the fatigue life of epoxAC was approximately 4 times longer than that of reference (see strain level of 200 μstrains in Table 1), and this fatigue lifetime difference was considered in the present analysis.
- The LCCA analysis considered only the agency costs and ignored the user costs during (re)paving operations (e.g., user delay cost, accident cost, and extra fuel consumption cost). The life-cycle agency cost includes all operating costs from the mate-

rial supply to mixing, construction, M&R, and EOL (i.e., A1-C). It should be mentioned that using epoxy binder in asphalt mixes requires equipment modification in the plant. Thus, the cost change due to the use of epoxAC is mainly associated with the cost of binder and production equipment, or the agency cost difference due to the use of epoxAC is primarily caused by the cost of purchasing the epoxy binder and modifying equipment during the A1-A3 processes. An earlier study noted that the total cost of epoxy asphalt production is close to \$ 44/m^2 (i.e., the material cost of the epoxy binder is in the order of \$ 22/m^2, batch plant expenses, and installation are approximately \$ 22/m^2) (OECD 2005). For this analysis, the costs of A4-A5 and C for the reference and epoxAC were assumed to be equal.

Table 1. Fatigue lifetime of studied materials at different tensile strain levels.

Tensile Strain [µstrain]	25	100	200	300
reference, N_{f_ref}	1,25E9	1,65E6	6,01E4	8,66E3
epoxAC, N_{f_epoxAC}	3,2E10	1,18E7	2,27E5	2,25E4
N_{f_epoxAC}/ N_{f_ref}	25,7	7,2	3,8	2,6

According to the material supplier, the cost of epoxy-asphalt binder is € 6.000/ton. The cost of a standard asphalt binder is approximately € 520/ton. Thus, the cost of epoxy-modified asphalt binder, which is formulated by 20% of epoxy-asphalt and 80% of standard binder, is € 1.880/ton, or the initial cost of the epoxAC binder is 3,1 times higher than the reference one. Hence, the initial cost of the reference and epoxAC binders is € 2,1/m^2 and € 6,5/m^2, respectively. Assuming that the cost of reference (SMA NL 8B: 6,7% binder content, 30-mm thickness, 5,5% air void content, 2,45 t m-3 mix density) is approximately € 80/ton, then the additional cost of epoxAC is € 4,4/m^2.

The net present value (NPVC) of the paving costs, which is assumed equal to the repaving costs, is calculated by

$$NPV_C = C_{initial} - \frac{C_{terminal}}{(1+r)^{n_e}} + \sum_{i=1}^{N=[\frac{n_e}{n_l}]} \frac{C}{(1+r)^{n_k}} \quad (1)$$

where $C_{initial}$ is the initial construction cost, $C_{terminal}$ is the terminal product value, C is the future (re)paving cost, n_e is the analysis period, n_l is the product service life, $N=[n_e/n_l]$ is the number of future (re)paving actions for a product during the analysis period of ne years; r is the discount rate, n_k is the number of years from initial construction to the kth expenditure (Gu & Tran 2019).

In this study, the total service life of epoxAC was assumed as the analysis period with 4% discount rate. The epoxAC mix lasts almost 4 times longer than the reference mixes or shows a service life of 48 years (i.e., n_e = 84 years, n_l = 12 years). The NPV_C of reference and epoxAC is hence calculated as € 13,4/m^{2,} and € 13,5/m^2, respectively, or the unit cost of a square meter pavement with reference and epoxAC is € 13,4 and € 13,5, respectively.

4 LIFE CYCLE INVENTORY AND LIFE CYCLE IMPACT ASSESSMENT

Life cycle inventory (LCI) estimates the consumption of resources and the quantities of waste and emissions associated with the mix production and its components. For the production and transport to the market of the raw materials needed for producing the studied materials, LCI was used from Ecoinvent 3.5. Inventories were taken from the National Milieu Database for asphalt and mineral aggregates, which does not include transport from the refinery to the asphalt mix production plant.

Table 2. Environmental impact score of studied materials.

		reference mix		epoxAC mix	
Environmental impact	Unit	A1-A3	Total	A1-A3	Total
Environmental cost indicator (MKI)	€	10,73	6,27	14,29	9,96
Abiotic depletion (ADPE)	kg Sb-eq	3,5E-5	1,9E-5	1,1E-4	8,9E-5
Depletion of fossil energy carriers (ADPF)	kg Sb-eq	1,8E+0	1,0E+0	1,9E+0	1,1E+0
Global warming (GWP)	kg CO_2-eq	8,6E+1	5,3E+1	9,8E+1	6,6E+1
Ozone depletion (ODP)	kg CFC-11-eq	9,0E-6	6,1E-6	9,9E-6	7,1E-6
Photochemical ozone creation (POCP)	kg ethene-eq	1,8E-1	9,0E-2	2,1E-1	1,2E-1
Acidification (AP)	kg SO_2-eq	5,2E-1	2,7E-1	5,7E-1	3,3E-1
Eutrophication (EP)	kg PO_4^{3-} - eq	5,3E-2	2,9E-2	6,3E-2	4,0E-2
Human toxicological effects (HTP)	kg 1,4-DB-eq	2,3E+1	1,4E+1	5,0E+1	4,2E+1
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DB-eq	2,6E+0	1,8E+0	4,8E+0	4,1E+0
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DB-eq	1,1E+4	6,1E+3	1,1E+4	6,3E+3
Terrestrial ecotoxicity (TETP)	kg 1,4-DB-eq	3,5E-1	1,7E-1	3,6E-1	1,9E-1

The environmental impact categories assessed were acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), and smog creation potential (SCP). Table 2, supplied by Dura Vermeer Infra Participaties B.V., records the environmental impact per category of a declared unit of 1 ton of reference and epoxAC. The material and production phases are the main source of contributions for all impact categories and differences between the two studied materials. The results indicate that the environmental cost indicator (MKI) of epoxAC is equal to € 9,96 and higher than that of the reference mix (€ 6,27).

As mentioned above, it is assumed that epoxAC could last 4 times longer than reference mixes; thus, the total MKI of epoxAC is € 19,92; of the reference, one is € 31,35. Therefore, the incorporation of epoxy binder in asphalt leads to significantly lower environmental impact than the unmodified asphalt (i.e., reference) over the analysis period reflecting the environmental benefits of using the epoxAC technology for roadways.

5 OVERALL PERFORMANCE

The weighted environmental and economic cost scores were calculated for reference and epoxAC assuming different weight scenarios. Although the initial construction cost of epoxAC is significantly higher than that of the reference, the overall score of epoxAC in all weight scenarios is lower than that of the reference mix due to its higher service life (Table 3). For example, the overall performance for the reference mix is € 22,41, and the overall performance score for epoxAC is € 16,72, assuming a weight of 50% for economic and 50% for environmental factors.

Table 3. Life cycle performance of the studied materials at different weight scenarios.

Environmental-Economic	70-30	60-40	50-50	46-60	30-70
reference (€)	18,83	20,62	22,41	24,19	25,98
epoxAC (€)	18,00	17,36	16,72	16,08	15,43

6 SUMMARY

This research aimed to evaluate the potential environmental impact of epoxy-modified asphalt used as a pavement material and identify what determines the environmental performance of the epoxy asphalt technology through life cycle assessment. Results indicated that incorporating epoxy binder in asphalt could lead to significantly lower environmental impact than unmodified asphalt. Such benefits are attributed to the minimal maintenance interventions of pavement with epoxy and their remarkably higher service life over the analysis period. Although the initial price of epoxy-modified asphalt production and construction was substantially higher than that of standard asphalt mixes, the overall score of epoxy-modified asphalt pavement in all weight scenarios was lower than that of the reference structures, reflecting the sustainability benefits of using this technology for roadway pavements.

7 ACKNOWLEDGMENTS

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8 REFERENCES

Alabaster, D., Forrest, J., Waters, J. & Herrington, P. 2017. Implementation of a Long Life Low Noise Surface. *In World Conference on Pavement and Asset Management.* Milan Italy, 12-16 June.

Apostolidis, P., Liu, X., Erkens, S. & Scarpas, A. 2019. Evaluation of Epoxy Modification in Bitumen. *Construction and Building Materials* 208: 361-368.

Apostolidis, P., Liu, X., Erkens, S. & Scarpas, A. 2020. Use of Epoxy Asphalt as Surfacing and Tack Coat Material for Roadway Pavements. *Construction and Building Materials* 250: 118936.

Apostolidis, P., Liu, X., Erkens, S. & Scarpas, A. 2022. Oxidative Aging of Epoxy Asphalt. *International Journal in Pavement Engineering* 23(5): 1471-81.

Gu, F. & Tran, N. 2019. Best Practices for Determining Life Cycle Costs of Asphalt Pavements. *NCAT Report* 19-03.

Herrington, P. 2010. Epoxy-Modified Porous Asphalt. *NZ Transport Agency Research Report* 410.

Hicks, R. & Epps, J. 2000. Life Cycle Costs for Asphalt-Rubber Paving Materials. *Australian Asphalt Pavement Association*.

Jing, R., Apostolidis, P., Liu, X., Naus, R., Erkens, S. & Skarpas, A. 2021. Effect of Recycling Agents in Rheological Properties of Epoxy Bitumen. *Road Materials & Pavement Design*.

Lu, Q. & Bors, J. 2015. Alternate Uses of Epoxy Asphalt on Bridge Decks and Roadways. *Construction and Building Materials* 78: 18-25.

OECD. 2005. Economic Evaluation of Long-Life Pavements: Phase 1.

OECD. 2017. Long-Life Surfacings for Roads: Field Test Results.

Rangelov, M., Dylla, H. & Sivaneswaran, N. 2021. Life Cycle Assessment of Asphalt Pavements with Recycled Post-Consumer Polyethylene. *Transportation Research Record* 2675(12): 1393-1407.

Widyatmoko, I. & Elliott, R. 2014. Strength Characteristics and Durability of Epoxy Asphalts. *Proceedings of the Institution of Civil Engineers*, 1300029.

Youtcheff, J., Gibson, N., Shenoy, A. & Al-Khateeb. G. 2006. The Evaluation of Epoxy Asphalt and Epoxy Asphalt Mixtures. *Proceedings of the Canadian Technical Asphalt Association* 51: 351-368.

Zegard, A., Smal, L., Naus, R., Apostolidis, P., Liu, X., Van de Ven, M., Erkens, S. & Scarpas, A. 2019. Long-Lasting Surfacing Pavements using Epoxy Asphalt: Province of North Holland Case Study. *Transportation Research Board 98th Annual Meeting*, Washington D.C. United Stated.