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Investigation of Fatigue Performance of Hot Mix Asphalt Mixtures Modified with Elvaloy and Phosphoric Acid (PPA) as an Alternative to SBS Polymer

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Abstract: In this study, the combined use of Elvaloy and phosphoric acid (PPA) was investigated to enhance the performance of asphalt concrete (Hot Mix Asphalt - HMA) layers used in flexible pavement structures under increasing traffic loads and environmental conditions. These additives, considered as alternatives to Styrene-Butadiene-Styrene (SBS) polymer, were evaluated solely for their effects on the mechanical performance of HMA mixtures. Binders modified with Elvaloy/PPA at specified proportions were used to produce HMA specimens, and indirect tensile fatigue tests were conducted on these samples. The experimental results indicated that the addition of Elvaloy and PPA improved the mechanical properties of mixtures prepared with bituminous binders, extended fatigue life, and enhanced the strength and deformation resistance of asphalt mixtures at the selected proportions. The findings suggest that the Elvaloy/PPA additive combination could be a viable alternative to SBS polymer and has the potential to extend the service life of hot mix asphalt. Thus, it was concluded that the use of these additives contributes to improving HMA performance and supports sustainable pavement design.

Keywords: Hot mix asphalt, Elvaloy, Phosphoric acid, Polymer modification, Fatigue performance

Introduction

Asphalt is one of the oldest construction materials and has been highly valued since ancient times due to its waterproofing and adhesive properties (Janoo & Korhonen, 1999). In the early stages, natural asphalt was processed at high temperatures to remove oily fractions and preserve high molecular weight components, which allowed it to be used in various engineering applications thanks to its thermoplastic characteristics. Today, asphalt is obtained as a high-viscosity residue from the distillation of crude oil, and its properties vary depending on both the origin of the crude oil and the production processes (Lav & Lav, 2004). Due to its complex structure, asphalt is still not fully understood. Although various methods have been employed to investigate its composition (Francken, 1998; Kumar et al., 2006; Nicholls, 1998; Sengoz & Isikyakar, 2008), it is generally accepted that asphalt is a colloidal system composed of asphaltenes and maltenes (Tayfur et al., 2007). The degree of dispersion of asphaltenes within maltenes and the characteristics of hydrocarbons determine critical engineering properties such as fatigue cracking resistance, rutting resistance, low-temperature cracking resistance, and oxidation resistance. In particular, oxidation leads to the hardening of asphalt, making it brittle and susceptible to cracking (Kok & Yilmaz, 2009). To improve its engineering performance, asphalt is frequently modified with polymers. Depending on their structural characteristics, the polymers used for asphalt modification are classified into three main groups: plastomers, elastomers, and reactive polymers. Plastomers (e.g., polyethylene, polypropylene) exhibit limited compatibility with asphalt, which often results in phase separation problems (Cortizo et al., 2004; Gorkem & Sengoz, 2009; Vlachovicova et al., 2007). To reduce this incompatibility, modification techniques with polar groups are applied. On the other hand, thermoplastic elastomers are the most widely used group of polymers in the asphalt industry. Styrene-butadiene-styrene (SBS) and styrene-isoprene-styrene (SIS) block copolymers are particularly important representatives, as they absorb oily fractions, swell, and form a three-dimensional polymeric network within asphalt, thereby improving its rheological properties (Meyer et al., 2017). For this reason, a considerable number of studies have been conducted on SBS-modified asphalts (Meyer et al., 2017; Singh & Kumar, 2019; Stark & Jaunich, 2011). Although SBS modification improves elasticity and high-temperature performance, it suffers from the drawback of limited compatibility, which leads to phase separation at elevated temperatures. Unlike plastomers and thermoplastic elastomers, reactive elastomeric terpolymers (RET) provide a different approach to asphalt modification. RETs form a three-dimensional system through covalent cross-linking under the influence of heat, pressure, or catalysts. This structure eliminates the ability of the material to melt or dissolve, thereby creating a permanent network. Maleic anhydride-modified elastomers, ethylene-based copolymers containing epoxy rings, and ethylene terpolymers with glycidyl methacrylate and acrylate groups are examples of RETs used in asphalt modification.

Asphalt has been used as a valuable construction material since ancient times due to its waterproofing and adhesive properties (Janoo & Korhonen, 1999). In the early periods, natural asphalt was processed at high temperatures to remove oily fractions and, thanks to its thermoplastic characteristics, was utilized in various engineering applications. Today, asphalt is obtained as a high-viscosity residue from crude oil distillation, and its properties vary depending on the production process and the origin of the crude oil (Lav & Lav, 2004). Due to its complex structure, the internal composition of asphalt has not been fully understood. Research conducted using various methods (Francken, 1998; Kumar et al., 2006; Nicholls , 1998; Sengoz & Isikyakar, 2008)has revealed that asphalt is a colloidal system composed of asphaltenes and maltenes (Tayfur et al., 2007) The dispersion of asphaltenes within maltenes and the nature of hydrocarbons determine critical engineering properties such as fatigue cracking resistance, rutting resistance, low-temperature performance, and oxidation resistance. In particular, oxidation leads to the hardening of asphalt, making it brittle and prone to cracking (Kok & Yilmaz, 2009).

Polymer modification is a widely used approach to improve the performance of asphalt. Polymers are generally classified into three groups: plastomers, elastomers, and reactive polymers. Plastomers (e.g., polyethylene, polypropylene) exhibit limited compatibility with asphalt, often leading to phase separation (Cortizo et al., 2004; Vlachovicova et al., 2007), whereas thermoplastic elastomers are among the most successful additives in the asphalt industry. Styrene-butadiene-styrene (SBS) and styrene-isoprene-styrene (SIS) copolymers absorb maltenes, forming a three-dimensional polymeric network that enhances the rheological properties of asphalt. Studies on SBS-modified asphalts (Meyer et al., 2017; Singh & Kumar, 2019; Stark & Jaunich, 2011)have demonstrated improvements in elastic response and high-temperature performance; however, limited compatibility at elevated temperatures results in phase separation, which is a major drawback (Liang et al., 2017). In contrast, reactive elastomeric terpolymers (RET) offer a different approach to asphalt modification. RETs undergo covalent cross-linking under the influence of heat, pressure, or catalysts, forming a permanent three-dimensional network that eliminates the ability to melt or dissolve. Examples of RETs used in asphalt modification include maleic anhydride-modified elastomers, ethylene-based copolymers containing epoxy rings, and ethylene terpolymers incorporating glycidyl methacrylate and acrylate groups.

Although numerous studies in the literature have focused on SBS modification, research on the combined use of Elvaloy and phosphoric acid (PPA) remains limited. This study addresses this gap by investigating the effects of these additives on the mechanical performance of hot mix asphalt (HMA) used in flexible pavements, thereby proposing a novel approach as a potential alternative to SBS. The originality of this work lies in the combined use of Elvaloy and PPA at specific proportions, which is aimed at extending fatigue life, enhancing strength, and improving deformation resistance. Thus, the findings not only demonstrate performance improvements but also introduce a promising method that can contribute to sustainable pavement design.

Materials and Method

Materials and Preparation of Modified Bitumen

In this study, B 50/70 grade bitumen supplied from TÜPRAŞ Batman Refinery was used as the base binder. The neat bitumen was modified with Elvaloy and phosphoric acid (PPA), which were provided by Komsa Company. Within the scope of the experimental design, Elvaloy and PPA were incorporated into the base bitumen at three different proportions (0.8%+2%, 0.9%+1%, and 1%+0%) to prepare the target binders. The binder preparation process consisted of the following steps:

- The neat bitumen was kept in an oven at 180 ± 5 °C for 30 minutes to become fluid.

- The fluid bitumen was then transferred into the metal container of the mechanical mixer in 500 g portions.
- To ensure a homogeneous thermal environment, the container was placed on a heater stabilized at 180 ± 5 °C and kept until thermal equilibrium was reached.
- After the addition of Elvaloy into the hot bitumen, the mixture was stirred for 5 hours using a mechanical mixer operating at 800 rpm.

Subsequently, PPA was added, and the mixing process was continued for an additional 30 minutes (Figure 1). The abbreviations of the neat and Elvaloy/PPA-modified binders used in this study are presented in Table 1, while the gradation and physical properties of the aggregates are given in Table 2.

Table 1. Abbreviations used for bituminous binders in the study

Additive used	Additive ratio used by binder weight (%)			
Elvaloy	0.8	0.9	1	0
PPA	0.2	0.1	0	0
Impression	E1	E2	E3	Pure

Table 2. Aggregate properties and gradation

					Coarse		Fine		Filler		Specification limit	Test Standard
Los Angeles abrasion (%) ASTM D131					25		-		-		Maks. 35	ASTM C-131
Weather resistance ($MgSO_4$) ASTM C88					12		-		-		Maks. 10	ASTM C-88
Smooth and long grain (%) BS 812					20		-		-		Maks. 10	ASTM D-4791
Water absorption (%) ASTM C127					0.8		-		-		-	-
Bulk specific gravityASTM C127, C128					2.521		2.558				-	-
Apparent specific gravityASTM D854					-		-		2.596		-	-
Aggregate gradation												
Sieve diameter (mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	-	-
% Passing	100	95	88	65	35	23	14	10	8	6	-	-

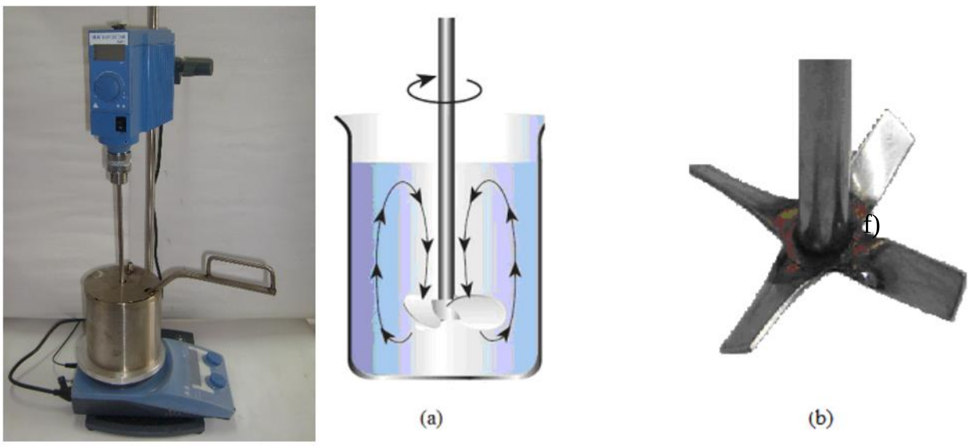

Figure 1. Laboratory mixing device; (a) mixing effect and (b) four blades

Hot mix asphalt (HMA) specimens were prepared using neat and Elvaloy/PPA-modified binders. The specimens were compacted according to the Marshall method by applying 75 blows to each side. The limestone used in the mixtures was supplied from the Karayazı region of Elazıg. The optimum bitumen content was determined based on mixtures prepared with the neat binder, and the modified mixtures were produced using the same bitumen content. Table 3 presents the volumetric properties of the neat and modified mixtures prepared with 5% bitumen content, including air voids (Va), voids filled with asphalt (VFA), voids in mineral aggregate (VMA), bulk specific gravity (Gmb), as well as mixing and compaction temperatures. The mixing and compaction temperatures of the mixtures were determined using the rotational viscometer method, corresponding to viscosity values of 170 ± 20 cP and 280 ± 30 cP, respectively (JP, 2004). The evaluation results indicated that the prepared mixtures met the volumetric requirements of the Highway Technical Specifications (HTS).

Table 3. Volumetric properties of mixture samples

Mixtures	Bitumen (%)	Mixing temperature (ºC)	Compaction temperature (ºC)	Va (%)	VFA (%)	VMA (%)	Gmb
Pure	5	171	158	3.78	74.3	14.7	2.292
E1	5	184	175	3.69	74.7	14.6	2.295
E2	5	182	173	3.92	73.5	14.8	2.289
E3	5	180	170	3.56	74.0	14.9	2.285

Fatigue Tests

Bituminous materials used in highway pavements are subjected to short-term repeated stresses with each passing vehicle load. Over time, these stresses lead to the formation of micro-damages within the material, which gradually accumulate and evolve into fatigue cracks. Fatigue cracking is one of the most common types of distress in hot mix asphalt, characterized by crack initiation and progressive propagation under repeated loading. The indirect tensile fatigue test is commonly used to evaluate fatigue behavior, where cylindrical specimens are subjected to repeated compressive loads along the vertical diametral plane. This loading configuration induces tensile stresses perpendicular to the applied load direction, eventually causing the specimen to fracture through its middle section. The tests were performed under stress-controlled conditions using a UTM device, and the test system, equipped with a temperature-controlled chamber, enabled experiments at various temperatures beyond the standard test condition. Prior to testing, specimens were conditioned at the target temperature for at least three hours. Specimen dimensions, load frequency, load increment durations, and applied stress levels were pre-defined in the system. Once the specimen was placed in the loading frame, LVDT (linear variable differential transformer) sensors were adjusted to measure vertical deformations, and the test was initiated. Loading continued until complete failure of the specimen. Fatigue life was defined either as the point of significant slope change on the load repetition deformation curve or as the intersection of tangents drawn to the second and third regions of the curve (Aragão et al., 2010; Khodaii & Mehrara, 2009).

Results and Discussion

In the indirect tensile fatigue tests, repeated loading was applied to the specimens until failure occurred, thereby determining the maximum number of load repetitions (N_{max}) and the corresponding deformation at this point (δ_{max}). The fatigue life (N_f) was calculated from the intersection of tangents drawn to the second (II) and third (III) regions of the load–deformation curve.

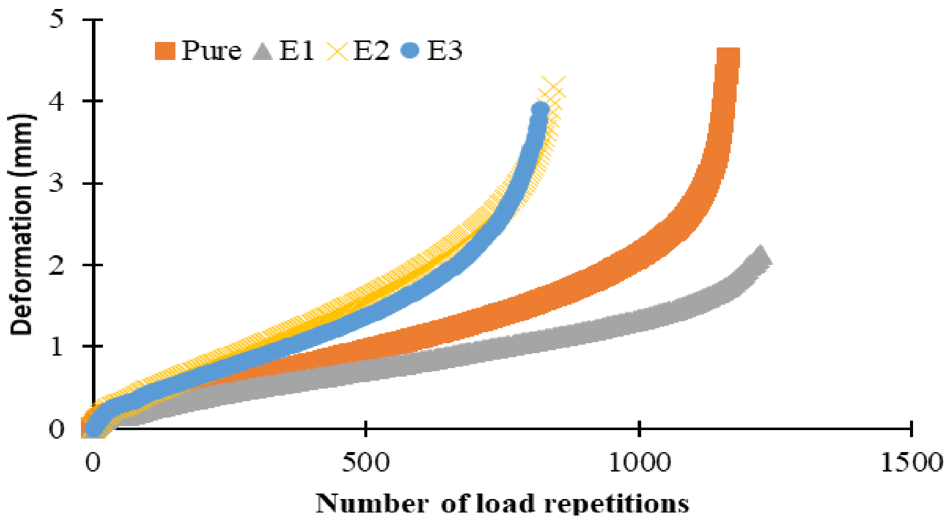

Figure 2. Relationship between deformation and load repetition number of the mixtures at 300 kPa stress level

The tangent for the third region was taken from the point where the slope of the curve began to change, and equations for both regions were derived in Excel, with their intersection used as the basis for N_f determination. The point at which the deformation rate increased was considered as the load repetition number corresponding to crack initiation (N_i). For this purpose, a slope–load repetition curve was plotted, and the point where the slope began to increase was defined as N_i. Consequently, the difference between the total fatigue life (N_f) and the crack initiation load repetitions (N_i) was defined as the crack propagation load repetitions (N_p). In addition, during the interval between N_i and N_f, the number of load repetitions required to produce each 1 mm of deformation (r_f) was determined. The relationship between deformation and load repetitions obtained from tests conducted at a stress level of 300 kPa is presented in Figure 2.

As shown in Figure 2, the lowest number of load repetitions required for failure was observed in mixtures prepared with the E3 binder containing the Elvaloy/PPA combination, while the highest number of load repetitions was obtained in mixtures prepared with the E1 modified binder. Examination of the deformation values revealed that the highest deformation occurred in mixtures prepared with the neat binder, whereas the use of additives reduced the deformation corresponding to the maximum load repetitions. This indicates that although the incorporation of additives increases the number of load repetitions the specimens can withstand, it reduces the flexibility of the mixtures and results in a more brittle fracture behavior. At the stress level of 300 kPa, the average values obtained from three specimens were evaluated. The effect of additive use on the load repetitions required for crack initiation (N_i) is presented in Figure 3, on fatigue life (N_f) in Figure 4, on the load repetitions required for crack propagation (N_p) in Figure 5, and on the maximum load repetitions (N_{mak}) in Figure 6.

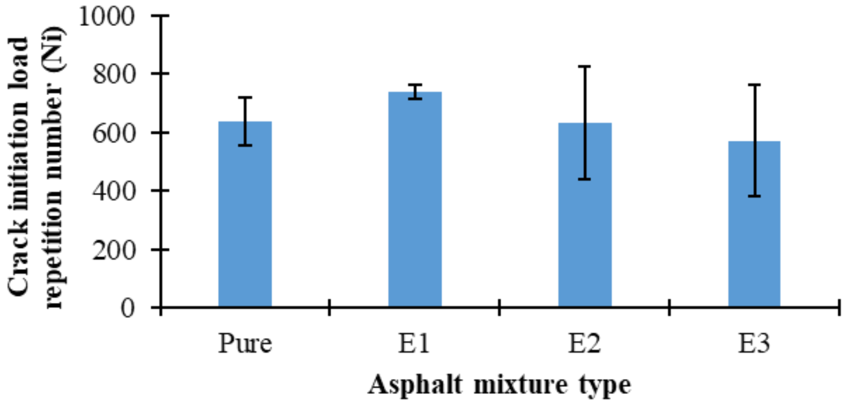

Figure 3. Crack initiation load repetition number (N_i) – mixture type relationship

As seen in Figure 3, at the stress level of 300 kPa, the use of Elvaloy+PPA generally increased the crack initiation load repetitions (N_i). At this level, the use of the E1 modified binder resulted in a 16.04% increase in Ni values compared to the neat mixture. In contrast, mixtures prepared with E2 and E3 modified binders showed decreases of 0.47% and 10.06%, respectively, in N_i values compared to the neat binder. It was also observed that the Ni values of mixtures prepared with the E2 binder were very close to those of the mixtures prepared with the neat binder.

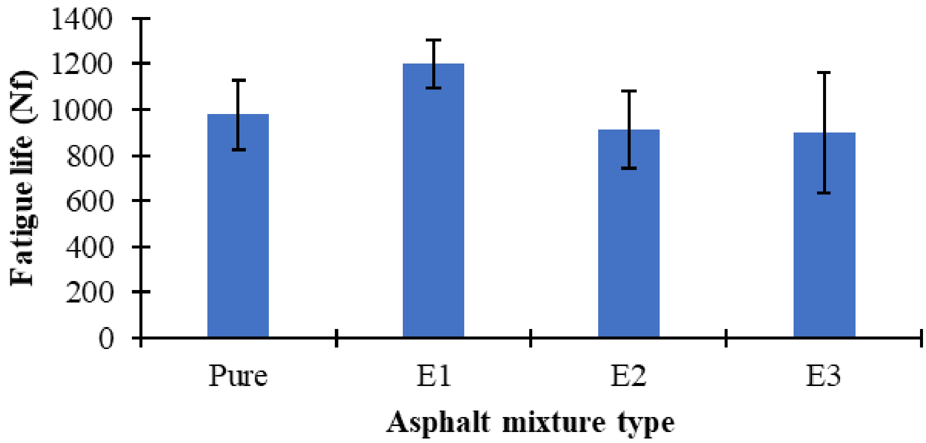

Figure 4. Fatigue life (N_f) – mixture type relationship

Based on the fatigue life (N_f) values obtained from the intersection points of the tangents drawn to the second (II) and third (III) regions of the load–deformation curve, it was observed that, similar to the crack initiation load repetitions, the use of additives increased the N_f values. At the stress level of 300 kPa, the use of the E1 binder resulted in an 11.55% increase in N_f compared to the neat mixture. In contrast, mixtures prepared with E2 and E3 binders at the same stress level exhibited decreases of 6.95% and 7.98%, respectively, compared to the neat binder. As shown in Figure 4, the highest fatigue life was achieved in mixtures prepared with the E1 binder, while the lowest value was obtained in mixtures prepared with the E3 binder.

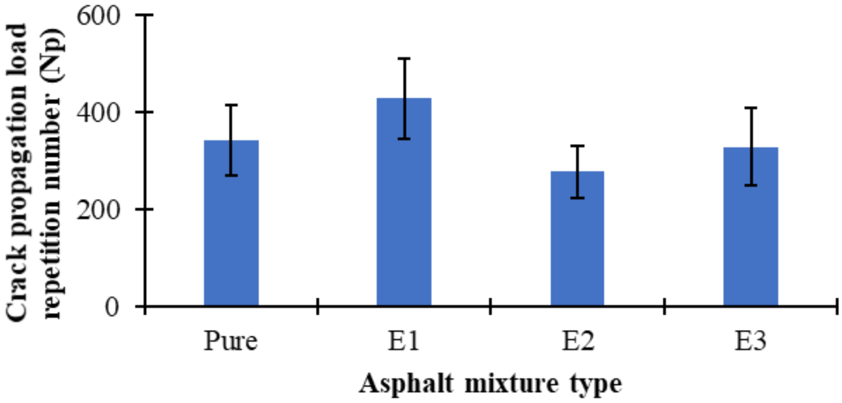

Figure 5. Crack propagation load repetition number (N_p) – mixture type relationship

As shown in Figure 5, the crack propagation load repetitions (N_p) were obtained as the difference between the fatigue life (N_f) and the crack initiation load repetitions (N_i). At the stress level of 300 kPa, the highest Np value was observed in mixtures prepared with the E1 binder, while the lowest values were recorded in mixtures prepared with the E3 binder. At this stress level, the use of the E1 binder resulted in a 2.92% increase in N_p compared to the neat mixture. In contrast, the mixtures prepared with the E2 and E3 binders showed decreases of 19.01% and 74.09%, respectively, in Np values compared to the neat binder.

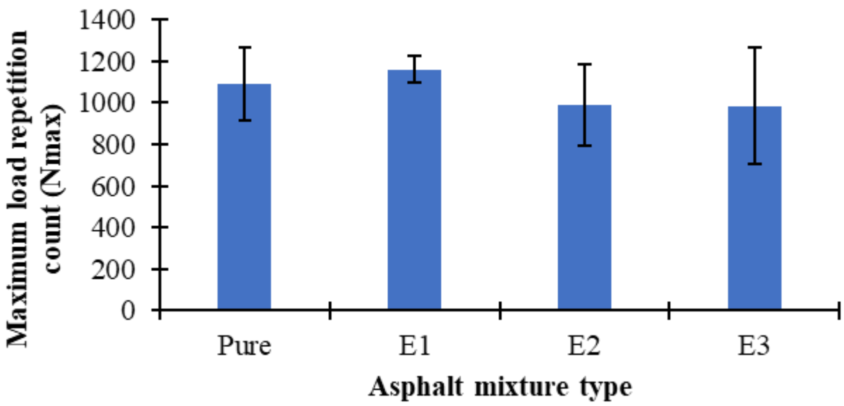

Figure 6. Relationship between maximum load repetition number and type of contribution

As seen in Figure 6, the use of binder E1 at a stress level of 300 kPa resulted in an increase in the maximum load cycle count. At this level, Nmax values of mixtures prepared with binder E1 increased by 0.46% compared to the pure binder, while decreases of 9.09% and 9.55% occurred in mixtures prepared with binders E2 and E3, respectively.

Conclusion

In this study, the fatigue behavior of flexible pavement mixtures incorporating modified bituminous binders prepared with neat bitumen and Elvaloy/PPA additives was investigated. Indirect tensile fatigue tests were conducted at different stress levels, and the results were evaluated in terms of N_i (number of load repetitions to crack initiation), N_f (fatigue life), N_p (number of load repetitions for crack propagation), and N_{max} (maximum number of load repetitions).

The experimental findings demonstrated that the incorporation of Elvaloy/PPA additives had a significant influence on the fatigue performance of the mixtures. In particular, the E1-modified binder provided the greatest improvement compared to the neat binder, with a 16.04% increase in Ni and an 11.55% increase in N_f. Limited improvements in N_p and N_{max} values were also observed with the use of the E1 binder. Conversely, mixtures prepared with E2 and E3 binders exhibited reductions in both N_i and N_f compared to the neat binder. The lowest performance was recorded for the E3 binder, where both fatigue life and crack propagation duration were significantly reduced.

An examination of the deformation values revealed that the neat binder exhibited the highest deformation, while the use of additives reduced the deformation levels. This indicates that although modified binders extend fatigue life and improve resistance to load repetitions, they reduce the flexibility of the mixtures and lead to a more brittle fracture behavior. Overall, the results demonstrated that the fatigue performance of hot mix asphalt can be enhanced by using Elvaloy/PPA additives at appropriate proportions. In particular, the E1 proportion provided the most balanced and favorable results in terms of fatigue life and crack initiation, suggesting that this additive combination has the potential to be considered as an alternative to SBS.

Scientific Ethics Declaration

*The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

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Conflict of Interest

*The authors declare that they have no conflicts of interest

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