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Investigation of Mechanical Properties of Hot Mix Asphalt Modified with Elvaloy and Polyphosphoric Acid

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Abstract - In order for the bituminous hot mix layers to resist the increased traffic load and volume as well as the adverse environmental conditions for a long time without being deformed, the bituminous binder used in the mixture has been commonly modified with the Styrene-Butadiene-Styrene (SBS) polymer. The high demand for SBS makes it difficult to supply and therefore brings on the use of alternative additives. In this study, the combined use of Elvaloy and phosphoric acid (PPA) was investigated. Additionally, the effects on the mechanical properties of bituminous mixtures were examined. Modified binders were prepared using Elvaloy/PPA additives mixed under specified conditions. Hot mix asphalt (HMA) samples prepared with these binders were subjected to Marshall stability and flow, indirect tensile stiffness modulus, and indirect tensile fatigue tests to comprehensively evaluate the effects of modified binders on the mechanical properties of bituminous hot mixtures. As a result, the bituminous hot mix tests revealed that asphalt mixtures improved their mechanical properties at the specified ratios.

***Keywords*:** Elvaloy, PPA, Modification, Mechanical Properties, HMA

1. Introduction

Generally, asphalt is a construction material with a complex internal structure. Despite the use of new methods and technologies in the investigation of asphalt's chemistry and internal structure [1, 2], fully understanding its internal structure has remained challenging. Overall, asphalt has been recognized as a colloidal system composed of complex compounds with varying levels of polarity and molecular weights, as represented by asphaltenes and maltenes [3]. The degree of dispersion of asphaltenes in maltenes and the characteristics of hydrocarbons have influenced the physical properties of asphalt, such as fatigue cracking, rutting resistance, low-temperature cracking resistance, and oxidation resistance. Oxidation causes asphalt to harden, making it brittle and vulnerable to cracking [4].

To improve its engineering properties, asphalt has often been modified with polymers. This has significantly enhanced the thermomechanical properties of asphalt, particularly its resistance to the challenging pavement conditions mentioned above [5]. The polymer content is typically in the range of 2% to 5% by weight; a higher polymer content has been considered an economic disadvantage.

The most successful group of polymers used in the asphalt industry is thermoplastic elastomers. When thermoplastic elastomers are incorporated into asphalt, the butadiene phase of the copolymer swells due to the absorption of the oil fractions (i.e., maltenes). As a result, the original volume of the polymer increases by approximately 4 to 10 times. This phenomenon has been identified as the key to developing a three-dimensional (3D) polymeric network in an asphalt mixture; the SBS has transferred its elastomeric properties to the entire mixture while maintaining its melting capability at high temperatures. When polymers are exposed to heat and pressure or the effect of a catalyst, cross-linking occurs. Under these conditions, an internal three-dimensional network is formed through covalent bonds between the polymer molecules, leading to the loss of melting or dissolving ability. Thermoplastic elastomers modified with maleic anhydride, ethylene-based copolymers containing epoxy rings, and recently available ethylene terpolymers with glycidyl methacrylate and an ester group (typically methyl, ethyl, or butyl acrylate) all belong to a class of reactive elastomeric terpolymers (RET) used for asphalt modification.

Although RET modification enhances compatibility with asphalt, caution must be taken when chemical bonds are formed, resulting in a polymer-asphalt gel without melting capability [6, 7]. Consequently, lower amounts of RET have been required for asphalt modification [8]. This has limited the application of RET PMA mixtures. However, laboratory tests have shown superior resistance to deformation and fatigue cracking. In the United States, polyphosphoric acid (PPA) has been used since the 1970s to improve the engineering properties of asphalt mixtures [9]. However, the mechanism of this asphalt modification remains not fully understood, as various perspectives expressed in the literature by [10, 11] suggest. As a general rule, the addition of a small amount of PPA (0.5% by weight) has been identified as potentially altering the temperature and aging resistance of paving asphalts by reacting with destabilizing components formed during thermal processes.

The modification of asphalt binder with Elvaloy (Elv) and polyphosphoric acid (PPA) has been found to result in better performance. However, such modification can increase the mixing and compaction temperatures of the asphalt binder. In this study, the effect of using Elvaloy and polyphosphoric acid together on the properties of bituminous hot mixtures was investigated.

2. Materials and Method

2.1. Bitumens and additive

In the study, B50/70 grade bitumen obtained from TÜPRAŞ Batman refinery was used as the base binder. The base binder was modified with Elvaloy and PPA additives. The Elvaloy and PPA used in the study were supplied by Komsa company. In this study, Elvaloy and PPA were mixed in three different ratios (0.8% + 2%, 0.9% + 1%, and 1% + 0%) and added to the base bitumen to prepare the target binders. The bitumens containing Elvaloy were mixed using a mechanical mixer operating at 800 rpm for 5 hours, after which PPA was added to the mixture and stirred for an additional 30 minutes to obtain the modified binders. The abbreviations for the base and Elvaloy/PPA binders used in the study are presented in Table 1.

Table 1. The 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
Display	E1	E2	E3	Pure

2.2. Marshall Stability and Flow Test

The Marshall Stability and Flow Test applied to HMA (Hot Mix Asphalt) samples is performed to determine the maximum resistance to deformation (stability) and the vertical deformation that occurs at the moment of maximum load (flow) in the samples. Before starting the test, the heights of the compacted and cooled samples are measured and recorded. Then, the samples are placed in a water bath at a temperature of 60±1°C and left for 40-60 minutes. At the end of this period, the sample is removed from the water and placed in such a way that the breaking jaw is centered. The sample is then loaded at a speed of 50±2 mm/min. The Marshall stability and flow test setup is shown in Figure 1. In the test, the maximum load and the deformation values at the moment the maximum load is reached are recorded. After the sample is removed from the water, the test must be completed within 40 seconds. The standard sample height of 63.5 mm is assumed for the test. For samples with different heights, stability correction factors are used.

Fig. 1. Marshall stability and flow test setup

2.3. Indirect Tensile Stiffness Modulus Test

One of the most important performance characteristics of bituminous hot mixes is the stiffness modulus, which is a measure of the ability of bituminous layers to distribute loads. The most common form of strain-deformation measurements used to evaluate elastic properties is the measurement of stiffness modulus in indirect tension mode. The stiffness modulus is calculated using the applied stress and the resulting unit deformation. Before the test, the samples are conditioned at the test temperature for at least 3 hours. Thanks to the climate chamber, the test can be conducted at different temperatures outside the standard conditions. Values such as sample height, sample diameter, estimated Poisson's ratio, load application time, load increment times, target horizontal deformation, and estimated stiffness modulus are entered into the software in advance.

2.4. Indirect Tensile Fatigue Test

Bituminous materials used in highways are subjected to short-term loads from every vehicle that passes over them. These loads cause micro-damages in the material, and these micro-damages lead to fatigue cracks in the long term. Fatigue cracking is a type of deterioration that gradually increases after crack formation due to repeated loads, and it is the most common type of damage seen in bituminous hot mixes. In the indirect tensile fatigue test, cylindrical test samples are subjected to repeated compressive loads in the vertical axial plane. This loading generates tensile stresses perpendicular to the applied load direction, causing the sample to split from its center in the vertical direction.

3. Results and Discussions

3.1. Marshall Stability and Flow Test Results

As seen in Figure 2, the use of additives has increased the Marshall stability values. The mixtures prepared with E1 modified bitumen exhibited the highest stability values. The mixtures prepared with pure bitumen showed the lowest stability values. It was determined that the most effective modification was achieved by using Elvaloy and PPA together, resulting in a 1.024-fold increase compared to pure binder usage. The least effective additive was found to be when Elvaloy was used at a 1% ratio, which resulted in a 4.96% increase compared to pure binder usage.

In the case of using E2 binder, the stability value of the mixture was found to be 0.07% lower than that of the pure binder. When the Marshall ratio values presented in Figure 2 were examined, it was found that the MQ values generally increased with the use of additives. The MQ values of mixtures prepared with E1 and E2 modified bitumens were found to be 13.84% and 3.65% higher, respectively, compared to the mixtures prepared with pure binder. It was determined that the MQ value of the mixture prepared with E3 binder was 2.38% lower than that of the mixture prepared with pure binder.

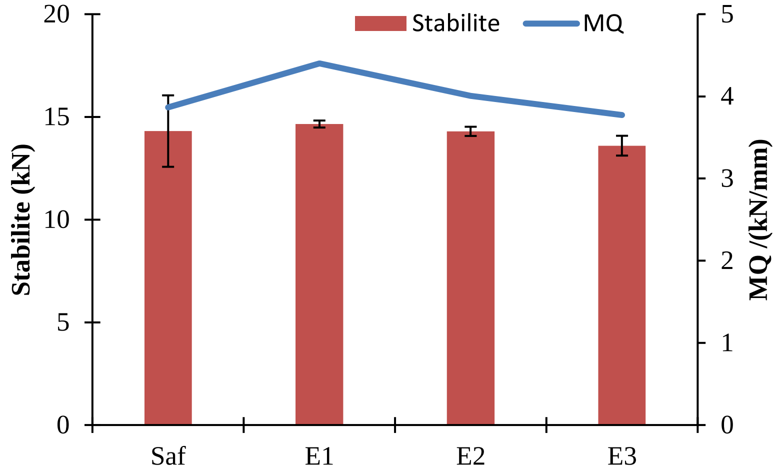

Fig. 2. Change in stability and MQ values of mixtures with additive use

2D and 3D RSM plots are given in Figure 2. The graphs show the effect of SEBS ratio (B) and temperature (A) variables on G*/sinδ values for Iraqi bitumen. G*/sinδ varies with temperature and SEBS ratio. As the temperature increases, the G*/sinδ value tends to decrease; this indicates that the stiffness of the asphalt decreases and becomes more prone to deformation at high temperatures. A significant increase in G*/sinδ value is observed as the SEBS ratio increases, indicating that SEBS improves the performance of bitumen by increasing the elastic properties. The graph shows that the G*/sinδ value peaks near the optimum SEBS ratio and temperature. When the 2D graph is analysed, it is clearly seen that high G*/sinδ values are obtained at low temperatures and high SEBS ratios in this graph where G*/sinδ values are shown with isoclines according to SEBS ratio and temperature combinations. For example, when the SEBS ratio approaches 4% and the temperature is in the range of 52-58°C, G*/sinδ values exceed 8000 Pa. In general, increasing the SEBS content significantly improves the elastic modulus of Iraqi bitumen and increases its resistance to deformation at high temperatures. However, the stiffness of bitumen decreases as the temperature increases. This highlights the modification effect of SEBS and shows the importance of determining the appropriate SEBS ratio and temperature range for optimum performance.

3.2. Indirect tensile stiffness modulus (ITSM) test results

In Figure 3, it can be observed that the ITSM values of the mixtures increased with the use of modified bitumen. The mixtures prepared with E1 binder had the highest ITSM values, while the mixtures prepared with E3 binder had the lowest ITSM values. At 25°C, the ITSM value of the mixtures prepared with E1 binder was found to be 14.7% higher than those prepared with pure binder. The results indicated that the most effective modified bitumen was obtained by using 0.2% PPA for bitumen modification, while the modified bitumen with Elvaloy showed the lowest effectiveness.

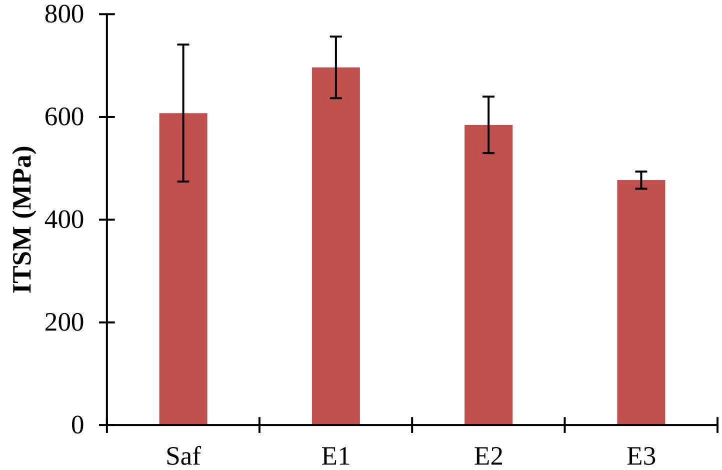

Fig. 3. Change of ITSM values according to mixture type.

3.3. Indirect tensile cyclic loading test results

In the indirect tensile fatigue test, repeated loading was applied until fracture occurred in the samples. In this way, the maximum load repetition number (N_{max}) and the amount of deformation at the maximum load repetition number (δ_{max}) were determined. n the load-deformation curve, the fatigue lives were determined by the intersection of the tangents drawn from sections II and III. The tangent in section III was taken from the point where the slope started to change. In an Excel format, sections II and III of the curve were divided into two separate parts, and the equations of the tangents drawn through the identified points were determined. By equating the two tangents, the fatigue lives (N_f) of the mixtures were calculated. The point where the deformation rate increased (the boundary between sections II and III) was identified as the load repetition number required for crack initiation (N_i). To determine the crack initiation load repetition number, a slope-load repetition number graph was plotted, and the point where the slope began to increase was taken as the crack initiation load repetition number (N_i). The difference between the fatigue life (N_f) and the crack initiation load repetition number (N_i) was used to obtain the crack propagation load repetition number (N_p). The deformation-load repetition number relationship obtained from the tests conducted at a stress level of 300 kPa is presented in Figure 4.

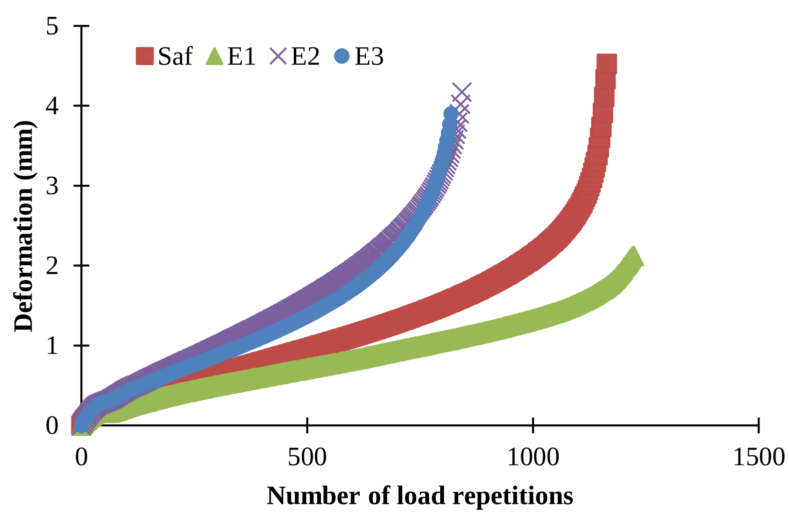

Fig. 4. Deformation-load repetition number relationship of the mixtures at 300 kPa stress level.

The variation in the average number of load repetitions required for crack initiation (N_i) obtained from three samples at a stress level of 300 kPa with the use of additives is presented in Figure 5. The variation in the average fatigue life (N_f) values with additive use is shown in Figure 6. The variation in the average number of load repetitions required for crack propagation (N_p) with additive use is provided in Figure 7, while the variation in the average maximum load repetition number (N_{max}) with additive use is illustrated in Figure 8. Upon examining Figure 5, it was determined that the use of Elvaloy + PPA as an additive increased the crack initiation load repetition numbers (N_i) at a stress level of 300 kPa. When E1 was used at this stress level, the Ni values increased by 16.04% compared to the unmodified mixture. However, with E2 and E3 modified bitumens, the Ni values decreased by 0.47% and 10.06%, respectively, compared to the mixtures prepared with the unmodified binder. When Ni values were analyzed, it was observed that the N_i values of the mixtures prepared with the E2 binder were similar to those of the mixtures prepared with the unmodified binder.

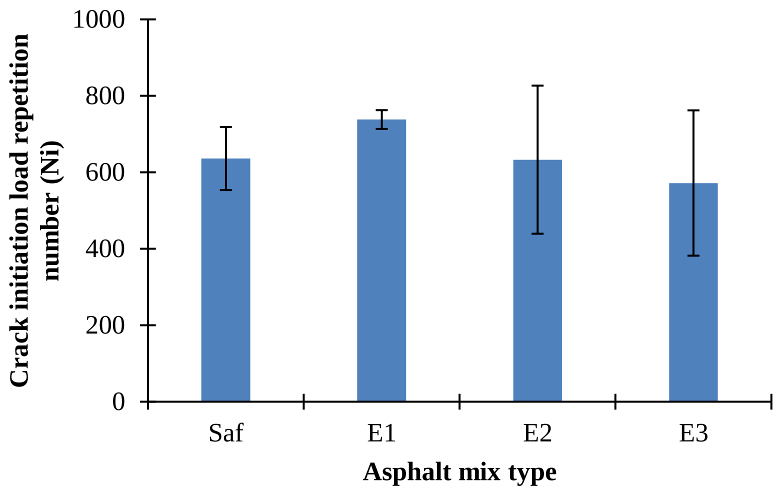

Fig. 5. Crack initiation load repetition number (N_i) - mixture type relationship

In the load repetition versus deformation graph, the fatigue life values (N_f) obtained from the intersection points of the tangents of Sections II and III showed an increase with the use of additives, similar to the crack initiation load repetition numbers. At a stress level of 300 kPa, the use of the E1 binder resulted in an 11.55% increase in N_f values compared to the unmodified mixture. However, when E2 and E3 binders were used, the N_f values decreased by 6.95% and 7.98%, respectively, compared to the unmodified mixture. Upon examining Figure 6, it is evident that the highest fatigue life was obtained from mixtures prepared with the E1 binder, while the lowest fatigue life was observed in mixtures prepared with the E3 binder.

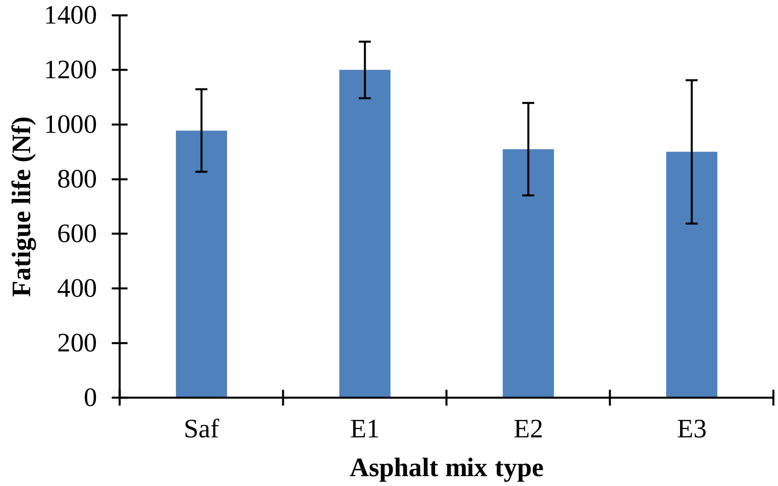

Fig. 6. Fatigue life (N_f) – mixture type relationship

The crack progression shown in Figure 7 was obtained from the difference between the values of N_f and N_i for the number of load cycles (N_p). At a stress level of 300 kPa, the highest Np value was determined for the mixture prepared with binder E1, while the lowest values were found for the mixtures prepared with binder E3. At a stress level of 300 kPa, the N_p values with binder E1 increased by 2.92% compared to the pure mixture. At the same stress level, when binders E2 and E3 were used, the N_f values decreased by 19.01% and 74.09%, respectively, compared to the pure mixture.

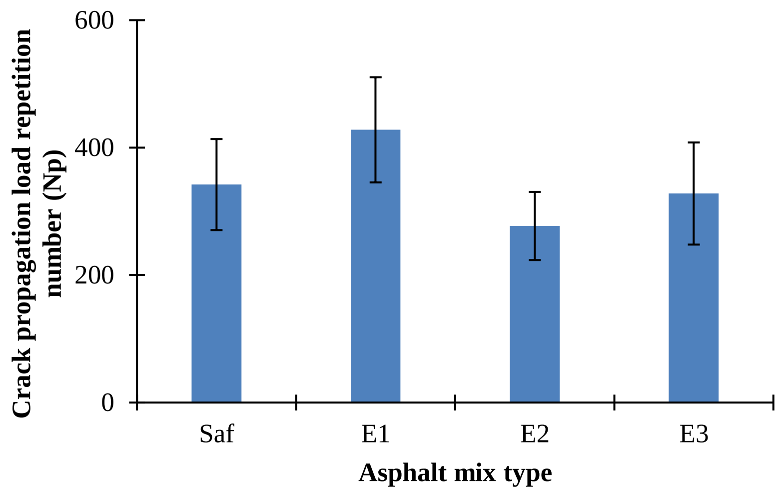

Fig. 7. Crack propagation load repetition number (N_p) - mixture type relationship

As shown in Figure 8, the maximum number of load cycles increased with the use of binder E1 at a stress level of 300 kPa. When binder E1 was used at this stress level, the N_{max} values increased by 0.46% compared to the pure mixture, while the use of binders E2 and E3 resulted in a decrease of 9.09% and 9.55%, respectively. When the N_i, N_f, and N_{max} graphs are evaluated together, it was determined that the fatigue life of the mixtures increased with the use of binder E1.

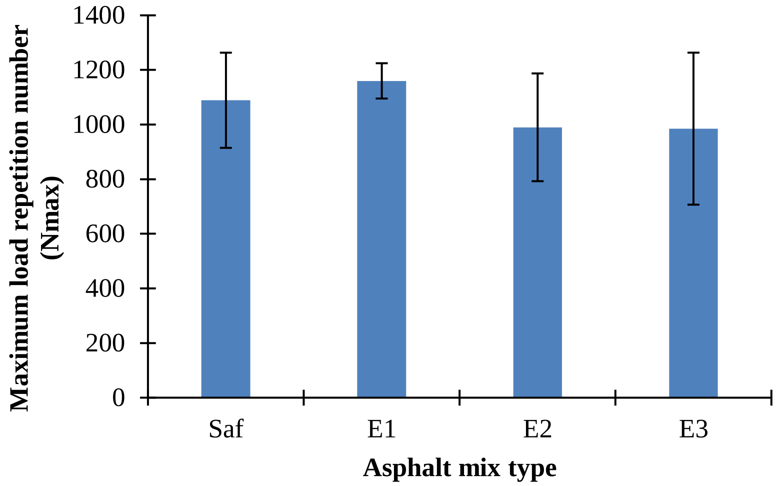

Fig. 8. Maximum load repetition number - contribution type relationship

4. Conclusion

This study investigated the effects of Elvaloy and PPA additives, which could be potential alternatives to the commonly used SBS additive in bitumen modification, on the performance of bituminous binders and hot mix asphalts, and compared them with the pure binder. With the use of additives, the Marshall stability values increased. It was determined that the mixtures prepared with E1 modified bitumen had the highest stability values, while the mixtures prepared with pure bitumen had the lowest stability values. It was observed that the ITSM values of the mixtures increased with the use of modified bitumen. The mixtures prepared with binder E1 had the highest ITSM values, while those prepared with binder E3 had the lowest ITSM values. It was determined that the mixtures prepared with binder E3 required the lowest number of load cycles to cause fracture, while the mixtures prepared with E1 modified bitumen required the highest number of load cycles. When the deformations were examined, the pure binder exhibited the highest deformation. At a stress level of 300 kPa, the use of Elvaloy+PPA as an additive material resulted in an increase in the crack initiation load cycle numbers (N_i). As with the crack initiation load cycles, it was determined that the use of additives increased the fatigue life (N_f) values. At a stress level of 300 kPa, the mixture prepared with binder E1 had the highest N_p values, while the mixtures prepared with binder E3 had the lowest values. At a stress level of 300 kPa, the maximum number of load cycles increased with the use of binder E1.

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