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Evaluation of Different Additives on Mechanical Properties and Performance of Hot Mix Asphalt Using Marshall Stability and ITSM Tests

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Abstract: This study comprehensively evaluated the mechanical performance of hot mix asphalt (HMA) mixtures prepared with neat and modified binders using Marshall stability and Indirect Tensile Stiffness Modulus (ITSM) tests. Marshall stability test results revealed that the incorporation of polymeric and reactive additives increased the stability values of the mixtures compared to those produced with neat binder. Among the additives investigated, the 611 elastomer demonstrated the highest improvement in stability, achieving up to 1.80 times higher values than the neat mixture. Other additives, such as 701, SBS, and CR, also enhanced stability, albeit to varying extents. The ITSM test results indicated that the stiffness modulus of the mixtures increased with higher elastomer content. The 611 elastomer exhibited the most significant impact on stiffness among the tested elastomers, while 701 and SBS showed comparable performance. Furthermore, higher ITSM test temperatures resulted in decreased stiffness values across all mixtures. The number of load repetitions required to initiate cracking was found to be lowest in the mixtures containing neat binder and highest in mixtures containing 4% of the 611 elastomer, indicating superior fatigue resistance. Overall, both Marshall and ITSM tests confirmed that modified binders, particularly those incorporating the 611 elastomer, significantly enhance the mechanical properties of HMA mixtures, improving their resistance to deformation and cracking under load.

Keywords: Hot mix asphalt, Modified bitumen, Marshall stability, Indirect tensile stiffness modulus

Introduction

Road transportation is the most widely used mode of transport for both freight and passenger movement worldwide, including in our country, owing to its ability to provide flexible and rapid transport over short and medium distances, enable door-to-door delivery without requiring any other mode of transport, and offer ease of vehicle planning and availability. Road transport plays a significant role in our daily lives. It has maintained its importance from ancient times to the present day by facilitating life in both passenger and freight transportation. The adequacy and standards of a country's transportation network are also indicators of its level of development. According to data from the Turkish General Directorate of Highways (KGM) as of January 2023, there are a total of 29,178 km of roads paved with Hot Mix Asphalt (HMA) on motorways, state roads, and provincial roads, while a total of 36,184 km of surface-dressed roads exist on state and provincial roads (Official Website of the General Directorate of Highways, 2023). Highways can be defined as all structures constructed along a designated route, adhering to specific geometric standards, at appropriate natural ground elevations, allowing vehicles to travel at the desired speed, safety, and comfort levels. The road pavement is defined as a layered structure placed over the subgrade, typically consisting of the sub-base, base, and surfacing layers, designed to reduce the loads from vehicles to levels that the subgrade can bear, protect the subgrade, and provide a smooth rolling surface.

On medium and heavily trafficked roads, surfacing layers, which are the most expensive components of the pavement structure and are in direct contact with vehicle tires, are constructed to carry traffic loads and protect the other pavement layers from adverse environmental effects. These surfacing layers can be constructed using various techniques, ranging from surface dressing to Hot Mix Asphalt (HMA). Surface dressings may be applied in one or multiple layers, involving the spraying of bitumen onto a suitable base, followed by spreading and compaction of aggregate. Hot Mix Asphalt (HMA) is one of the most expensive yet durable types of surfacing. HMA is produced by heating and mixing aggregate and bitumen in a stationary plant, transporting the mixture to the application site, and compacting it at a specified temperature. The primary function of bituminous binders in the mixture is to ensure adhesion and cohesion in HMA. Aggregates, on the other hand, provide internal friction resistance and stability to the mixture. Additionally, bituminous binders bind the aggregate particles together to prevent disintegration under traffic loads, create smooth surfaces that enhance driving comfort, and fill the voids within the mixture to ensure impermeability.

Distresses occurring in Hot Mix Asphalt (HMA) can generally be classified into three main categories: deformation, fracture (cracking), and disintegration (Hınıslıoğlu & Hattatoğlu, 2003). Cracks in HMA are further categorized into those caused by traffic loading and those unrelated to traffic effects. Various factors, such as the thickness of pavement layers and the material properties of HMA, influence crack formation (Garcia, 2002; Jajliardo, 2003). Traffic-induced cracking may result either from the passage of heavy axle loads once or a few times or from the repeated movement of vehicles over the pavement. Cracks formed due to numerous vehicle passes are referred to as fatigue cracks. In the first case, cracking occurs when the stress imposed by the heavy axle load exceeds the flexural-tensile strength of asphalt concrete. In fatigue, cracks develop due to the accumulation of permanent deformations resulting from repeated axle loads. Apart from traffic loads, cracking may also arise due to environmental factors such as temperature fluctuations and moisture. Cracking in HMA can be classified into several types, including alligator (fatigue) cracking, shrinkage cracking, edge cracking, joint cracking, transverse cracking, reflection cracking, and slippage cracking (Ağar & Umar, 1991).

In recent years, numerous studies have focused on applying the principles of fracture mechanics to HMA, owing to the prevalence of cracking in road pavements. Fracture refers to the separation of materials into multiple pieces under stress. The nature of fracture varies between materials and is generally dependent on the applied stress, temperature, and strain rate. Fracture typically occurs in two stages: the first stage involves "crack initiation," and the second stage involves "crack propagation" (Özdemir, 2006). From a macroscopic perspective, fractures are categorized as brittle, ductile, and creep fractures. Brittle fractures occur without any plastic deformation. In ductile materials, significant plastic deformation occurs prior to fracture. Creep fracture, on the other hand, results from creep deformation under constant stress or load at elevated temperatures. Macroscopically, creep fracture involves plastic deformation and therefore resembles ductile fracture. However, from a microscopic viewpoint, creep fracture is distinct from ductile fracture (Özdemir, 2006).

In light of the ongoing quest for more durable and sustainable pavement materials, this study aims to systematically investigate the effects of various polymeric and reactive additives on the mechanical behavior of hot mix asphalt mixtures. By employing both Marshall stability and Indirect Tensile Stiffness Modulus (ITSM) tests, the research provides a comprehensive assessment of how these additives influence the resistance of asphalt mixtures to deformation, stiffness variations, and fatigue performance. The outcomes are expected to contribute valuable insights toward optimizing binder modification strategies and enhancing the long-term performance of asphalt pavements under diverse service conditions.

Materials and Method

Materials

In this study, the B70/100 reference bitumen produced by the Batman Refinery was used. The density of the reference bitumen employed is 1.033 g/cm³. Due to climatic conditions, the 70/100 grade is the most widely used binder in Turkey. The general properties of the bitumen utilized in the study are presented in Table 1(A. M. Özdemir, 2025). Five different additives (SBS, 701, 611, CR, and Elvaloy-PPA) were used for bitumen modification. The CR used in the study was supplied by Samsun Akın Plastik Company, while Elvaloy and PPA were procured from Komsa Company. The SBS (Kraton D 1101) additive produced by Shell, as well as 701 and 611, were provided by Mpolimer Company. The ground tire rubber (CR) was obtained using a mechanical shredding method and sieved through a No. 40 mesh before being used in the study. The properties of the additives are provided in Table 2. The additives utilized in the study are shown in Figure 1.

Table 1. General properties of 70/100 bitumen

Properties	Unit	Standard	Results
Penetration	mm^{-1}	EN 1426	87.4
Softening Point	˚C	EN 1427	52.6
Flash Point	˚C	EN ISO 2719	230
Viscosity 135˚C /165˚C	cP	ASTM D4402	562.5/162.5

Table 2. Properties of the additives used in the study

Properties	SBS	701	611
Molecular structure	Liner	Liner	Radial
Styrene/butadiene ratio	31/69	33/67	31/69
Density (cm/m3)	0,94	0,93	0,94
Oil content	Yok	Yok	Yok
Viscosity (5%, cps)	-	14	24
Melt index (190°C/kgw)	<1	<1	<1
Tensile strength (kgw/cm2)	324	220	200
Hardness	70	80	83
Ash content	-	0,2	0,2
Elongation at break (%)	880	600	700

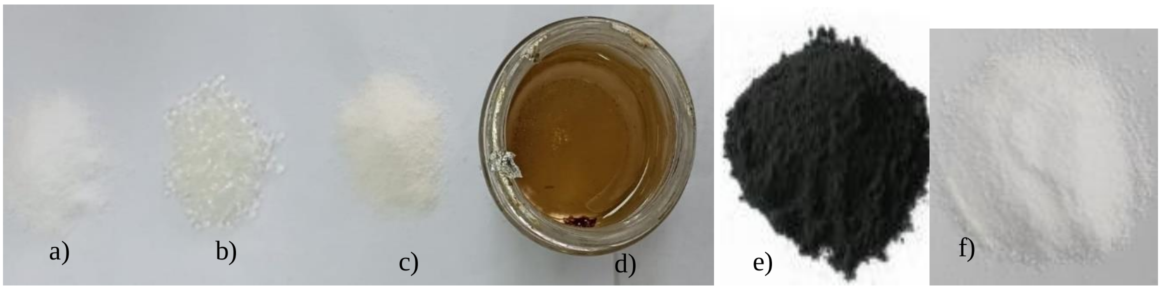

Figure 1. Additives used in the study: (a) SBS polymer, (b) Elvaloy, (c) 611 polymer, (d) PPA, (e) CR, (f) 701 polymer

Preparation of Modified Bitumen

In this study, modified bitumens were prepared using a reference binder (70/100) with the incorporation of SBS, Enprene 611, Enprene 701, CR, Elvaloy, and PPA additives. The production procedure for elastomer-modified bitumen was adopted from previous studies (Yalcin & Demirbag, 2022). In the initial stage, the neat bitumen was heated for 30 minutes in an oven at 180 ± 5 °C to achieve a fluid state, after which 800 grams of bitumen was transferred into a metal mixing vessel. To ensure a uniform heat source, the bitumen inside the metal vessel was placed into a heating jacket set at 180 ± 5 °C, and the system was maintained at this temperature until thermal equilibrium was achieved. Subsequently, the additives were incorporated into the bitumen at predetermined dosages (%2, %3, %4 SBS; %2, %3, %4 Enprene 611; %2, %3, %4 Enprene 701; %4, %6, %8 CR; %3 Elvaloy; and %0.2 PPA). To ensure accurate comparison of the results of the modified bitumen binders, the same procedure was employed for the preparation of all modified samples.

Following the addition of the additives, the bitumens containing the modifiers were mixed for 4 hours using a mechanical mixer operating at 2700 rpm to produce the modified binders (Yalcin & Demirbag, 2022). Specifically, in the case of the modified bitumen with 3% Elvaloy, the mixing process was interrupted after 3.5 hours to add 0.2% PPA, after which mixing continued for an additional 30 minutes to complete the blending. The additive dosages employed during the modification process were determined by considering values commonly preferred in the literature and industry applications. Upon completion of the preparation of all modified binders, they were subjected to short-term and long-term aging processes. In the nomenclature used for the experimental results, “C” denotes the neat binder, while in the modified binders, the number on the left side indicates the percentage of additive incorporated into the neat binder, and the term on the right denotes the type of additive used.

Preparation of Hot Mix Asphalt Samples

To prepare the mixture specimens, aggregates were weighed in quantities determined according to the gradation specified in Table 5.2, ensuring a total mass of 1100 grams for each specimen. The design bitumen content for the neat mixture was determined through analyses and set at 4.67%. To prevent the binder content from affecting the mechanical properties of the mixtures, the Hot Mix Asphalt (HMA) specimens containing elastomer additives were prepared with the same bitumen content (4.67%) as the mixture without elastomers. All mixture specimens were produced based on the aggregate gradation given in Table 3. In order to avoid the influence of binder content on the mechanical properties of the mixtures, both the neat and modified mixtures were prepared using identical bitumen content. The prepared mixtures were compacted into cylindrical Marshall specimens with diameters of 10 cm and 15 cm and an approximate height of 6 cm. Compaction was performed using a rotary compactor applying a static pressure of 600±18 kPa at an inclination angle of 1.25±0.02°, aiming for a 4% air void content. Subsequently, the 15 cm specimens were cut in half, notches were introduced, and semi-circular specimens were prepared. Notches were made at depths of 1 cm and 2 cm, respectively. Asphalt mixture samples used in the project are given in Figure 2.

Table 3. Aggregate gradation used in the asphalt mixture

Category	**Values**									
Sieve Size (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 2. Asphalt mixture samples prepared during the project study

Marshall Stability and Flow Test

First, the heights of the prepared asphalt mixture specimens are measured. The specimens with recorded heights are then placed in a water bath at 60°C for approximately one hour (Figure 3). Afterwards, the specimens are removed from the water bath, positioned in the testing device, and subjected to loading at a rate of 50 mm/min (Figure 4).

During the test, both the maximum load and the corresponding deformation at the point of maximum load are determined and recorded. The test must be conducted within 40 seconds after the specimen is removed from the water bath. The standard height of the specimens used in the experiment is known to be 63.5 mm. The average values of the determined stability and flow are calculated. Stability and flow values are established in this way. Specimens whose flow values deviate by more than 20% from the average flow, or whose stability values deviate by more than 15% from the average stability, are excluded from the evaluation. To assess deviations of the specimens' stability and flow values from the mean, the average of the remaining specimens is calculated. The retained Marshall stability test is applied to determine the moisture damage resistance of hot mix asphalt mixtures.

Figure 3. Keeping the samples in a water bath at 60±1°C

Figure 4. Performing Marshall stability and flow test

Indirect Tensile Stiffness Modulus Test

To experimentally determine the stiffness modulus of Hot Mix Asphalts (HMAs), direct compression, indirect tensile, and torsion tests can be employed. These test methods involve the application of periodic loads and the measurement of instantaneous deformations during these processes. The stiffness modulus is calculated as the ratio of the applied stress to the recoverable strain. Compared to direct compression tests, indirect tensile tests are more frequently used due to their higher sensitivity to the influence of the binder in the mixture (Kök, 2007; Zoorob & Suparma, 2000).

The Indirect Tensile Stiffness Modulus (ITSM) test, which is a non-destructive, deformation-controlled test defined by the BS EN 12697-26 standard (BS 12697, 2004), was conducted using Cooper's Nottingham Asphalt Tester (NAT) equipment. ITSM is the most commonly utilized test for determining the stiffness modulus of asphalt specimens using the NAT machine, as shown in Figure 5. The dimensions of the specimens were 100±2 mm in diameter and 40±2 mm in thickness. The test was performed under standard conditions with a target horizontal deformation of 5 µm, a rise time of 124 ms, and a test temperature of 20°C.

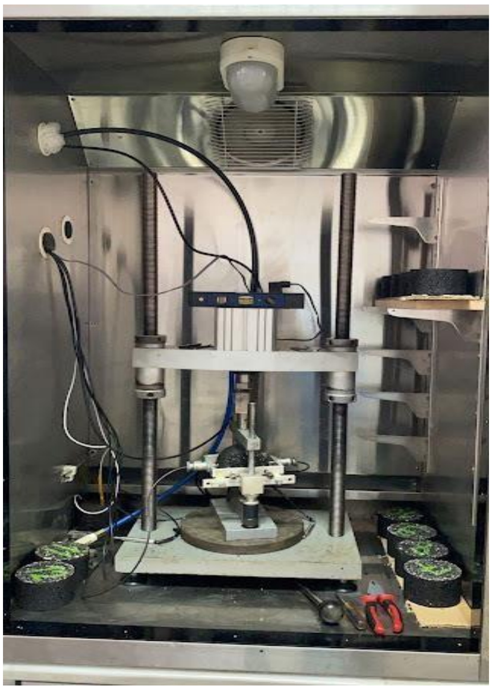

Figure 5. Indirect tensile stiffness modulus test

Results and Discussion

Marshall Stability and Flow Test Results

Marshall stability and flow tests were performed on the prepared Hot Mix Asphalt (HMA) specimens to determine their maximum resistance to deformation and the amount of deformation occurring under the maximum applied load, thereby evaluating the mixtures' resistance to permanent deformation. For the Marshall stability and flow tests, the mixture specimens were conditioned in water at 60°C for 60 minutes prior to testing. Flow and Marshall stability measurements were conducted using three specimens for each type of mixture. A total of 15 different mixtures were prepared using neat bitumen and thirteen different modified bitumen's. As illustrated in Figure 6, the use of additives led to an increase in the stability values of the mixture specimens. The highest stability value was obtained in mixtures containing 4% of the 611 elastomer, while the lowest stability value was recorded for the neat binder. Following the neat binder, the lowest stability value among the mixtures was observed in the MC mixture. Among the elastomer additives, the 611 elastomer provided the best stability performance.

The stability value of the neat binder prepared under modified bitumen mixing conditions was 1.04 times higher than that of the original neat binder. The Marshall stability values of the 701 and SBS elastomers were found to be similar to each other. It was determined that the stability values of the 4-611, 3-611, and 2-611 asphalt mixtures were 1.80, 1.46, and 1.30 times higher, respectively, than that of the neat mixture. Similarly, the stability values of the 4-701, 3-701, and 2-701 asphalt mixtures increased by factors of 1.58, 1.42, and 1.27, respectively, compared to the neat mixture. For the 4SBS, 3SBS, and 2SBS asphalt mixtures, the stability values were 1.48, 1.35, and 1.23 times higher, respectively, than that of the neat mixture. The stability values of the 8CR, 6CR, and 4CR asphalt mixtures were determined to be 1.47, 1.31, and 1.19 times higher, respectively, than that of the neat mixture. Among the 15 different mixtures tested in this study, the maximum resistance to deformation was achieved with the 611 elastomer. The stability values of asphalt mixtures containing CR exhibited results similar to those of mixtures containing the 701 elastomer.

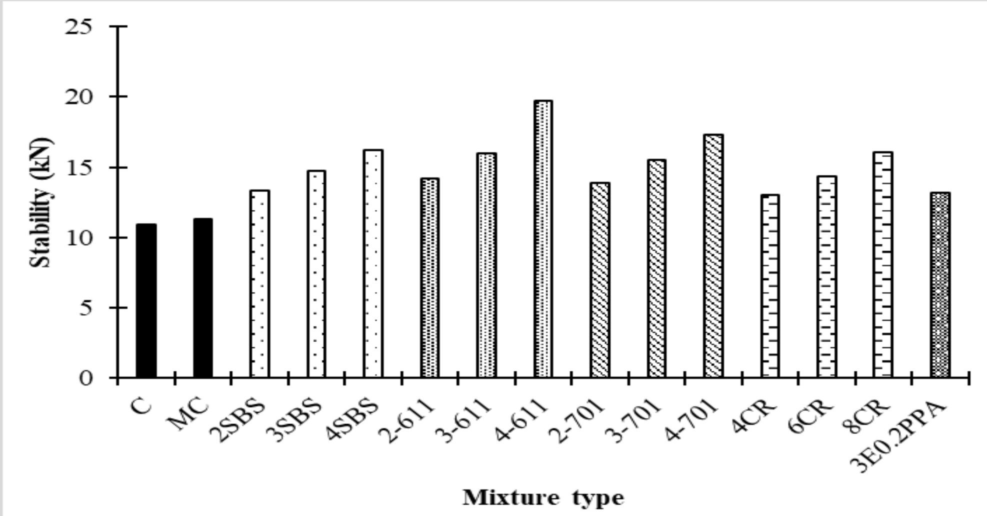

Figure 6. Marshall stability values of mixtures

Indirect Tensile Stiffness Modulus (ITSM) Test Results

The Indirect Tensile Stiffness Modulus (ITSM) test is specified in the BS DD 213 standard, and the experimental work was carried out in accordance with this standard (BS DD 213, 1993). Within the scope of this test, the stiffness of Hot Mix Asphalt (HMA) specimens prepared using neat binder as well as bitumens modified with 611, 701, and SBS was determined. For each type of mixture, three specimens were used in the test. Since the specimens were not damaged during this test, they were subsequently utilized in fatigue testing. The ITSM test on the mixture specimens was performed at test temperatures of 20°C and 30°C using the UMATTA (Universal Material Testing Apparatus) testing device. In the test, five preliminary loadings were applied to the specimen by the testing apparatus to establish the load required to achieve the target horizontal deformation. Subsequently, five test loadings were performed on the specimen to determine the stiffness of the HMA specimens under dynamic loads. The ITSM value of a mixture specimen was determined by calculating the average of the five ITSM values obtained from the five load pulses. In the experimental study, the loading rise time was set at 124 ms, the loading period at 3000 ms, and the target deformation at 5 µm, with the Poisson's ratio assumed to be 0.35. While determining the ITSM values of the mixture specimens, each specimen was tested at least twice, and the average of the two ITSM values obtained from the same specimen was calculated. For the second test, the specimen was rotated by 90°. If the deviation between the two ITSM values obtained from the same specimen exceeded 10%, the specimen was rotated an additional 90°, and the test was repeated. When three ITSM values were obtained from the same specimen, the average of the two values showing less than 10% deviation was taken as the ITSM value for the mixture specimen. The variation in ITSM values of mixtures prepared with neat and modified bitumens is presented in Figure 7.

As shown in Figure 6.2, it was determined that the stiffness values of mixtures prepared with neat binder subjected to the conditions used for modified bitumen preparation were higher than those of mixtures prepared with the neat binder alone. As indicated in the figure, the stiffness value increases as the elastomer content in the neat binder increases. Among the three elastomers, the 611 elastomer was found to be the most effective in terms of stiffness. The stiffness values of the 701 and SBS elastomers were also observed to be similar to each other. Moreover, an increase in the ITSM test temperature led to a decrease in the stiffness values of the mixtures. At 20°C, the stiffness values of the 4-611, 3-611, and 2-611 asphalt mixtures were found to be 2.68, 2.42, and 2.15 times higher, respectively, than that of the neat mixture. For the 4-701, 3-701, and 2-701 asphalt mixtures, the stiffness values increased by factors of 2.58, 2.19, and 1.81, respectively, compared to the neat mixture. Similarly, at 20°C, the stiffness values of the 4SBS, 3SBS, and 2SBS asphalt mixtures were determined to be 2.46, 2.12, and 1.66 times higher, respectively, than that of the neat mixture. The stiffness values of the 8CR, 6CR, and 4CR asphalt mixtures at 20°C increased by factors of 2.31, 1.94, and 1.47, respectively, compared to the neat mixture. At 30°C, the stiffness values of the 4-611, 3-611, and 2-611 asphalt mixtures were found to be 2.78, 2.52, and 2.17 times higher, respectively, than that of the neat mixture. For the 4-701, 3-701, and 2-701 asphalt mixtures, the corresponding increases were 2.58, 2.19, and 1.81 times, respectively. The stiffness values of the 4SBS, 3SBS, and 2SBS asphalt mixtures at 30°C were 2.61, 2.21, and 1.97 times higher, respectively, than that of the neat mixture. The stiffness values of the 8CR, 6CR, and 4CR asphalt mixtures at 30°C were determined to be 2.32, 2.01, and 1.48 times higher, respectively, than that of the neat mixture. It was observed that the ITSM value of the 3E0.2PPA binder exceeded that of the mixtures containing 2% elastomer. An evaluation of the ITSM test results revealed that the highest ITSM values were obtained in mixtures prepared with 4% of the 611 elastomer, and it was confirmed that the incorporation of additives increased the ITSM values of the mixtures.

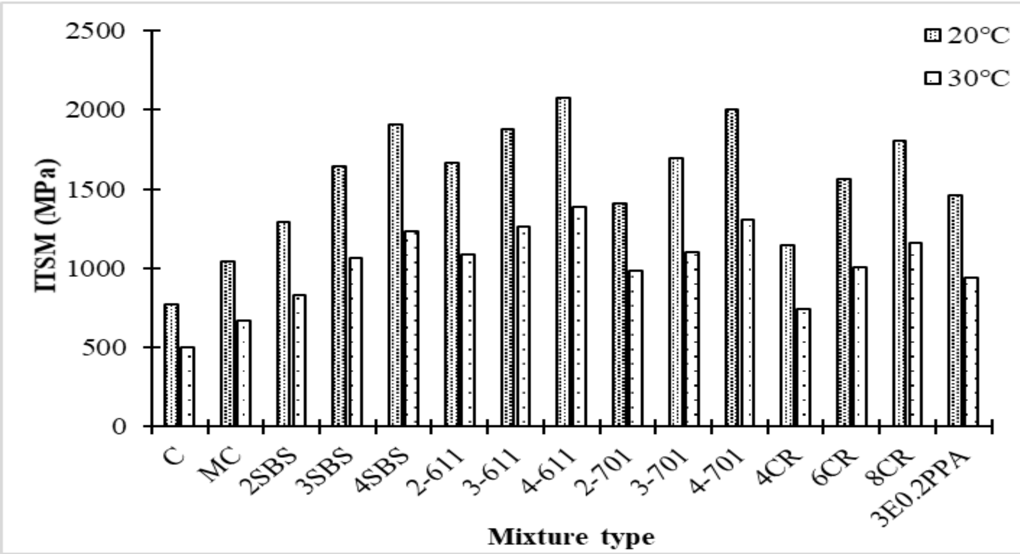

Figure 7. ITSM values of mixture samples

Conclusion

This study investigates the effects of various polymeric and reactive additives on the mechanical properties of hot mix asphalt mixtures, focusing particularly on deformation resistance, stiffness, and fatigue performance. Among the 15 different mixtures examined in this study, the highest resistance to deformation was achieved with the 611 elastomer. The stability values of asphalt mixtures containing CR were found to be similar to those of mixtures containing the 701 elastomer. Among the three elastomers, the 611 elastomer was determined to be the most effective in terms of stiffness. The stiffness values of the 701 and SBS elastomers were also found to be quite similar to each other. Furthermore, an increase in the ITSM test temperature resulted in a reduction in the stiffness values of the mixtures. It was determined that the number of load repetitions required to induce fracture in the mixture specimens was lowest in the mixtures prepared with neat bitumen (C) and highest in the 4-611 mixture.

Scientific Ethics Declaration

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

Conflict of Interest

*The authors declare that they have no conflicts of interest.

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