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Mechanical Characteristics of Environmentally Friendly Permeable Pavement: Enhanced Porous Asphalt

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ABSTRACT

This study explores the mechanical properties of porous-asphalt pavement, focusing on the influence of various polymers (elastomeric and reactive elastomeric terpolymers) and different aggregate compositions. Two aggregates were utilized: one is exclusively limestone-based and the other is a blend of limestone and basalt aggregates. The research findings unveiled that mixtures containing the conventional bitumen failed to meet the Cantabro loss-test criterion required for porous asphalt, necessitating a maximum threshold of 20%. In contrast, asphalt mixtures modified with polymers exhibited notably superior performance, particularly in terms of permeability, Cantabro loss and the ratio of indirect tensile strength. These results underscore the significant impact of polymer modification on enhancing the crucial mechanical properties of porous asphalt. Therefore, the study suggests the adoption of polymer-modified asphalt as a viable strategy to improve pavement longevity and overall performance, promoting its use for sustainable and durable infrastructure.

Keywords: Porous asphalt, Permeability, Modified porous asphalt, Porous-asphalt design, Polymer modification, Cantabro loss.

INTRODUCTION

Porous asphalt presents a highly promising alternative for effective stormwater management. The notable feature of a substantial air-void ratio inherent in the porous-asphalt structure facilitates water infiltration from the road surface into the pavement. Consequently, this mechanism ensures the removal of water from the pavement surface by leveraging the transverse and longitudinal slopes of the road. Furthermore, the aggregate-gradation design of porous asphalt, typically characterized by an open gradation, contributes to mitigating noise generated by the friction between the wheels and the road surface. The asphalt's porous nature allows for the absorption of noise, thereby aiding in reducing noise-related issues associated with road transportation.

Additionally, the open gradation exhibited by porous-asphalt pavements imparts an enhanced resistance against slipping. This feature can be attributed to the design's ability to provide improved traction, which helps minimize the likelihood of accidents or loss of control by motorists (Japan Highway Public Corporation, 1994).

Porous asphalt is generally designed with a high air-void content between 18% and 22% (Shahnewaz et al., 2023). Such high percentages of air-void would cause an age-hardening-related problem. Air-void content primarily affects the oxidation rate by managing the oxygen access to react with bitumen. Because of a high amount of air voids in porous asphalt, the aging resistance of the pavement becomes crucial. Aging makes bituminous materials firmer and more brittle, raising the possibility of pavement failure, such as ravelling and cracking (Hagos et al., 2009).

Polymer-modified bitumens (PMBs) are essential in enhancing the aging resistance and prolonging the service life of porous asphalt. In comparison to unmodified bitumens, PMBs demonstrate enhanced aging properties. This improvement is achieved by mitigating the impact of aging-related issues, such as increased stiffness and vulnerability to failures, like raveling and cracking, commonly associated with high air-void content in porous asphalt (Nielsen et al., 2004); (Yusoff et al., 2019). Additionally, PMBs contribute to extending the pavement's service life by increasing the thickness of the asphalt film. This augmented film thickness improves durability, creating a protective barrier against aging processes and external environmental factors. Consequently, the utilization of PMBs aids in the development of asphalt pavements with enhanced longevity, heightened resistance to aging-related problems and reduced susceptibility to common failure modes.

Usually, styrene-butadiene-styrene (SBS)-modified bitumen, crumb rubber-modified bitumen (CRMB) and high-viscosity bitumen (HVB) are utilized to enhance the mechanical properties of asphalt pavement (Gupta et al., 2019). Ma et al. (2018) tested the impact of different modifiers on porous-asphalt mixtures. Their study involved four types of polymer- modified bitumen within the porous-asphalt mixture: HVB, SBS-modified bitumen, PG76-22 and PG70-22. Based on their findings, HVB boosts the compressive strength of the porous asphalt in comparison with SBS-modified specimens and the increase in viscosity of modified bitumen enhances the cohesion; therefore, a lesser amount of drain-down is detected (Ma et al., 2018); (Chen et al., 2012). Additionally, owing to high viscosity, the stability and endurance of abrasion similarly increase (Ma et al., 2018); (Chen et al., 2013); (Liu and Cao, 2009). Introducing these particular polymer modifiers significantly enhances various essential aspects of porous-asphalt pavement. These modifiers collectively augment the mechanical characteristics of the asphalt, including its ability to resist rutting, cracking and aging while providing increased durability and longevity. The combined utilization of SBS, CRMB and HVB ultimately contributes to creating more resilient, longer-lasting and high-performing porous-asphalt pavement, consequently reducing the expenses associated with maintenance and extending the pavement's lifespan.

Consequently, the high viscosity of bitumen indicates a good-quality asphalt mixture concerning cohesion, rutting performance, abrasion resistance, compressive strength and drain-down. Shirini and Imaninasab (2016) explored the impact of crumb rubber on enhancing porous asphalt's mechanical properties. Their experimental study compared porous-asphalt specimens with different crumb-rubber percentages (10%, 15% and 20%) against those containing a 5% SBS additive. Assessments included evaluating moisture resistance, rutting, moisture sensitivity and permeability. Their findings revealed that adding crumb rubber and SBS additive notably decreased permeability and enhanced rutting resistance. Notably, the study concluded that while adding rubber to flexible modules improves rutting resistance and moisture sensitivity up to a certain threshold, excessive amounts could compromise these properties (Shirini and Imaninasab, 2016).

Furthermore, Ozay et al. (2013) investigated the impact of modified bitumen with Styrene-Butadiene-Styrene (SBS) and TafPack-Super (TPS) additives on porous-asphalt pavements according to Japanese standards. Their analysis involved several tests, including bitumen drain-down, indirect tensile strength, rutting, Cantabro loss and permeability. The study demonstrated that SBS-modified specimens exhibited better bitumen drain-down and indirect tensile strength results. In contrast, the TPS-modified specimens showed superior performance in rutting, Cantabro loss and permeability (Özay and Öztürk, 2013).

This research study aims to evaluate the specific characteristics of porous-asphalt pavement using diverse polymers, including elastomeric and reactive elastomeric terpolymers, in conjunction with various aggregates. Its primary objective is to comprehensively assess the mechanical properties of porous-asphalt pavement by employing tests, such as the Marshall test, permeability analysis, drain-down assessment and indirect tensile strength testing. This study encompasses two distinct types of aggregates, limestone and basalt, along with two varieties of polymers: elastomeric polymers, such as Styrene-Butadiene-Styrene (SBS), and reactive elastomeric terpolymers, specifically Elvaloy. These experimental tests are conducted to evaluate and analyse the mechanical behaviour and performance attributes of porous-asphalt pavement specimens.

LITERATURE REVIEW

Recent research has extensively examined the various critical aspects of porous asphalt, highlighting its multifaceted advantages in improving environmental sustainability and enhancing infrastructure functionality. Notably, research conducted by Wang et al. (2022) emphasized the significance of porous asphalt in managing stormwater run-off. That research underscored its capability to facilitate natural infiltration, effectively reduce surface-water run-off and enhance water quality within urban areas.

Furthermore, investigations by Liu et al. (2023) and Bozkurt and Karakaş (2022) have focused explicitly on the acoustic benefits of porous asphalt. The unique structure of porous asphalt allows for sound penetration and absorption and has consistently proven effective in mitigating traffic-related noise, particularly in urban settings. Research conducted by Zhang and Kevern (2021) contributes to our understanding of the durability and performance of porous asphalt under diverse climatic conditions and heavy traffic loads. The findings confirm the resilience and suitability of porous asphalt across various weather scenarios, reinforcing its practical application in different regions. Additionally, recent work by Thives et al. (2023) has emphasized the environmental advantages of porous asphalt. They have highlighted its role in reducing surface water-run-off, positively impacting drainage systems and promoting overall sustainability in urban environments.

Moreover, research conducted by Xu et al. (2022) delved into material modifications, specifically the integration of polymers and their impacts on porous asphalt's mechanical properties and performance. That research demonstrated the enhanced durability and strength of such modified mixtures.

MATERIALS AND METHODS

Materials

Conventional Bitumen

The conventional bitumen employed in this study corresponds to 50/70 penetration grade. The pertinent physical properties of the conventional bitumen are elucidated in Table 1.

Table 1. Physical properties of the conventional bitumen

Test	Specification	Result	Specification limits
Penetration (25 ºC; 0.1 mm)	ASTM D5 EN 14264	65	50-70
Softening point (ºC)	ASTM D36 EN 1427	51	46-54
Ductility (25 ºC; cm)	ASTM D113	100	-
Specific gravity	ASTM D70	1.030	-
Flash point (ºC)	ASTM D92	260+	230 (min)
Penetration index (PI)	-	0.35	-
Rolling thin-film oven test (RTFOT)	ASTM D2872-12		
Change of mass (%)	-	0.160	0.5 (max.)
Penetration after RTFOT (25 ºC; 0.1 mm)	ASTM D5 EN 1426	53	50 (min.)
Retained penetration after RTFOT (%)	ASTM D36 EN 1427	82	50 (min.)
Softening point after RTFOT (ºC)	ASTM D36 EN 1427	58	48 (min.)

Polymer Modifiers

Two elastomeric polymers; namely, Styrene-Butadiene-Styrene (SBS), as well as the reactive elastomeric terpolymer (Elvaloy), were employed for the modification process in this study. The SBS polymer used in this study was Kraton D-1101, provided in powder form, while the reactive elastomeric terpolymer type utilized was Elvaloy® 4170, obtained in pellet form.

Preparation of PMB Specimens

To prepare the polymer-modified bitumen (PMB) specimens, SBS® and Elvaloy® were blended with the unmodified bitumen at 5% and 1.5%, respectively. These specific amounts were selected based on prior research studies (Sengoz and Isikyakar, 2008); (Topal, 2010); (Almusawi et al., 2021); (Ozdemir et al., 2021); (Kaya et al., 2020); (Kaya et al., 2019a); (Kaya et al., 2019b). The rationale for utilizing these percentages is grounded in the findings and recommendations presented in these studies.

Aggregates

The porous-asphalt specimens in this study were prepared using two distinct aggregate types, limestone and basalt, sourced from the Dere Beton/Izmir quarry. Essential properties of the aggregates utilized in the study are presented in Table 2.

Table 2. The physical properties of limestone and basalt aggregates

Test	Specification Limits	Test Standard	Limestone	Basalt
L.A. abrasion (%)	≤25	TS EN 1097-2	22.3	13.7
Water absorption of aggregate (%)	≤2	TS EN 1097-6	1.05	0.6
Resistance to ware (%)	≤20	TS EN 1097-1	18	15
Magnesium-sulfate test (%)	≤10	TS EN 1367-2	9.2	7.7
Particle shape (Flakiness Index) (%)	≤15	TS EN 933-3	6.6	4.8

This study employed two distinct aggregate sets to produce the porous-asphalt mixtures. The first aggregate set was exclusively comprised of limestone aggregate. Conversely, the second aggregate set was a combination of basalt serving as the coarse aggregate and limestone utilized as the fine particles. The sets' gradation was chosen per the Turkish standards and given in Table 3.

Table 3. Gradation of the two sets of aggregates

Sieve No.	Selected Gradation (%)		Specification Limit (%)
	1# Set	2# Set	
¾ in	100	100	100
½ in	90	95	90-100
3/8 in	63	70	63-77
No.4	11	25	11-35
No.10	10	15	10-20
No.80	5	7	5-10
No.200	3	4	3-7

Methods

Design of Porous-asphalt Mixtures

The design approach for porous-asphalt mixtures differs from that of dense graded asphalt in several aspects due to the substantial variance in air-void content between the two mixture types. The air-void content profoundly influences the stability and abrasion properties of the specimen, making these factors more critical in the design process for porous-asphalt mixtures.

In conventional hot-mix asphalt design, multiple specimens are typically produced with varying bitumen contents and the optimum bitumen content is determined as the value corresponding to the median air-voids in the mixture, typically around 4%. However, for the design of porous-asphalt mixtures, determining the optimum bitumen content involves considering additional factors, including the air-void content, Cantabro abrasion value and stability value. It is crucial to ensure that these values fall within the specified limits, as outlined in Table 4. For Marshall's design, three test specimens are prepared for each chosen asphalt content, with bitumen contents ranging from 3% to 5%. Similarly, three specimens are utilized for other tests and the average results are calculated.

Table 4. Porous-asphalt design criteria

Properties	Test Standard	Specification Limits
Number of Blows	TS EN 12697-30	50
Air Voids, (%)	-	18-22
Particle Loss (Cantabro), (%), max.	TS EN 12697-17	20
Stability, (kg), min.	TS EN 12697-34	300
Permeability Value, (m/s), x10^{-3} Vertical/Horizontal	TS EN 12697-19 -	0.5-3.5
Schellenberger Bitumen Drain-down, (%), max.	TS EN 12697-18	0.3
Indirect Tensile Strength (ITS) Ratio, (%), min.	TS EN 12697-12 TS EN 12697-23	80

In the investigation's conclusive phase, verifying the permeability value, bitumen drain-down and the Indirect Tensile Strength (ITS) ratio of the asphalt-mixture specimens is essential, based on the determined optimum bitumen content.

● Permeability

Permeability is a decisive characteristic of porous asphalt. It is an essential distinction between dense-graded and porous-asphalt mixtures. Optimizing asphalt performance in diverse environmental conditions can significantly enhance its real-world effectiveness. This can be achieved by understanding the interplay between horizontal permeability, which manages surface-water run-off and enhances safety in wet conditions and vertical permeability, which channels water downward, aiding stormwater management and reducing strain on drainage systems. These permeability characteristics in the field mitigate flooding, enhance water infiltration and sustain porous-asphalt functionality.

In the permeability test, a column of water with a fixed altitude is applied to a cylinder-shaped specimen and permitted to penetrate across the specimen for a monitored time in either a vertical or a horizontal path regulated by the measured parameter.

The flow rate of the water Q_v or Q_h determines the permeability value K_v or K_h. The experiment is performed at ambient temperature. The permeability value considered acceptable for porous asphalt typically falls within the range from 0.5 to 3.5 × 10^{-3} (m/s) (CEN, 1998).

The vertical permeability of the specimen can be measured with the following Eq. (1).

$$K_v = \frac{4 * Q_v * l}{h * \pi \ D^2} \tag{1}$$

where, K_v is the vertical permeability (m/s), Q_v is the vertical flow across the specimen (m^3/s), l is the depth of the specimen (m), h is the actual altitude of the water column (m) and D is the diameter of the specimen (m).

The horizontal permeability can be measured with Eq. (2).

$$K_h = \frac{Q_h * l}{(H + P + 0.5\ l) * (\pi * D * l)} \tag{2}$$

where K_h is the horizontal permeability (m/s), Q_h is the horizontal flow across the specimen (m^3/s), l is the depth of the specimen (m), P is the altitude of the lower tube that is fixed to the specimen (m) and D is the diameter of the specimen (m).

● Schellenberger Bitumen Drain-down Test

Due to their distinctive gradation structure, porous-asphalt mixtures typically contain more bitumen than dense-graded hot-mix pavements (Aschenbrener and Far, 1994). During the production phase, the elevated temperature causes the excess-bitumen content in the porous asphalt mixture to become fluid, separating bitumen from the aggregate mixture through a process known as drain-down (Figures 1 and 2).

Figure (1): Keeping the mixture in an oven at 170 °C for 1 hour

Figure (2): Glass beaker after bitumen-drain-down test

It is essential to control the drain-down characteristics of the porous asphalt; therefore, the Schellenberger bitumen drain-down test is among the design criteria for porous-asphalt mixtures. The porous asphalt mixture's bitumen drain-down (BD) value can be calculated using Eq. (3). BD holds significant importance in porous-asphalt mixture design, as it directly impacts the overall mixture performance, particularly regarding its resistance to permanent deformation. As per the specification, the maximum permissible value for drain-down is 0.3% (ASTM D6390-11).

$$BD = 100 \times \frac{W_5 - W_3 - W_6}{W_4 - W_3} \tag{3}$$

where w_3 is the weight of the beaker (g), w_4 is the weight of the beaker combined with batch (g), w_5 is the weight of the beaker along with retained material after upturning (g) and w_6 is the weight of the dried residue retained on the sieve (g).

● Indirect Tensile Strength Ratio (ITSR)

The test method employed in this study utilizes the concept of indirect tensile strength to assess the mechanical properties of asphalt mixtures. Testing cylindrical specimens is required for this purpose. Two sub-groups of cylinder specimens are created to analyze the effect of moisture conditioning on the indirect tensile strength of asphalt mixtures. These divisions go through several conditioning procedures. The second sub-group is sub-merged in water at a specific conditioning temperature, with specimens placed in a water bath at (40±2)°C for (72±2) hours. Meanwhile, the first sub-group remains dry at room temperature. Following the conditioning time, both sub-groups' indirect tensile strengths are calculated at a specific temperature related to the bitumen grade. To measure the effect of moisture conditioning, the ratio of the indirect tensile strength of the dry sub-group to that of the water-conditioned sub-group is determined. Eq. (4) calculates this ratio, the Indirect Tensile Strength Ratio (ITSR).

$$ITS = \frac{(2000 \times P_{max})}{\pi \times t \times D} \tag{4}$$

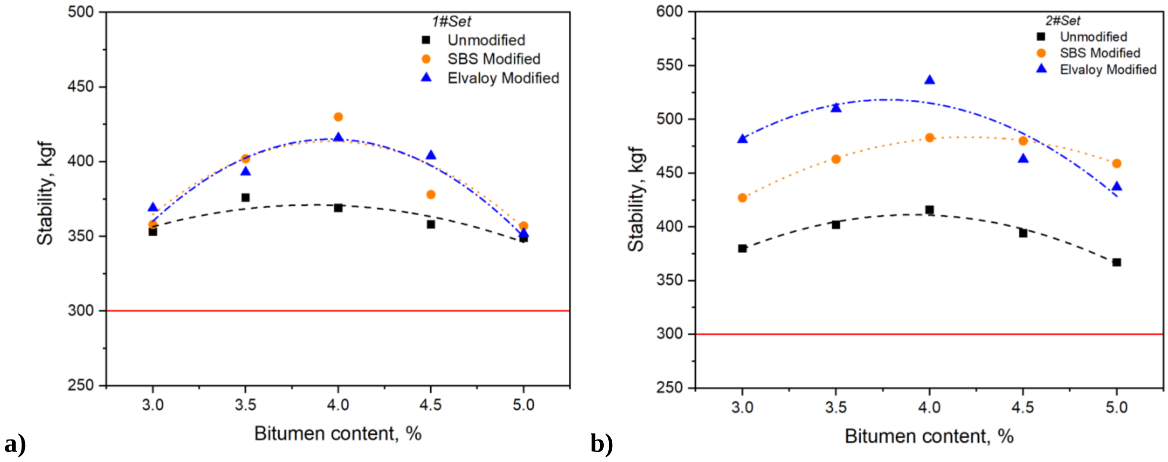
where ITSR is the indirect tensile strength ratio (%), ITSw is the average indirect tensile strength of the wet sub-group, (kPa) and ITSd is the average indirect tensile strength of the dry sub-group (kPa).

RESULTS AND DISCUSSION

Optimum Bitumen Content

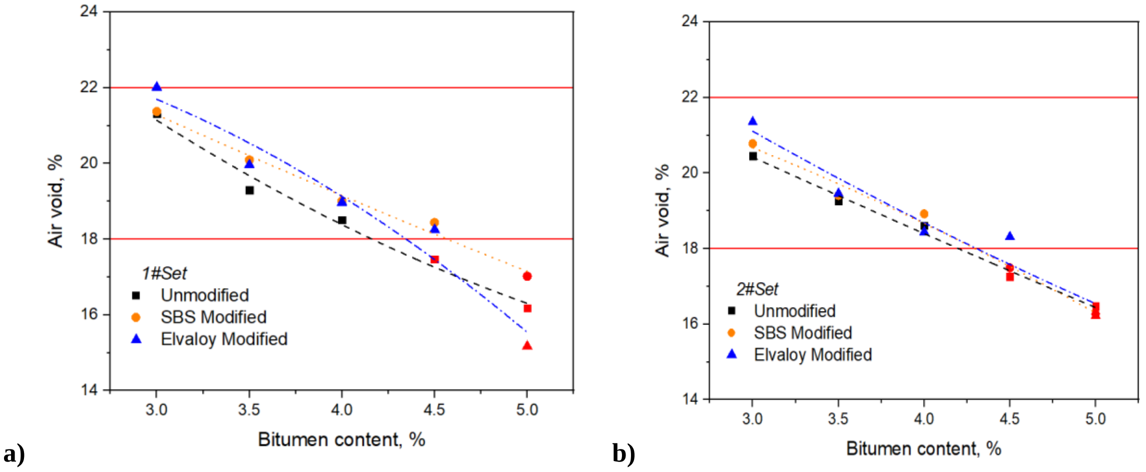
The Marshall-design approach produced unmodified porous asphalt, Styrene-Butadiene-Styrene (SBS)-modified and Elvaloy-modified specimens. These specimens were tested for stability, air-void content and Cantabro particle loss. The objective was to determine the optimal bitumen content for 1#Set and 2#Set aggregate types. The findings are presented in Figures (3-5).

The optimal bitumen content is defined as the value that satisfies the criteria of the Turkish standard (TS EN 12697-17) for porous-asphalt mixture: a minimum stability of 300 kg, an air-void content within the range from 18% to 22% and a maximum Cantabro particle loss of 20%. The figures represent the upper and lower limits of the specified standards by red straight lines. Additionally, any specimens that failed to meet the criteria above are explicitly highlighted in red.



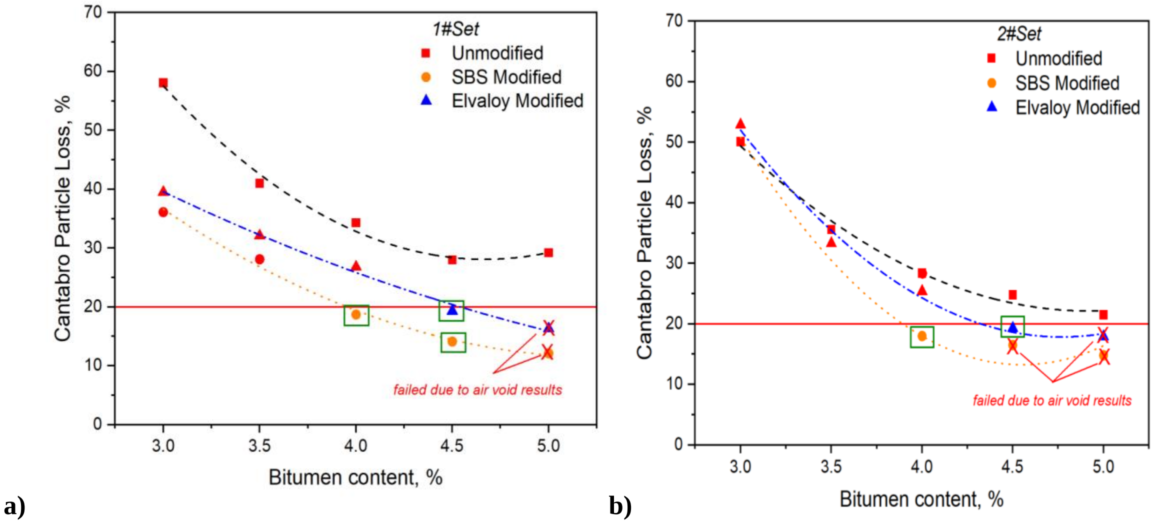
a) b)

Figure (3): Marshall-stability results of the mixtures a) 1#Set b) 2#Set



a) b)

Figure (4): Air-void results of the mixtures a) 1#Set b) 2#Set



a) b)

Figure (5): Cantabro particle-loss results of the mixtures a) 1#Set b) 2#Set

Figure 3 depicts the Marshall stability-test results for the 1# Set and 2# Set mixtures that surpassed the standard limit of 300 kg. The incorporation of polymer modification demonstrates improved Marshall stability values compared to the mixtures prepared with unmodified bitumen. Notably, the mixtures containing a combination of basalt and limestone aggregates (2# Set) exhibit higher stability values than those comprising solely limestone aggregate (1# Set) for each bitumen content. This difference can be attributed to the enhanced durability properties of basalt aggregate. It is also important to note that the polymer-modified specimens exhibit similar Marshall stability values when made using limestone aggregate. Nevertheless, the Elvaloy-modified mixture is more stable than the SBS-modified mixture when the basalt aggregate is included in the 1# Set mixtures. This demonstrates how the Elvaloy polymer modification, especially when combined with basalt material, can enhance the stability of the porous-asphalt combinations.

Figure 4 illustrates a clear inverse relationship between the bitumen and air-void content in the porous-asphalt mixtures. As the bitumen content increases, the air-void content decreases. The air-void results comply with the criteria of up to 4.5% bitumen content for both aggregate types, whether the mixtures were prepared with conventional bitumen or with polymer-modified bitumens. However, it should be noted that when the bitumen content reaches 4.5%, the unmodified mixture prepared with both aggregate sets fails to meet the specified criteria. In contrast, the Elvaloy polymer-modified mixture, using both aggregate sets, manages to maintain an acceptable air-void content at the same bitumen content. Also, it is worth noting that both the unmodified and polymer-modified specimens containing 5% bitumen did not meet the specification requirements for each aggregate set. Overall, the results from Figure 4 underline the intricate relationship between bitumen content and air voids, emphasizing the critical role of polymer modification in maintaining air-void criteria and demonstrating the threshold at which higher bitumen content adversely impacts air-void characteristics in porous-asphalt mixtures.

Based on Figure 5, it is evident that the Cantabro-loss test results indicate that the mixtures utilizing unmodified bitumen fail to meet the upper limit of 20% specified for any combination of bitumen content or aggregate sets. When basalt aggregate was introduced, the Cantabro particle loss increased for all specimens prepared with unmodified and modified bitumens. However, polymer-modified specimens successfully met the requirements for both aggregate sets when the bitumen content was either 4.5% or 5%. Similarly, SBS-modified specimens containing 4% bitumen satisfied the criteria for both aggregate sets. Overall, the data from Figure 5 highlights the limitations of unmodified bitumen in meeting Cantabro-loss specifications, the sensitivity of mixtures to basalt aggregate and the beneficial effects of polymer modifications, especially at higher bitumen contents, in effectively reducing Cantabro particle loss in porous-asphalt mixtures.

Figures (3-5) demonstrate that, regardless of the kind of aggregate, using unmodified bitumen to produce porous-asphalt pavement is not advised. The ideal bitumen amount for the Elvaloy-modified specimens, however, was found to be 4.5% for both aggregate sets, because other bitumen values did not comply with the established limitations. The optimum bitumen content for the SBS-modified specimens with only limestone aggregate (1#Set) could be 4% or 4.5%, since both matched the requirements. Figure 3 shows that stability values performed better at 4% SBS polymer-modified bitumen content than at 4.5%. 4% is therefore chosen as the ideal bitumen content for 1#Set. However, 4% is considered the content of SBS polymer-modified bitumen percentage when basalt material is used, as other bitumen contents failed to meet the standard limits.

Permeability

The bitumen content directly influences the permeability properties of the specimens. When the bitumen content in the asphalt mixture exceeds the optimum level, it fills the porous structure excessively, leading to pore blockage. As a result, the permeability of porous asphalt decreases, rendering the pavement ineffective.

Permeability tests were conducted to evaluate the permeability of the polymer-modified mixes prepared with the determined optimum bitumen contents. The results of these tests are presented in Figure 6.

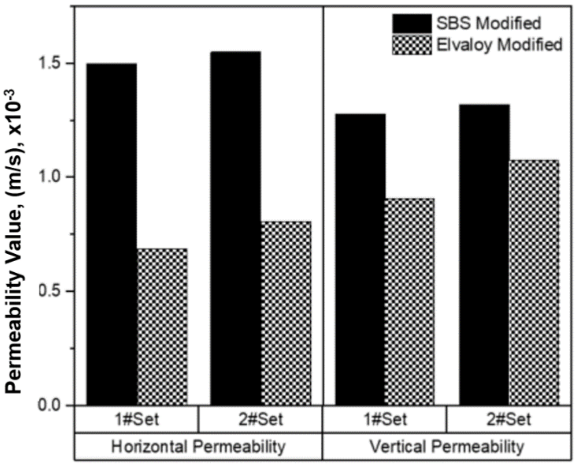


Figure (6): Permeability results of the modified specimens

The findings revealed that the horizontal permeability and vertical permeability of the SBS-modified mixtures were greater than those of the Elvaloy-modified mixtures, regardless of the aggregate set. More excellent permeability leads to improved water drainage and increased skid resistance within the mixture. Consequently, based on the results, it is possible to say that polymer modification, particularly with SBS, has a positive impact on the mixture's water drainage and skid-resistance performance. This discrepancy can be attributed to the higher bitumen content employed in the Elvaloy-modified mixtures than in the SBS-modified specimens. The increased bitumen content creates a thicker film surrounding the aggregate particles, reducing the presence of air voids, which hinders water from passing through. Hence, the reduction in air voids is directly correlated with the permeability of the porous asphalt.

According to Figure 6, the polymer-modified mixtures from 2# Set, consisting of a blend of limestone and basalt aggregates, demonstrated marginally higher permeability results than the other set. This disparity can be attributed to basalt aggregate in the 2# Set, particularly in the coarse particle portion. Including basalt aggregate necessitates increased compaction effort during mixing, which may impact the mixture's permeability characteristics.

Schellenberger Bitumen Drain-down Test Results

Figure 7 displays the drain-down results. According to the results, regardless of the aggregate set, the drain-down value (%) is less for the SBS-modified combination than for the Elvaloy-modified mixture. This can be due to the viscous character of bitumen treated with SBS polymers and the mixture's comparatively low bitumen percentage. In other words, the SBS-modified bitumen specimens show a stiffer consistency and more robust adhesive qualities, leading to less drain-down. A higher drain-down, which signifies the loss of bitumen from the asphalt mixture, increases maintenance needs or even reconstruction. Given this, it can be concluded that SBS and Elvaloy modifications contribute to lower maintenance costs and extended service life for porous-asphalt mixtures.

Figure 7 further emphasizes how the selection of aggregate within the mixture affects the outcomes of the drain-down. Mainly, the basalt aggregate-containing 2# Set showed more drain-down. According to research conducted by Radenberg et al. (2016) and Karacasu and Akalin (2020), basalt aggregate tends to have lesser adhesion qualities.

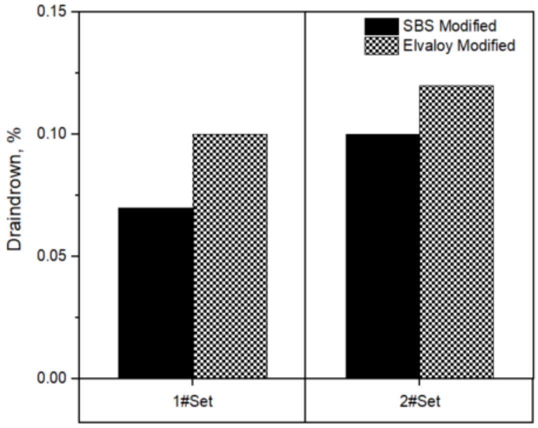


Figure (7): Drain-down-test results

Indirect Tensile Strength (ITS) Ratio

Along with the ITSR (ITS ratio) results, Figure 8 shows the ITS (Indirect Tensile Strength) values for both wet (ITSw) and dried (ITSd) specimens. The findings show that the ITS values of the dry specimens are higher than those of the conditioned specimens. The variation in ITS values can be ascribed to various factors. The moisture within the asphalt mixture, specifically water, can potentially diminish the interfacial bonding between the asphalt binder and the aggregate particles. This compromised bonding, caused by the moisture content, can have a detrimental impact on the overall strength and performance of the asphalt, resulting in lower ITS values when exposed to wet conditions.

On the contrary, in dry conditions, the absence of moisture-related effects enables a stronger interfacial adhesion between the asphalt binder and the aggregate particles. This improved bonding enhances strength characteristics, leading to higher ITS values.

In addition, the SBS-modified specimens show somewhat higher ITS values than the Elvaloy-modified specimens, regardless of conditioning (wet or dry) and aggregate type.

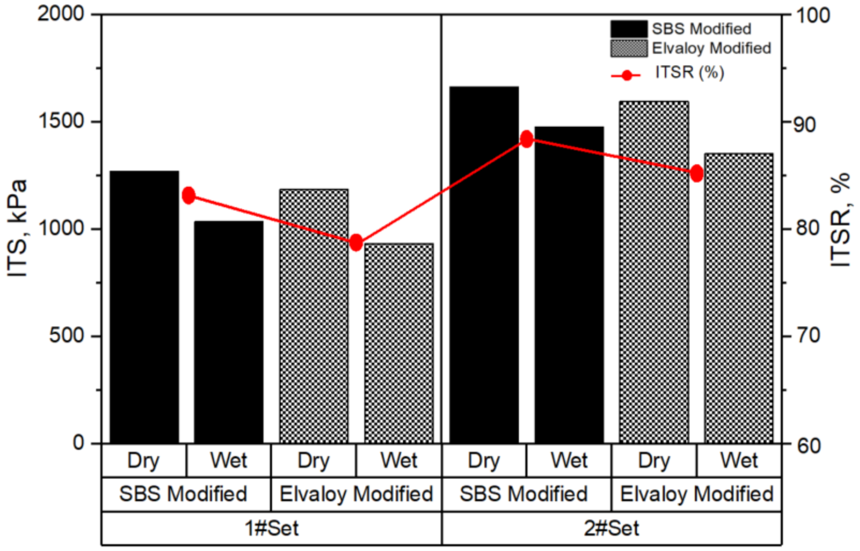


Figure (8): ITS and ITSR values of the specimens

Additionally, among the two aggregate sets, the specimens of limestone and basalt (2#Set) demonstrate significantly higher ITS values. This can be attributed to the superior durability characteristics of the basalt aggregate. Furthermore, when SBS is utilized as a modifier in combination with limestone and basalt aggregates, it enhances the performance of the porous-asphalt pavement.

Figure 8 also illustrates that the SBS-modified specimens exhibit higher ITSR values than the Elvaloy-modified specimens. Furthermore, in terms of aggregate type, it is evident that specimens containing basalt aggregate in the mixture (2#Set) display higher ITSR values.

CONCLUSIONS AND RECOMMENDATIONS

The characteristics of porous-asphalt pavement using different polymers (elastomeric and reactive elastomeric polymers) and aggregate types have been investigated by the following tests: Marshall design (stability, air-void, Cantabro particle loss); permeability, drain-down and ITS tests). According to the results, the main conclusions of the study are given below:

1. The utilization of conventional bitumen within both mixtures failed to meet the criteria of porous asphalt; therefore, it is a must to utilize modified bitumen in porous-asphalt pavement.
2. The variation of the aggregate types within the mixture affected the Marshall-test results; however, the determined optimum bitumen content did not change between the two sets produced by the same polymer-modified bitumen.
3. Based on the findings, it is reasonable to conclude that the SBS-modified specimens required a lower optimum bitumen content than the Elvaloy-modified specimens, regardless of the aggregate set.
4. Regarding permeability tests, the permeability values of the 2# Set (limestone + basalt) were slightly higher than those of the 1#Set. This is directly related to using coarse aggregate as a basalt type. Also, the properties of asphalt are significantly affected by the chemical composition of the aggregates used. The calcium carbonate content of limestone enhances the binding capacity of the mix, while the mineral composition of basalt provides superior mechanical strength. By utilizing these aggregates in a balanced manner, taking advantage of their distinct chemical and physical attributes, the resulting asphalt mixes exhibit improved mechanical

characteristics, offering a combination of durability, strength and workability.

5. The specimens incorporating a combination of limestone and basalt (2#Set) exhibit significantly higher ITS values, which can be attributed to the enhanced durability characteristics of the basalt aggregate.

Future studies should explore additional mixture performance properties such as rutting resistance, fatigue resistance and moisture susceptibility and further investigate the impact of different polymer additives in porous asphalt modifications.

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