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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

The Effect of Different Mixing and Compaction Temperatures on the Particle (Cantabro) Loss in Porous Asphalt Pavements

Farklı Karıştırma ve Sıkıştırma Sıcaklıklarının Poroz Asfalt Kaplamaların Parça Kaybına Etkisi

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Abstract

Porous asphalt (PA) is a type of pavement with an open-graded aggregate that contains higher air voids than the conventional asphalt pavements after compaction, which allows precipitation waters to infiltrate from the pavement surface to the lower layers. The particle loss in the wear layer causes surface deterioration, which affects pavement performance. In addition, the porosity nature of porous asphalt leaves the pavement under the effect of air and water continuously, which accelerates the oxidation rate and affects the surface properties of the pavement. Moreover, these factors can affect the bitumen-aggregate bond strength and cause cohesion degradation within the asphalt film, causing the bitumen to peel from aggregate. The performance of porous asphalt, particularly strength and durability, is greatly affected by compaction temperature. Higher compaction temperatures can reduce the air voids of the mix, so the required mix densities may not be achieved. In this study, the particle loss of porous asphalt samples prepared at 3 different compaction temperatures by using unmodified bitumen, SBS®, Elvaloy®, and Sasobit® modified bitumen was investigated and the optimum mixing and compaction temperature was determined.

Keywords: *Porous asphalt, compaction temperature, particle loss, modified porous asphalt, porous asphalt design, polymers.*

Öz

Poroz asfalt, sıkıştırma sonrasında geleneksel asfalt kaplamalara göre daha yüksek hava boşlukları içeren, yağış sularının kaplama yüzeyinden alt katmanlara sızmasına izin veren, açık gradasyonlu agregaya sahip bir kaplama türüdür. Aşınma tabakasındaki parçacık kaybı, kaplama performansını etkileyen yüzey bozulmasına neden olur. Ayrıca poroz asfaltın gözenekli yapısı, kaplamayı sürekli olarak hava ve suyun etkisi altında bırakmakta, bu da oksidasyon hızını hızlandırmakta ve kaplamanın yüzey özelliklerini etkilemektedir. Ayrıca, bu faktörler bitüm-agrega bağ mukavemetini etkileyebilir ve asfalt film içinde kohezyonun bozulmasına neden olarak bitümün agregadan soyulmasına neden olabilir. Poroz asfaltın performansı, özellikle mukavemet ve dayanıklılık, sıkıştırma sıcaklığından büyük ölçüde etkilenir. Daha yüksek sıkıştırma sıcaklıkları karışımın hava boşluklarını azaltabilir, dolayısıyla gerekli karışım yoğunlukları elde edilemeyebilir. Bu çalışmada, modifiye edilmemiş bitüm ve SBS®, Elvaloy®, Sasobit® modifiyeli bitüm kullanılarak 3 farklı sıkıştırma sıcaklığında hazırlanan gözenekli asfalt numunelerinin parçacık kaybı araştırılmış ve optimum karıştırma ve sıkıştırma sıcaklığı belirlenmiştir.

Anahtar Kelimeler: *Poroz asfalt, sıkıştırma sıcaklığı, parça kaybı, modifiye poroz asfalt, poroz asfalt dizayn, polimerler.*

1. Introduction

Porous asphalt is a type of pavement designed with a higher percentage of air voids to allow water from precipitation or other factors to drainage the pavement surface faster than conventional asphalt pavement. Generally, the air void content is recommended to be between 18% and 25% to ensure adequate permeability during heavy rainfall [1]. The percentage of coarse aggregates is greater than 85% and creates a coarse-grained skeleton that develops stone-on-stone contact and high associated air void content, allowing water to flow through the internal structure of PA mixtures [2]. Porous asphalt has been widely used in flexible pavement construction in recent years. Bitumen or asphalt binders are used to bind the aggregate particles together. Binders are known to deform and flow at high temperatures but become brittle at low temperatures. While the abrasive effect of the vehicle wheel on the pavement surface, especially in high-stress areas, can initiate particle loss, it can also cause peeling with the effect of water. This leads to a pavement problem known as scattering, which is more dominant in porous asphalt than in dense asphalt [3,4]. The structure of porous asphalt causes faster oxidation and embrittlement of the binder compared to conventional dense mix [5]. The mixture's resistance to particle loss depends not only on the oxidation resistance of the binder, but also on binder film thickness, aggregate gradation, and percentage of air voids [6]. The effect of temperature is very important especially during mixing, laying and compaction processes in the construction of strong and durable pavements [7]. This is because the bitumen is heated to obtain the required viscosity to allow the aggregates to stick together better. However, prolonged heating will cause the

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bitumen to oxidize and harden, resulting in serious damage to the pavement after paving [8]. Compaction number and compaction temperature are critical factors determining the performance of a porous asphalt mix. However, there is no widely accepted method for the design of PA mixtures, and the compression number and compression temperatures used in different institutions are not the same. It is essential to evaluate the effect of compaction on the performance of porous asphalt mixtures and to determine the optimum compaction and compaction temperature, and this is of great importance for the design of porous asphalt mixtures [9]. The Cantabrian test can simulate the rolling impact created by the traffic on the road [6]. The Cantabrian test is commonly used to evaluate the resistance to particle loss by abrasion and the effect of impact on porous mixes [10]. Abrasion loss is an important parameter for gauging bonding properties between aggregates and bitumen. This test is commonly used in Japan to evaluate the particle loss resistance of porous asphalt under winter conditions [11].

1.1. literature Review

Inadequate compaction of porous asphalt mixes causes the mix's stiffness to fall short of service prerequisites. In contrast, excessive compaction tends to crush the aggregate and alter the gradation, losing the pavement's drainage and noise reduction benefits. Consequently, controlling the road performance of a porous asphalt mixture requires sufficient compaction [12-13]. A specific temperature limit is established during the compaction of porous asphalt to ensure optimal pavement performance [12]. Maintaining a consistent temperature throughout the compaction process is essential for creating porous asphalt pavement with significant air void connectivity, ensuring solidity and longevity. The high viscosity of bitumen, which hinders compaction efforts, means that low compaction temperatures can affect both density and the bond between aggregate and bitumen [15]. According to Renken [16], reducing the compaction degree to achieve a higher void content is deemed inappropriate. This is because resistance to deformation and particle loss (raveling) heavily relies on a high degree of compaction. Conversely, Poulikakos et al. [17] reported that the Cantabro test is a distinctive porous asphalt evaluation method commonly used to assess mixture resistance to stripping and particle loss resulting from traffic impact and abrasion. Due to its exposure to significant moisture levels, porous asphalt is more susceptible to moisture damage compared to traditional dense mixtures. Previous studies on Polymer Modified asphalt have investigated the influence of mixing and compaction temperatures on the indirect tensile strength [18]. The indirect tensile strength provides insights into the tensile characteristics of the asphalt mixture, which are closely related to the pavement's susceptibility to cracking [19] [20]. Porous asphalt, designed to facilitate stormwater infiltration through interconnected air voids, presents unique challenges in compaction. Unlike conventional dense-graded asphalt mixes, which prioritize minimizing air voids, the compaction process for porous asphalt requires a nuanced approach to preserve its permeability. Achieving structural stability without compromising the integrity of the void network is paramount. Excessive compaction can lead to pore collapse and a subsequent reduction in permeability, undermining the pavement's intended functionality. Consequently, ongoing research endeavors to refine compaction techniques, focusing on adjustments in production temperature and rolling methods to optimize porous asphalt performance.

2. Materials and Methods

In this section, firstly, the determination methods of mixing and compaction temperature specifications adopted by different standards will be presented, followed by the properties of the bitumen, polymers, and the type of aggregates.

2.1. Materials

In this study, the base bitumen with 50/70 penetration grade, has been used. Some of the conventional tests have been applied to measure the physical properties, as illustrated in Table 1.

Table 1. Physical properties of the base bitumen

Test	Specification	Results	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.)

Two different elastomeric type polymers; Styrene Butadiene Styrene (SBS®), Reactive Elastomeric Terpolymer type – Elvaloy® and organic warm mix asphalt (WMA) additive (Sasobit®) were utilized for the modification. SBS®, Elvaloy®, and Sosabit® contents were selected as 5%, 1.5% and 3% of bitumen weight, respectively. The polymer and WMA contents were determined based on past research [21-25]. Table 2 illustrates the physical properties of the SBS® and Elvaloy®. Additionally, Table 3 shows the physical and chemical properties of Sasobit®. The production conditions for PMB and WMA samples are provided in Table 4 [26-29].

The porous asphalt samples were prepared using two different aggregate types (limestone and basalt), which were collected from the Dere Beton/Izmir quarry. Some of the physical properties of the aggregates are presented in Table 5. The aggregate gradation has been chosen as a Type - 2 based on the Turkish Specifications.

Two aggregate series were utilized to manufacture the porous asphalt samples. The #1 series was formed using only limestone aggregate, while the #2 series was formed by mixing the coarse particles of the basalt with the fine particles of the limestone. The gradation of the two series was selected according to Turkish standards (Figure 1).

Table 2. The physical characteristics of SBS® and Elvaloy® polymers.

Physical properties	Specification	SBS® Kraton D 1101	Elvaloy® 4170
Molecular structure	-	Linear	Linear
Specific gravity	ASTM D792	0.94	-
Tensile strength at break (MPa)	ASTM D 412	31.8	31.8
Shore hardness (A)	ASTM D 2240	71	-
Physical form	-	Powder, pellet	Powder, pellet
Melt flow rate	ASTM D-1238	<1	8
Processing temperature (◦ C)	-	150–170	-
Elongation at break (%)	ASTM D 412	875	-
Density	-	-	0.557

Table 3. The physical and chemical properties Sasobit®.

Property	Sasobit®
Colour	Off-white to pale brown
Odor	Practically odorless
Congealing point	>90 C (ASTM D 938)
Molecular weight	Approx. 1000
Density at 25°C	0.9 g/cm^3
pH values	Neutral
Initial boiling point	271°C (ASTM 6352)
Flash point	285°C (ASTM D 92)

Table 4. Production detailed regarding the additives and modifications.

Modifier Type		Per. (%)	Production Conditions: Mixing Temp. (ºC)	Mixing Duration (min)	Shearing Rate (rpm)
Polymer	SBS Kraton® D1101	5	180±5	120	2000
	Elvaloy® 4170	1.5	190	120	200
WMA	Sasobit	3	120	10	1000

Table 5. The physical properties of limestone and basalt aggregates.

Test	Specification Limits	Test Standard	Limestone	Basalt
Resistance to fragmentation (Los Angeles), %	≤25	TS EN 1097-2	22.3	13.7
Resistance to abrasion (Micro-Deval), %	≤20	TS EN 1097-1	18	15
Fastness weathering (With $MgSO_4$ loss), %	≤10	TS EN 1367-2	9.2	7.7
Flakiness Index %	≤15	TS EN 933-3	6.6	4.8
Water Absorption %	≤2	TS EN 1097-6	1.05	0.6

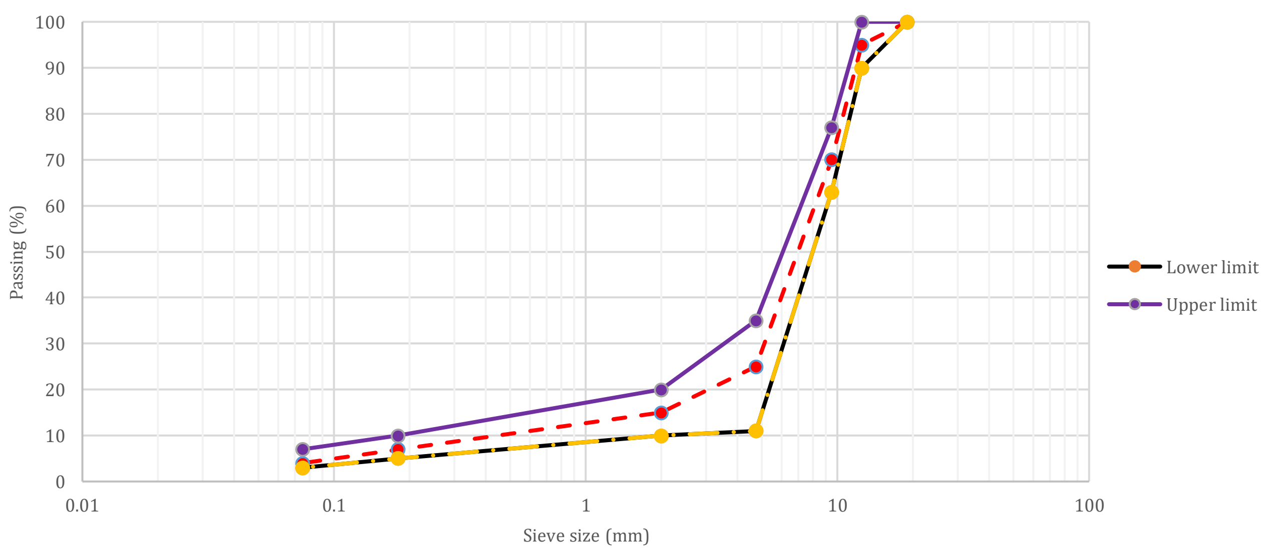

Figure 1. Utilized Aggregate Gradation.

2.2. Methods of Determining Mixing and Compaction Temperatures

The Equiviscous method (ASTM D 2493) is used while the mixing compression temperature is found for dense gradations. However, a special method has not been propounded for porous asphalt. In the porous asphalt specification used in Turkey, the compaction temperature is determined as 145±5 °C since modified bitumen is used. Since the mixing and compaction temperature is an important criterion in terms of pavement performance, it has been tried to suggest the optimum mixing and compaction temperature for porous asphalt designs, in addition to the specification, by making trials.

2.2.1.Equiviscous Method (ASTM D 2493)

The detailed procedure of this method is explained in the American Society for Testing and Materials under the Designation of D2493. The focus of the experiment is to measure the viscosity of the bitumen samples at two temperatures (135 °C and 165 °C). For this purpose, the Brookfield viscometer is suggested where the shear rate is fixed at 6.8 1/s. The obtained viscosity values are plotted on a log viscosity versus temperature chart. Mixing and compaction temperatures viscosity values correspond to 170 ± 20 mPa s and 280 ± 30 mPa s [30-31].

2.2.2.Proposed Method for Porous Asphalt Pavement

In the porous asphalt Turkish specification, the compression temperature is determined as 145±5 °C. However, determining an optimum mixing compression temperature is important in terms of piece loss of porous asphalt pavements. It is thought that the piece loss will give variable values according to the type of bitumen to be used, the bitumen modifying additive, and the type of aggregate. Therefore, a study was carried out within the compression temperature limits allowed by the specification. Porous asphalt samples were prepared using pure bitumen and SBS®, Elvaloy®, Sasobit® modified bitumen, and 2 different aggregate groups of limestone and limestone-basalt mixture. Mixtures prepared with polymer-modified bitumen are compaction at 140 °C, 145°C, and 150°C, and mixtures prepared with warm mix asphalt modified at 3 different temperatures, 120°C, 125°C, and 130°C, and the particle loss values of the mixtures are examined. The optimum mixing and compaction temperature was tried to be found.

2.3. Resistance to Abrasion Loss of Asphalt Samples

The Cantabro test is carried out to find the percentage of porous asphalt pavements particle loss against loads. Three Marshall samples are prepared for each design. The weights of the samples before the experiment are recorded as W1. Then, a single cylindrical sample is placed in the Los Angeles test device without metal balls and 300 cycles are made. When the number of cycles is completed, the sample is removed from the device and weighed W2. The test is repeated in the same way for each remaining sample. The particle loss value is found with the help of the formula in equation 1.

$$P = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

Where;

P = Abrasion loss (%)

W1 = Mass before test (g)

W2 = Mass after test (g)

3. Results and Discussions

In general mixing-compaction temperatures of dense graded asphalt mixtures are determined by the conventional method depending on the viscosity value of the bitumen. Mixing-compaction temperatures of mixtures can be found by using different methods [30-31]. However, this method may not be suitable for porous asphalt, because it has a high void ratio due to its porous asphalt structure, the mixing-compaction temperatures determined by traditional methods may cause excessive compression and close the gaps and prevent the pavement from working for its intended purpose.

Worldwide specifications often do not specify a method for determining the mixing-compaction temperatures of porous asphalt. In Turkey, compaction temperature was determined as 145±5 °C when using modified bitumen. By using different mixing-compaction temperatures that support the specification, the optimum mixing and compaction temperature has been tried to determine as a result of the part loss values of the prepared mixtures.

With only limestone aggregate, 3 samples were prepared by adding bitumen at the rate of 4% of the mixture weight for each bitumen type at different mixing-compaction temperatures. The prepared porous asphalt mixtures were subjected to the abrasion test after being kept at room temperature for 2 days. Considering the effect of the room temperature in which the experiment was carried out on the test results, care was taken to conduct the test under appropriate conditions. Particle loss values of mixtures prepared with unmodified bitumen and SBS®, Elvaloy®, Sasobit® modified bitumen at 3 different mixing-compaction temperatures are given in Figure 2 and Figure 3. The results shown are the average values of 3 samples prepared for each bitumen.

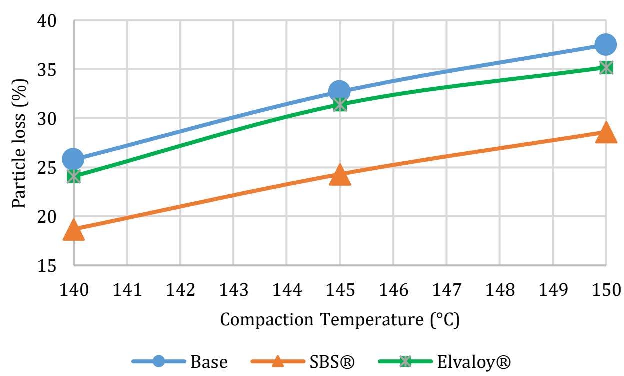

Figure 2. Particle loss results regarding limestone aggregate with PMB.

When analyzing the particle loss values of porous asphalt mixtures containing solely limestone aggregate, it is observed that the compaction temperature is set at 140°C when using base bitumen and SBS or Elvaloy modified bitumen, and at 120°C when Sasobit modified bitumen is employed. The main reason for determining these values is the compaction temperature at which the loss of parts is minimal.

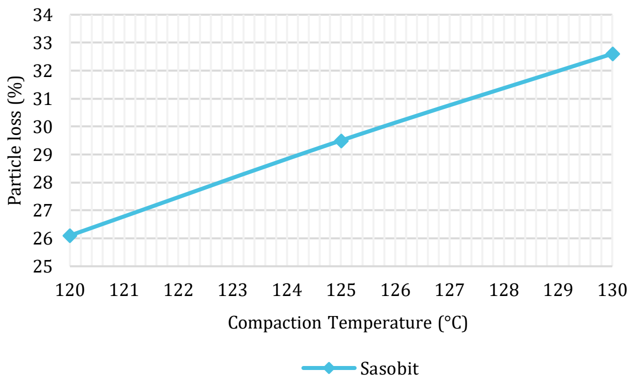

Figure 3. Particle loss results regarding limestone aggregate with Sasobit® WMA additive.

Samples were prepared with the limestone-basalt aggregate combination mixture, base bitumen and SBS®, Elvaloy®, Sasobit® modified bitumen, and samples containing bitumen up to 4% of the mixture weight at 3 different mixing-compaction temperatures. The values were found by taking the average of the particle loss results of the mixtures prepared as 3 samples for each bitumen variety. Relevant part loss values are shown in Figure 4 and Figure 5.

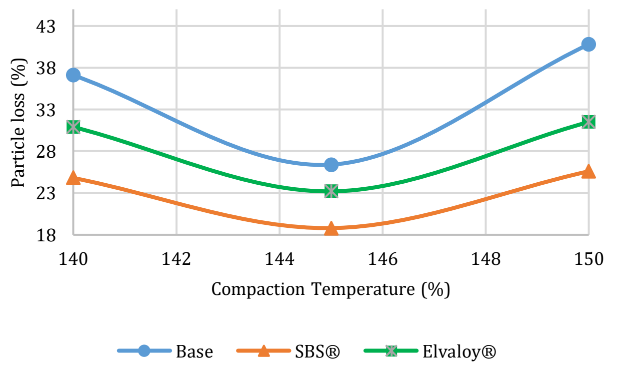

Figure 4. Particle loss results regarding basalt-limestone aggregate with PMB.

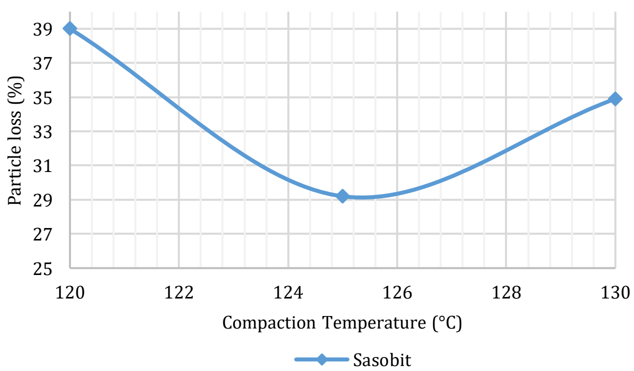

Figure 5. Particle loss results regarding basalt-limestone aggregate with Sasobit WMA additive.

4. Conclusion

The optimum compaction temperature was determined according to the particle loss values of the porous asphalt samples prepared using a limestone-basalt aggregate mixture. This design gave the minimum part loss value at a higher compaction temperature than the mixtures made using only limestone aggregate. It is thought that one of the reasons for this is the use of different gradation. For the design made with this aggregate mixture and using unmodified bitumen and SBS®, Elvaloy® modified bitumen, the optimum compaction temperature was determined as 145°C, and when Sasobit® modified bitumen was used, it was determined as 125°C. The compression temperature is the main factor in determining these temperatures, which gives the minimum value of particle loss.

When the results obtained using two different aggregate groups and four different bitumen types were compared, it was seen that a higher compaction temperature was required for the limestone-basalt aggregate mixture compared to the design using only limestone. The main reason is that a higher compression temperature is required to enable the aggregate particles to adhere to each other in the mixture so that two different aggregate types can perform as a single material.

It is considered necessary to find an optimum mixing-compaction temperature with the Cantabro loss approach within the limits of the compaction temperature specified in the specification in order to better represent the field conditions of the mixture to be designed and applied to the field.

The results indicate that gradation, aggregate type, types of bitumen modification and mixing-compaction temperature are factors that significantly affect abrasion loss. Porous asphalts are more prone to particle loss due to high air voids, resulting in less adhesion between aggregate particles. It is thought that the higher particle loss value of the warm mix asphalt additive is due to the fact that the aggregates do not stick to each other by compaction at low temperatures. Studies can be carried out on porous asphalt design by using different warm mix asphalt additives. In order to better represent the field conditions, the prepared porous asphalt samples should be tested with the conditioning method and the freeze-thaw effect in the field should be examined.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval and has no conflicts of interest with any individual or institution.

Author Contribution Statement

All authors contributed equally to the conception, design, execution, and interpretation of the study, as well as the preparation and revision of the manuscript.

References

[1] Kamar, F.H.A., Sarif, J.N., 2009. Proc. of 13th Conf. of the Road Eng. Ass. of Asia and Australasia (REAAA), p. 9-07.

[2] Ma, X., Zhou, P., Jiang, J., Hu, X., 2020. High-temperature failure of porous asphalt mixture under wheel loading based on 2D air void structure analysis. Construction and Building Materials, Vol. 252, p. 119051. DOI: 10.1016/j.conbuildmat.2020.119051.

[3] Kandhal, P.S., Mallick, R.B., 1998. Open graded friction course: state of the practice. Washington, DC, USA: Transportation Research Board, National Research Council.

[4] Huber, G., 2000. Performance survey on open-graded friction course mixes. Transportation Research Board, Vol. 284.

[5] Herrington, P.R., Reilly, S., Cook, S., 2005. Porous asphalt durability test. Wellington: Transfund New Zealand.

[6] Kandhal, P.S., Mallick, R.B., 1999. Design of new-generation open-graded friction courses. NCAT Report, No. 99-3.

[7] Luxman, N.N., Hassan, N.A., Jaya, R.P., Warid, M.M., Azahar, N.M., Mahmud, M.Z.H., Ismail, S., 2019. Effect of compaction temperature on porous asphalt performance. IOP Conference Series: Earth and Environmental Science, Vol. 244(1), p. 012011. DOI: 10.1088/1755-1315/244/1/012011.

[8] Capitão, S.D., Picado-Santos, L.G., Martinho, F., 2012. Pavement engineering materials: Review on the use of warm-mix asphalt.

Construction and Building Materials, Vol. 36, pp. 1016-1024. DOI: 10.1016/j.conbuildmat.2012.06.038.
[9] Wang, X., Ren, J., Hu, X., Gu, X., Li, N., 2021. Determining optimum number of gyrations for porous asphalt mixtures using superpave gyratory compactor. KSCE Journal of Civil Engineering, Vol. 25(6), pp. 2010-2019. DOI: 10.1007/s12205-021-1005-x.
[10] Khedoe, R.N., Woldekidan, M.F., van de Ven, M., van Emst, G., 2006. Possible use of C-Fix in Special Applications: Porous Asphalt. In Wegbouwkundige Werkdagen 2006, pp. 1-10.
[11] Poulikakos, L.D., Partl, M.N., 2003. A comparison of Swiss and Japanese porous asphalt through various mechanical tests.
[12] Masad, E., Scarpas, A., Rajagopal, K.R., Kassem, E., Koneru, S., Kasbergen, C., 2016. Finite element modelling of field compaction of hot mix asphalt. Part II: Applications. International Journal of Pavement Engineering, Vol. 17(1), pp. 24-38.
[13] Cheng, Z., Li, X., Yang, Q., Liang, N., Chen, L., Zheng, S., Wang, D., 2023. Study on Compaction Properties and Skeleton Structural Characteristics of Porous Asphalt Mixture. Sustainability, Vol. 15(18), p. 13911.
[14] McDaniel, R.S., Thornton, W.D., Dominguez, J.G., 2004. Field evaluation of porous asphalt pavement. SQDH Report No. 2003-4. Purdue University.
[15] Hassan, A., Mahmud, M., Adi, N., Rahmat, N., Hainin, M., Jaya, R.P., 2016. Effects of air voids content on the performance of porous asphalt mixture. Journal of Engineering and Applied Sciences, Vol. 11(20), pp. 11884-11887.
[16] Renken, P., 2000. Perspective on optimisation of porous asphalt surface course. In Proceedings of the 2nd Eurasphalt and Eurobitume Congress, Book 2-Session 3.
[17] Takahashi, S., Poulikakos, L.D., Partl, M.N., 2003. Evaluation of improved porous asphalt by various test methods. In Sixth International RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials, pp. 230-236.
[18] Tayfur, S., Ozen, H., Aksoy, A., 2007. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. Construction and Building Materials, Vol. 21(2), pp. 328-337. DOI: 10.1016/j.conbuildmat.2005.08.014.
[19] Harish, L., 2014. The Permeability and Indirect Tensile Strength Characteristics of Porous Asphalt Mixes. Vol. 5, pp. 62-67.
[20] Luxman, N.N., Hassan, N.A., Jaya, R.P., Warid, M.M., Azahar, N.M., Mahmud, M.Z.H., Ismail, S., 2019. Effect of compaction temperature on porous asphalt performance. IOP Conference Series: Earth and Environmental Science, Vol. 244(1), p. 012011. DOI: 10.1088/1755-1315/244/1/012011.
[21] Sengoz, B., Isikyakar, G., 2008. Analysis of styrene-butadiene-styrene polymer modified bitumen using fluorescent microscopy and conventional test methods. Journal of Hazardous Materials, Vol. 150(2), pp. 424-432. DOI: 10.1016/j.jhazmat.2007.04.122.
[22] Topal, A., 2010. Evaluation of the properties and microstructure of plastomeric polymer modified bitumens. Fuel Processing Technology, Vol. 91(1), pp. 45-51. DOI: 10.1016/j.fuproc.2009.08.007.
[23] Almusawi, A., Sengoz, B., Topal, A., 2021. Evaluation of mechanical properties of different asphalt concrete types in relation with mixing and compaction temperatures. Construction and Building Materials, Vol. 268, p. 121140. DOI: 10.1016/j.conbuildmat.2020.121140.
[24] Ozdemir, D.K., Topal, A., McNally, T., 2021. Relationship between microstructure and phase morphology of SBS modified bitumen with processing parameters studied using atomic force microscopy. Construction and Building Materials, Vol. 268, p. 121061. DOI: 10.1016/j.conbuildmat.2020.121061.
[25] Kaya, D., Topal, A., Gupta, J., McNally, T., 2020. Aging effects on the composition and thermal properties of styrene-butadiene-styrene (SBS) modified bitumen. Construction and Building Materials, Vol. 235, p. 117450. DOI: 10.1016/j.conbuildmat.2019.117450.
[26] Oner, J., 2019. Rheological characteristics of bitumens prepared with process oil. Građevinar, Vol. 71(7), pp. 559-569. DOI: 10.14256/JCE.2587.2018.
[27] Topal, A., Sengoz, B., Kok, B.V., Yilmaz, M., Dokandari, P.A., Oner, J., Kaya, D., 2014. Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic zeolite additives. Construction and Building Materials, Vol. 57, pp. 38-44. DOI: 10.1016/j.conbuildmat.2014.01.093.
[28] Oner, J., Sengoz, B., 2018. Effect of polymers on rheological properties of waxy bitumens. Revista de la Construcción, Vol. 17(2), pp. 279-295. DOI: 10.7764/rdlc.17.2.279.
[29] Oner, J., Sengoz, B., Rija, S.F., Topal, A., 2017. Investigation of the rheological properties of elastomeric polymer-modified bitumen using warm-mix asphalt additives. Road Materials and Pavement Design, Vol. 18(5), pp. 1049-1066. DOI: 10.1080/14680629.2016.1206484.
[30] Almusawi, A., Sengoz, B., Topal, A., 2021. Investigation of mixing and compaction temperatures of modified hot asphalt and warm mix asphalt. Periodica Polytechnica Civil Engineering, Vol. 65(1), pp. 72-83.
[31] Almusawi, A., Sengoz, B., Topal, A., 2021. Evaluation of mechanical properties of different asphalt concrete types in relation with mixing and compaction temperatures. Construction and Building Materials, Vol. 268, p. 121140. DOI: 10.1016/j.conbuildmat.2020.121140.