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Investigation of usability of mineral fiber in stone mastic asphalt

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Abstract: Stone mastic asphalt (SMA) pavements were developed to prevent rutting, abrasion, and various pavement deteriorations and to increase the life of the superstructure. They certainly stand out with their high grain contact, stone-stone interlocking ability, and high bitumen ratio on heavy-traffic roads with heavy axle loads. This study aimed to investigate the effects of basalt fiber in different sizes, partly cellulose, and partly basalt fiber addition, on the drain down of the performance of bitumen and the changes in rutting performance as additives to stone mastic asphalt pavements. To determine the absorption performance of bitumen fiber additives, 19 mixtures were pre-pared and the Schellenberger drain down test was carried out. The results, including the witness mixture, showed that the Schellenberger test result was below the value specified in the motorway technical specification by a maximum of 0.3%. For the Hamburg wheel tracking test (HWTT) additive and witness mixtures were prepared at optimum bitumen ratios using a gyratory compactor. HWTT was applied to the mixtures numbered 1, 4, 10 and 14, which have the best the Schellenberger drain down performance, and the witness sample. As a result of the experiments, the highest rutting deformation was measured at the samples using 12mm basalt fiber at the rate of 0.2%. The lowest rut deformation was measured in samples containing 12mm basalt fiber at the rate of 0,3% and cellulose fiber at the rate of 0.2%. It was determined that the combined use of cellulose and basalt fiber mixture improved the resistance against rutting by 37%. As a result of the HWTT, it was determined that stone mastic asphalt mixtures with basalt and cellulose fiber additives were more resistant to rutting than the witness and basalt-only mixtures.

Keywords: Stone mastic asphalt, Schellenberger bitumen drain down test, Hamburg wheel tracking test, basalt fiber, cellulosic fiber.

1. Introduction

Stone mastic asphalt (SMA), is a mixture type developed to reduce permanent deformations caused by studded tires (Wan et al. 2014;Cetin et al. 2020;). With increasing vehicular traffic and the rising cost of operating and maintaining roads, finding ways to improve the performance of bituminous mixtures has become an imperative. This type of pavement was standardized in Turkey in 1999 and is widely used. In SMA mixtures, coarse aggregate is used in large quantities compared to asphalt mixtures with dense gradation. The high ratio of coarse aggregate in SMA mixtures causes large gaps between aggregate particles. To close these gaps, bitumen or modified bitumen called mastic mortar is used with filler, fine aggregate, and fiber or another stabilizing material that prevents the drainage of binder. (EAPA 1998; Dong, Zheng, and Qie 2013).

Researchers are constantly trying to improve the performance of asphalt mixtures. Bituminous binders or mixtures need to be modified to prevent deteriorations for example rutting, fatigue and cracking resistance (Akpolat 2022). Fibers have been used to improve pavement materials in many parts of the world for decades and are gaining more attention of late because of their success. Agents of stabilization, reinforcement, and homogeneous dispersion, fibers also work to prevent the leaching of bitumen in SMA mixtures (NCHRP Synthesis 475, 2015). Fibers penetrate the bitumen structure together with the fillers to form part of the mastic mortar between the aggregates. These fibers, themselves, act as fillers and retainers in stone mastic asphalt mixtures due to their small weight and chain network.

This also prevents the bitumen from leaching and flowing out of the coarse aggregate, ensuring its homogeneous distribution and compaction. Therefore, reinforcement of the mixture with fibers increases the ductility, plastic limit, and tensile strength of asphalt (Abdelaziz, Karim, and Katman 2003; Huang et al. 2020). Cellulosic fibers are plant-based fibers mostly derived from woody plants or recycled paper. They have a coarse texture, a porous surface, and a diameter varying along its length (ASTM International 1999; Structural et al. 2003; Huang et al. 2020;). Since the amount of bitumen used in SMA mixtures is higher than that of other asphalt mixtures, bitumen runoff is also a problem. Cellulosic fiber prevents bitumen from leaching, and it also prevents vomiting in the pavement. Basalt fiber is a mineral fiber produced by melting crushed basalt, a hard, dense, and stable igneous rock found in almost every corner of the world, and then bending or extruding at about 1500°C (Singha 2012; Wu et al. 2021).

Although it is commonly used in construction, industry, and road engineering, it is not widely known that basalt can be used in manufacturing and made into fine fibers. Nowadays, Basalt fiber is gaining more attention in asphalt pavement engineering due to its excellent technical performance and environmental benefits (Wu et al. 2021). Basalt product does not react harmfully with air or water; it is non-flammable and explosion-proof. When in contact with other chemicals, it does not initiate any reaction that can harm personal health or the environment (Sharma 2016). Cetin et al. (2022) in their study, revealed that the addition of basalt fiber to porous asphalt significantly improved the strength properties of the mixture compared to the control sample. They observed that as the basalt fiber increased, the permeability of the mixture decreased. Hwang et al. (2020) in their study, cellulose and basalt fiber were added to stone mastic asphalt (SMA) simultaneously to investigate the effects of hybrid modification on the performance improvement of the asphalt mixture. The results generally showed that all fibrous samples outperformed the control group in performance tests. After careful analysis, it seemed evident that cellulose fiber significantly improves drainage, ductility, and fatigue, while basalt fiber has a greater effect on improving permanent deformation, shear strength, and stress sensitivity.

On the other hand, Cetin et al. (2020) in their study, the effects of basalt fiber on the performance of SMA blends were investigated as an alternative to cellulosic fiber additives in preventing drainage. Results showed that the addition of 0.6% basalt fiber to 8% dry-weight aggregate at 25°C significantly increased the modulus of elasticity and tensile strength of the samples. In addition, 0.4% basalt fiber blended samples were observed in order to provide the greatest resistance to permanent deformation according to the results of the static uniaxial creep test performed at 40°C. Wu et al. (2021) in their study, they evaluated the long-term performances of SMA-13 (SMA with aggregate nominal maximum particle size of 13.2 mm) using basalt fiber and lignin fiber to determine the effect of fiber type on the long-term performance of stone mastic asphalt. The results of the rutting test and uniaxial penetration test showed that the high-temperature performance of SMA-13 containing basalt fiber was better than that of SMA-13 containing lignin fiber. While Wan et al. (2014) investigated the effect of fiber type on the road performance of stone mastic asphalt. For this reason, SMA-13 uses three different fibers: lignin fiber, polyester fiber, and basalt mineral fiber were used as an example. The results showed that SMA 13 mixtures using mineral fibers exhibit optimum high temperature and low temperature, SMA mixtures using lignin fibers exhibited optimum water stability. Besides, Dong et al. (2013) stated, the effect and mechanism of action of three different fiber types, nylon fiber, polyester fiber, and basalt mineral fiber, on the pavement performance of stone mastic asphalt were investigated with comparative analyses for the optimization of the pavement performance of SMA. The results determined that the basalt mineral fiber mixture had the most suitable coating performance among the three types of mixtures selected in this study.

Stone mastic asphalt mixes are sensitive to drain down because they contain more bitumen than hot mix asphalts. For this reason, stabilizers are used to prevent the bitumen material from drain down during the storage-transportation-paving-compacting processes (Aslan et al. 2018). Fibers are the one of the stabilizers frequently used in SMA (NCHRP Synthesis 475, 2015). Few studies were found on SMA after the traditional bituminous hot mixes, which generally worked more on the ratio of basalt fiber. In fact, most of the studies in the literature worked on only one type of fiber, and none focused on both cellulosic fiber and basalt fiber. In the present research, the effects on SMA stability were investigated by trying the combination of cellulosic fibers and basalt fibers of different sizes.

2. Materials and methods

2.1. Materials

The study used basalt fibers of two lengths, 12 mm, and 26 mm, and aggregates sourced from Dalama Limestone Quarry, a bituminous binder in the 50/70 penetration class, and Hypercell cellulose fiber. These components were chosen to meet the criteria specified in the Highways Technical Specification (KGM 2013) to produce SMA.

2.1.1. Aggregate properties

The results obtained from the tests conducted on the coarse aggregate, fine aggregate, and filler are presented in Table 1, while Figure 1 illustrates the aggregate granulometry curve.

Table 1. Results of aggregate tests.

Type of rock		Dunite/Gabbro - Limestone		
	Coarse aggregate	Fine aggregate	Filler	Test standard
Volume specific gravity	2.930	2.872		TS EN 1097-6
Apparent specific gravity	2.989	2.937	2.825	
Absorption %	0.675	0.766		
Effective specific gravity of mixture (experiment)			2.929	ASTM D-2041
Effective specific gravity of mixture (calculate)			2.933	
Polishing value			-	TS EN 1097-8
Methylene blue			1.25	TS EN 933-9
$MgSO_4$ freezing loss, %			2.8	TS EN 1367-2
Los Angeles wear loss, %			22.0	AASHTO T-96
Flatness index, %			13.0	BS 812

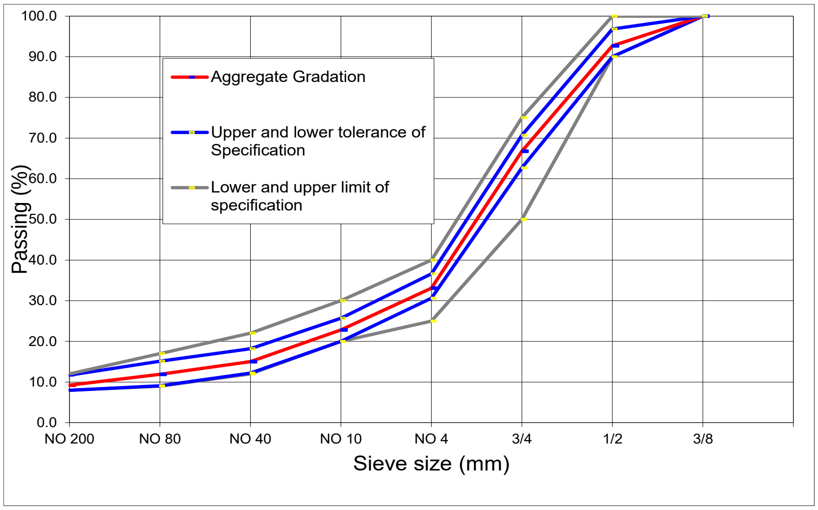

Figure 1. Gradation curve and specification limits for the SMA.

2.1.2. Binder properties

The tests conducted on the bitumen are provided below (Table 2).

Table 2. Results of bitumen tests.

Modified Bitumen Specific Gravity	1.029	TS 1087
Modified Bitumen Penetration, dmm	52.7	TS EN 1426
Modified Softening Point, °C	69.3	TS EN 1427
Bituminous binder to be used in manufacturing	Type	Modified Bitumen
	Class	50/70

2.1.3 Basalt fiber and hypercell cellulose fiber

In this study basalt and hypercell cellulose fiber was used for modifying the mixture. Basalt fiber properties are shown in the Table 3. Basalt and hypercell cellulose fiber are presented in Figure 2.

Table 3. Basalt and hypercell cellulose fiber technical specifications

Basalt fiber	Technical specifications	SI
	Tensile strength	4840 MPa
	Elasticity Modulus	89 GPa
	Application temperature limits	±982˚C
	Specific gravity	60-2,8 g/cm^3
	Fiber diameter	9-23 µm
Hypercell cellulose fiber		
	Appearance	Granular
	Application temperature limits	>250 ˚C
	Pallet diameter	5 (mm)
	Average fiber length	800 µm
	Specific gravity	0,6 g/cm^3

Figure 2. (a) Basalt fiber and (b) hypercell cellulose fiber.

2.2. Mixture preparation

The design conducted using the Marshall Method with 2 x 50 impacts resulted in the determination of the optimum bitumen content as 6.00% by weight (100g dry aggregate + 6.00g suitable bitumen + 0.35g fiber) relative to the dry aggregate. Additional results regarding the optimum bitumen content can be found in Table 4 below.

Table 4. Other results in optimum bitumen.

	Design
Optimum Bitumen	6.00
Bulk Density	2.565
Air voids, %	3.38
Voids of mineral aggregates, %	16.7

2.3. Determination of basalt fiber additive ratios

In this experimental study, the Schellenberger bitumen drain down test was conducted to determine the ratio of basalt and cellulose in the mixtures produced with basalt mineral fiber and cellulosic fiber. The test was performed based on the optimum bitumen ratio of 6.0% obtained from the design mixtures that included the addition of cellulose along with basalt fiber. A total of 19 different mixtures were produced for this purpose, and their values are presented in Table 5. Basalt fiber was added to the mixture at rates ranging from 0.0% to 0.4% in two different lengths, namely 12 mm and 26 mm. The cellulosic fiber was used at a fixed rate of 0.35% in the control mixture, while the other mixtures were designed to have values between 0% and 0.2%.

The Schellenberger test was initially performed on the mixtures listed in Table 5 to evaluate the drain down performance of bitumen. Subsequently, the Hamburg Wheel Tracking Test was conducted on the mixtures with the best drain down performances, along with a control mixture, to assess the behavior of fiber additives in terms of plastic deformation or permanent deformation. The details of the applied experiments and their results are given in the test method section.

Table 5. Fiber ratios of the samples prepared for the experiments.

	Cellulosic fiber	Basalt fiber	
		12mm	26mm
Witness	0.35%	0	0
Mixture 1	0	0.2%	0
Mixture 2	0	0.3%	0
Mixture 3	0	0.4%	0
Mixture 4	0	0	0.2%
Mixture 5	0	0	0.3%
Mixture 6	0	0	0.4%
Mixture 7	0.1%	0.2%	0
Mixture 8	0.1%	0.3%	0
Mixture 9	0.1%	0.4%	0
Mixture 10	0.1%	0	0.2%
Mixture 11	0.1%	0	0.3%
Mixture 12	0.1%	0	0.4%
Mixture 13	0.2%	0.2%	0
Mixture 14	0.2%	0.3%	0
Mixture 15	0.2%	0.4%	0
Mixture 16	0.2%	0	0.2%
Mixture 17	0.2%	0	0.3%
Mixture 18	0.2%	0	0.4%

2.4. Schellenberger bitumen drain down test

The drain down test was conducted to measure the amount of bitumen that separates from the SMA mixture. The procedure involved the following steps:

1. Prepare a 1000-grams (International System of Units (SI) SMA mixture at a temperature of 135 ± 5 °C for normal bituminous mixtures or 145 ± 5 °C for modified bitumen mixtures.
2. Preheat a 1000 ml glass beaker at 110°C for 15 minutes and weigh it with an accuracy of 0.1 grams.
3. Transfer the prepared SMA mixture into the preheated glass beaker and cover it (Figure 3 (a) and (Figure 3 (b).
4. Place normal bituminous mixtures in an oven at 175°C or modified bituminous mixtures at 185°C for exactly 1 hour ±1 minute.
5. Remove the mixture from the oven and empty it from the glass beaker without shaking (Figure 3 (c)).
6. Clean the glass beaker with if any aggregate adheres to it.
7. Weigh the glass beaker with an accuracy of 0.1 grams and subtract the weight of the empty beaker.
8. The amount of bitumen drained is determined by calculating the proportion of the tested mixtures weight at the beginning.
9. According to the Highway Technical Specification, the maximum allowed drain down of bitumen should be 0.3%. Performance of less than 0.2% is considered good, between 0.2% and 0.3% is acceptable, and greater than 0.3% is considered poor (KGM 2013).

Figure 3 illustrate the bitumen drain down.

Figure 3. Schellenberger bitumen drain down test.

3. Experimental results and evaluation

The Schellenberger drain down test results were obtained to evaluate the performance of different fiber ratios in meeting the requirement of a maximum bitumen drain down of 0.3%, as specified in the Highways Technical Specification. The test was conducted on 19 mixtures, aiming to examine the impact of fiber additive ratios and the length of basalt mineral fiber. The mixture configurations were as follows:

1. One sample without any fiber additive.
2. Six samples with basalt mineral fiber at lengths of 12 mm and 26 mm, with concentrations of 0.2%, 0.3%, and 0.4%.
3. Six samples with a combination of 0.1% cellulosic fiber and 0.2%, 0.3%, and 0.4% basalt fiber.
4. Six samples with a combination of 0.2% cellulosic fiber and 0.2%, 0.3%, and 0.4% basalt fiber.

The test results obtained from these experiments are presented in Figure 4, illustrating the drain down performance for the different mixture configurations.

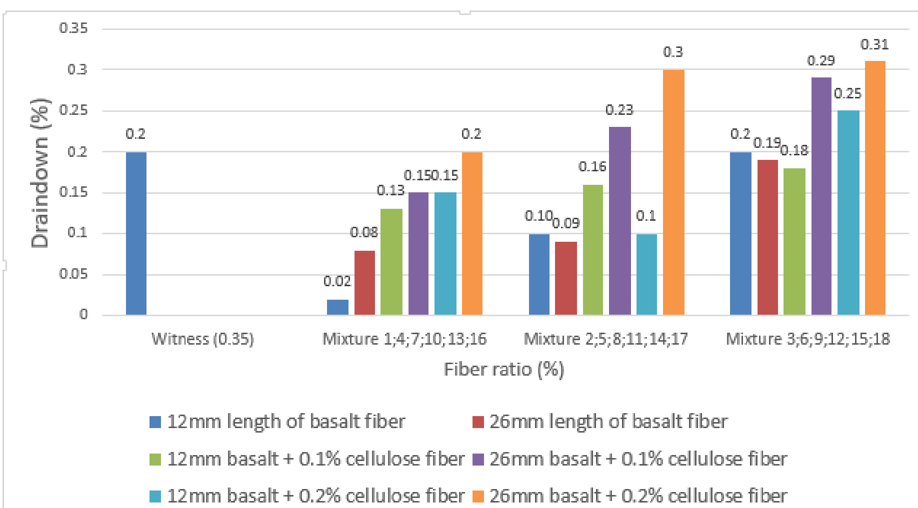

Figure 4. Drain down test of SMA with different fiber combinations.

According to the Highways Technical Specification, the maximum acceptable value for bitumen drain down is 0.3%. A drain down amount of less than 0.2% is considered good, between 0.2% and 0.3% is acceptable, and anything above 0.3% is not accepted. The results of the tests indicate that the SMA sample without fibers exhibited drain down loss, of about 0.2%.

However, apart from the sample containing 26mm basalt fiber and 0.2% cellulose fiber, all other samples remained below the maximum value of 0.3% based on the Schellenberger test results, as per the highway technical specification.

When considering the use of basalt fiber, the sample with 12mm basalt fiber at a rate of 0.2% showed the best results. Additionally, when both cellulosic fiber and basalt fiber additives were included in the mixture, the sample with 12mm basalt fiber at a rate of 0.3% and 0.2% cellulose fiber demonstrated the best performance. Indicating that the inclusion of fibers, whether cellulosic or basalt, or a combination of both, led to a significant improvement in the drain down of the asphalt mix.

To evaluate the impact of the mixture values on the rutting performance, the samples with the best drain down performance, namely Witness, 1, 4, 10, and 14, were selected for the Hamburg rutting test.

3.1.1. *4.1. Hamburg wheel tracking test (HWTT)*

The experimental study includes the Hamburg wheel track test (HWTT) to assess the rutting resistance of the stone mastic asphalt (SMA) mixtures. The HWTT was first developed by Helmut Wind in Hamburg, Germany. SMA specimens with a diameter of 50 mm, prepared using the Superpave Gyratory Compactor, were cut 13 mm from the edges using a cutting machine to achieve the appropriate dimensions for the test molds, as shown in Figure 5.

During the HWTT, water at a temperature of typically 40-50 °C, with a preference for 50 °C, is used. The experiment employs steel wheels with a diameter of 204 mm and a width of 47 mm. Each specimen is subjected to a load of 703 N applied by the cylindrical steel wheels. The steel roller wheels make 52 passes per minute. The wheel load is applied to the mixture until either a maximum of 10010 passes is reached or a maximum deformation limit of 20 mm at the center of the sample is observed, resulting in the formation of a wheel track. Once the mixtures reach the specified transition or deformation, the device automatically stops, and the experiment concludes, as depicted in Figure 6, which illustrates the samples after cutting and mixture conditions before and after the HWTT.

(Aschenbrener, Terrel, and Zamora 1994; E-c et al. 2000; Han and Shiwakoti 2016; Izzo and Tahmoressi 1999). References are provided for further information on the Hamburg Wheel Track Test.

Figure 5. Mixtures cut with an asphalt-cutting machine.

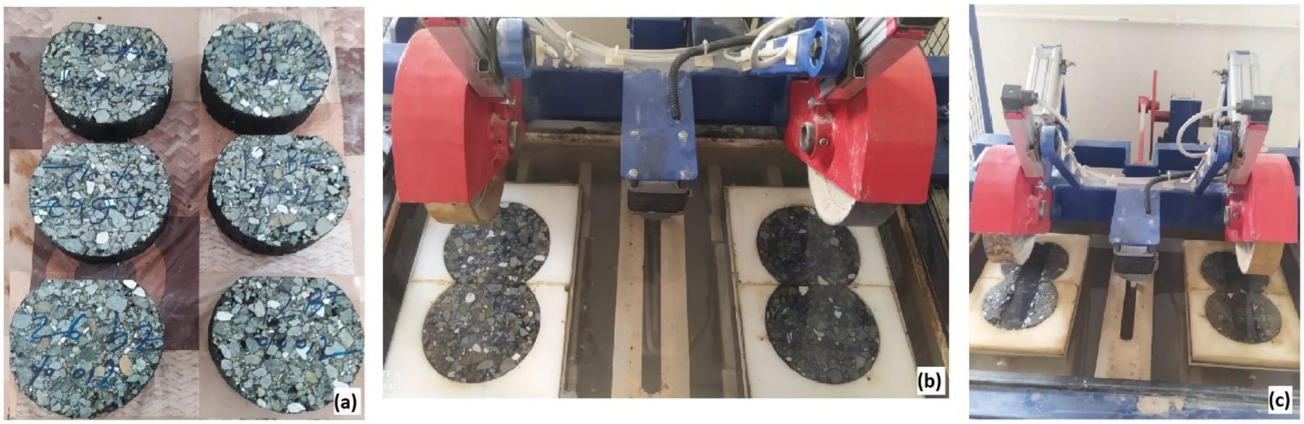

Figure 6. (HWTT) Samples after cutting (a) and condition of mixtures before (b) and after (c) testing.

After initiating the Hamburg rutting test, the water temperature was set to 50 ºC, and the rutting depths at 50, 100, 200, and 10010 revolutions were measured and recorded. The average rutting depths were calculated by taking the mean of these values. The resulting rutting performances of the stone mastic asphalt mixture samples from the Hamburg Wheel Tracking Test are presented below in Figure 7.

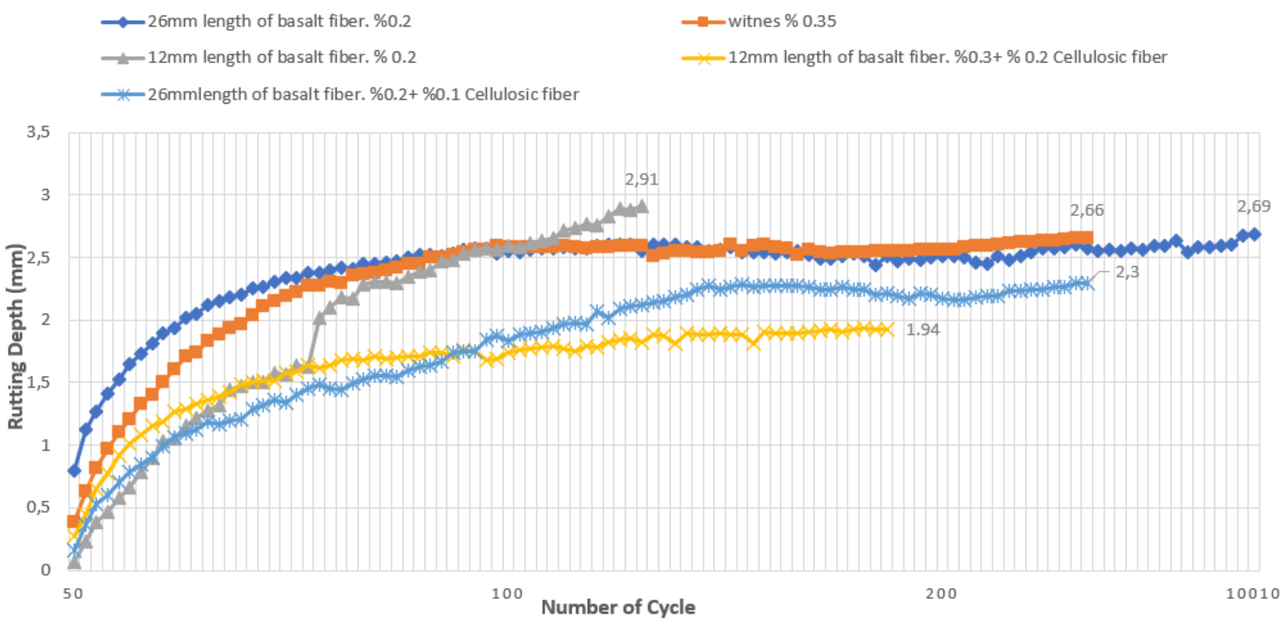

Figure 7. Hamburg wheel tracking test of SMA with different fiber combinations.

According to the results of the Hamburg wheel-tracking test, the highest amount of rutting occurred in the 12 mm-long basalt fiber mixture with a ratio of 0.2%. The second-highest rutting was seen in the 26 mm-long basalt fiber additive mixture with a ratio of 0.2%. The third-highest amount of wheel tracks occurred in the 0.35% cellulosic fiber-doped mixture. High rutting amount in the fourth row was observed in the 26 mm basalt fiber 0.2% and 0.1% cellulosic fiber added mixture. The lowest amount of rutting was observed in the 12 mm basalt fiber 0.3% + 0.2% cellulosic fiber mixture. When the data was evaluated, it was determined that the mixture with cellulosic admixture in the ratio of 0.3% and 0.2% of basalt fiber length of 12 mm had the highest resistance to wheel marks. Experiment results are shown in Table 6.

Table 6. Hamburg wheel tracking test results.

Mixture No.	Number of cycles			
	50	100	200	10010
Witness	0.39	2.27	2.59	2.66
Mixture 1	0.07	1.58	2.56	2.91
Mixture 4	0.8	2.55	2.58	2.69
Mixture 10	0.16	1.75	2.12	2.3
Mixture 14	0.27	1.68	1.85	1.93

4. Conclusions and recommendations

All the samples in the study yielded Schellenberger bitumen drain down test results below.

1. For Schellenberger bitumen drain down test the specified maximum value of 0.3% in the highway technical specification. However, when solely using basalt fiber, the optimal result was achieved with a 12 mm length fiber at a ratio of 0.2%.

2. When both cellulose and basalt fibers were added to the mixture samples simultaneously, the best performance was observed with a 12 mm basalt fiber ratio of 0.3% and a 0.2% cellulosic fiber ratio.

Table 7 presents the percentage change compared to the witness mixture after the drain down test results.

Table 7. Effect of basalt fibers on drain down performance.

Mixture No.	Drain down value change rate	Mixture No.	Drain down value change rate
Witness	35%	Mixture 10	57%
Mixture 1	94%	Mixture 11	34%
Mixture 2	71%	Mixture 12	17%
Mixture 3	43%	Mixture 13	57%
Mixture 4	77%	Mixture 14	71%
Mixture 5	74%	Mixture 15	29%
Mixture 6	46%	Mixture 16	43%
Mixture 7	63%	Mixture 17	14%
Mixture 8	54%	Mixture 18	11%
Mixture 9	49%	-	-

In future experimental studies, it is recommended to investigate the impact of using fibers with different lengths and ratios on the changes in bitumen drain down.

Regarding the results of the Hamburg wheel tracking test, the following observations were made.

1. The addition of basalt and cellulose additives to the stone mastic asphalt mixture samples improved their resistance to rutting compared to the witness sample and the samples with basalt alone.

2. According to the test results, the mixture samples containing 12 mm basalt fiber at 0.3% and 0.2% cellulose fiber showed approximately 19% higher resistance to rutting compared to the additive-free mixture.

3. Similarly, the samples with 26 mm basalt fiber at 0.2% and 0.1% cellulose fiber exhibited approximately 39% higher resistance to rutting compared to the mixture without additives.

4. The 12 mm basalt fiber showed approximately 50% higher resistance to rutting compared to the additive-free mixture, and it was approximately 37% more resistant compared to the mixture with 0.35% cellulose fiber.

5. These findings indicate that increasing the amount of basalt fiber and cellulose fiber additives in stone mastic asphalt mixtures reduces the likelihood of rutting on the wear layer.

Table 8 illustrates the variations in rutting performance of the basalt fiber-added mixtures compared to the witness mixture.

Table 8. The Hamburg wheel tracking test results.

Mixture No.	Number of cycles			
	50	100	200	10010
Witness	0.39	2.27	2.59	2.66
Mixture 1	0.07	1.58	2.56	2.91
Recovery rate	82%	30%	1%	9%
Mixture 4	0.8	2.55	2.58	2.69
Recovery rate	51%	12%	-	1%
Mixture 10	0.16	1.75	2.12	2.3
Recovery rate	59%	30%	22%	16%
Mixture 14	0.27	1.68	1.85	1.94
Recovery rate	44%	35%	40%	37%

Indeed, water temperature is a significant factor that can influence the amount of rutting deformation in the Hamburg wheel tracking test. Conducting the test at different temperatures and comparing the results can provide valuable insights.

In this study, the utilization of 12 mm and 26 mm basalt fibers in the laboratory-prepared stone mastic asphalt mixture samples is a notable approach. Exploring the effects of fibers with different lengths and ratios can further investigate the alterations in the engineering properties of the mixture. This experimentation can contribute to a comprehensive understanding of how different fiber characteristics impact the performance and behavior of the asphalt mixture.

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