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Research Article

Usability of Pumice, Ignimbrite and Perlite in Stone Mastic Asphalt

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Abstract

The usability of pumice, ignimbrite (Ahlat stone), and perlite powders as aggregate material in stone mastic asphalt production was investigated in this study. These aggregates were used as filler in asphalt samples that were subjected to standard tests applied to pavement before it can be used in highways. Los Angeles abrasion rate was found to be 73% for pumice, 78% for Ahlat stone and 67% for perlite. In this study, 4 different types of stone mastic asphalt (SMA) were made. In Basalt-SMA (BAS-SMA); basalt was used as coarse aggregate, fine aggregate and filler in the mixture. In Pumice-SMA (PUM-SMA); basalt was used as coarse aggregate and fine aggregate, and pumice was used as filler. In Ahlat Stone-SMA (AS-SMA); basalt was used as coarse aggregate and fine aggregate, and Ahlat stone was used as filler. In Perlite-SMA (PER-SMA); basalt was used as coarse aggregate and fine aggregate, and perlite was used as filler. As a result of the study, BAS-SMA stability and flow values were found to be 979 kg and 2.88 mm. PUM-SMA stability and flow values were found to be 940 kg and 3.24 mm. AS-SMA stability and flow values were found to be 965 kg and 3.20 mm. PER-SMA stability and flow values were found to be 937 kg and 3.19 mm. These tests provided reference values for the specifications of SMA. Test results show that pumice, Ahlat stone and perlite cannot be used as fine or coarse aggregates in SMA mixtures. The test results show that pumice, Ahlat stone and perlite can only be used as filler in SMA mixtures.

Keywords: Asphalt pavement, Stone mastic asphalt (SMA), Pumice, Perlite, Ignimbrite, Ahlat stone.

Pomza, İgnimbirit ve Perlitin Taş Mastik Asfaltta Kullanılabilirliği

Öz

Bu çalışmada, pomza, ignimbrit (Ahlat taşı) ve perlitin taş mastik asfalt üretiminde agrega malzemesi olarak kullanılabilirliği araştırılmıştır. Bu agregalar, karayollarında kullanılmadan önce kaldırıma uygulanan standart testlere tabi tutulmuş asfalt örneklerinde filler malzeme olarak kullanılmıştır. Los Angeles aşınma oranı pomza için %73, Ahlat taşı için %78 ve perlit için %67 olarak bulunmuştur. Bu çalışmada 4 farklı tip taş mastik asfalt (TMA) yapılmıştır. Bazalt-TMA'da (BAZ-TMA); karışımda kaba agrega, ince agrega ve filler olarak bazalt kullanılmıştır. Pomza-TMA'da (POM-TMA); kaba agrega ve ince agrega olarak bazalt, filler olarak pomza kullanılmıştır. Ahlat taşı-TMA'da (AT-TMA); kaba agrega ve ince agrega olarak bazalt, filler olarak Ahlat taşı kullanılmıştır. Perlit-TMA'da (PER-TMA); kaba agrega ve ince agrega olarak bazalt, filler olarak perlit kullanılmıştır. Çalışma sonucunda BAZ-TMA stabilitesi ve akma değerleri 979 kg ve 2,88 mm olarak bulunmuştur. POM-TMA stabilitesi ve akma değerleri 940 kg ve 3,24 mm olarak bulunmuştur. AT-TMA stabilitesi ve akma değerleri 965 kg ve 3,20 mm olarak bulunmuştur. PER-TMA stabilitesi ve akma değerleri 937 kg ve 3,19 mm olarak bulunmuştur. Bu testler TMA'ın şartname referans limitlerini sağlamıştır. Test sonuçları, pomza, Ahlat taşı ve perlitin TMA karışımlarında ince veya kaba agrega olarak kullanılamayacağını göstermektedir. Test sonuçları, pomza, Ahlat taşı ve perlitin TMA karışımlarında sadece filler olarak kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Asfalt kaplama, Taş mastik asfalt (TMA), Pomza, Perlit, İgnimbirit, Ahlat taşı.

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1. Introduction

Various asphalt mixtures are used in flexible pavement, including stone mastic asphalt (SMA). SMA was developed to reduce the deformation that leads to wheel traces in asphalt. SMA was first applied in Germany in 1968 and was developed by Zichner (Yardim and Aslan 2013; Arslan 2014). SMA has been used in many European countries, and has been studied extensively in the road-engineering literature. Arslan (2014) tested the effects of basalt, limestone and sandstone aggregates used in SMA on the performance and physical properties of the pavement to understand the interchangebility of these materials. Arslan found that limestone and sandstone can be substituted for basalt aggregate while causing no change in the properties of the asphalt. Kutluhan (2008) investigated the wheel-trace performance of various asphalts in the laboratory, and found that coarse-aggregate modified-bitumen SMA samples had the fewest wheel traces. Kofteci (2018) found that pumice can be used in an appropriate proportion (4%) as a replacement for cellulose fibers in SMA. Alp (2018) found that SMA can be used to reduce cost and improve performance of bridge and viaduct pavements, by increasing the service life of the pavement.

SMA mixtures are typically 70-80% coarse aggregate, 20-30% fine aggregate, 6-7% asphalt cement, 8-14% filler and 0.3-1.5% fiber (Tasdemir 1993; Kennhpohl 1993). These mixtures are very resistant to deformation from wheel traces, and are very durable due to their high bitumen content (Saglik and Gungor 2008; Sengül 2011). High-quality magmatic rocks obtained by crushing granite and basalt are typically used as coarse and fine aggregates in SMA production. The aggregate polishing value of tough and jagged aggregates such as basalt and granite is high. If the aggregates used in the pavement have good gradation and the polishing value is high, the pavement's resistance against roughness and skidding will be high (Orhan 2012). Brilliance offers better visibility under road lighting (Gencer et al 2017). Durable road provides advantage in terms of maintenance factor in all kinds of engineering processes (Cengiz and Cengiz, 2018; Cengiz, 2019). Fillers of stone dust or slaked lime are usually added to the aggregate to achieve the appropriate gradation (Umar and Yayla 1998).

Ahlat stone filler is a waste rock material. Also, Ahlat stone, perlite and pumice are inexpensive materials. Therefore, Ahlat stone, perlite and pumice were evaluated in SMA mixtures. The strength of the basalt aggregate is high. Therefore, Ahlat stone, perlite and pumice were used in combination with basalt in SMA mixtures. This study evaluated the usability of pumice, perlite, and Ahlat stone aggregates for filler materials in SMA mixtures. The all-basalt (BAS-SMA) sample served as the reference SMA mixture. Tests were used to find the bitumen ratio, void ratio, practical density, voids in mineral aggregate, voids filled with asphalt, and the stability and flow of SMA prepared using the three materials as filler. The test results of each of the samples prepared with pumice (PUM), perlite (PER), and Ahlat stone (AS) fillers were compared against those from the reference SMA sample and the standard specification limits of Highways General Directorate (2013) for SMA pavement. The test results show that pumice, AS and perlite can all be used as fillers in SMA mixtures, and that these stones are not suitable for use as fine or coarse aggregate.

2. Materials and methods

2.1. Materials

Photographs of the aggregate materials we used to prepare SMA samples are shown in Fig. 1.

Fig. 1. Aggregates Used in the Test Samples: (a) Pumice (b) Ahlat stone (c) Perlite

Basalt is a volcanic and very hard rock (Yilmaz et al. 2006). Basalt is resistant to water absorption, corrosion, frost, impact, and friction (Akilli 2012; Kahveci and Kadayifci 2013). Pumice is a pyroclastic rock (Turkel and Kadiroglu 2007). Pumice includes many independent pores, which are separated from each other by a glassy membrane (Oguz and Turker 1997; Ozkan and Tuncer 2001). Perlite and Ahlat stone (AS) are volcanic rocks (Tasdemir 1998; Bulgurcu 2009; Gokce et al. 2010). The ignimbrites that constitute AS are the products of eastern Turkey's Nemrut volcano, AS tends to be found of light brown and dark brown colors. Because of the low compressive strength of AS, it is not typically used in concrete mixtures (Simsek and Erdal 2004; Bakis 2016). However, AS is inexpensive and readily available in eastern Turkey, so its suitability for use in asphalt is of interest. The chemical compositions of basalt, pumice, perlite and AS aggregates are listed in Table 1 (Ozkan and Tuncer 2001; Yilmaz et al 2006; Turkel and Kadiroglu 2007; Azizi 2007; Ozturk 2012; Kazanci and Gurbuz 2014).

Table 1. Chemical Properties of Basalt, Pumice, Perlite and Ahlat Stone

Component	Basalt (%)	Perlite (%)	Ahlat stone (%)	Pumice (%)
SiO_2	45.0-50.0	71.0-75.0	64.11	60.0-75.0
Al_2O_3	13.0-18.0	12.5-18.0	16.01	13.0-15.0
Na_2O+K_2O	3.5-7.5	3.4-9.0	8.0-13.0	7.0-8.0
CaO	7.0-18.0	0.5-2.0	1.64	1.0-2.0
Fe_2O_3	2.0-5.0	0.1-1.5	4.91	1.0-3.0
MgO	4.0-9.0	0.02-0.5	0.24	1.0-2.0
TiO_2	0.0-3.0	0.03-0.2	0.44	-
FeO	5.0-9.0	0.0-0.1	-	-
P_2O_5	0.1-1.0	-	-	-

2.2. Methods

Four different kinds of SMA samples were prepared. In Basalt-SMA (BAS-SMA); basalt was used as coarse, fine and filler aggregate. In study, BAS-SMA is reference SMA among SMA types. Basalt was used as coarse and fine aggregate in the three test samples of PUM-SMA, PER-SMA, and AS-SMA, and the pumice, perlite, and Ahlat stone (AS) was used as filler material. Tests determined the bitumen ratio, void ratio, practical density, voids in mineral aggregate, voids filled with asphalt, and the stability and flow values of each SMA sample. All tests were performed according to Turkish national construction standards.

2.2.1. Los Angeles Abrasion Tests

Los Angeles abrasion tests were carried out as specified by TS EN 1097-2 (2015). This test determines the abrasion resistance of coarse aggregates using the standard Los Angeles abrasion machine. A total of 5000 ± 5 grams of coarse aggregate were used in each test. The machine timer was adjusted to a speed of 32 rpm and to go through a maximum of 500 revolutions. After 500 revolutions of the Los Angeles abrasion test device, the aggregates were removed from the device. The aggregates remaining in the 1.6 mm sieve were then placed in the drying oven and dried at 110 ± 5ºC until a constant dry weight (m) was reached.

$$\mathrm{LA} = \frac{(5000 - \mathrm{m})}{50} \qquad (1)$$

Los Angeles abrasion value (LA) of coarse aggregates was calculated from Eq. (1) as a percentage.

2.2.2. Water Absorption and Specific Gravity Tests

Water absorption and specific gravity tests were carried out according to TS EN 1097-6 (2015). In water absorption tests, aggregates were left in the curing pool at 20 ± 5°C for 3 days until they reached a constant weight. Aggregates were then removed from the curing pool, dried, and weighed. This process gave the initial weight (W1) of the aggregate samples. The samples were then placed in the drying oven and dried at 105 ± 5ºC for 3 days until a constant dry weight (W2) was reached.

$$\mathrm{Waw} = \frac{(\mathrm{W1} - \mathrm{W2})}{\mathrm{W2}} \times 100 \qquad (2)$$

The water absorption (Waw) of the aggregates was calculated from Eq. (2), in terms of percent by weight. The specific gravity (ρ) of the filler aggregates in the four different SMA mixtures was calculated from Eq. (3), in terms of g/cm^3.

$$\rho = \frac{\mathrm{M4}}{\mathrm{M4} - (\mathrm{M2} - \mathrm{M3})} \qquad (3)$$

The symbols in Eq. (3) denote:

M2: Pycnometer weight + weight of water-saturated specimen + water weight in pycnometer
M3: Pycnometer weight + water weight in pycnometer
M4: Weight of specimen dried in the drying oven

To test these properties, sieve analysis of the aggregates used in SMA production was performed in accordance with standards published by Turkey's General Directorate of Highways. The material remaining on a No. 4 sieve were tested to determine the absorption and specific gravity of the basalt coarse aggregate that was used in our samples.

Pumice, perlite and AS aggregates were not used as coarse or fine aggregates in the SMA samples, but were only used as filler material. In the specific gravity tests of filler aggregate, materials passing through a No. 200 sieve were tested. Fig. 2 shows photographs of the weighing of filler materials in pycnometer for the sake of determining specific gravity.

(a) **Pumice** (b) **Ahlat stone** (c) **Perlite**

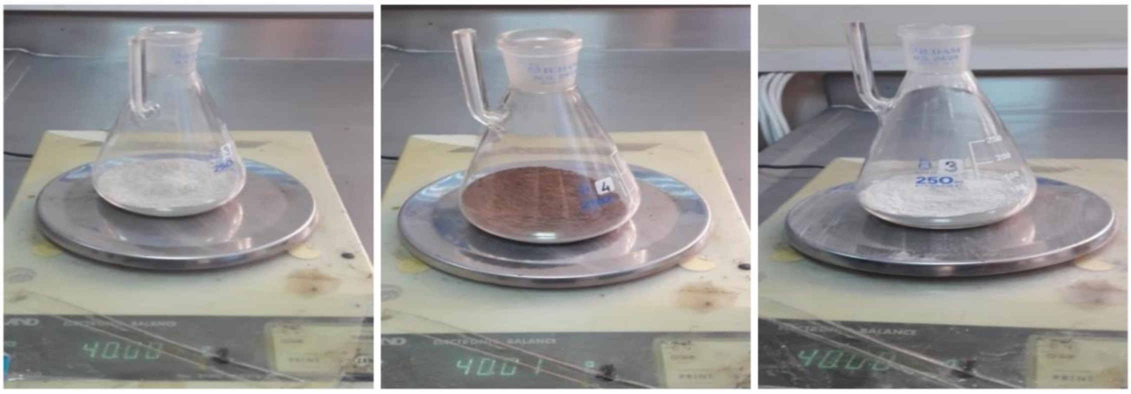

Fig. 2. Weighing the Filler Materials in Pycnometer for Determining Specific Gravity: (a) Pumice (b) Ahlat stone (c) Perlite

The pycnometer was filled with water until the filler materials were covered. Then, the filler materials in the pycnometer was subjected to vacuum by heating. Pycnometer with vacuumed samples were filled in with water as shown in Fig. 3 and were left in a water bath at 25°C for 24 hours. The pycnometer was then dried and weighed after they were removed from the water bath.

Fig. 3. Pycnometer Filled With Water

2.2.3. Bitumen and Marshall Mix Design Tests

To test the bitumen, penetration tests were carried out according to TS EN 1426 (2015). Flash point, softening point, and specific gravity tests were carried out according to TS 1171 (2006) and TS 120 EN 1427 (2015). 50/70 penetration bitumen was used in the SAM samples, in accordance with TS EN 12597 (2014). The bitumen was obtained from the Batman refinery. Fiber was added to all SMA samples at the same proportion of 0.3%. SMA tests were carried out according to the Marshall Mix design method, which will be detailed below (Orhan 2012).

2.2.4. Preparation of Stone Mastic Asphalt

The production process for our SMA samples is shown in Figs 4 and 5.

(a) **Mixer** (b) **SMA mixture** (c) **SMA briquette**

Fig. 4. SMA production: (a) Mixer (b) SMA Mixture (c) SMA Briquette

The mixture was placed in a Marshall mold and then compacted by applying 50 blows to each side of the specimen.

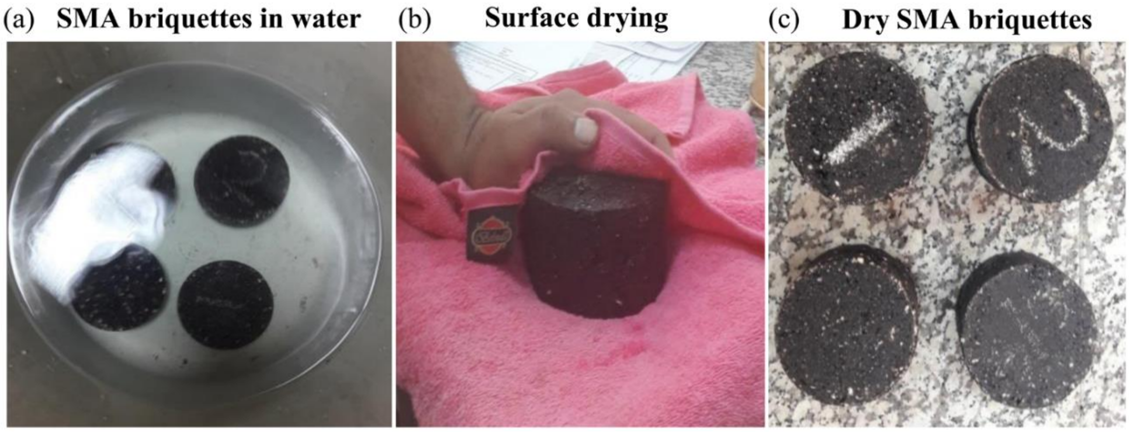

Fig. 5. SMA briquettes: (a) SMA Briquettes in Water (b) Surface Drying (c) Dry SMA Briquettes

In the Marshall Stability tests, the heights of all briquette samples were measured. Samples were then weighed in dry air and water, and the saturated surface weight and specific gravity of the samples were calculated. The properties of the samples we prepared are listed in Table 2.

Table 2. SMA Mixture Properties

Test	BAS-SMA	PUM-SMA	AS-SMA	PER-SMA
Bitumen penetration (25°C), 0.1 mm	63	63	63	63
Bitumen specific gravity, g/cm^3	1.03	1.03	1.03	1.03
Bitumen absorption, %	0.66	0.68	0.66	0.65
Bulk specific gravity, g/cm^3	2.755	2.708	2.724	2.772
Effective specific gravity, g/cm^3	2.805	2.757	2.772	2.775
Apparent specific gravity, g/cm^3	2.855	2.804	2.821	2.825

BAS-SMA was prepared as a reference SMA mixture. From the BAS-SMA mixture, 18 briquettes were pressed, and the bitumen content was increased by 0.5% in each sample starting from 5.5% to 8%.

3. Results and Discussion

3.1. Aggregate Tests

3.1.1. Sieve Analysis

The gradation ratios in Table 3 were used when preparing the four different SMA samples.

Table 3. Gradation Ratios of Aggregates in 4 Different Types of SMA Mixtures

Sieve Size			Gradation Limits	
mm	in.	SMA Gradation	Minimum	Maximum
19.1	3/4	100	100	100
12.7	1/2	92.5	90	100
9.52	3/8	67.7	50	75
4.76	No. 4	32.6	25	40
2.00	No. 10	23.0	20	30
0.42	No. 40	15.2	12	22
0.177	No. 80	12.6	9	17
0.075	No. 200	10.7	8	12

Gradation curves of the aggregates are shown in Fig. 6. As seen in Fig. 6, the gradation curves of aggregates are within the limits listed in Table 3.

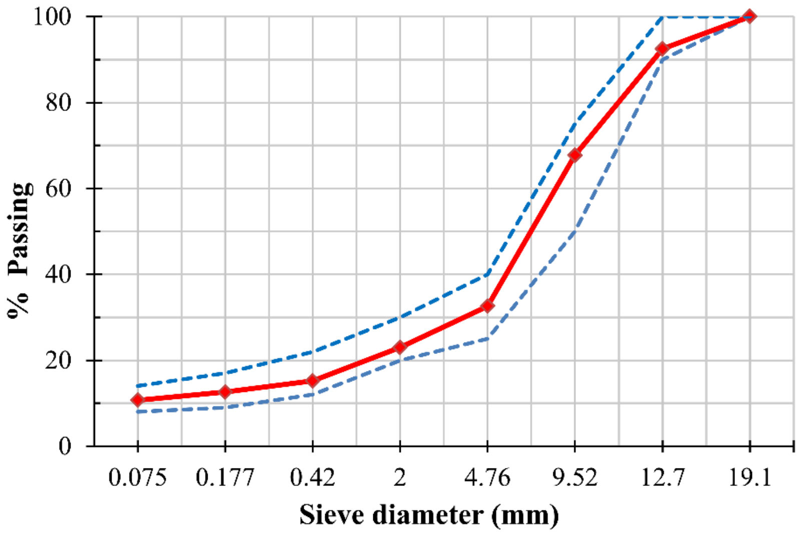

Fig. 6. Gradation Curve of Aggregates

Fig. 6 shows that the gradation ratios of all the aggregates used to form the SMA samples are within the standard specification limits of Highways General Directorate (2013).

3.1.2. Los Angeles (LA) Abrasion Test

LA test results are shown in Table 4.

Table 4. Los Angeles Abrasion Test Results

Test	**Aggregates**				**Specification Limits**
	Basalt	Ahlat stone	Perlite	Pumice	%
Los Angeles Abrasion, %	14	78	67	73	≤ 25

The high abrasion values of the Ahlat stone (AS), pumice, and perlite seen in Table 4 indicate that these aggregates have porous structure. The percentages of material lost after abrasion are 14% for basalt, 78% for AS, 67% for perlite, and 73% for pumice. These values do not meet the specified limit, because maximum specification limit is 25%. For this reason, pumice, AS, and perlite aggregates cannot be used as coarse or fine aggregates in an SMA mixture. These test results restricted our use of pumice, AS and perlite aggregates to serve only as filler material.

3.1.3. Specific Gravity Tests

Test results of the aggregates used in the study and the associated limits specified in the General Directorate of Highways standards are listed in Table 5.

Table 5. Aggregate Test Results

Test	**Ahlat stone**	**Perlite**	**Pumice**	**Basalt**	**Specification limits**
Apparent specific gravity (coarse aggregate), g/cm^3	2.325	2.217	2.262	2.854	-
Bulk specific gravity (coarse aggregate), g/cm^3	1.651	1.995	1.497	2.746	-
Absorption (coarse aggregate), %	17.55	5.01	22.59	1.39	≤ 2.0
Specific gravity (filler), g/cm^3	2.539	2.567	2.415	2.822	-

The filler specific gravity was found to be 2.539 g/cm^3 for AS, 2.567 g/cm^3 for perlite, 2.415 g/cm^3 for pumice and 2.822 g/cm^3 for basalt. The low bulk specific gravity values of AS, pumice and perlite aggregates seen in Table 5 confirm that these aggregates have porous structure. The specified maximum limit of water absorption for SMA production is 2%. The water absorption percent is 17.55% for AS aggregate, 5.01% for perlite aggregate and 22.59% for pumice aggregate, none of which meet the water absorption limit, so these materials are further ruled out for use as coarse aggregate.

3.1.4. Bitumen test

Table 6 shows the test results for the 50/70 penetration bitumen we tested.

Table 6. Bitumen Test Results

Test	Value	Specification Limits	
		Min.	Max.
Flash point, °C	250	230	-
Softening point, °C	52.8	46	54
Penetration (100 g, 25°C, 5 s), 0.1 mm	63	50	70
Bitumen specific gravity, g/cm^3	1.03	-	-

The bitumen test results in Table 6 indicate that the bitumen had a specific gravity of 1.03 g/cm^3, penetration of 63 mm, flash point of 250°C and a softening point of 52.8°C. These results confirm that bitumen we obtained is suitable for use in SMA.

3.1.4. Marshall stability test

The stability value of BAS-SMA is 979 kg. The bitumen percentage of BAS-SMA is 6.65%, and the flow value of BAS-SMA is 2.88 mm. The stability and flow values of BAS-SMA are plotted in Fig. 7.

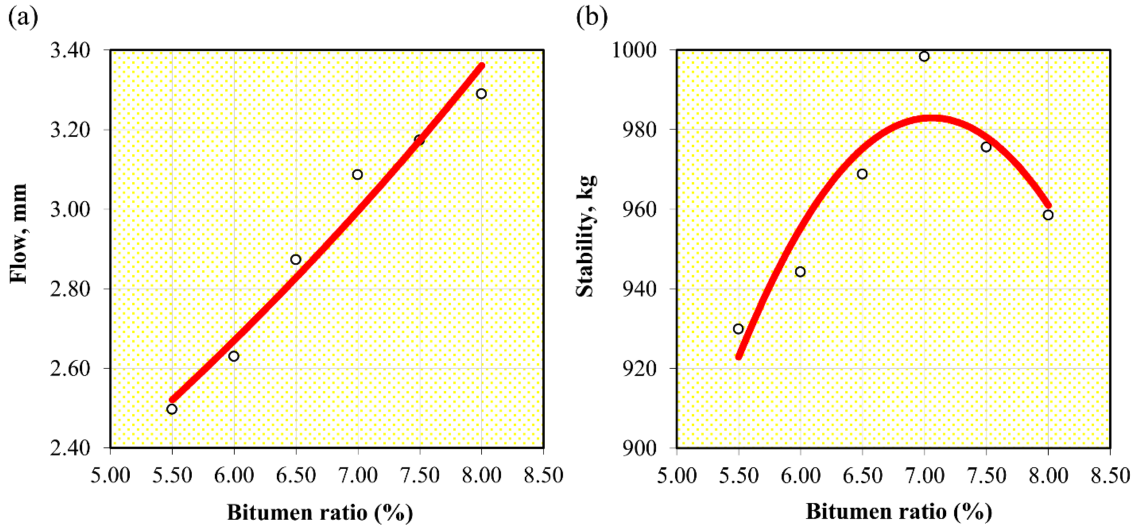

Fig. 7. Stability and Flow Graphs of BAS-SMA

21 briquettes were prepared from the PUM-SMA mixture, and the bitumen content was increased by 0.5% in each sample, starting from 5% to 8%. The stability and flow of the PUM-SMA samples are plotted in Fig. 8.

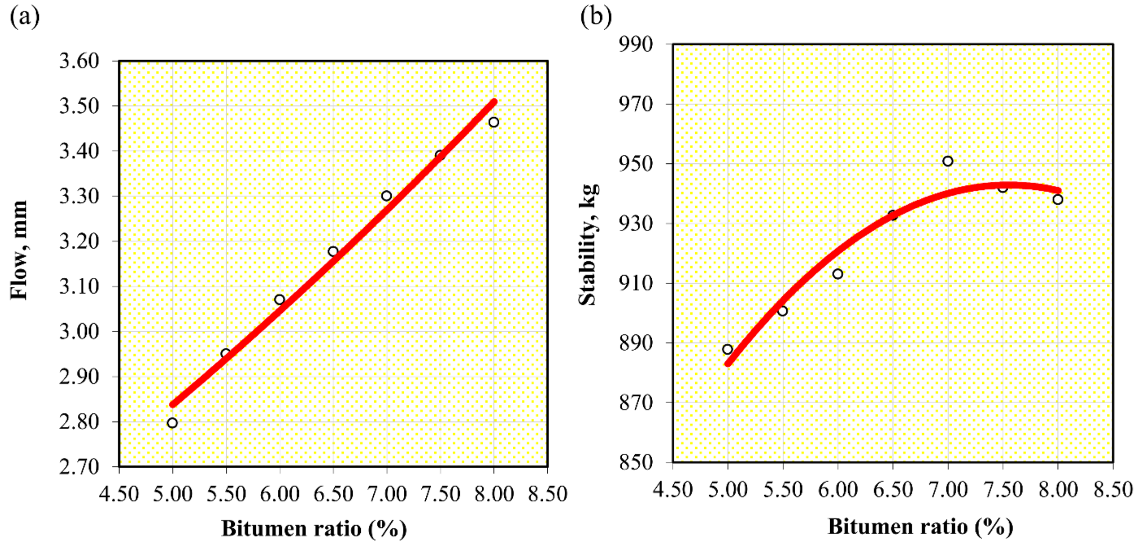

Fig. 8. Stability and flow graphs of PUM-SMA

The bitumen content of the PUM-SMA samples is 6.90%. The stability value of PUM-SMA is 940 kg. Flow value of PUM-SMA is 3.24 mm. 18 briquettes were prepared from the PUM-SMA mixture, increasing the bitumen content by 0.5% in each sample from 5% to 7.5%. The stability and flow values of the AS-SMA are plotted in Fig. 9. The bitumen percentage of AS-SMA is 6.80%. Stability value of AS-SMA is 965 kg. Flow value of AS-SMA was is 3.20 mm.

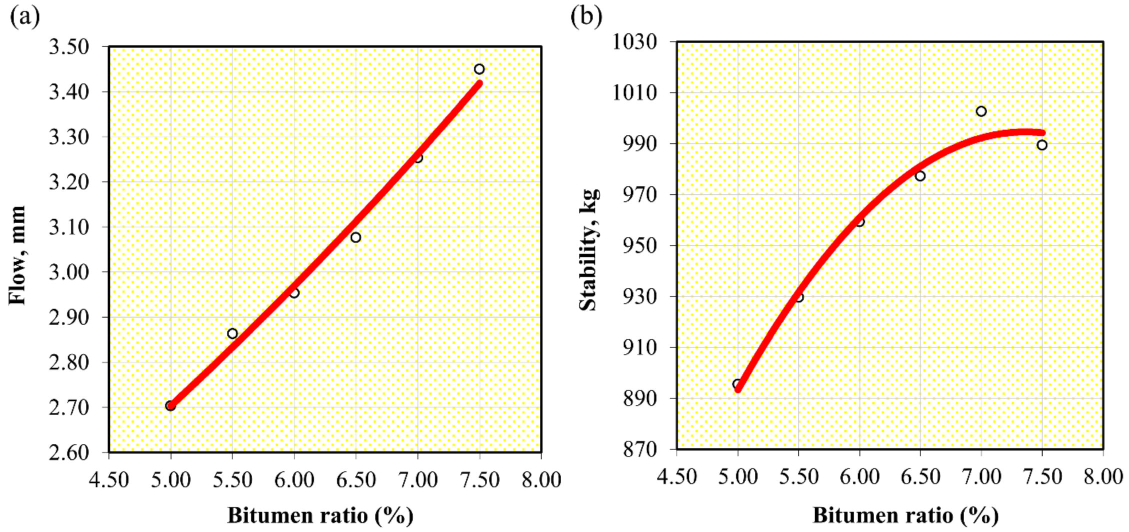

Fig. 9. Stability and Flow Graphs of AS-SMA

21 briquettes were prepared from the PER-SMA mixture, and the bitumen was increased by 0.5% in each briquette, starting from 5% to 8%. The bitumen percentage of PER-SMA is 6.80%. The stability value of PER-SMA is 937 kg. The flow value of PER-SMA is 3.19 mm. Stability and flow plots of PER-SMA are shown in Fig. 10.

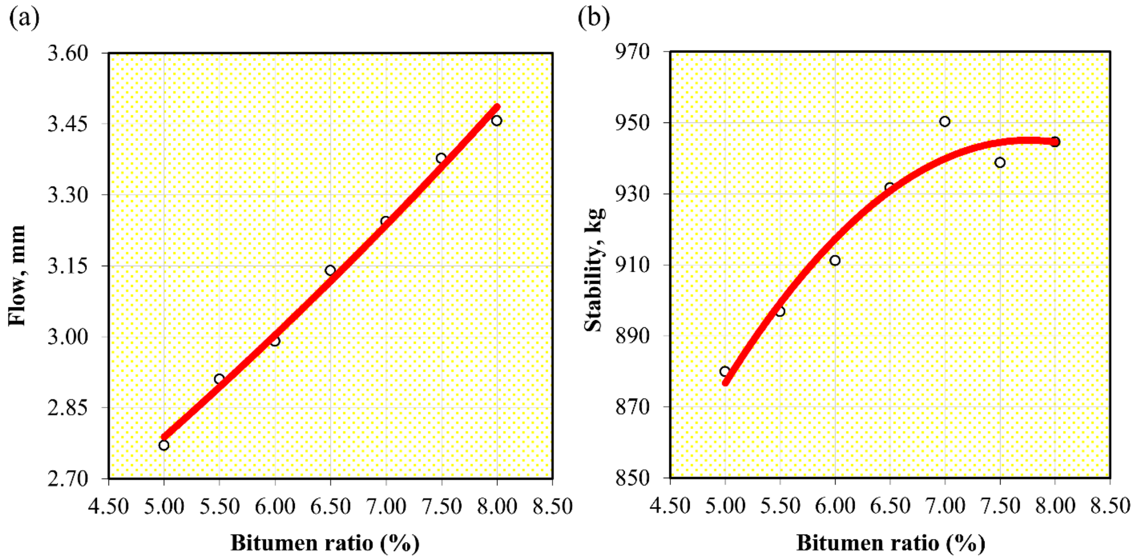

Fig. 10. Stability and Flow Graphs of PER-SMA

The bitumen ratio, void ratio, practical density, voids in mineral aggregate, voids of filled with asphalt, and the Marshall stability and flow values of SMA samples were determined in the present tests. These results were compared with the reference SMA (BAS-SMA) and the limits in the Turkish national standards.

These standards give the stability limit of a minimum of 750 kg and require a flow values in the range of 2-4 mm for SMA used in Turkish highways. Test results for all SMA samples are shown in Table 7.

Table 7. Test Results for SMA Samples

SMA properties	BAS-SMA	PUM-SMA	AS-SMA	PER-SMA	Specification limits	
					Min.	Max.
Bitumen ratio, %	6.65	6.90	6.80	6.80	-	-
Void ratio, Vh, %	3.00	3.00	3.00	3.00	2	4
Practical density, Dp, g/cm^3	2.455	2.412	2.428	2.429	-	
Voids in mineral aggregate, VMA, %	16.50	16.70	16.50	16.70	16	-
Voids of filled with asphalt, VFA, %	81.30	82.00	82.50	81.00	-	-
Stability (kg)	979	940	965	937	750	-
Flow (mm)	2.88	3.24	3.20	3.19	2	4

As shown in Table 7, the practical densities of all samples with alternative filler aggregates are within 1.7% of the density of the all-basalt reference sample. The void ratios of all SMA samples we tested are 3%, which is within the specified range of 2-4%. As shown in Table 7, the voids filled with asphalt percentage of all SMA samples are all within 1.5% of the reference sample.

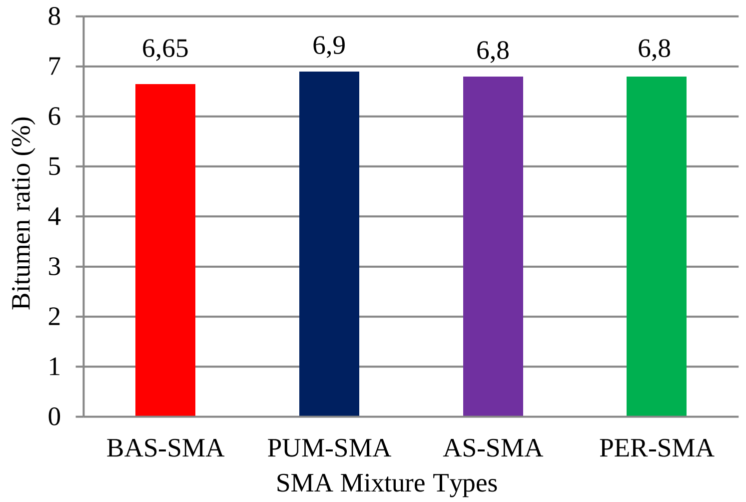

Fig. 11. Bitumen Ratios of SMA Mixture Types

The bitumen ratios of *SMA Mixture Types* are shown in Table 7 and Fig. 11. As shown in Fig. 11, the bitumen ratios of BAS-SMA, PUM-SMA, AS-SMA and PER-SMA are 6.65%, 6.90%, 6.80% and 6.80%, respectively.

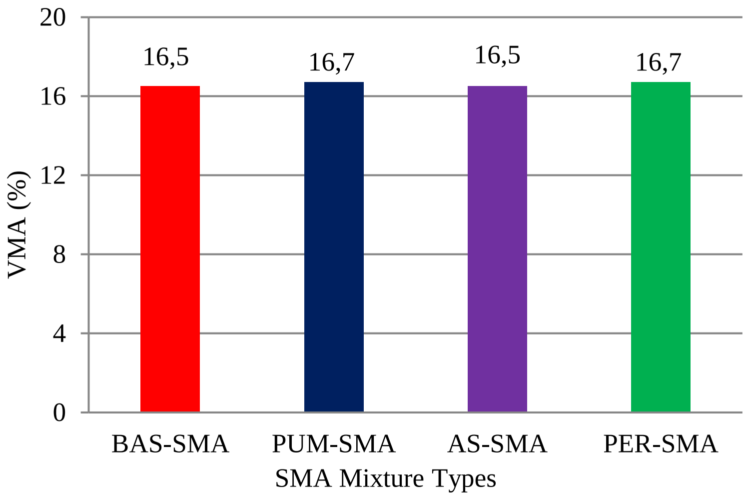

Fig. 12. Void in Mineral Aggregate (VMA) Values of SMA Mixture Types

VMA values of *SMA Mixture Types* are shown in Table 7 and Fig. 12. As shown in Fig. 12, VMA values of BAS-SMA, PUM-SMA, AS-SMA and PER-SMA are 16.50%, 16.70%, 16.50% and 16.70%, respectively. As shown in Table 7 and Fig.12, the void in mineral aggregate (VMA) percentages of all SMA samples are all over the standard minimum of 16%.

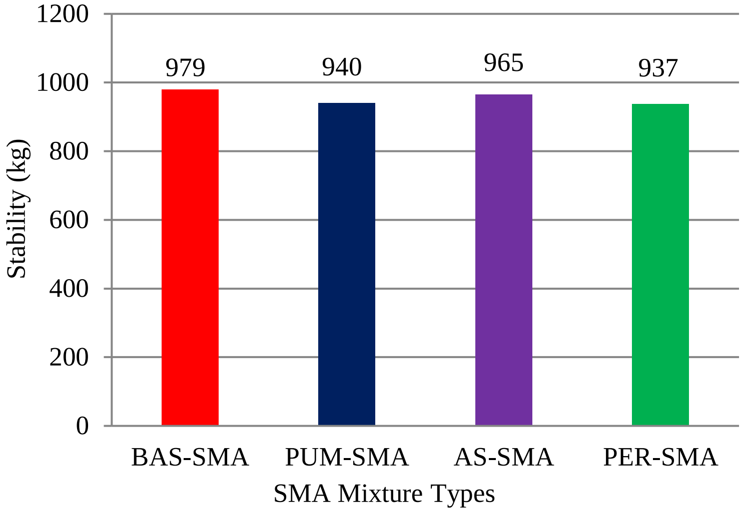

Fig. 13. Stability Values of SMA Mixture Types

The stability values of *SMA Mixture Types* are shown in Table 7 and Fig. 13. As shown in Fig. 13, the stability values of BAS-SMA, PUM-SMA, AS-SMA and PER-SMA are 979 kg, 940 kg, 965 kg and 937 kg, respectively. As shown in Table 7 and Fig.13, the stability values of all SMA samples are all over the standard minimum of 750 kg.

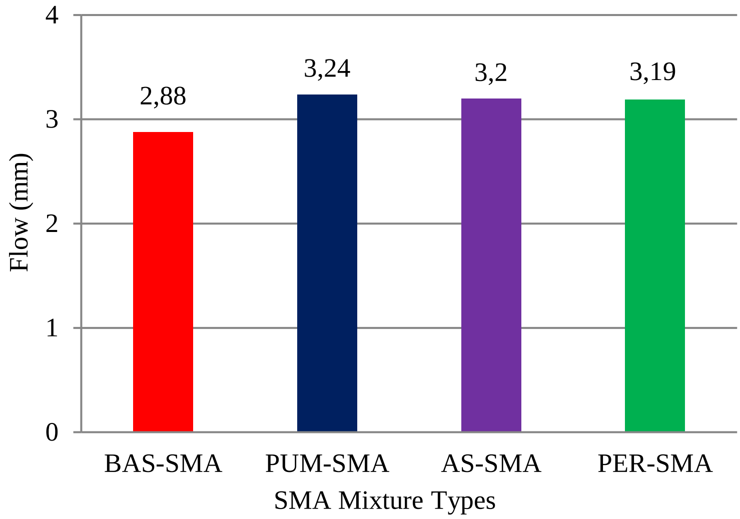

Fig. 14. Flow Values of SMA Mixture Types

The flow values of *SMA Mixture Types* are plotted in Table 7 and Fig. 14. As shown in Fig. 14, the flow values of BAS-SMA, PUM-SMA, AS-SMA and PER-SMA are 2.88 mm, 3.24 mm, 3.20 mm and 3.19 mm, respectively. As shown in Table 7 and Fig.14, the flow values of all SMA samples are within the standard limits.

4. Conclusion

Four different types of SMA were prepared and tested to determine the suitability of inexpensive and readily available porous rock for use in SMA pavement. Basalt was used as the coarse, fine, and filler aggregate in the reference samples. In the three other types of SMA we tested, basalt was used for coarse and fine aggregate, and pumice (PUM), Ahlat stone (AS), and perlite (PER) were tested as filler materials. We found that none of these porous rocks are suitable for use as coarse or fine aggregate in SMA mixtures. These stones can, however, be used as filler aggregate in the proportion of 10.7% by weight.

Ahlat stone filler is a solid waste that contributes to environmental pollution and waste landfills. Besides Ahlat stone filler, pumice filler is another solid waste that contributes to environmental pollution and forms waste fields. Hence, the use of these waste filler materials in SMA reduces the production cost of SMA. Therefore, it can be said that the cost of SMA aggregate will decrease by 10.7%.

All the SMA samples we tested had sufficient void ratios according to standard SMA specifications, and all had acceptable voids in the percentage of mineral aggregate. The bitumen ratio of the reference sample was the lowest of the samples we tested, and the bitumen ratio of PUM-SMA was the highest. The Marshall-test stability and flow values of all the SMA samples meet the standard specifications in Turkish highway codes.

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