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Effect of Gradation Variation on Mixture Properties in Stone Mastic Asphalt Mixtures with Carbon Fiber and Hybrid Aggregate

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Due to advantages like abrasion resistance, increased operating and service life, high coarse aggregate content and high resistance to deformation, increased fatigue life, and others, stone mastic asphalt (SMA) mixtures have recently become a popular asphalt pavement type in road sections such as highways, tunnels, and bridges. There hasn't been much research on the topic, despite the fact that gradation significantly affects the performance of SMA combinations. In this study, the experimental findings of three distinct gradations of SMA mixtures with hybrid materials (basalt coarse aggregate, limestone fine aggregate) and carbon fiber were compared. As a result, it was concluded that the hybrid aggregate used with carbon fiber, maximum aggregate size, and coarse aggregate % had a positive impact SMA mixtures.

Keywords: carbon fiber, gradation, hybrid aggregate, Marshall design, stone mastic asphalt.

1. INTRODUCTION

Since the 1980s, the rapid increase in the traffic loads on highways and increase in tire pressures, and wheel loads, has caused deterioration such as especially rutting, fatigue cracks, etc. in asphalt road pavements. In recent years, the use of stone mastic asphalt (SMA) mixtures in the wear layers of pavements has become increasingly widespread, especially in European countries and Turkey, to produce rut-resistance, highly durable mixtures and to increase the service life of the road pavement.

The most common problems in SMA mixtures are drainage of bitumen and bleeding, and in addition, the workability of this type of mixture is very difficult compared to traditional mixture types, so mixing and compaction temperatures are high (170 – 190 °C). Therefore, cellulosic fiber, rubber, polymer, etc., stabilizing additives are used to ensure the workability of the mastic at high temperatures. In all asphalt mixture types, the type and gradation of the aggregate, as well as the bitumen-aggregate bond, are among the most important factors affecting durability when exposed to heavy traffic and different environmental conditions [1 – 3]. Aggregate type and gradation have a significant influence on the mechanical properties and durability of asphalt mixes, as aggregates consist of approximately 93.5' of the minimum of SMA asphalt mixes [3 – 5]. The basic principle of SMA is based on coarse aggregate gradation, and for any SMA mixture it is essential to ensure proper stone-to-stone contact with quality aggregates [6]. The type of composition of the SMA aggregate blend is typically known as a gap-graded mineral mixture [7].

Pasetto and Baldo [8] investigated the permanent deformation resistance of the mixtures via repeated load axial and wheel tracking tests. The test results indicate that the aggregate matrix could have a different and strong influence on the mechanical properties, depending on the physical characteristics and the content of the marginal components, as well as on the gradation and the volumetric properties of the asphalt mixture. Hafeez et al. [9] the effect of selected aggregate gradations in conventional stone mastic asphalt mixtures and determined that the rutting deformation resistances and stiffnesses of the mixtures increased with increasing aggregate size. Sarang et al. [9] are investigated the performance of SMA with two aggregate gradations. Maximum aggregate sizes of 16 and 13 mm were adopted to prepare SMA mixture samples (SMA-1 and SMA-2). It was concluded that the mixture with a 16 mm maximum aggregate size was better than the mixture with a 13 mm maximum aggregate size. SMA-1 mixture was better resistant to rutting, and in the wheel-tracking test, deformations were 0.4 – 0.7 mm less than SMA-2. Liu et al. [10] investigated the nominal maximum aggregate size (NMAS) on the performance of stone matrix asphalt. It was concluded that the increase of NMAS contributed to the improvement of the rutting resistance of SMA mixtures. However, a decrease in NMAS showed better cracking and raveling resistance. Also, the permeability rate of SMA mixtures was primarily affected by the air voids. White and Almutairi [11] compared the laboratory and field performance of dense graded and stone mastic asphalt mixtures (DGA and SMA) that was serviced as runway pavement. It was concluded that SMA performed equal to or better than DGA, particularly with regard to surface texture and wet friction and it is recommended that ungrooved SMA as a runway surface in the future.

Muniandy and Aburkaba [12] study assessed the moisture sensitivity behavior of the laboratory performance-based properties of Stone Mastics Asphalt (SMA) mixtures using four different mineral fillers (limestone, ceramic

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waste, coal fly ash, and steel slag as reference). The selected mineral filler fraction was blended in three different ratios, 100/0, 50/50 and 0/100, exceeding 75 and 20 microns, and the effects of these fillers and particle size on the SMA mixture properties were determined. The coarse aggregate and fine aggregate fractions were kept constant throughout the study and the binder content of each aggregate mixture was optimized using the Marshall Mixture Design Method. The results of the study showed that SMA blends were not prone to moisture damage and the use of these fillers was very effective in improving Marshall Stability, Modulus of Stiffness (Sm) and Tensile Strength Ratio (TSR). Samples containing ceramic waste with a 50/50 filler ratio had a modulus of stiffness 1.03 times higher than the reference mixture, while coal fly ash and steel slag with a 50/50 filler ratio showed little value. Samples containing ceramic waste with a fill ratio of 0/100 showed the least reduction in tensile strength ratio and Marshall Stability, while steel slag and coal fly ash retained TSR of 85 and more than 80 percent, 85 and 70 percent, respectively.

Tayh and Alghrery [13] investigated the effect of nominal maximum aggregate size (NMAS) and gradation on SMA volumetric and mechanical properties. A total of 9 SMA mixture series were studied each with three NMASs with three different aggregate gradations and an asphalt binder (styrene butadiene styrene SBS) modified binder. It revealed that the voids and voids filled with bitumen (VFA) and voids in mineral aggregate (VMA) of the samples increased with a decrease in NMAS. SMA samples with higher NMAS have lower optimum asphalt than those with lower NMAS. According to the laboratory study, SMA blends produced using the upper limit of gradation showed the highest mechanical properties in terms of Marshall Stability and indirect tensile strength. It has also been noted that SMA mixtures with larger NMAS have higher ITS and Marshall stability than the others. These results were concluded due to the larger proportion of coarse aggregate in the SMA mixture.

Çetin [14] investigated the moisture sensitivity properties of additive added SMA mixtures. C class and F class fly ash and slaked lime were used as additional filling. The effects of additives on the strength and moisture sensitivity of SMA samples prepared in the laboratory were investigated. As a result of the study, it was concluded that Class C fly ash significantly improved the moisture sensitivity of the mixtures. While the slurry method did not give the expected improvement in C class fly ash added mixtures, it showed a positive effect on F class fly ash and slaked lime added mixtures.

Yue et al. [15] the mixture properties with different gradations were assessed using the Marshall Mixture design method. Then, the performance of HMA mixtures was evaluated under the effects of high temperature and water cycles by applying wheel tracking loading and Indirect Tensile Strength (ITS) tests. The results showed that 3B mixes recorded the lowest rutting depth and highest water damage resistance in hot areas compared to ordinary asphalt mixture samples, with a gradation within a range of + 4 % to – 2 % of the upper and lower specification limits.

The main objective of this research is to prepare SMA with carbon fiber mixture samples with three different aggregate gradations and compare them based on their performance in various mechanical mixture tests. Coarse aggregates with Los Angeles abrasion value of 30 % were observed to give better performance to SMA [16]. Unlike previous studies, in this study, the SMA Marshall design was carried out for three different aggregate gradations by using coarse aggregate as basalt, fine aggregate as limestone, limestone mineral filler and carbon fiber as stabilizer, and it was determined how aggregate gradation affects the mechanical properties of SMA.

2. MATERIALS AND METHODS

2.1. Materials

In the study, limestone obtained from Afyonkarahisar as mineral filler and fine aggregate and basalt-based aggregate extracted from Kütahya Region as coarse aggregate were used. aggregate mechanical and physical properties are given in Table 1.

Table 1. Aggregate properties

Aggregate tests	Values, g/cm^3	
	Limestone	Basalt
Coarse aggregate volume specific gravity (>No:4)	2.721	2.673
Coarse aggregate apparent specific gravity (>No:4)	2.730	2.772
Fine aggregate volume specific gravity (No:4–No:200)	2.186	–
Fine aggregate apparent specific gravity (No:4–No:200)	2.592	–
Carbon Black filler apparent specific gravity (<No:200)	2.930	–
Water absorption, % (>No:4)	0.4	4.0
Water absorption, % (No:4–No:200)	4.0	8.7
Loss of Los Angeles abrasion, %	23.1	15.8
Impact loss, %	5.03	3.50
$NaSO_4$ freezing loss, %	0.69	7.53

B50/70 penetration grade bitumen originating from Aliağa Refinery, which was obtained from Afyonkarahisar. Asphalt production facilities were used as the binder material. Bitumen properties are given in Table 2.

Table 2. Properties of B50/70 penetration grade bitumen

Properties	Values	Specification
Refinery	Aliağa	–
Penetration class	50/70	–
Penetration grade of bitumen sample (at 25 °C)	52.13	ASTM D5-06e1
Specific gravity, g/cm^3	1.035	ASTM D70-09e1
Softening point, °C	46.65	ASTMD36/D36M-09
Flash point, °C	264	ASTM D92-05a
Ductility, 5 cm/dk	>100 cm	ASTM D113-07
Viscosity (at 135 °C/cP)	495.0 cP	ASTM D4402-06
Viscosity (at 165 °C/cP)	131.0 cP	

5 mm long, 0.2 % by weight carbon fiber was used in SMA mixtures as a stabilizer. The carbon fiber samples were taken from DOWAKSA Advanced Composite Materials Company in Yalova. The material properties of the carbon fiber used are given in Table 3. Three different SMA aggregate gradations used in the study are shown in

Fig. 1. The maximum aggregate size (D_{max}), which is important for the performance of SMA mixtures, the nominal maximum size through which the majority of aggregates pass, the fineness modulus (F.M.) of the aggregates, and the percentage of coarse aggregate remaining on the No:4 sieve is given in Table 4.

Table 3. Properties of B50/70 penetration grade bitumen

Properties	Values	Standard
Tensile strength, MPa	4900	ISO 10618
Tensile modulus, GPa	250	ISO 10618
Unit deformation, %	2.0	ISO 10618
Density, g/cm^3	1.79	ISO 10119
Yield, g/1000 m	1600	ISO 1889

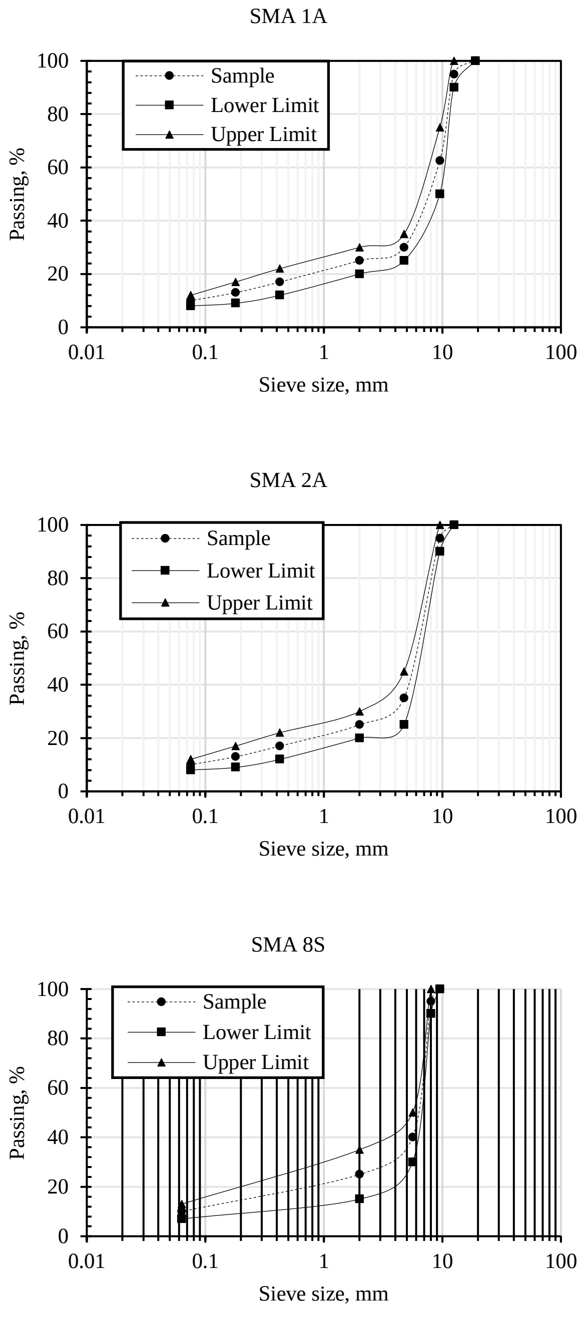

Fig. 1. SMA Gradations of 1A, 2A and 8S series

FM is the value obtained by dividing the cumulative % sum of the materials remaining on the sieve in the sieve sets that follow each other in two layers, by one hundred. As the fineness modulus decreases, the amount of fine material in the sand increases. Since the amount of fine material in the unit volume will increase, the ability to wrap the gravel will also increase. As the fineness modulus increases, the fine material will decrease and the coarse aggregate will increase, so the packing ratio of the sand to the gravel will decrease. As the fineness modulus decreases, the finer material increases. The fineness modulus is calculated by the equation given in Eq. 1.

$$F.M. = \frac{\Sigma\,(\text{Cumulative percentage retained on specified sieves})}{100}. \quad (1)$$

Table 4. SMA gradation properties

SMA series	*D*max, mm	Nominal max. size, mm	Finess modulus, FM	Percentage coarse aggregate
1A	19.0	12.5	5.45	67.5
2A	12.5	12.5	5.15	65.0
8S	9.5	8.0	2.30	70.0

2.2. Methods

The experimental study consists of two stages. In the first stage, Marshall design was carried out for three different series, and then ultrasonic pulse velocity (UPV), Cantabro, two electrode volume resistivity and Shellenberger bitumen drainage tests were performed on the samples with optimum bitumen percentage. The method flow chart of the study is given in Fig. 2.

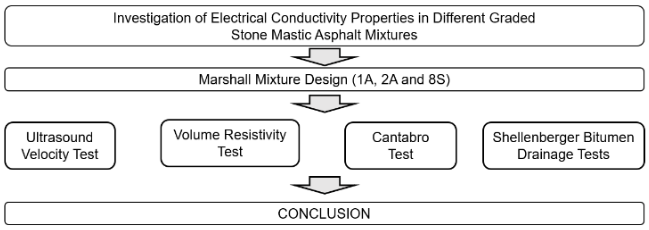

Fig. 2. Flow chart of study method

2.2.1. Marshal design test

Experimental studies, Marshall design of 1A, 2A and 8S series TMA samples were performed. Batch aggregate mixtures were prepared in accordance with the gradation curve in the middle of the GDH specification [17] Type-1A, 2A and German 8S TL Asphalt-StB 07 [18] stone mastic asphalt wear layer design limits. Since carbon fiber is used in the mixtures, no cellulosic fiber is used. Three separate SMA samples were produced for each of the bitumen percentages of 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 by weight. To determine the weight-volume relationships on the samples, their air, water, and surface dry saturated weights as well as height and diameters were measured. In addition to these, the samples were subjected to the Marshall stability-flow test. From the results obtained, graphs showing how some properties such as stability, density, and flow change depending on the amount of bitumen were prepared. These are:

– the change in percent of bitumen by weight of bitumen versus stability;

– change in percent of bitumen by weight versus bulk specific gravity;
– change in percent of bitumen by weight versus void filled with bitumen (VFB);
– change in percent of bitumen by weight versus % of void;
– change in percent of bitumen by weight versus void in mineral aggregates (VMA);
– change in percent of bitumen by weight versus Marshall flow value;
– change in percent of bitumen by weight versus Marshall Quotients (MQ).

2.2.2. Ultrasound velocity test

The ultrasound pulse velocity (UPV) test is one of the non-destructive methods used to gauge the durability and quality of asphalt. Concrete density and interior fissures have an impact on this test [19]. The fundamental idea behind this test is to time how long it takes an ultrasonic wave to go through the material [20].

2.2.3. Volume resistivity test

For measuring electrical conductivity, the two-probe approach was employed. At a temperature of 25 °C, electrical resistivity measurements were performed. First, the conductive gel was applied to the specimens' electrical contact points. The ends of the cylindrical asphalt concrete samples were fitted with two copper plate electrodes attached to a multimeter. Following the measurement of resistance, the electrical resistivity of the sample was determined using Eq. 2 second Ohm's law:

$$\rho = \frac{RS}{L}, \tag{2}$$

where R is the measured resistance (Ω); S is the electrode conductive area (m^2); L is the internal electrode distance (m); ρ is the electrical resistance (Ω.m).

2.2.4. Cantabro test

ASTM D7064-08 [21] was used to conduct the Cantabro test. In this test, at room temperature (25 °C), Marshall compressed samples were fed into the Los Angeles (LA) abrasion machine without steel spheres. For 300 rotations, the machine was operated at a speed of 30 to 35 rpm. The Cantabro loss was quantified as a percentage of the test sample's starting weight through weight loss.

2.2.5. Schellenberger bitumen drainage test

Due to the gap grading of the aggregates, bitumen drainage can be seen in SMA mixtures. SMA blends contain specific amounts of fiber to avoid this. The Schellenberger test was used in this investigation to ascertain if bitumen drainage took place or not.

3. RESULTS AND DISCUSSION

3.1. Marshal design results

As a result of the optimum bitumen amount was calculated as 6.50 %, 6.78 and 6.50 % for the 1A, 2A and 8S series, respectively. The changes between the Marshall Stability value and the percent bitumen by weight are shown in Fig. 3.

The maximum stability values of the 1A, 2A, and 8S series were obtained as 1020, 877, and 1322 kg, respectively. In the stability results, it is thought that the stability value of the 8S mixture with a higher percentage of coarse aggregate will also be higher and its ability to carry traffic load will be better. With the increase in the amount of bitumen, a decrease in the stability values of all series was also obtained.

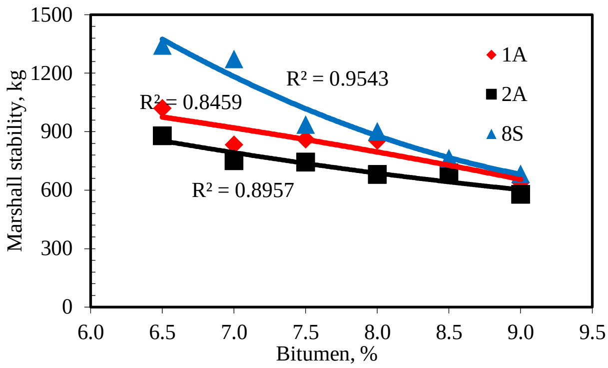

Fig. 3. The changes between the Marshall stability value and the percent bitumen

Another important property of bituminous hot mixes is density. As the density increases, its physical properties such as durability, impermeability and stability are expected to be better. It is known that aging caused by bitumen oxidation is slower in mixtures with high density, and as a result, an increase in durability and a decrease in raveling deterioration due to stripping are expected [22]. The changes in the practical specific gravity values versus the percent by weight of bitumen in the samples belonging to the SMA series are shown in Fig. 4.

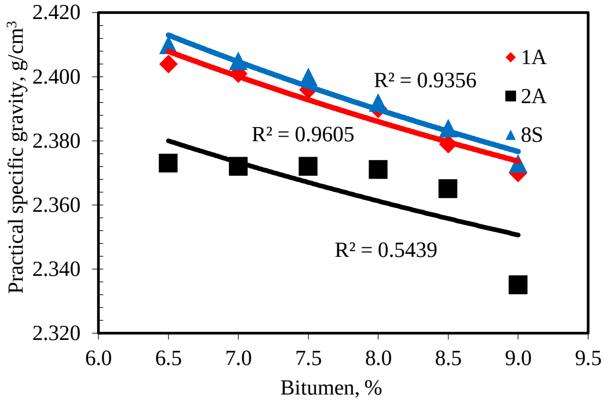

Fig. 4. The changes between the practical specific gravity and the percentage of bitumen

The highest practical specific gravity values were obtained as 2.404, 2.373 and 2.410 g/cm^3 for TMA 1A, 2A and 8S series, respectively. Practical specific gravity values increased with the increase of bitumen percentage in all series. The highest practical specific gravity value was obtained for the 8S series. As expected, the Marshall stability value was also found to be the highest in the 8S series (Fig. 3).

The voids filled with bitumen (VFB) is an effective feature on the plasticity, durability and friction coefficient of the bituminous hot mixture pavement, and this feature is also effective in the formation of a definite bitumen film around the aggregate particles. This is a very important issue in terms of the durability of the asphalt pavement. The friction coefficient of asphalt pavements is related to the bitumen percentage and void percentage in bituminous hot mixtures as well as the surface texture of the pavement [23]. In SMA series 1A, 2A and 8S, the percentage of VFB was obtained as 88 %, 81 % and 94 %, respectively. According to the GDH [17], there is no upper or lower limit for the SMA design in the amount of VFB. While the highest percentage of VFB was seen in the 8S series, the lowest value was seen in the 2A series (Fig. 5).

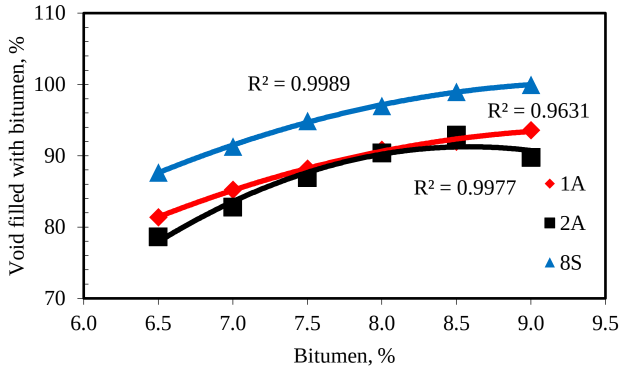

Fig. 5. The changes between the VFB and the percentage of bitumen

The void property is also an important design factor for hot bituminous hot mixtures. The most important reason for defining this limit range is to prevent a possible bleeding deterioration in bituminous hot mixtures. The reason for determining the upper limit is to guarantee the impermeability of bituminous hot mixtures, to ensure sufficient stability and to reduce the oxidation of bitumen [23]. The changes in the percentage of void versus the percentage of bitumen are shown in Fig. 6.

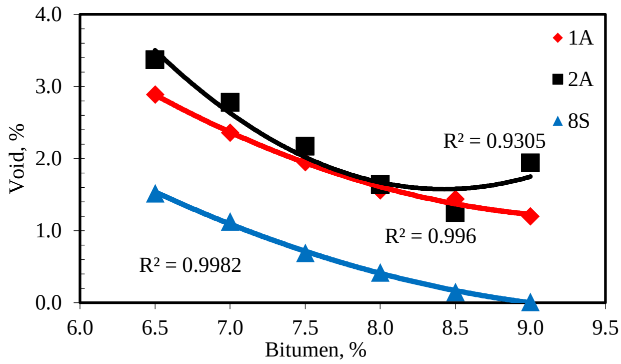

Fig. 6. The changes in the percentage of void versus the percentage of bitumen

The void percentages corresponding to the optimum bitumen percentage for SMA 1A, 2A and 8S series samples were calculated as 2.9 %, 2.9 % and 1.5 %, respectively. The void percentage of 8S series samples is slightly less than the specification limits. The fact that the maximum grain size (D_{max}) of the 8S series is lower than the other series is thought to have an effect on this result. Void % of 1A and 2A series are within the specification limit (2 – 4 %).

The flow value is a property that reflects the plasticity and flexibility properties of bituminous hot mix pavements and is also known as the deformation value corresponding to the load at the time of fracture of Marshall samples. Flow is an indirect measure of the internal friction of compacted mixtures. There is a linear inverse relationship between flow value and internal friction [22]. The relationship between flow value and percent bitumen by wt. is shown in Fig. 7. The flow values corresponding to the optimum bitumen percentage in the 1A, 2A and 8S series are 4.40, 4.75 and 4.40 mm respectively. According to the flow results, the plastic deformation tendency of the 2A series samples is higher than the others. In the 1A and 2A series, a similar change occurred in the flow values with the increase in the bitumen ratio. However, in 8S series, it was observed that the change in flow values with the increase of bitumen ratio was higher than that of 1A and 2A samples. This may be because the percentage of void is lower than the others.

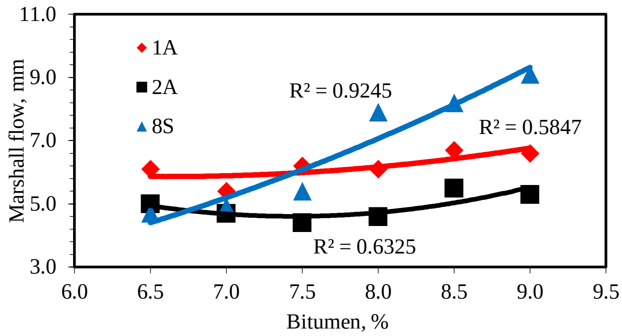

Fig. 7. The changes in the Marshall flow versus the percentage of bitumen

The voids in mineral aggregates (VMA) are the air voids between aggregate particles, including bitumen-filled voids in compacted asphalt pavement mixes. VMA represents the usable volume corresponding to the volume required for the bitumen and air gap in the mixture. Therefore, as the gap between the mineral aggregates increases, the thickness of the bitumen film on the aggregates increases and the durability of the mixture increases. The relationship between the VMA and the percent by weight of bitumen is given in Fig. 8. The VMA percentages corresponding to the optimum bitumen percentage in the 1A, 2A and 8S series were found as 15.80, 16.00 and 12.30, respectively. According to the test results, it is thought that 1A and 2A series will be more durable than 8S series.

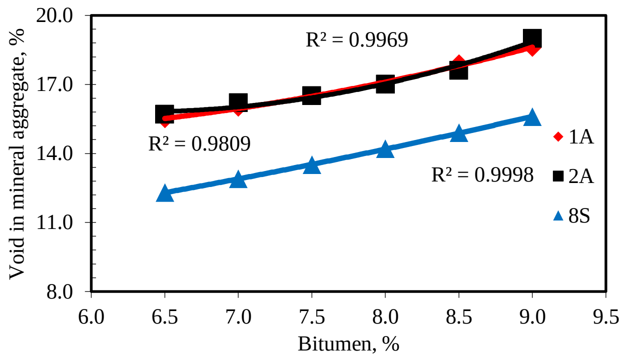

Fig. 8. The changes in the VMA versus the percentage of bitumen

Another important factor to consider in bituminous hot mix design is the Marshall quotient (MQ). It is also known as the ratio of Marshall Stability value to flow value. MQ is an empirical stiffness value and is used to evaluate the quality of asphalt mixtures. MQ can be used as a measure of the material's resistance to permanent deformation in service. Samples with high MQ values are expected to break with high deformation [22]. The relationship between MQ and the percentage of bitumen is given in Fig. 9.

Marshall quotient values for 1A, 2A, and 8S SMA series were determined as 1.40, 1.70, and 1.73 kN/mm, respectively. The test results show that the samples of the 8S series are less prone to permanent deformation than the other mixtures. The fact that the coarse aggregate percentage of 8S series samples is higher than the other samples is thought to affect this result. The Marshall quotient values decrease with increasing bitumen ratio in all series.

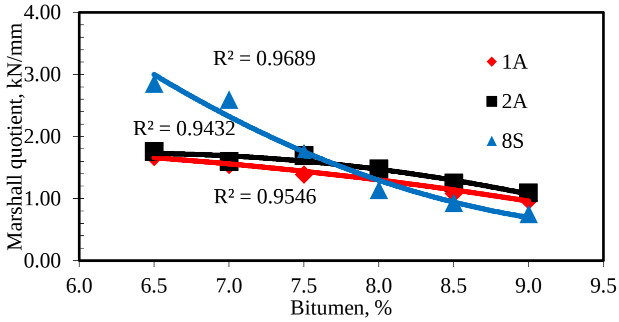

Fig. 9. The changes in the Marshall quotient versus the percentage of bitumen

3.2. Ultrasound pulse velocity (UPV) test results

To see the effect of gradation change in 2A, 1A and 8S samples, the UPV test was performed and the transition velocities in the samples were given comparatively (Fig. 10). It is seen from the changes in the velocities that there is a relationship between the UPV and the gradation of the sample series. There is an increase in the UPV between 6.5 – 7.0 % bitumen in all series, and then a decrease in the UPV. According to the Marshall method, the highest density values are generally obtained in these bitumen percentage ranges. The UPV values are also high in bitumen percentages where the material is dense. It is seen that the UPV is low in 8S samples with the highest percentage of coarse aggregate.

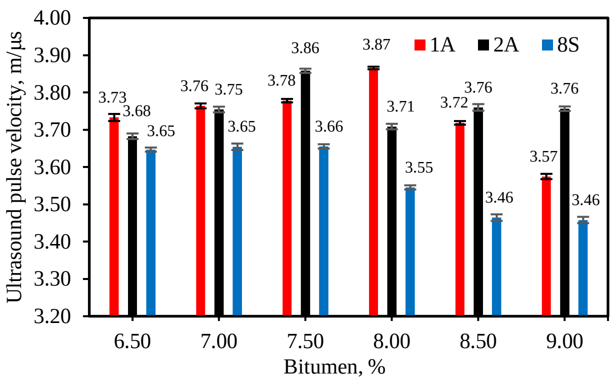

Fig. 10. The changes in the ultrasound pulse velocity versus the percentage of bitumen

The UPVs are also close to each other in the 1A and 2A series, where the maximum aggregate grain sizes and fineness modules are equal or close to each other.

3.3. Two electrode conductivity test results

Another test to assess the percentage of voids according to gradation is the two-electrode conductivity test. A direct proportional relationship was obtained between the void percentages of the mixtures and the volume resistivity values. According to the test results, the volume resistivity value of the 8S series with the lowest void percentage was obtained as the lowest (most conductive) (Fig. 11). Generally, it is expected that the volumetric resistivity will decrease with the decrease in the void.

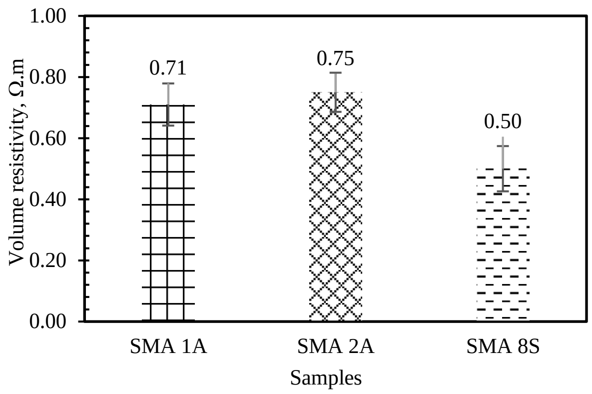

Fig. 11. Volume resistivity values of the SMA samples with different gradation

3.4. Schellenberger bitumen drainage test results

One of the most important problems in SMA mixtures is the danger of bitumen drainage in the mixture due to its gap-graded gradation.

To prevent this situation, fiber materials must be used in SMA mixtures and the Schellenberger bitumen drainage test is performed to measure the bitumen drainage percentage. Schellenberger drainage test results of SMA mixture samples are given in Fig. 12. The drainage value to GDH specification [17] limits should be less than 0.3 %. It was observed that the drainage values of all samples were below this limit. The highest drainage value was seen in the 8S series with the highest percentage of coarse aggregate (Fig. 12).

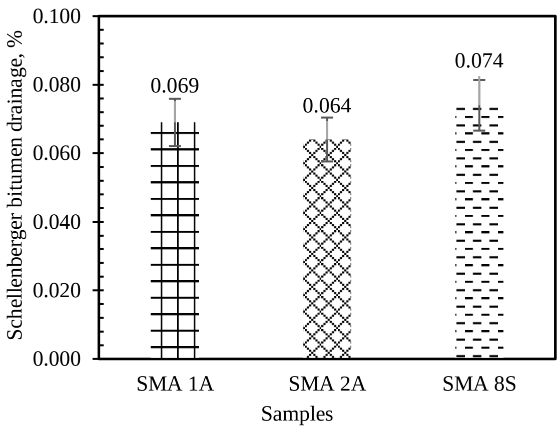

Fig. 12. Schellenberger drainage values of the SMA samples with different gradation

These test results also show that carbon fiber is quite effective in reducing bitumen drainage.

3.5. Cantabro test results

The Cantabro test is performed on stone mastic asphalt samples to assess the toughness and raveling resistance of the mixture. This test was conducted to evaluate the asphalt mix's ability to withstand degradation by estimating the percentage loss in compacted SMA samples using a Los Angeles Abrasion machine without steel balls. The Cantabro loss test results of the samples are given in Fig. 13. It is seen that the Cantabro loss values of all samples are less than 20 %, which is the GDH [17] limit value. An increase in Cantabro losses was also observed with the increase in the coarse aggregate percentage.

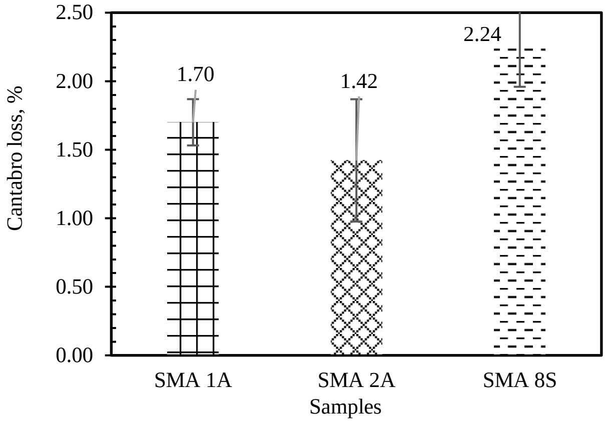

Fig. 13. Cantabro loss values of the SMA samples with different gradation

3. CONCLUSION

The following conclusions can be drawn from the experimental studies carried out to understand the effect of different SMA gradations on the mixture properties.

1. Marshall stability, flow, and conductivity of SMA mixtures with the same type of component properties but in different gradations properties were also obtained differently.
2. With the increase in the coarse aggregate percentage in the mixture, the void percentage decreased and the specific gravity values increased inversely. According to the results of the two electrode measurements, it was observed that the conductivity values increased as the void percentage decreased.
3. It was observed that even small changes in SMA gradations had an effect on the mechanical and physical properties of the mixture.
4. Test results show that the increase in the coarse aggregate percentage positively affects the mechanical properties such as Stability and Marshall quotient.
5. It has been observed that gradation is important in terms of bitumen drainage and Cantabro loss of SMA mixtures, and there is a tendency to increase bitumen drainage and Cantabro values with the increase in the percentage of coarse aggregate in the mixture.

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