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Investigation of the Effects of Porous Asphalt Mixtures Prepared with Different Modified Binders on the Performance Characteristics of Semi-Rigid Pavements

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ABSTRACT

In this study, the effects of porous asphalt mixtures prepared with different aggregate types and modified binders on the performance of semi-rigid pavements were examined. Porous asphalt mixtures were created using limestone and basalt aggregates along with 50/70 and 160/220 penetration grade bitumen, as well as modified binders containing SBS (Styrene-Butadiene-Styrene) polymer and CR (Crumb Rubber) additives. In the first stage of the study, physical and mechanical tests were conducted on the aggregates, and binder tests were performed on the bitumen samples. In the second stage, modified binders were prepared in different ratios, the optimal modification percentages were determined, and porous asphalt mixtures were produced accordingly. In the third stage, semi-rigid pavement specimens were prepared by injecting suitable cement mortar into the voids within the porous asphalt mixtures, and performance tests were conducted. The results indicated that mixtures prepared with 6.5% CR and 3.5% SBS-modified binders exhibited improved performance characteristics, and for cement mortar mixtures, a water/cement ratio of 0.50 and the use of 2% superplasticizer additive yielded a high-strength and highly flowable cement mortar.

Keywords: Porous asphalt, semi-rigid pavement, limestone, basalt, SBS (Styrene-Butadiene-Styrene), CR (Crumb Rubber).

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1. INTRODUCTION

A road pavement is designed by taking into account evaluations related to traffic loads, ground conditions, environmental factors, and available construction materials. In this context, two different pavement design systems, flexible and rigid pavements are traditionally used in road construction [1]. Flexible pavements are generally constructed using bituminous and granular materials while rigid pavements are a type of structure that incorporates crushed stone, sand, and cement as a binder. Flexible pavements are widely used globally as road surfaces due to their performance under traffic loads, high resistance to skidding, good serviceability, and driving quality [2]. However, in recent years, with the rapid development of urbanization and the increase in traffic load and volume, permanent deformations in flexible pavements have become significantly more prevalent. Additionally, due to the aging of asphalt binders in asphalt mixtures and their sensitivity to low and high temperatures, road maintenance costs have also increased substantially [3].

Concrete pavements, however, present considerable challenges in usage due to the need for joints that accommodate thermal movement, limitations in construction time, and the slow setting time during the construction and maintenance phases. Additionally, to mitigate noise caused by joints and improve the generally low driving quality of concrete pavements, it is necessary to balance the effects of differential expansion and contraction [4]. As a result, semi-rigid pavements have emerged as an alternative type of road surface to eliminate the limitations caused by traditional pavements, such as flexible asphalt pavements and rigid pavements, by combining the flexibility derived from asphalt and the rigidity provided by cement components [5].

Semi-rigid pavement is a new generation pavement type known for its high load-bearing capacity and excellent resistance to wheel ruts, making it durable and long-lasting [6]. It consists of porous asphalt with 25-35% air voids, into which a highly flowable mortar is poured to fill the air voids [7]. Due to its jointless structure, high strength, impermeability, durability, and fuel resistance, semi-rigid pavements are a viable option for the construction and rehabilitation of industrial floors, bus terminals, parking areas, loading platforms, and high-traffic zones [8].

Semi-rigid pavements consist of three main stages: the construction of porous asphalt concrete, the injection of cement mortar to fill the voids, and the removal of excess injection material from the surface of the pavement. This is achieved through the combination of porous asphalt and high-performance cement mortar [9]. After a curing period ranging from a few hours to several days, the cement binds with the asphalt mixture, increasing the overall strength of the composite and, as a result, allowing the pavement to exhibit semi-rigid properties [10]. Compared to traditional open-graded mixtures, the porous asphalt used in semi-rigid pavements must not only provide stability, tensile strength, and wear resistance, but also ensure sufficient penetration of the injection material, allowing the porous asphalt skeleton to have adequate porosity for the formation of a dense skeletal structure in the semi-rigid pavement [11]. The porous asphalt, which forms the skeleton system of the semi-rigid pavement, is constructed using a large amount of coarse aggregate and bitumen as the binder. During the pavement design process, cement-binder mortar should be injected under the influence of gravity, without compaction or vibration, to ensure that the pores within the porous asphalt have sufficient void space [12].

In their study, Sunil et al. investigated the effect of aggregate gradation selection on the mechanical properties of semi-rigid pavement mixtures. The results of the research indicated that the selected ASTM gradation with a bitumen content of 4.5% exhibited better strength properties and fatigue life [13]. In their study, Bharath et al. developed a cement-injected bituminous mixture design and evaluated it through experiments conducted under both laboratory and field conditions. For comparison, a conventional dense-graded bituminous concrete mixture was used. The results indicated that the cement-injected bituminous mixtures exhibited better indirect tensile strength, modulus of resistance, and wheel rut performance compared to traditional bituminous mixtures [14]. In his study, Karami investigated the stability and durability of semi-flexible bituminous mixture samples by exposing them to a specified area for 7, 90, 180, and 240 days. As a result, it was observed that both the primary and secondary durability indices significantly increased, with the first and second durability indices for the Marshall test showing an approximate daily increase of 0.9% and 52.3%, respectively. Additionally, the wheel rut resistance increased by 1.9% and 119% for the primary and secondary durability indices, respectively [15]. In their study, Hasan and Sugiarto aimed to determine the compressive strength, flexural strength, shrinkage, permeability, durability, and stress-strain relationship of semi-flexible pavement using waste tire rubber powder as an additive. The results indicated that waste rubber tire powder incorporated into liquid asphalt at 3%, 4%, and 5% concentrations showed the best performance at 5% concentration. Additionally, cement mortar with cement content replaced by natural zeolite at 0%, 5%, 15%, and 25% showed the best properties at a 15% replacement ratio [16]. In their study, Saboo et al. proposed a mathematical approach to determine the optimal proportion of mortar components for a semi-flexible pavement. Based on experimental results, they concluded that regardless of the combination, a minimum of 2% naphthalene superplasticizer and 1% polycarboxylate superplasticizer were required to achieve the desired flow time. Additionally, they found that the flow time and compressive strength were related to the type of superplasticizer used [17]. In their study, Khan et al. investigated the effect of gamma radiation treatment on waste polyethylene terephthalate (PET) to produce a cementitious mortar that meets the necessary flow and strength properties for semi-flexible pavement surfaces. According to the experimental results, after one day of curing, the compressive strength decreased by 59% to 78% with normal PET use, while using irradiated PET recovered 20% to 24% of the lost compressive strength [18]. In their study, Wang et al. evaluated the addition of Carboxyl Latex as an additive to cement mortar to improve the performance of semi-flexible pavement mixtures and assessed the degree of performance enhancement of the cement mortar. According to the experimental results, the use of carboxyl latex additive reduced the wheel rut resistance of the pavement material by 30%, increased dynamic stability by 40%, raised strain energy density by 1.6 times, and improved freeze-thaw resistance by 93% [19].

Although semi-rigid pavements are considered an alternative to traditional pavement types, there is currently no comprehensive mix design guideline available globally. While existing studies have provided detailed information on material properties, proportions, quantities, and layer thicknesses, further research and additional sources are necessary to establish more precise and standardized guidelines.

In the first section of the study, information will be provided about the materials used in the porous asphalt mixture samples, which form the skeleton of the semi-rigid pavement structure. In the second section, based on the results of the binder tests, the most suitable modified additive ratios will be used to prepare separate porous asphalt mixtures for each type of aggregate. In the third section, semi-rigid pavement mixture samples will be prepared by injecting a cement mortar mixture, designed to have the appropriate composition, into porous asphalt samples with sufficient void content. The prepared mixtures will be subjected to Marshall stability, Cantabro (particle loss), permeability, and compressive strength tests. Additionally, flowability and compressive strength tests will be conducted on the cement mortar mixtures. As a result, this study provides a detailed analysis of the effects of different types of aggregates and modifications on the semi-rigid pavement design with porous asphalt mixtures. It has been determined that the findings of this research will serve as a significant reference for the literature and future studies.

2. MATERIAL

Semi-rigid pavements are constructed in two stages: in the first stage, porous asphalt mixtures with a void percentage of 25-35% are prepared. In the second stage, cement mortar is poured into the voids within the porous asphalt mixtures, and the mixture samples undergo a curing process for a specified period. The materials used in the preparation of semi-rigid pavements are shown schematically in Figure 1. Details regarding the semi-rigid pavement design are provided in subsequent subsections.

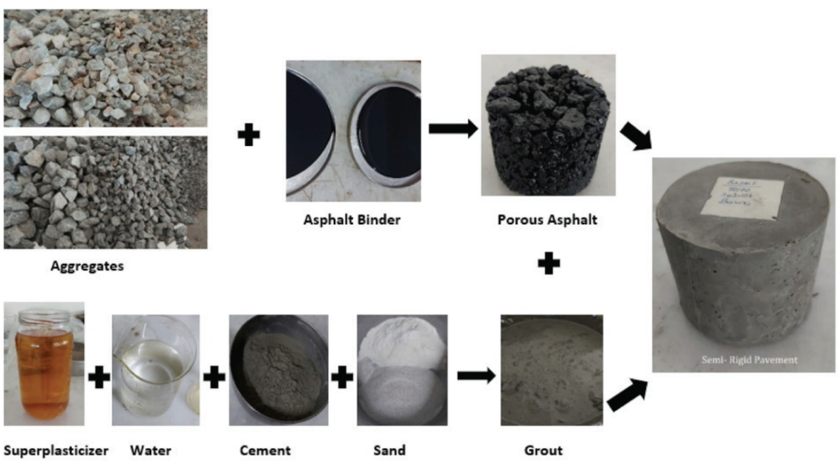

Fig 1 - The preparation process of semi-rigid pavements

2.1. Aggregates

To prepare the semi-rigid mixture samples, porous asphalt mixtures were first prepared. Two different types of aggregates, basalt and limestone, were used in the porous asphalt mixtures. Separate mixtures were prepared for each type of aggregate. The particle distribution of the aggregates was selected as Type-2, based on the gradation and limit values specified in the Highways Technical Specifications for porous asphalt mixtures (Table 1).

Table 1 - Gradation and Limit Values of Porous Asphalt [20]

Sieve Size		**Type-1**	**Type-2**	**Type-3**	**Type-4**	**Tolerance Limits**
Inch, No	mm	Passing %	Passing %	Passing %	Passing %	%
3/4”	19	100	100	100		
1/2"	12.5	5-15	90-100	85-95	100	±4
3/8”	9.5	-	63-77	5-15	85-95	±4
No.4	4.75	5-12	11-35	5-15	5-12	±3
No.10	2.00	5-10	10-20	5-10	5-10	±3
No.80	0.180	-	5-10	-	-	±3
No.200	0.075	3-5	3-7	3-5	3-5	±2

According to the aggregate particle size distribution, the maximum particle size was selected as 12.5. The data obtained from the experiments conducted on the aggregates are provided in Table 2.

Table 2 - Physical and Mechanical Properties of Aggregates

<table>
<tr><th>Sieve Size (mm)</th><th>Gra-dation values</th><th colspan="2">Flatness index values</th><th colspan="2">Water Absorption (%)</th><th colspan="2">Apparent Specific Gravity (gr/cm^3)</th><th colspan="2">$MgSO_4$ Missing (%)</th><th colspan="2">Micro-Deval Abrasion Value (%)</th></tr>
<tr><td></td><td></td><td>Limestone</td><td>Basalt</td><td>Limestone</td><td>Basalt</td><td>Limestone</td><td>Basalt</td><td>Limestone</td><td>Basalt</td><td>Limestone</td><td>Basalt</td></tr>
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<tr><td>19</td><td>96.75</td><td>19.2</td><td>16.1</td><td>-</td><td>-</td><td>-</td><td>-</td><td></td><td></td><td></td><td></td></tr>
<tr><td>12.5</td><td>93.5</td><td>11.6</td><td>19.6</td><td>0.50</td><td>1.25</td><td>2.75</td><td>2.78</td><td rowspan="2">8%</td><td rowspan="2">4.5%</td><td rowspan="3">19%</td><td rowspan="3">17%</td></tr>
<tr><td>9.5</td><td>67.8</td><td>19.7</td><td>10.9</td><td>0.20</td><td>1.25</td><td>2.72</td><td>2.74</td></tr>
<tr><td>4.75</td><td>28.75</td><td>19.6</td><td>19.6</td><td>0.68</td><td>1.48</td><td>2.70</td><td>2.74</td><td></td><td></td></tr>
<tr><td>2</td><td>15.5</td><td>-</td><td>-</td><td>1.16</td><td>1.99</td><td>2.60</td><td>2.73</td><td></td><td></td><td></td><td></td></tr>
<tr><td>0.180</td><td>8</td><td>-</td><td>-</td><td>1.66</td><td>1.43</td><td>2.62</td><td>2.71</td><td></td><td></td><td></td><td></td></tr>
<tr><td>0.075</td><td>4.5</td><td>-</td><td>-</td><td>1.77</td><td>1.56</td><td>2.76</td><td>2.58</td><td></td><td></td><td></td><td></td></tr>
</table>

2.2. Bitumen and Modified Binders

The effects of two different pure bitumens and two different binders with additives on the mixture samples have been investigated. Pure bitumens with penetration grades of B 50/70 and B 160/220, obtained from Turkish Petroleum Refineries, were used for the purpose of bitumen modification, two of the most commonly preferred polymer additives in the literature, styrene-butadiene-styrene (SBS) [21] and crumb rubber (CR), were employed in this study. Modified bitumens were prepared by adding SBS in percentages of 2%, 3%, 3.5%, 4%, and CR in percentages of 6%, 6.5%, 7%, 8%, 10%, and 12% to the B 160/220 penetration grade bitumen (Figure 2). The properties of SBS polymer and CR additives are given in Table 3 and Table 4.

Fig.2 - (a) SBS Polymer, (b) CR

Table 3 - Physical Properties of Kraton D 1101 (SBS) Polymer

Properties	Kraton D 1101
Molecular Structure	Linear
Styrene/Rubber Ratio	31/69
Specific Gravity	0.94
Tensile Strength (MPa)	31.8
Hardness	71
Physical Form	Porous, Fine-Grained
Melting Index	< 1
Elongation (%)	880

Table 4 - Elemental Analysis of CR Additive Material [22]

Elemental Analysis of Crumb Rubber					
C (%)	H (%)	S (%)	O (%)	Moisture (%)	Ash (%)
68.3	7.1	1.7	22.9	0.5	3

Table 5 - Properties of Pure and SBS-Modified Binders

Properties	Bitumen Type											
	50/70		160/220		%2 SBS		%3SBS		%3.5 SBS		%4 SBS	
Penetration (100g,25°C),0.1mm	53.5		163.5		117.2		90.6		77.7		74.8	
Specific Gravity	1.02		1.00		1.00		1.00		1.00		1.06	
Penetration Index	-0.73		0.27		0.97		0.60		0.93		1.36	
Softening Point	51.3		43.0		49.1		50.9		54.1		56.4	
Viscosity (Pa.s)	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C
	587.5	165	312.5	100	650	237.5	937.5	262.5	1000	300	1150	350

Binder tests were conducted on both pure and modified bitumens, with the results presented in Table 5 for pure and SBS-modified binders, and in Table 6 for CR-modified binders.

Table 6 - Properties of CR-modified binders

Properties/Bitumen Type	%6 CR		%6.5 CR		%7 CR		%8 CR		%10 CR		%12 CR	
Penetration (100g, 25°C), 0.1mm	77		82.5		74.4		59.3		56.7		49.5	
Specific Gravity	1.00		1.1		1.1		1.0		1.0		1.0	
Penetration Index	0.27		0.60		0.42		0.34		0.83		1.05	
Softening Point	51.5		52.0		52.5		54.7		57.5		60.2	
Viscosity (Pa.s)	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C
	725	312.5	837.5	250	900	352	1450	362.5	1988	625	3213	937.5

For the production of semi-rigid mixture samples, the proportions of modified additives were first determined based on the binder test results, and the porous asphalt samples were prepared for each aggregate type separately with a void ratio of 27%. In preparing the porous asphalt mixture samples, the optimum bitumen content was determined as 4% and used. The prepared porous asphalt samples were compacted using a Marshall hammer

The proportions of modified binder additives to be used in the mixture samples were determined based on experimental results. According to the binder test results, 50/70 and 160/220 pure bitumen, as well as binders modified with 3.5% SBS and 6.5% CR, were used in the mixture samples. After determining the binder amount, the mixture samples were prepared separately for each aggregate type, and their performances were compared.

2.3. Cement

In this study, CEM I 42.5 R type Portland cement obtained from the Elazig cement factory was used in the design of the semi-rigid pavement.

2.4. Mixing Water

Tap water from Elazig Municipality has been used as the mixing water in the cement mortar.

2.5. Additive Materials

In this study, a superplasticizer additive was used to ensure the workability of the cement mortar. The reason for using the superplasticizer in the mortar mixture is that the voids in the porous asphalt mixture specimens need to be filled to the maximum level with mortar, and the mortar should have sufficient workability and fluidity for effective filling [23].

Fluid Optima 280 is a next-generation superplasticizer supported by polycarboxylates. It is especially recommended for concrete that requires high early and final strength, maintaining consistency in all seasons. By enabling concrete production with a low water/binder ratio, it enhances the impermeability and strength of the concrete. Based on the manufacturer's usage recommendation, the superplasticizer additive was added during the last half of the mixing water in the mortar mix.

2.6. Sample Preparation:

To prepare semi-rigid mix samples, porous asphalt mix samples were first prepared and left to rest at room temperature. After preparing the porous asphalt mix samples, they were subjected to a pre-treatment before the injection of the cement paste. Due to the large number of Marshall samples, it was not suitable to perform injection in Marshall molds. Therefore, a protective film was used to seal the edges of the porous asphalt samples (Figure 3).

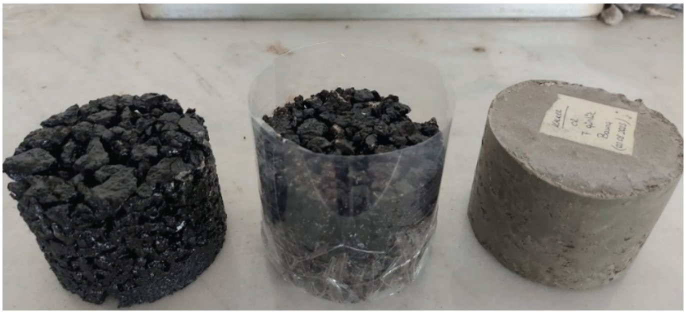

Fig 3 - The preparation of semi-rigid mix samples.

3. METHOD

3.1. Bitumen Drainage Experiment

The optimum bitumen content used in the porous asphalt mix is determined using the Schellenberg binder drainage test [24]. In the test, various methods such as the beaker method, enamel disk method, and basket method are used depending on the type of equipment used [25]. In this study, the beaker method was employed for the bitumen drainage test (Figure 4). The experiment was conducted according to the TS EN 12697-18 standard [26].

Fig.4 - Empty beaker where the bitumen residues remain

The experiment was conducted with porous asphalt mixtures prepared with 4.60%, 4.40%, 4%, 3.80%, and 3% bitumen for each aggregate type, both with pure and modified bitumen. The experiment was carried out twice on each mixture sample, and the averages were taken. The amount of bitumen drainage in the mixture is calculated using Equation 5.

$$B_D = \frac{W_5 - W_3 - W_6}{W_4 - W_3} \times 100 \qquad (5)$$

In Equation 5:

B_D: Bitumen drainage value, %

W_3: Mass of the beaker, g

W_4: Total mass of the beaker and asphalt mixture, g

W_5: Mass of asphalt binder adhered to the beaker, g

W_6: Mass of material retained on the sieve, g

3.2. Mortar Mixture to Be Used in the Design of Semi-Rigid Pavement

In the study, two different water/cement (w/c) ratios and four different additive material proportions were used for the mortar mixture in the design of semi-rigid pavement samples. The same coding was used for both aggregate types in the mixture naming. The materials used and their quantities are provided in Table 7.

Table 7 - Materials used in the cement mortar mixture and their quantities (%)

Mixture	Additive Type	Aggregate	Cement	Water	Additive Material	Water/Cement Ratio
CM 1	S1	26.8%	48.8%	24.4%	-	0.50
CM 2	S1	26.8%	48.8%	24.4%	0.8%	0.50
CM 3	S1	26.8%	48.8%	24.4%	1%	0.50
CM 4	S1	26.8%	48.8%	24.4%	2%	0.50
CM 5	S1	24.4%	48.8%	26.8%	-	0.55
CM 6	S1	24.4%	48.8%	26.8%	0.8%	0.55
CM 7	S1	24.4%	48.8%	26.8%	1%	0.55
CM 8	S1	24.4%	48.8%	26.8%	2%	0.55

In selecting the optimum cement mortar, workability and compressive strength are two important properties. To obtain a good semi-rigid pavement, the cement mortar must penetrate well into the voids of the porous asphalt mixture. For this, the cement mortar must have high workability (Figure 5).

The second important aspect is the compressive strength. The composition of semi-rigid pavements consists of approximately ¼ cement mortar. Therefore, the strength of the cement mortar significantly influences the overall strength of the design [27]. Among these properties, one of the most crucial factors to consider is the fluidity of the cement mortar, which must fully penetrate the depth of the porous asphalt surface layer without excessive compaction or vibration. Another factor is the compressive strength of the cement mortar, which significantly affects the final strength and durability characteristics of the semi-rigid mixtures. In this context, flowability and compressive strength tests of the mortar mixtures were also conducted in the study.

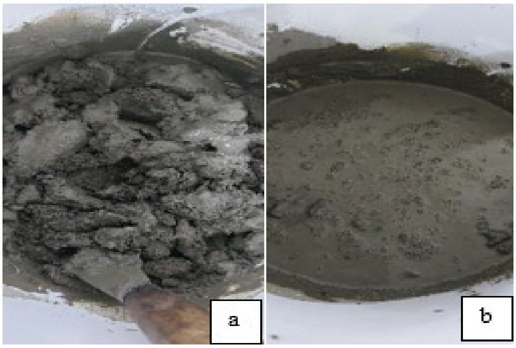

Fig. 5 - (a) Non-flowing mortar mixture, (b) mortar mixture becoming flowable with the addition of the additive

3.3. Flowability Experiment of Cement Mortar

The cement mortar must have a highly fluid consistency to fully penetrate the voids in the porous asphalt. The properties of the mortar used are among the key parameters that can affect the performance of semi-rigid pavements when exposed to heavy traffic loads and harsh weather conditions. The water/cement (w/c) ratio plays a significant role in achieving a high degree of flowability for the cement mortar. In this study, a w/c ratio of 0.50 and 0.55 was used. The flowability of the mortar was determined using a flow cone (Figure 6). The test was conducted according to ASTM C939-10 standard [28].

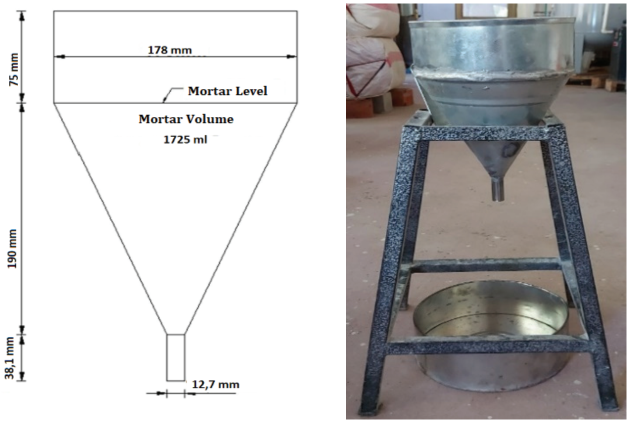

Fig. 6 - The flow cone used to determine the fluidity of the cement mortar

The ideal flow time for the cement mortar to fully penetrate the porous asphalt structure has been determined as 10-14 seconds based on the technical properties of the injection material for semi-rigid pavements [29].

3.4. Cement Mortar Compressive Strength:

The strength of the mortar material used in the semi-rigid pavement design is a crucial factor. In this context, compressive strength testing was conducted on mortar samples. The test utilized samples with dimensions of 50×50×50 mm. After determining the material proportions in the mixture, the prepared mixes were placed into 50 mm³ molds in two layers. The mortar was compacted using a table-type vibrator to ensure proper placement (Figure 7).

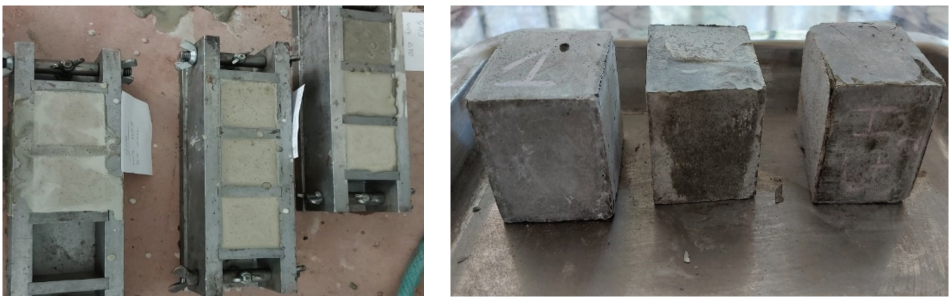

Fig.7 - The molds and samples used for the compressive strength of the cement mortar

The compressive strength test was conducted in accordance with the BS EN 196-1 standard [30]. The test was performed using a fully automated press machine at a speed of 2400±200 N/s .

The compressive strength values of the samples were determined using Equation 6.

$$f_m = \frac{P}{A} \tag{6}$$

In Equation 6:

f_m: Compressive strength, MPa

P: Maximum breaking load, N

A: Surface area of the sample, mm²

The compressive strength of the cement mortar samples at 28 days was determined to be approximately 50 MPa [31].

In the corresponding studies, bending tests are also applied to prismatic-shaped samples of cement mortar material. The bending property that was previously required in Turkish standards is no longer included in the current testing standards. As a result, the requirement to calculate the bending-tensile values of the mortar samples has been eliminated. According to the latest Turkish standards, bending strength is not mandatory; however, compressive strength tests are still conducted on prismatic samples. When reviewing American standards, compressive strength tests are applied to 50×50×50 mm cube samples. In this context, less material is used in preparing cube samples compared to prismatic mold samples. Therefore, in this study, the BS EN 196-1 standard was used, and only compressive strength tests were conducted on cube samples, without the need for bending-tensile tests.

3.5. Cement Mortar Ratio and Saturation Degree in Semi-Rigid Mixture Samples

After filling the voids in the porous asphalt mixtures, the mortar saturation degree and mortar ratio parameters, as well as the remaining porosity in semi-rigid pavements, are calculated. The degree of saturation (Sg) of the mortar material is used to calculate the amount of mortar material in the porous asphalt mixture and is calculated using Equation 7 [32].

$$S_g = \frac{(m_2 - m_1)}{\rho \times V \times V_a} \times 100 \quad (7)$$

In Equation 7:

S_g: Degree of saturation of the mortar material (%)

m_1: Weight of the sample before filling with mortar (g)

m_2: Weight of the sample after filling with mortar (g)

ρ : Density of the cement (g/cm^3)

V: Volume of the sample (cm^3)

V_a: Air voids of asphalt mixtures (%)

The ratio of the mortar mix is generally the volume of the mortar material to the target air void ratio. The calculation is made using Equation 8 [33].

$$G_r = \frac{m_0 - m_1}{\rho V_a} \quad (8)$$

In Equation 8:

G_r: The proportion of mortar material in porous asphalt mixtures (%)

m_1: The weight of the sample before filling with the mortar mixture (g)

m_2: The weight of the sample after filling with the mortar mixture (g)

ρ : The density of the cement (g/cm^3)

V_a: The air void ratio of the porous asphalt mixture (%)

One of the most important parameters that can affect the performance of semi-rigid pavements exposed to heavy traffic loads and harsh weather conditions is the degree of saturation. According to Chinese standards, the degree of saturation of the mortar must be greater than or equal to 92% [9].

3.6. Marshall Stability Experiment:

The test was conducted according to TS EN 12697-34 standard [34]. Marshall mixture design was used to prepare porous asphalt samples and Semi-Rigid samples for both aggregate types. Stability values of the mixtures before and after the injection of the cement mortar were determined for each separately (Figure 8).

Fig.8 - Placement of Porous Asphalt and Semi-Rigid mixture samples in the Marshall device

3.7. Cantabro Experiment

The test was conducted according to the TS EN 12697-17 standard specified for the particle (Cantabro) loss test in KTŞ (Highway Technical Specifications) [35]. The test was applied separately to both Porous Asphalt and Semi-Rigid mixture samples (Figure 9). In the test, each mixture sample was placed separately into the Los Angeles test apparatus without adding steel balls, and subjected to 300 revolutions at a speed of 3.1 rad/s to 3.5 rad/s (30 rpm-33 rpm).

Fig.9 - Mixture specimens after the Cantabro test

The Cantabro particle loss value is calculated using Equation 9.

$$PK = 100 \times \frac{W_1 - W_2}{W_1} \quad (9)$$

In Equation:

P: Particle loss value (%)

W_1: Initial weight of the sample (g)

W_2: Final weight of the sample after the test (g)

There is no standard or specification for semi-rigid mixtures in our country. Therefore, the Cantabro value for semi-rigid mixtures was determined as 50% of the maximum particle loss determined as a result of literature research [36].

3.8. Permeability Experiment

Within the scope of the study, a specially designed water permeability meter device based on the falling height principle was used for the permeability test. Falling level permeability testing based on the Darcy principle is performed on porous asphalt mixtures or clay samples. A standard procedure for falling load permeability testing was developed by the Florida Department of Transportation in 2000 [37]. Figure 10 shows a schematic view of the Karol-Warner falling level permeability device used in the study.

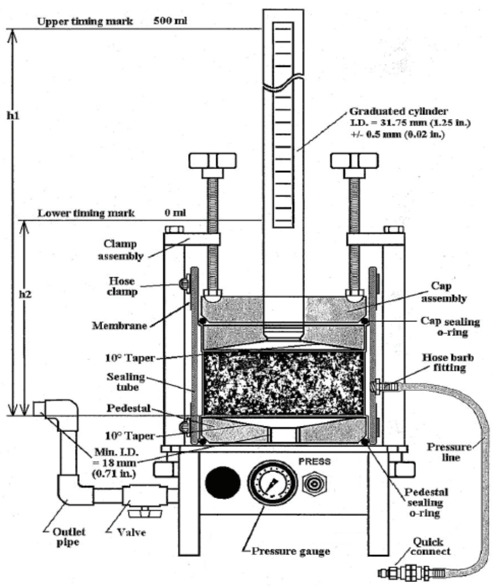

Fig.10 - Schematic view of the Karol-Warner permeability device

According to Fm 5-565, laboratory permeability testing is performed in a one-dimensional laminar flow where Darcy's law applies [37]. The sample is placed in a cylinder with a latex membrane and inflated to 68.9 kPa (10 psi) to prevent water from passing around the sample and to maintain pressure throughout the test. The tape measure placed on top of the device is filled with water and the time for the water level to drop from the initial level to the final level is recorded (Figure 11).

Fig.11 - Placement of samples in the permeability device

Permeability was calculated using Equation 10.

$$K = \frac{aL}{At} \times ln\left(\frac{h_1}{h_2}\right) \tag{10}$$

In Equation 10:
K: Permeability, cm/s
L: Length of the specimen, cm
A: Cross-sectional area of the material, cm²
t: Flow time, s
a: Area of the graduated cylinder, cm²
h_1: Initial water height, cm
h_2: Final water height, cm.

The permeability test was conducted separately for both porous asphalt and semi-rigid specimens. Permeability is expressed in both centimeters per second (cm/s) and meters per day (m/day). According to studies in the literature, the permeability of porous asphalt mixture specimens has been determined to be at least 100 m/day.

3.9. Compressive Strength

Semi-rigid pavements combine the characteristics of both flexible and rigid pavements. Therefore, the performance tests conducted for both types of pavements should also be applied to semi-rigid pavements. The compressive test is typically performed for rigid pavements and is used to determine the amount of compressive load a material can withstand without failure. The test was conducted in accordance with the TS EN 12390-3 standard [38].

The prepared semi-rigid mixture specimens were subjected to curing for 3 and 7 days. After the curing periods, the surfaces of each specimen were leveled on both sides using cement to ensure uniform distribution of the applied load across the entire surface.

The cylindrical specimens, with their surfaces leveled using cement, are placed in the concrete compression machine perpendicular to the casting direction. The test specimen is perfectly centered on the notches in the device, and the machine is then activated. The loading rate of the test was applied with a uniform stress increase of 0.25 MPa/s to 1 MPa/s to prevent any impact effects (Figure 12).

Fig. 12 - Placement of the semi-rigid mixture specimen in the concrete compression machine and the specimen after the test

The highest load displayed on the screen at the moment the test specimen breaks is recorded. The compressive strength of the specimen is calculated using Equation 11.

$$f_c = \frac{F}{A_c} \tag{11}$$

In Equation 11:

f_c: Compressive strength of the concrete test specimen (N/mm²)

F: Failure load (N)

A_c: Area of the specimen (mm²)

4. RESULTS AND DISCUSSION

4.1. Fluidity Test Results of Cement Mortar

In this study, the mixture ratios of the cement mortar injected into the porous asphalt mixture specimens to obtain semi-rigid pavement specimens were based on the mixture ratios used in the literature. As a result, two different w/c ratios were deemed appropriate for use in the cement mortar. Accordingly, a mixture containing 26.8% aggregate, 48.8% cement, and a w/c ratio of 50% was prepared, as well as another with 24.4% aggregate, 48.8% cement, and a w/c ratio of 55%. For each mixture type, both control specimens and mortar mixtures with

2%, 1%, and 0.8% superplasticizer additions were separately tested for fluidity and compressive strength. The test results are shown in Figure 13.

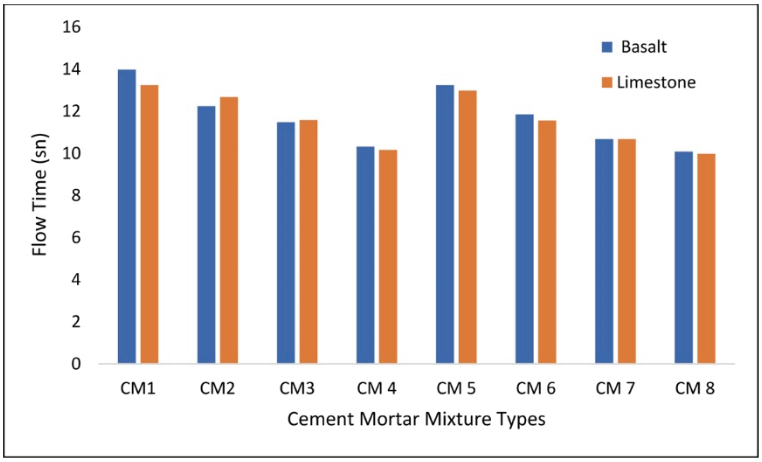

Fig.13 - Flow Time of Mortar Mixtures Prepared with Basalt and Limestone Aggregates

When the flow times of the cement mortar mixtures were examined, the flow time of the control specimen with a w/c ratio of 0.50 and no additives, prepared with basalt aggregate, was determined to be 13.98 seconds. Similarly, the flow time of the control specimen prepared with limestone aggregate and no additives was found to be 13.24 seconds. The flow times of the mortar mixtures with 2%, 1%, and 0.8% superplasticizer additives remained within the appropriate flow time range of 10 to 14 seconds, indicating their suitability. Since it was desired for the cement mortar injected into the voids of the porous asphalt to be highly flowable, the cement mortar mixtures with 2% additive, a w/c ratio of 50%, and flow times of 10.32 and 10.16 seconds for the CM 4 cement mortar were selected.

High flowability (short flow time) in hardened cement mortar materials can lead to poor mechanical properties. Furthermore, high flowability increases the likelihood of the mortar flowing out from the lower or side parts while being injected into the porous asphalt mixture. Low flowability (long flow time), on the other hand, makes it more difficult for the injection material to penetrate into the porous asphalt mixture, which can affect the injection speed and duration. The flow time range selected for this study is between 10 and 14 seconds. The majority of the prepared mixtures exhibited flow times within this range.

4.2. Compressive Strength Test Results of Cement Mortar

Cement mortars were prepared separately with limestone and basalt aggregates, and experiments were conducted. Two different w/c ratios and three different additives were incorporated into the mixtures, and compressive strength tests were performed on the specimens with various combinations. The comparison of the 7-day and 28-day compressive strengths for each mortar mixture type is presented separately in Figure 14 and Figure 15.

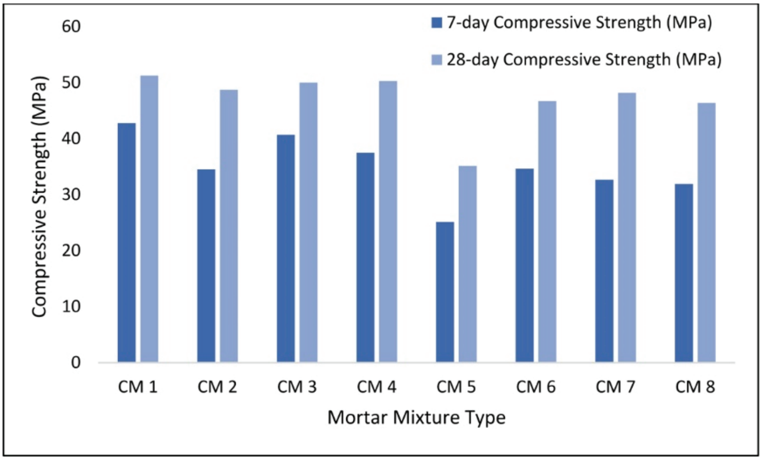

Fig.14 - 7-Day and 28-Day Compressive Strength Results of Mortar Mixtures Prepared with Basalt Aggregate

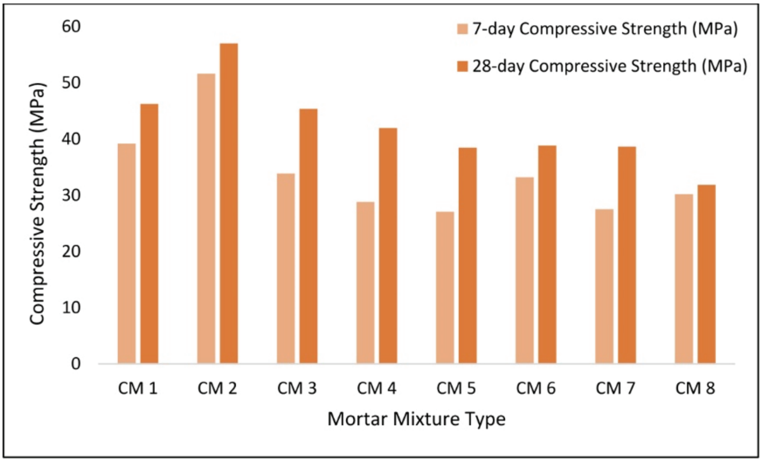

Fig. 15 - 7-Day and 28-Day Compressive Strength Results of Mortar Mixtures Prepared with Limestone Aggregate

When the results were examined, it was observed that as the curing time of the cement mortar increased, the compressive strengths of each mixture also increased. In the cement mortar prepared with basalt aggregate, the mixture with a w/c ratio of 0.50 exhibited the highest compressive strength. The control specimen, labeled CM1, had a 7-day compressive strength of 42.75 MPa and a 28-day compressive strength of 51.24 MPa. However, since the cement mortar injected into the porous asphalt was desired to be flowable, the mixture with the most ideal balance of flowability and compressive strength was selected. This mixture was the CM4 basalt aggregate mortar, with a w/c ratio of 0.50, 2% additive, a flow time of 10.32 seconds, and a 28-day compressive strength of 50.28 MPa. This mixture was used to obtain semi-rigid pavement specimens.

For the mortar mixtures prepared with limestone aggregate, the control specimen CM1 with a w/c ratio of 0.50 showed a 28-day compressive strength of 46.21 MPa, while the control specimen with a w/c ratio of 0.55 had a 28-day compressive strength of 38.45 MPa. The ideal mixture, considering both flowability and compressive strength, was selected as the CM4 limestone aggregate mortar, with a w/c ratio of 0.50, 2% additive, and a 28-day compressive strength of 41.94 MPa.

It was also noted that using an excessively high amount of superplasticizer could cause segregation within the mixture. Based on sources in the literature, the maximum allowable amount of superplasticizer in cement mortar was set at 2%. Therefore, in this study, the superplasticizer content was limited to a maximum of 2%.

Due to the lack of a national standard for semi-rigid pavement design in our country, the results from the experiments were evaluated in light of data collected from literature research. According to these findings, for the semi-rigid pavement specimens to be produced, the cement mortar's flow time should be between 10-14 seconds, with the 7-day compressive strength ranging from 10-30 MPa and the 28-day compressive strength ranging from 20-50 MPa. Additionally, the Chinese standards specify that the mortar's flow time should also be within the 10-14 second range, with 7-day compressive strength ≥15 MPa and 28-day compressive strength ≥30 MPa.

4.3. Mortar Ratio and Degree of Saturation

In the design of semi-rigid pavements, the mortar ratio and degree of saturation represent the connection between the internal voids within the mixture. According to the literature, the mortar saturation degree should be above 90%. This ensures proper penetration within the mixture, eliminating any gaps between the internal voids. The results of the mortar saturation degree for the semi-rigid mixtures prepared with basalt and limestone aggregates are presented in Figure 16.

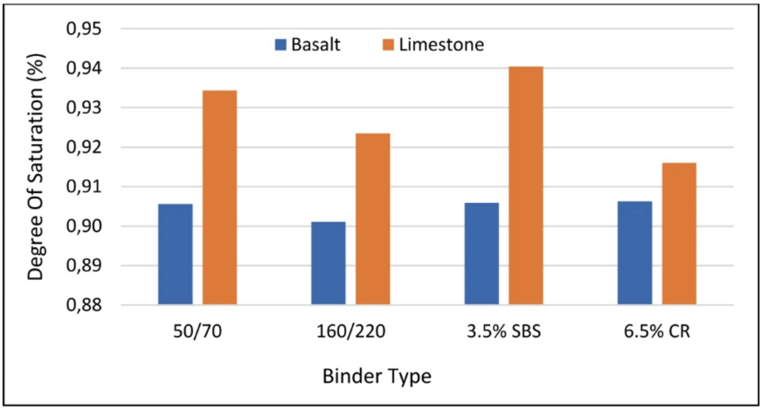

Fig. 16 - Mortar Saturation Degrees of Semi-Rigid Specimens Prepared with Basalt and Limestone Aggregates

Upon examining the test results, it was observed that the mortar saturation degrees of the semi-rigid mixtures prepared with limestone aggregates were higher than those prepared with basalt aggregates. The mortar saturation degrees for the basalt aggregate mixtures, according to bitumen grade, were 0.91%, 0.90%, 0.91%, and 0.91%, respectively. For the semi-rigid mixtures prepared with limestone aggregates, the saturation degrees were 0.93%, 0.92%, 0.94%, and 0.92%, respectively, based on bitumen grades. The literature indicates that the mortar saturation degree should be greater than 90%. All of the prepared mixtures had mortar saturation degrees above this threshold.

4.4. Bitumen Drainage Test

In this study, the test was conducted according to the TS EN 12697-18 standard. The test was performed on porous asphalt mixtures, prepared with both pure and modified aggregates, based on the bitumen content for each aggregate type. The bitumen drainage test results are presented in Figure 17.

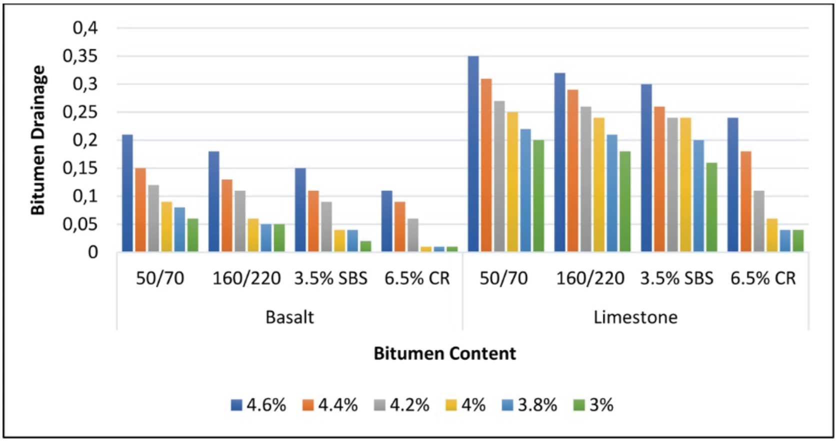

Fig. 17 - % Drainage Test Results According to Bitumen Content

According to KTS (Turkish Road Specifications), the Schellenberg bitumen drainage value in the design criteria for porous asphalt is set to a maximum of 0.3%. Based on the test results, it was found that the majority of the mixtures did not exceed the specified limit value. However, in the mixtures prepared with limestone aggregate using 50/70 pure bitumen, with an optimum bitumen content of 4.6% and 4.40%, and with 160/220 pure bitumen, where the optimum bitumen content was 4.60%, the values slightly exceeded the limit. The reason for this is that the surface of limestone aggregate is smoother compared to basalt aggregate, and with the use of a higher amount of bitumen, the bitumen drains more easily from the aggregate surface. In asphalt mixtures, an increase in the optimum bitumen content leads to higher costs. Therefore, it is not desirable to use an excessively high amount of bitumen in the mixture. Under these conditions, when the mixtures with the optimum bitumen content of 4% determined in the study were examined, it was found that they reached values below the limit of 0.3% and were considered usable in the mixture.

4.5. Marshall Stability Test Results

The Marshall stability test results for the porous asphalt mixture specimens are presented in Figure 18. According to the Marshall stability test results, the stability values of the porous asphalt mixtures prepared with basalt aggregate, based on bitumen grade, were 8.78 kN, 7.41 kN, 10.32 kN, and 10.54 kN, respectively. The stability values for the porous asphalt mixtures prepared with limestone aggregate were 7.20 kN, 6.96 kN, 8.66 kN, and 9.09 kN, respectively.

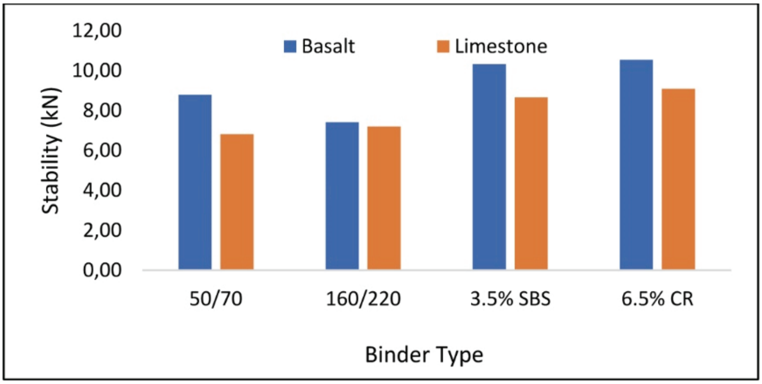

Fig. 18 - Marshall Stability Values of Porous Asphalt Specimens According to Binder Type

According to the design criteria for porous asphalt specified in the Highway Technical Specifications, the stability value must be a minimum of 300 kg (2.94 kN). The porous asphalt mixtures prepared with basalt and limestone aggregates that were subjected to the Marshall stability test in this study had stability values well above this limit. The mixtures prepared with both aggregate types met the specification limits [20].

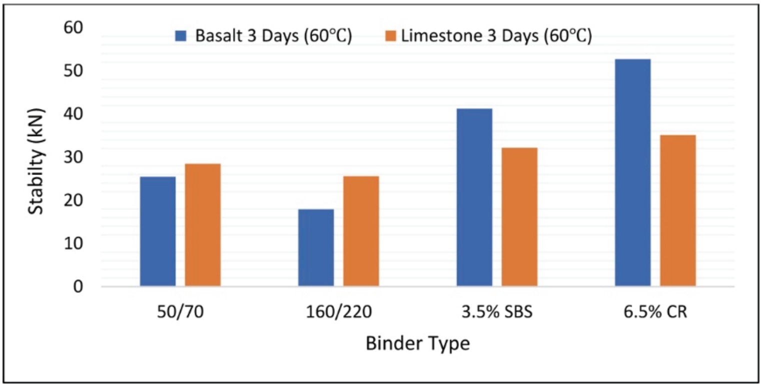

Fig. 19 - 3-Day Stability Values (60°C) of Semi-Rigid Mixtures Prepared with Basalt and Limestone Aggregates

For the semi-rigid specimens, the Marshall test was applied to the mixtures prepared with both basalt and limestone aggregates after 3 and 7 days of curing. Since the 7-day strength of the cement mortar was considered, the specimens were tested both in a dry state and after being placed in a 60°C water bath. The aim here was to reflect both the properties of bitumen and concrete in semi-rigid pavements, which combine the characteristics of both materials. The Marshall test was conducted on the specimens held in the 60°C water bath to reflect the properties of bitumen, as well as those kept dry to represent the concrete's characteristics. The stability values obtained from the Marshall test for the 3- and 7-day (dry, 60°C) semi-rigid specimens are presented in Figures 19, 20, and 21.

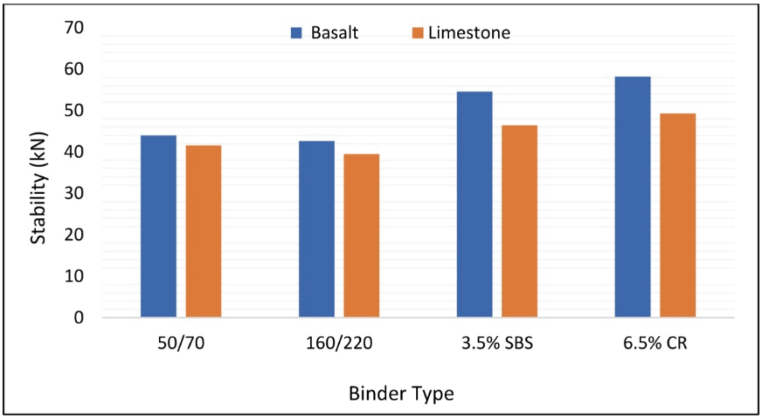

Fig. 20 - 7-Day (Dry) Stability Values of Semi-Rigid Mixtures Prepared with Basalt and Limestone Aggregates

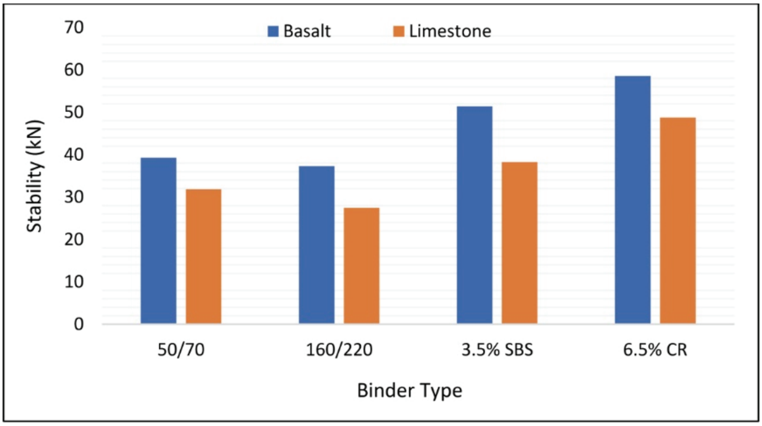

Fig. 21 - 7-Day (60°C) Stability Values of Semi-Rigid Mixtures Prepared with Basalt and Limestone Aggregates

The experimental results indicate that the Marshall stability values for the semi-rigid mixtures prepared with basalt aggregates were highest at 52.70 kN after a 3-day curing period for the mixture with 6.5% CR modified binder. In the case of porous asphalt mixtures, the stability for the basalt aggregate mixture with 6.5% CR was determined to be 10.54 kN, the stability value of the semi-rigid mixture increased significantly with the injection of cement mortar into the voids of the porous asphalt. For the semi-rigid mixtures prepared with limestone aggregates, the highest 3-day stability value was again found in the mixture with 6.5% CR, with a value of 35.09 kN. According to the 2013 KTS (Highways Technical Specifications), the stability value for mixtures used in the wearing course of bituminous hot mixes should be above 900 kg (8.83 kN), and the flow value should range between 2 and 4 mm. The Marshall test results show that the stability values of the semi-rigid mixture specimens are far above these limits. However, it is not entirely appropriate to assess the stability values of semi-rigid mixtures based on these specifications.

This is because semi-rigid mixtures are designed by injecting cement mortar into the porous asphalt, combining the properties of both bituminous mixes and concrete pavements. Therefore, the stability values should not be directly compared to those set for bituminous mixes alone. Figure 22 provides a comparative overview of the stability values for both porous asphalt and semi-rigid specimens.

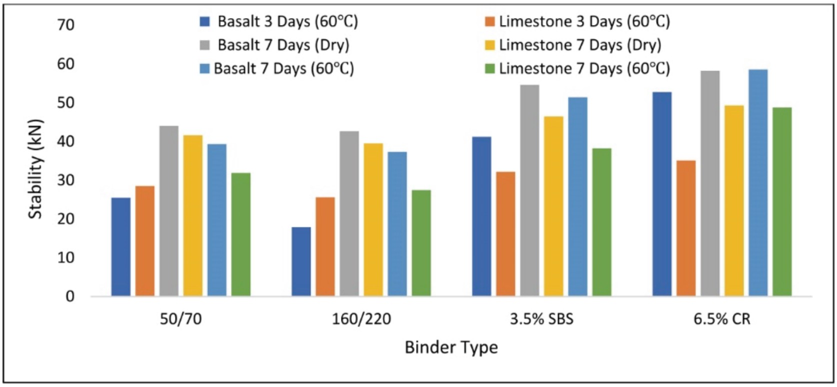

Fig.22 - The stability values of porous asphalt and semi-rigid mixture samples

When the stability values of porous asphalt and semi-rigid mixture samples are compared, a significant increase in stability values is observed for the semi-rigid mixture samples obtained by adding cement mortar to the porous asphalt samples, along with the curing time. When considering mixtures prepared with basalt aggregate, the highest stability value in the semi-rigid mixture samples was achieved after 7 days of curing with 6.5% CR modified binder. An increase was observed in the SBS-modified mixture with the modification of pure bitumen 160/220, while the stability value of the CR-modified mixture was higher compared to pure bitumen. Based on these results, it can be concluded that modified binders increase the stability values along with the curing time.

4.6. Particle Loss (Cantabro) Test Results

In this study, the Cantabro test was conducted to determine the resistance of porous asphalt mixture samples. The test was performed in accordance with the TS EN 12697-17 standard. Separate mixtures were prepared using pure and modified bitumen for basalt and limestone aggregates. Two samples were prepared for each mixture type, and the average of the Cantabro particle loss results was taken. In Figure 23, the particle loss values of the porous asphalt mixture samples are presented comparatively based on aggregate and binder types.

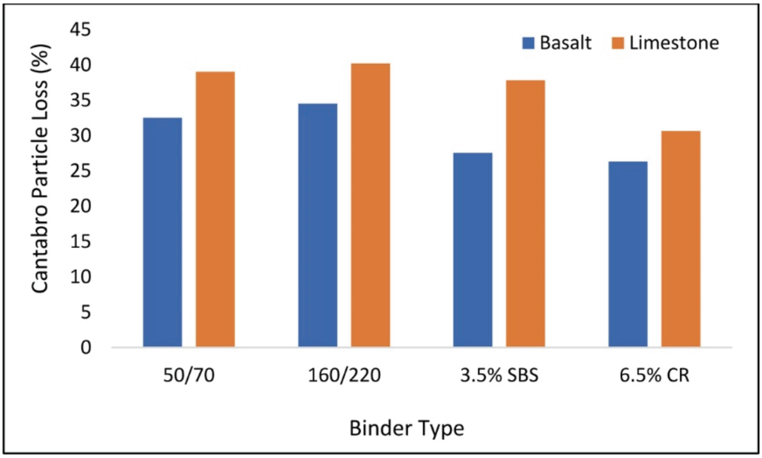

Fig. 23 - The particle loss results of the porous asphalt mixture samples

When the particle loss values obtained from the Cantabro test were examined, it was determined that the porous asphalt mixture samples prepared with both limestone and basalt aggregates exceeded the specified 20% limit value in the highway technical specifications. The particle loss values for the basalt aggregate were found to be 32.51%, 34.52%, 27.57%, and 26.31%, respectively, for different bitumen types. For the limestone aggregate, the fragmentation values according to the binder class were 39.05%, 40.22%, 37.82%, and 30.65%, respectively. With the addition of SBS and CR modified binders to pure bitumen 160/220, the particle loss values in the mixtures decreased. The lowest fragmentation resistance in the porous asphalt mixtures prepared with modified binders was achieved with the 6.5% CR modified binder for both aggregates. Based on these results, it was found that the porous asphalt mixtures prepared with basalt aggregates exhibited higher fragmentation resistance compared to those prepared with limestone aggregates. For normal wearing courses, the specified particle loss value limit for porous asphalt mixtures is 20%. However, it is not recommended to use this limit as a criterion for semi-rigid mixtures.

The reason is that the void percentage in traditional porous asphalt mixtures typically ranges from 18-22%, while the porous asphalt mixtures with a semi-rigid skeleton used in this study had a void percentage ranging from 25-30%. Additionally, while it is suggested that porous asphalt mixture samples be compacted with 50 blows, the mixtures prepared with basalt aggregate and limestone aggregate in this study were compacted with 35 blows. Considering these two factors, the Cantabro values of the mixtures did not meet the limit specified in the highway technical specifications.

The particle loss values obtained from the Cantabro test for 3-day semi-rigid mixtures are presented in Figure 24, and for 7-day semi-rigid mixtures in Figure 25.

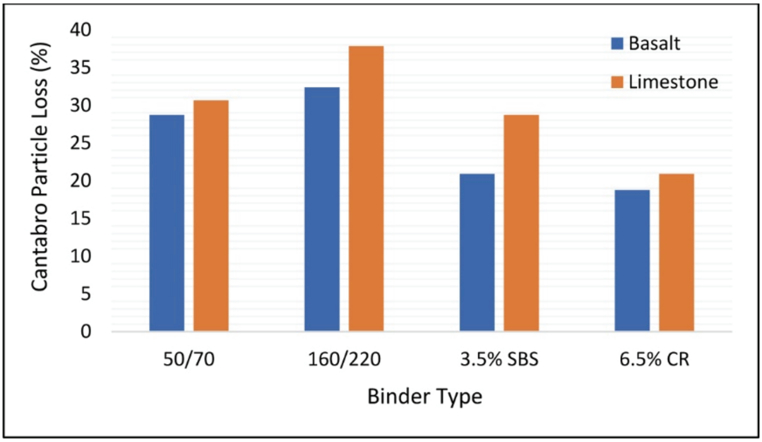

Fig. 24 - The 3-day particle loss values of the semi-rigid mixtures prepared with basalt and limestone aggregates

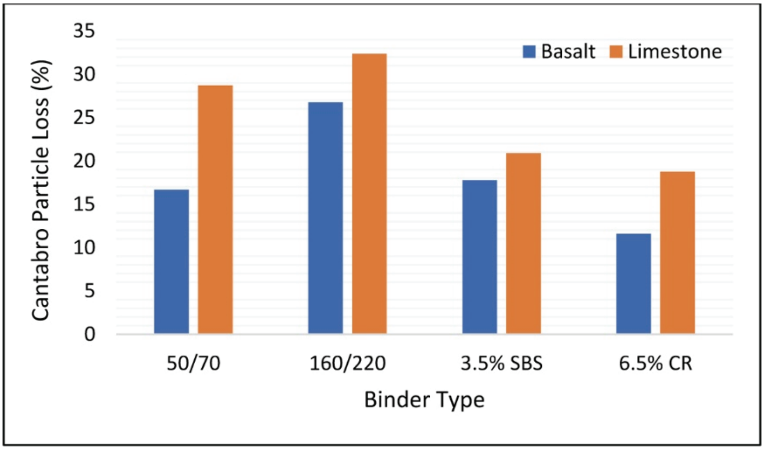

Fig. 25 - The 7-day particle loss values of the semi-rigid mixtures prepared with basalt and limestone aggregates

When the experimental results were examined, for the 3-day curing period, the fragmentation values for the basalt aggregate were determined as 28.71%, 32.35%, 20.89%, and 18.75%, respectively, depending on the bitumen type. For the mixtures with limestone aggregates, the values were 30.65%, 37.82%, 28.71%, and 20.89%, respectively. It was determined that the mixtures prepared with basalt aggregate were more resistant to particle loss compared to those prepared with limestone aggregate. After 7 days of curing, it was observed that, in general, the particle loss values decreased as the curing period increased. The particle loss value decreased for each mixture as the curing time progressed. This indicates that the binder inside the voids gains strength over time, resulting in reduced weight loss. In general, the particle loss values obtained from the experimental results were found to be below the specified limit value (max. 50%). The high particle loss values of the semi-rigid mixtures were attributed to the coarser gradation of the aggregate.

The comparative particle loss values of porous asphalt and semi-rigid samples after 7 days of curing are presented in Figure 26.

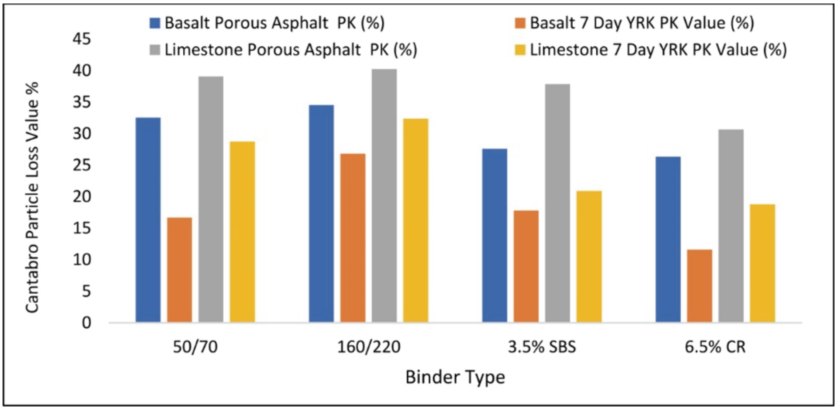

Fig. 26 - The Cantabro particle loss value of the porous asphalt and semi-rigid mixture samples

When the particle loss values of the porous asphalt mixtures and the semi-rigid mixtures obtained after the injection of cement mortar were examined, a noticeable decrease in the fragmentation values was observed for both aggregate types after the injection of cement mortar. This decrease can be attributed to the hardening of the cement mortar, which gains strength, and the formation of a strong interface connection between the bitumen, aggregate, and cement mortar. According to the Cantabro particle loss values, the lowest value was obtained in the basalt aggregate mixtures prepared with 6.5% CR modified binder.

4.7. Permeability Test Results

In this study, the Karol Warner vertical permeability test was conducted on the porous asphalt mixture samples. For the test, samples were prepared using both pure and modified bitumen's for each type of aggregate. A total of 16 samples prepared with basalt and limestone aggregates were tested. The results obtained from the test are presented in Figure 27.

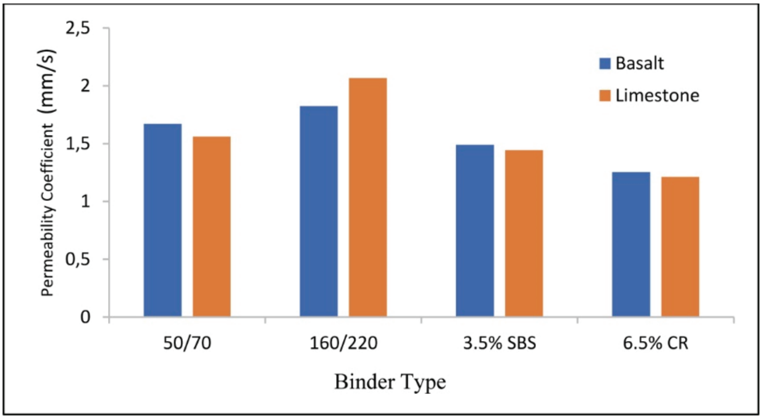

Fig. 27 - The permeability test results of the porous asphalt mixtures (mm/s)

In the highway technical specifications, the permeability value for the design criteria of porous asphalt mixtures is stated to be between 0.5-3.5 m/s * 10^{-3}. When the permeability test results are examined, the calculated permeability values for each aggregate and mixture type fall within the specified range. The permeability values for the mixtures prepared with basalt aggregates were 1.67, 1.82, 1.49, and 1.25 mm/s, respectively. The permeability coefficient values for the mixtures prepared with limestone aggregates were 1.56, 2.07, 1.44, and 1.21 mm/s, respectively. When reviewing previous studies, it is noted that in some global standards, the permeability coefficient value for porous asphalt design criteria ranges between 0.12-0.50 cm/s. Additionally, in various studies on porous asphalt mixtures, the minimum permeability for cement mortar to penetrate the voids in porous asphalt was determined to be 100 m/day. The permeability values of the porous asphalt mixture samples are presented in Figure 28 in terms of m/day.

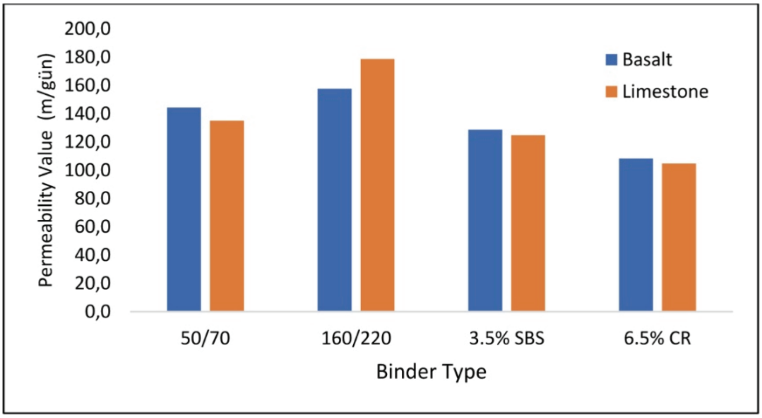

Fig. 28 - The permeability values of the porous asphalt mixtures (m/day)

When the permeability values of the porous asphalt samples were calculated in cm/s, the results fell within the range of 0.12-0.50 cm/s, which is the standard permeability coefficient range for porous asphalt pavement design criteria worldwide. This indicates that both basalt and limestone aggregates, as well as modified binders, can be used in the mixtures. Furthermore, when the permeability values were assessed in m/day, the mixtures prepared with each binder and aggregate met the minimum required value of 100 m/day. The permeability values of the mixtures prepared with modified binders were lower compared to those prepared with pure binders. This is due to the reduced void ratio in the mixtures with modified binders, which consequently results in a decrease in permeability. The permeability test results for the semi-rigid mixture samples after 3 days of curing are presented in Figure 29, and after 7 days of curing in Figure 30.

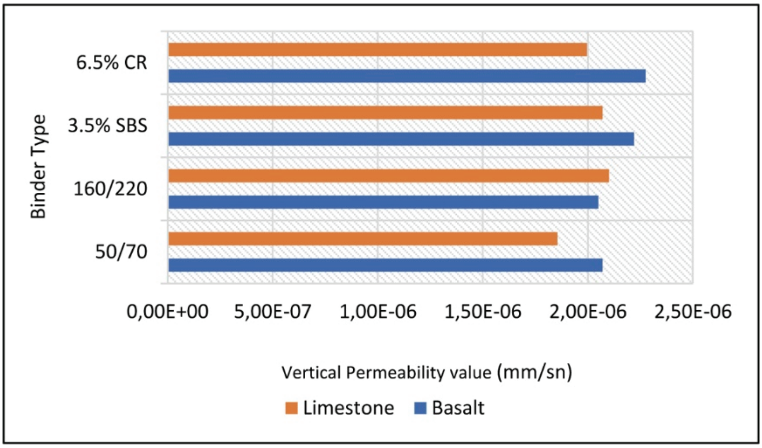

Fig. 29 - The 3-day permeability values of the semi-rigid mixtures prepared with basalt and limestone aggregates

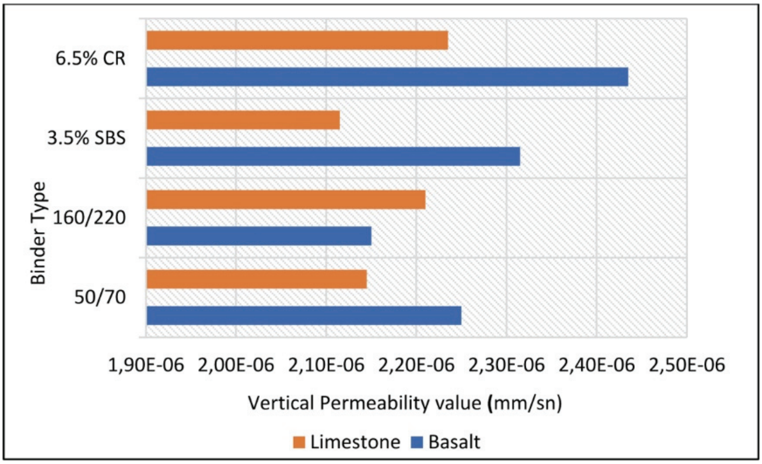

Fig. 30 - The 7-day permeability values of the semi-rigid mixtures prepared with basalt and limestone aggregates

When the permeability test results of the semi-rigid mixture samples presented in Figure 29 and Figure 30 are examined, it is observed that the permeability values are quite low for all samples. This indicates that the cement mortar was effectively injected into the voids of the porous asphalt, and no voids were left within the mortar and bitumen mixture.

4.8. Compressive Strength Test Results

Compressive testing is usually performed for rigid pavements. The test is used to determine the amount of compressive load a material can withstand without breaking. Semi-rigid mixture specimens prepared with basalt and limestone aggregate were prepared with 4 different bitumen. The experiment was repeated 2 times for each specimen and the results were averaged and evaluated. Semi-rigid specimens were subjected to compressive strength test after 3 and 7 days of curing. The data obtained as a result of the compressive strength tests are given in Figures 31 and 32 for 3 days and 7 days, respectively.

When evaluating the test results, the compressive strength values obtained after 3 days of curing were as follows: for the mixtures prepared with basalt aggregate, the values were 3.52 MPa, 2.95 MPa, 3.92 MPa, and 4.24 MPa, respectively. The highest compressive strength was achieved in the mixtures prepared with 6.5% CR modified binder. When examining the 3-day compressive strength of the semi-rigid mixtures prepared with limestone aggregate, the values were 3 MPa, 2.4 MPa, 3.1 MPa, and 3.4 MPa, respectively. As with the basalt aggregate mixtures, the highest strength was achieved with the 6.5% CR modified binder.

Regarding the 7-day compressive strengths, the values for basalt aggregate were 3.77 MPa, 3.25 MPa, 4.1 MPa, and 4.95 MPa, and for limestone aggregate, the values were 3.22 MPa, 2.97 MPa, 3.42 MPa, and 3.84 MPa, respectively. In both curing periods, the highest values were obtained in the samples prepared with basalt aggregate and 6.5% CR modified binder.

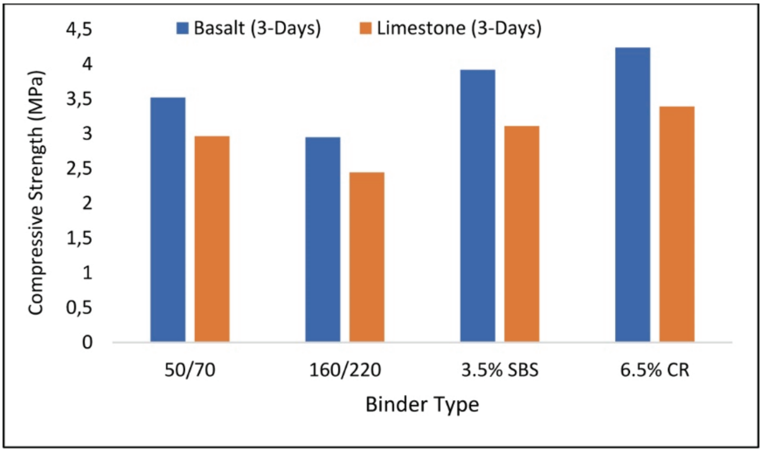

Fig. 31 - 3-day compressive strengths of semi-rigid mixtures prepared with basalt and limestone aggregate

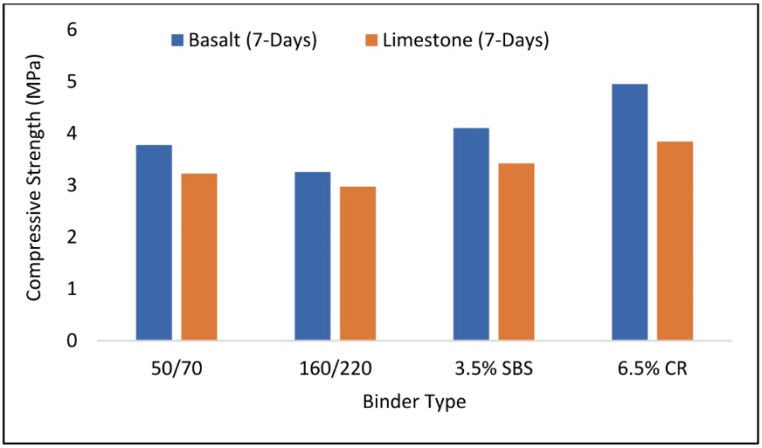

Fig. 32 - 7-day compressive strengths of semi-rigid mixtures prepared with basalt and limestone aggregate

As the curing time increased, the compressive strengths of the mixtures showed an increase for both aggregate types. To ensure that semi-rigid pavements have sufficient load-bearing capacity, they must possess adequate strength, and for the early opening to traffic, high early compressive strength (7 days) is preferred.

5. CONCLUSIONS

The results obtained from the experiments are summarized as items:

- According to the air void test for porous asphalt mixture experiments, the optimum bitumen amount of 4% was determined in the porous asphalt mixtures produced in the laboratory environment, although the 6 mixtures determined for the mixture samples according to the air void test had the targeted void ratios. The optimum amount selected for the porous asphalt mixtures prepared with basalt aggregate was determined to be suitable for the mixtures prepared with limestone aggregate. And the void ratio was found to be 27.15% for the selected optimum amount of 4% and it was determined that it was suitable for porous asphalt specimens, which is a skeleton structure created for semi-rigid pavements.
- According to the results of the bitumen percolation test, the Schellenberg bitumen percolation value was determined as maximum 0.3% in the porous asphalt design criteria according to the Highway Technical Specifications. Accordingly, it was determined that the majority of the mixtures did not exceed the specified limit value. It was determined that the optimum bitumen amount was 4.6% and 4.40% in 50/70 pure bitumen mixtures prepared with only limestone aggregate and the optimum bitumen amount was 4.60% in 160/220 pure bitumen mixtures. The reason for this is that the surface of the limestone aggregate is smoother than the basalt aggregate and it is easier for the bitumen to drain from the aggregate surface with the use of more bitumen.

- When the viscosity times of the cement mortar types were examined, it was determined that all mortar mixes were suitable because the viscosity times of the mortar mixes with 2%, 1% and 0.8% superplasticizer additives were within the viscosity time determined as 10 to 14 seconds. Since the cement mortar injected into the voids in the porous asphalt was required to be very fluid, CM 4 cement mortar mixes with an additive amount of 2%, a w/c ratio of 50% and viscosity times of 10.32 and 10.16 s, respectively, were selected.
- According to the test results, when the compressive strengths given according to the proportions of additives used in the cement mortar are examined, very high values were obtained in mortar mixtures prepared with both basalt aggregate and limestone aggregate. In order to select the most suitable mixture among the mortar combinations, the viscosity time and compressive strengths of the mortar were generally examined. Semi-rigid mix specimens were prepared by injecting the cement mortar into the porous asphalt mix specimens and each aggregate type was injected with its own type of aggregate mortar mix. Since fluidity is the most important factor in mortar mixtures prepared with basalt and limestone aggregates, CM 4 mortar mixtures with a w/c ratio of 0.50 using 2% additives were used to obtain semi-rigid mixture specimens.
- When the Marshall stability test results for the semi-rigid mix specimens were analyzed, the mixture prepared with basalt aggregate and 6.5% CR modified binder had the highest stability value. When the 3-day stability values of the semi-rigid mixtures prepared with limestone aggregate were analyzed, the highest value was determined in the mixtures prepared with 6.5% CR.
- When the stability values of porous asphalt and semi-rigid mix specimens were compared, a significant increase was observed in the stability values of semi-rigid mix specimens obtained by adding cement mortar into porous asphalt specimens with curing time compared to porous asphalt mixtures. According to the results, it is concluded that modified binders increase the stability values with the curing time.
- When the compressive test results obtained from the semi-rigid mixtures were evaluated, the highest compressive strength value was obtained in mixtures prepared with 6.5% CR modified binder where both basalt and limestone aggregates were used. When the compressive test results of both curing periods (3 and 7 days) were evaluated, the highest value was obtained in the samples prepared with basalt aggregate and 6.5% CR modified binder. The compressive strength of the mixtures increased for both aggregate types with increasing curing time. Semi-rigid pavements should have sufficient strength to ensure that they have adequate bearing capacity and high early compressive strength (7 days) should be preferred for earlier opening to traffic.
- When the fragmentation loss values of porous asphalt mixtures and semi-rigid mixtures obtained after the injection of cement mortar were analyzed, a certain decrease in fragmentation values for both aggregate types was obtained after the injection of cement mortar. This is due to the fact that the cement mortar gains strength as it hardens and provides a good interface connection between bitumen, aggregate and cement mortar. According to Cantabro particle loss values, the lowest value was obtained in basalt aggregate mixtures prepared with 6.5% CR modified binder.

- When the stability values of porous asphalt and semi-rigid mix specimens were compared, a significant increase was observed in the stability values of semi-rigid mix specimens obtained by adding cement mortar into porous asphalt specimens with the curing time compared to porous asphalt mixtures. Based on the results, it is concluded that modified binders increase the stability values with curing time.

- In order to reduce the risk of spontaneous cracking in semi-rigid mixtures and to reduce the risk of reduction in the bond strength of the cement-asphalt interface due to shrinkage, it was determined that the w/c ratio should be selected as low as possible when the fluidity of the injection material meets the injection requirements.

- For semi-rigid mixtures, the void percentage of porous asphalt mixtures and the aggregate gradation used in them are very important issues. In addition to these, the fluidity and strength of the mortar to be used in porous asphalt is another very important issue. The traditional cement mortar used in concrete design and the cement mortar used in obtaining semi-rigid mixtures are different from each other. Factors such as w/c ratios, additive ratios, fluidity, workability, resistance and durability in mortar mixtures are important parameters for the strength of the mortar. The higher the strength of the mortar, the higher the strength of the semi-rigid mixtures.

- As a result of the literature research and experimental data, it has been shown that the rutting, stability and crumbling resistance of semi-rigid mixtures are significantly higher than conventional asphalt mixtures and the initial construction cost is significantly lower than concrete pavements. Therefore, semi-rigid pavements can be recommended as an alternative to compensate for the damages and problems caused by flexible and rigid pavements.

- In further studies, the performance characteristics of porous asphalt properties with different grades should be evaluated using different compaction levels. In addition, since the inner cavity of porous asphalt is a 3-dimensional space structure and there is no definite direction for the infiltration of injection material in the cavity, studies should be carried out to use permeability simulation to clarify the direction, path, amount and speed of infiltration of the injection material inside.

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