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INVESTIGATION OF DESIGN AND PERFORMANCE CHARACTERISTICS OF MATERIALS USED IN CEMENT MORTAR MIXTURES DESIGNED FOR SEMI-RIGID PAVEMENTS

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Keywords
Semi Rigid Pavement, Cement Mortar, Material, Design.

Abstract
Semi-rigid pavements are a type of pavement constructed by injecting a flowable cement mortar into the voids of a compacted porous asphalt skeleton with a void percentage between 25-35%. Cement mortar is one of the most important components for semi-rigid pavements, but the properties of the mortar are not well researched. The design of cement mortar for semi-rigid pavements is different from the traditional cement mortar used for concrete design. In semi-rigid pavements, workability, flowability and strength of mortars play an important role in the performance level of mixtures. In this study, the properties, mixing ratios and performance characteristics of the materials in cement mortar used in the production of semi-rigid pavement systems were evaluated. In the study, the flowability and compressive strength properties of cement mortar prepared using two different aggregates, different w/c ratios and different proportions of superplasticizing admixtures were investigated. In addition, research on the materials, design and performance of cement mortar is summarized and presented. As a result of this study, it was determined that in order for the cement mortar to penetrate well into the voids in porous asphalt, the w/c ratio used should be kept low and the ratio of superplasticizing additive should be maximum 2%.

YARI RİJİT KAPLAMALAR İÇİN DİZAYN EDİLEN ÇİMENTO HARÇ KARIŞIMLARINDA KULLANILAN MALZEMELERİN TASARIM VE PERFORMANS ÖZELLİKLERİNİN İNCELENMESİ

Anahtar Kelimeler
Yarı Rijit Kaplama, Çimento Harcı, Malzeme, Tasarım.

Öz
Yarı rijit kaplamalar, boşluk yüzdesi %25-35 arasında olan sıkıştırılmış Poroz asfalt iskeletinin boşluklarına akıcı çimento harcının enjekte edilmesiyle inşa edilen bir kaplama çeşididir. Çimento harcı, yarı rijit kaplamalar için en önemli bileşenlerden biridir ancak harcın özelliklerine dair fazla araştırma yapılmamaktadır. Yarı rijit kaplamalar için çimento harcı tasarımı, beton tasarımı için kullanılan geleneksel çimento harcından farklıdır. Yarı rijit kaplamalarda, harçların işlenebilirliği, akışkanlığı ve mukavemeti karışımların performans seviyesinde önemli rol oynamaktadır. Bu çalışmada, yarı rijit kaplama karışımları elde etmek için kullanılan çimento harcı içerisindeki malzemelerin özelliklerinin, karışım oranları ve performans özellikleri değerlendirilmiştir. Çalışmada, iki farklı agrega, farklı s/ç oranları ile farklı oranlarda süperakışkanlaştırıcı katkı malzemesi kullanılarak hazırlanan çimento harcının akışkanlık ve basınç dayanımı özellikleri incelenmiştir. Ayrıca çimento harcının malzemeleri, tasarımı ve performansı üzerine yapılan araştırmalar özetlenmiş ve sunulmuştur. Bu araştırmadaki sonuçlar neticesinde, çimento harcının poroz asfalt içerisindeki boşluklara iyi nüfus edebilmesi için, kullanılan w/c oranın düşük tutulması ve süperakışkanlaştırıcı katkı malzemesinin oranının en fazla %2 oranında olması gerektiği belirlenmiştir.

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Highlights

- Cement mortar used in semi-rigid pavements
- Effect of w/c ratio in cement mortar
- Fluidity and strength of cement mortar
- Injecting cement mortar into voids in porous asphalt

Graphical Abstract

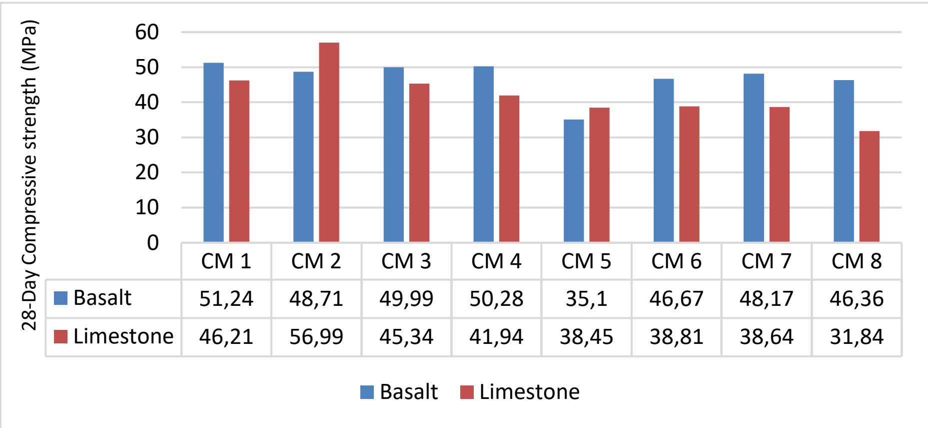

Figure. 28-day Compressive Strength Of Cement Mortars Prepared with Basalt and Limestone Aggregates

Purpose and Scope

The main objective of the study was to evaluate the material properties, mixing ratios and performance characteristics of the cement mortar used to obtain semi-rigid pavement mixtures.

Design/methodology/approach

In this study, the flowability and compressive strength properties of cement mortar prepared using two different aggregates, different w/c ratios and different proportions of superplasticizing admixtures were investigated. In addition, research on the materials, design and performance of cement mortar is summarized and presented.

Findings

When the viscosity times of the cement mortar mixtures were examined, it was determined that all mortar mixtures were suitable since the viscosity times of the mixture types with 2%, 1% and 0.8% superplasticizer additives were within the viscosity time determined as 10-14 seconds. Since the cement mortar injected into the voids in the porous asphalt is required to be very fluid, it would be appropriate to use 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 sec, respectively.

Originality

When the studies were examined, it was seen that the performance of semi-rigid pavements was generally investigated. It has been determined that there are no detailed studies on material selection and mixing of cement mortar material and there are few studies. In this study, appropriate mixing ratios for cement mortar used to obtain semi-rigid pavements were tried to be given by using aggregates of two different origins with different w/c ratios and superplasticizing admixtures at different ratios and the performances of the mixtures were investigated by performing fluidity and compressive strength tests on the mixtures.

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1. Introduction

Semi-rigid pavements are a hybrid type of pavement that combines the flexibility of flexible pavements with the high-strength properties of rigid pavements. They offer many advantages, such as high strength, good abrasion resistance, a comfortable vehicle ride, and easy maintenance. These pavements are particularly suitable for areas with heavy loads, such as highway toll stations, tunnel entrances and exits, city roads, bus stops, and traffic light intersections (Afonso et al., 2016).

Semi-rigid pavement was first introduced in airport road construction in France in the 1960s. Since then, semi-rigid pavement systems have attracted significant research interest due to their structural advantages. In recent years, its application has expanded, making it widely used across Europe (Husain et al., 2014). Semi-rigid pavements were used extensively during the 1970s and 1980s across Africa, the South Pacific, the Far East, and North America, as well as in many European countries, including the UK and Spain. They were applied on major road networks, yielding positive results in terms of both functional and structural performance. Today, semi-rigid pavements are widely used in European countries like Germany, England, Italy, and the Netherlands, as well as in Asian countries such as China, Malaysia, Singapore, and India. They are applied in various settings, including highways, bridge deck coatings, tunnel linings, industrial areas with heavy machinery traffic, airport aprons, and metrobus stations, where high levels of chemical compounds and fuel spills are common (Corradini et al., 2017; Gong et al., 2019; Hassan et al., 2018).

Semi-rigid pavements are constructed in three main stages. The first stage involves the laying of porous asphalt concrete, which is a combination of porous asphalt and high-performance cement mortar. In the second stage, cement mortar is injected to fill the voids within the asphalt layer. Finally, in the third stage, any excess injection material is removed from the pavement surface (An et al., 2018). After a curing period lasting from several hours to several days, the cement bonds with the asphalt mixture, enhancing the overall strength of the composite. As a result, the pavement exhibits semi-rigid properties, providing improved durability and performance (Gong et al., 2019). By utilizing both rigid and flexible pavement materials, semi-rigid pavement offers advantages such as superior resistance to tread wear, high load-carrying capacity, and excellent ride comfort.

Porous asphalt mixtures used in semi-rigid pavements typically have a minimum air void content of 20%. However, in practical applications, this ratio can increase to 30-35% (Cihackova et al., 2015). Given that the air voids in porous asphalt mixtures are partially filled with grouting materials, an initial air void content of 20-35% is recommended as a prerequisite for asphalt mixtures.

If the initial air void content is reduced to less than 20%, and considering the low permeability of semi-rigid pavements, the injection materials despite being sufficiently fluid may not effectively fill the air voids in the asphalt mix. Therefore, semi-rigid pavements may lack homogeneous mechanical properties and sufficient resistance to traffic and environmental loads (Hassani et al., 2020).

Compared to conventional open-graded mixtures, porous asphalt used in semi-rigid pavements offers not only stability, tensile strength, and abrasion resistance, but the porous asphalt skeleton must also have sufficient porosity to allow adequate penetration of the injection material, enabling the formation of a dense skeletal structure in the semi-rigid pavement(Afonso et al., 2016).

Porous asphalt, which forms the skeletal system of semi-rigid pavement, is made with a high proportion of coarse aggregate and bitumen as the binder. During pavement design, cement binder mortar should be injected under the influence of gravity, without compaction or vibration, to ensure that the pores in the porous asphalt remain sufficiently open for proper filling (Husain et al., 2014).

The optimum binder is essential to ensure that the aggregates remain securely in place without being either under-coated or over-coated. A thin binder film does not provide enough hardness to protect the aggregates from friction and wear, and the bitumen will oxidize over time, compromising durability. Studies have shown that an insufficient binder film thickness can lead to aggregate breakage and pavement cracking (Hardiman et al., 2004). Conversely, an excessively thick binder film can cause the binder to flow too much during mixing, transportation, and paving. This excessive flow can clog the voids in the porous asphalt after paving, significantly reducing the properties of the mix.

Semi-rigid pavement is composed of porous asphalt and cement mortar, and therefore its performance depends on the characteristics of both components. Some factors affecting the performance of semi-rigid pavement are as follows:

•*Grading of porous asphalt mixture*; The choice of aggregate gradation plays an important role in the performance of the properties of the final mix. For the preparation of porous asphalt mixtures, a one-dimensional aggregate is usually used in an open graded asphalt mixture. For semi-rigid pavement applications, 90-95% coarse aggregate, 4-5% sand and 2-4% filler are usually used in the design of porous asphalt mixtures (Hassan et al., 2018).

•*Void ratio of porous asphalt mix*; If the void ratio in porous asphalt mixtures is low, the cement mortar cannot be injected into the voids sufficiently, resulting in a weak connection within the mixture. A high void ratio means that a large amount of cement mortar is used. This causes the mixture to behave like a very hard structure (Gong et al., 2019).

•*Bitumen Type*; The type of bitumen used in porous asphalt mixtures has a significant influence on the properties of the semi-rigid pavement layer. When a harder bitumen is used, the hardness and compressive strength resistance of the pavement increases considerably at high temperatures (Fediuk et al., 2017). However, with the use of a harder binder and repetition of traffic loads, cracking of the pavement occurs. The effect of modified and conventional binders on the performance characteristics of semi-rigid pavement specimens has been analyzed by many researchers. It was found that the modified binder significantly improved the strength of semi-rigid specimens and the modification of conventional binders.

•*W/c ratio in cement mortar*; The cement mortar used in semi-rigid pavement surfaces must be highly fluid in order to fully penetrate the voids in the porous asphalt structure. Therefore, the w/c ratio plays a major role in improving the strength and fluidity of the cement mortar(Corradini et al., 2017).

•*Admixtures and other supplementary cementitious materials*; Materials such as w/c ratio, additives, polymers in cement mortar have a significant influence on the design of semi-rigid pavement. There is little research on the different compositions and performance of cement mortars for semi-rigid pavement design. Controlling the viscosity of the cement mortar plays an effective role in ensuring that it fully penetrates into the voids of the porous asphalt skeleton and that the mixture provides sufficient strength. If the viscosity of the mortar is low, some voids at the base of the specimen may not be filled, on the other hand, a high w/c ratio leads to a decrease in the overall strength of the mixture. Superplasticizer additive ratios should be used at a relatively low w/c ratio to achieve high fluidity (An et al., 2018).

•*Degree of saturation of cement mortar*: The degree of saturation of the cement mortar indicates the extent to which the air voids in the porous asphalt mixture are filled with mortar (Luo et al., 2020). The degree of saturation is one of the important parameters affecting the performance of semi-rigid mixtures subjected to heavy traffic loading and poor weather conditions. The degree of mortar saturation is not only a function of its injection into the air voids in the porous asphalt mixture, but also depends on the morphological characteristics, size and structure of the voids, which directly affect the interlocking of voids in porous asphalt mixtures (Vavrik et al., 2001).

High-fluidity cement mortar serves as an injection material that can penetrate the porous asphalt mix due to its fluidity, forming a fiber-like network structure within the asphalt (Guo & Hao, 2021). The water-cement ratio is a critical factor influencing both the fluidity and strength of cement mortar. The fluidity of the mortar is positively correlated with the water-cement ratio and negatively correlated with the sand-cement ratio (Vijaya et al., 2009). However, shrinkage may occur in the mix when the water-cement or sand-cement ratio is too high. The design of grouting materials for semi-rigid pavements differs from traditional cement mortar used in concrete. In semi-rigid pavements, the workability, flowability, and strength of the mortar are crucial factors that influence the performance of the mixture.

If the fluidity is insufficient, the air voids in the porous asphalt mixture will not be adequately filled, resulting in semi-rigid pavements that lack the required durability and strength to withstand applied loads (Figure 1).

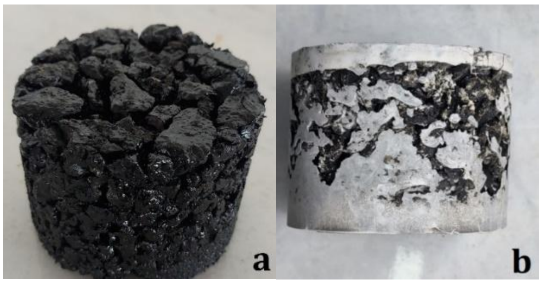

Figure 1. (a) Low air void content of porous asphalt mix and (b) insufficient cement injection

It has been stated that the optimum water-binder ratio for the cement mortar used in semi-rigid pavements should be less than 0.55%, with mineral powder content generally kept below 20% and sand content at approximately 15% (Zhiqiang et al., 2016). Zhang et al. investigated the composition and formulation of cement mortar in mixtures, determining suitable formulations for use in semi-rigid pavement. They examined the effects of flowability, strength, and shrinkage on the cement mortars, and compared various mix designs to identify the most suitable one (Zhang et al., 2020). Sunil et al.evaluated the performance and mechanical properties of semi-rigid pavement mixtures using different aggregate gradations (Sunil et al., 2019). Hasani et al. conducted both laboratory and field evaluations of the design and construction of semi-rigid pavements. They assessed the pavement's performance under loading, resistance to impacts, and resistance to fuel and oil leaks. Additionally, they provided insights into the field evaluation method and discussed the current challenges associated with semi-rigid pavement design (Hassani et al., 2020). Chen et al. conducted an extensive literature review on semi-rigid pavement design, summarizing the design principles, materials, technical requirements, design methods, and testing procedures (Chen et al., 2023). Han et al. investigated the effect of partially replacing cement with waste polyethylene terephthalate (PET) and fly ash (FA) in cement mortars used for semi-rigid pavement design, focusing on the strength and fatigue properties of the mixtures (Khan et al., 2023).

In general, studies have been conducted on semi-rigid mix design, porous asphalt mix design(Gong et al., 2022; Ling, Chen, et al., 2022; Zhao & Yang, 2022) , cement mortar materials (Pei et al., 2016; Yajun et al., 2013), the performance of cement mortar (Davoodi et al., 2021; Khan, Sutanto, Napiah, et al., 2022; Koting et al., 2014), and semi-rigid pavement design (Hu et al., 2022; Li et al., 2022; Ling, Sun, et al., 2022; Wang & Juan, 2020).

Upon reviewing the studies, it was found that the performance of semi-rigid pavements had been widely investigated. However, there were few detailed studies on material selection and the mixing of cement mortar, with limited research in this area.

In this study, by using aggregates from two different sources, varying the water-cement (w/c) ratios and adding superplasticizing admixtures at different ratios, suitable mixing ratios for cement mortar used in semi-hard pavement were determined. The performance of the mixtures was evaluated. The study begins by presenting a detailed analysis of the factors affecting the design of semi-rigid pavements. The following sections provide information on the properties of the materials used to prepare cement mortar, the mortar mixtures, and the experiments conducted. Finally, a comprehensive evaluation of the materials and formulations for semi-rigid pavement mixtures is presented, along with recommendations. Rough fluidity and compressive strength tests. The main objective of the study is to evaluate the material properties, mixing ratios, and performance characteristics of the cement mortar used in semi-rigid pavement mixtures.

2. Materials

Within the scope of the study, porous asphalt mixtures, which are the skeleton of the semi-rigid pavement, were prepared. Separate porous asphalt mixture samples were prepared for basalt and limestone aggregate. Separate cement mortars were prepared for each aggregate to be injected into the voids in the porous asphalt mixtures. CEM I 42.5 Portland cement and superplasticizer additives were used in the cement mortar. The properties of the materials used are listed as items.

2.1. Cement

Within the scope of the study, CEM I 42.5 R type Portland cement obtained from Elazığ cement factory was used in the semi-rigid pavement design. The content of the cement used was stated by the manufacturer as 95%-100% clinker and 0%-5% minor additional components. The physical and mechanical properties of the cement used are given in Table 1.

Table 1. Mechanical and physical properties of cement material

Mechanical and Physical properties	Results	Requirements according to TS EN 197-1	Analysis Method
Compressive Strength 2 days, N/mm²	Min. 20	Min. 20	EN 196-1
Compressive Strength 28 days, N/mm²	42.5-62.5	42.5-62.5	EN 196-1
Initial setting time of concrete, min	Min. 60	Min. 60	EN 196-3
Expansion, mm	Max. 10	Max. 10	EN 196-3

Additionally, chemical analysis using the glass tablet method with XRF was conducted on the CEM I 42.5 R strength cement obtained from the Elazığ Seza cement factory using the fusion method (Figure 2).

Figure 2. Preparation of cement in glass tablet form using the fusion method

The analysis method using XRF is a non-destructive technique that performs element analysis by measuring the characteristic wavelength and intensity generated from the interaction of X-rays with the analyzed material. With this method, the oxide components of Si, Al, Fe, and Ca in the cement are determined. The chemical analysis results are presented in Table 2.

Table 2. Chemical analysis results of the cement

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LSF	C_3S	C_3A
Value (%)	19.84	5.28	3.36	60.52	2.38	3.31	94.59	45.84	8.31

2.2. Aggregate

In this study, two types of aggregate were used: basalt and limestone. Necessary tests were conducted on each aggregate to determine their properties, and their effects within the mixture were compared. The basalt aggregate to be used was obtained from BAYSAN Construction Materials Ltd. in Seke village, Ahlat district of Bitlis, while the limestone aggregate was sourced from a marble quarry located in the Bitlis region (Figure 3).

Figure 3. Limestone (a) and basalt (b) aggregates used in the study

Chemical analyses of the basalt and limestone aggregates used in the study were performed using the glass tablet method with XRF, utilizing the fusion technique. The preparation of the samples as glass tablets for chemical analysis is shown in Figure 4.

Figure 4. Conversion of basalt and limestone aggregates into glass tablet form

The chemical analysis results of the aggregates are presented in Table 3.

Table 3. Chemical analysis results of basalt and limestone aggregates

Compounds	Basalt Aggregate (%)	Limestone Aggregate (%)
BaO	0.04	-0.01
SiO_2	55.43	1.93
Al_2O_3	16.84	0.15
Fe_2O_3	8.49	0.14
CaO	4.77	52.74
MgO	1.97	1.38
K_2O	2.59	0.03
Na_2O	4.61	0.06
TiO_2	1.66	0.00
P_2O_5	0.20	0.05
Mn_3O_4	0.18	0.00
LSF	2.64	929.12
C_3S	-527.13	198.84
Aluminium Ratio	1.98	1.08
Silica Ratio	2.19	6.74
C_2S	556.35	-144.41
C_4AF	25.84	0.42
Liquid Phase	78.80	2.24
C_3A	30.26	0.16
Total Alkali	6.32	0.08
Loss on Ignition	2.91	43.33

Aggregates have been used in both porous asphalt mixtures and cement mortar mixtures. The physical and mechanical properties of the limestone and basalt aggregates are presented in Table 4. It has been determined that the test results meet the limit values specified in the standards.

Table 4. Physical and mechanical properties of the aggregates

Sieve Size (mm)	Gradation values	Flatness index values		Water Absorption (%)		Apparent Specific Gravity (gr/cm³)		$MgSO_4$ Missing (%)		Micro-Deval Abrasion Values (%)	
		Limestone	Basalt	Limestone	Basalt	Limestone	Basalt	Limestone	Basalt	Limestone	Basalt
25	100	-	-	-	-	-	-				
19	95-100	19.2	16.1	-	-	-	-				
12.5	90-100	11.6	19.6	0.50	1.25	2.75	2.78	8%	4.5%	19%	17%
9.5	63-77	19.7	10.9	0.20	1.25	2.72	2.74				
4.75	11-35	19.6	19.6	0.68	1.48	2.70	2.74				
2	10-20	-	-	1.16	1.99	2.60	2.73				
0.180	5-10	-	-	1.66	1.43	2.62	2.71				
0.075	3-7	-	-	1.77	1.56	2.76	2.58				

2.3. Mixing Water

The quality of mixing water plays an important role in the preparation of concrete. The water used in the mixture should be as clean as possible and free from harmful substances. Drinking water can be used as mixing water for the produced mortar. In this study, the municipal water supply of Elâzığ was used in the design of the mixtures. The analysis results of the municipal water provided by Elâzığ Municipality are presented in Table 5.

Table 5. Analysis results of Elazığ Municipality tap water

Parameter	Method	Directional value	Result
Color	Physical	Normal	
Cloudiness	Turbidimeter	Normal	
Odor	Physical	Normal	
Conductivity	Conductivity meter	2500 μS/cm	656 μS/cm
pH	pH meter	6.5-9.5	7.3
Nitrate	Spectrophotometric	0-500 ppb	9.7
Chloride	Spectrophotometric		0.4
Iron	Spectrophotometric	0.2	Yok

2.4. Chemical Additive

In this study, a superplasticizer additive was used in the mortar mixture for obtaining semi-rigid pavement samples. The reason for using a superplasticizer in the mortar mixture is that the voids in the porous asphalt mixture samples need to be filled to the maximum level with mortar, thus requiring the mortar to have fluid consistency and adequate workability. Fluid Optima 280 is a new generation polycarboxylate-based superplasticizer. It is particularly recommended for concrete that requires high early and ultimate strength while maintaining consistency in all seasons. By enabling concrete production at low w/c ratios, it enhances the impermeability and strength of the concrete. Following the manufacturer's usage recommendations, the superplasticizer additive was incorporated into the mortar mixture during the second half of the mixing water. The technical specifications of the chemical additive used, provided by the manufacturer, are presented in Table 6.

Table 6. Technical specifications of the additive used in the mortar mixture

Property	Superplasticizer additive	Standard Values	Examination Method
Homogeneity	Homogeneous	Homogeneous	Visual inspection
Appearance/Color	Brown	Brown	Visual inspection
Density (g/cm³)	1.050±0.02 gr/cm³		ISO 758
pH value	4.00±1		ISO 4316
Amount of additive (%)	-		EN 480-8
Soluble chloride in water (%)	<%0.1		EN 480-10
Alkali amount (%)	Suitable		EN 480-12
FT-IR Spectrum active component	Suitable		EN 480-6

2.5. Bitumen

In the conducted study, to determine the degree of saturation of the voids within the porous asphalt, the most suitable cement mortar mixture was prepared using an optimum bitumen content of 4%. Samples of porous asphalt mixtures with a void ratio of 27% were prepared for each type of aggregate. In this context, 50/70 pure bitumen obtained from Turkish Petroleum Refineries was used in the mixtures. According to the binding test results conducted on the 50/70 pure bitumen, it has been determined that the properties of the bitumen meet the technical specifications as presented in Table 7.

Table 7. 50/70 Properties of Pure Bitumen

Property	Results	Specification limits	Standard
Specific Weight	1.02	1.01/1.06	TS EN 15326+A1
Penetration	53.5	50/70	TS EN 1426
Softening Point (°C)	51.3	49/56	TS EN 1427
Viscosity 135 °C (pa.s)	587.5	-	AASHTO TP48
Viscosity 165 °C (pa.s)	165	-	

3. Method

3.1. Preparation of Cement Mortar Mixture

In this study, while obtaining semi-rigid pavement design samples, two different w/c ratios and four different additive material proportions were used for the basalt and limestone aggregates in the mortar mixture. The same coding was applied for both types of aggregate in the naming of the mixtures. The materials used and their quantities are presented in Table 8.

Table 8. 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					0.8	
CM 3					1	
CM 4					2	
CM 5		24.4		26.8	-	0.55
CM 6					0.8	
CM 7					1	
CM 8					2	

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

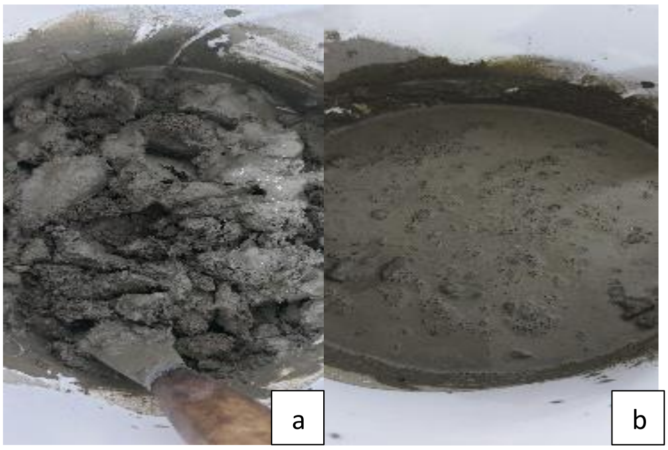

Figure 5. (a) Non-fluid mortar mixture, (b) Mortar mixture that becomes fluid with additive

The second important aspect is compressive strength. The composition of semi-rigid pavements consists of approximately ¼ cement mortar. Therefore, the strength of the cement mortar significantly affects the overall strength of the design. Among these properties, the most critical consideration is the fluidity of the cement mortar, which must completely penetrate the depth of the porous asphalt surface layer without excessive compaction and vibration. Another factor is the pressure of the cement mortar, which significantly influences the final strength and durability characteristics of the semi-rigid mixtures. In this context, flowability and compressive strength tests were conducted on the mortar mixtures in the study.

3.2. Fluidity of Cement Mortar

The cement mortar, which is one of the important components in a semi-flexible pavement, contributes to high compressive strength and rigidity. For the cement mortar to fully penetrate the voids in the porous asphalt, it must have a highly fluid consistency. The properties of the mortar are significant parameters that can affect the performance of semi-rigid pavements when exposed to heavy traffic loads and adverse weather conditions. The water/cement (w/c) ratio plays an important role in achieving a high degree of fluidity in the cement mortar. In this study, a w/c ratio of 0.50 and 0.55 was used.

For the fluidity test of the mortar used in semi-rigid pavement mixtures, different types of funnels, such as the Marsh flow cone, Malaysian mortar flow cone, Leeds flow cone, and flow funnel tests, are utilized (Khan, Sutanto, Yusoff, et al., 2022).

In this study, the fluidity value of the mortar was determined using a flow cone. The test was conducted according to the ASTM C939-10 standard (Astm:C939-10, 2010). A quantity of 1725 ml of the prepared mortar was poured into the flow cone apparatus, allowing it to flow out. The time required to empty the flow cone was measured in seconds and recorded as the flow of the cement mortar (Figure 6).

Figure 6. Flow cone used to determine the fluidity of cement mortar

The higher the flow time, the lower the fluidity of the mortar, making it more difficult to penetrate the voids in the mixture. However, the standard flow time depends on the geometry and size of the flow cone used. For the cement mortar to fully penetrate the porous asphalt structure, the ideal flow time has been determined to be 10-14 seconds according to the technical specifications of the injection material for semi-rigid pavements(Davoodi et al., 2021).

3.3. Compressive Strength of Cement Mortar Materials

The strength of the mortar material used for the semi-rigid pavement design is a crucial factor. In this context, compressive tests were performed on the mortar samples. Samples of 50×50×50 mm were used in the experiment. After determining the material ratios in the mixture, the prepared mixtures were filled into 50 mm^3 sample molds in two layers and placed using a table-type vibrator (Figures 7).

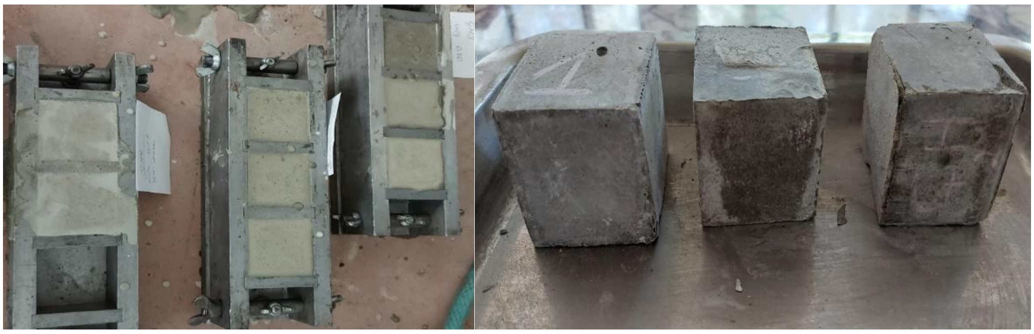

Figure 7. Molds and samples used for the compressive strength of cement mortar

The samples were kept in molds for 24 hours to set, and wet jute cloths were placed over the samples to prevent moisture loss. After 24 hours, the samples were removed from the molds and placed in a curing tank at a temperature of 20±2°C for curing periods of 7 and 28 days. The test was conducted in accordance with the BS EN 196-1 standard (British Standards Institution BSI, 2016). The compressive test was performed using a fully automated press machine at a speed of 2400±200 N/s (Figure 8).

Figure 8. Fully automated press machine

The experiment was conducted on a total of 48 samples, with 3 samples from each of the different combination mortar mixtures, according to the curing durations (Figure 9). Mortar mixtures were prepared separately for each type of aggregate.

Figure 9. Samples of cement mortar after the applied compressive strength test

The compressive strength values of the samples were determined using Equation 1.

$$f_m = \frac{P}{A} \tag{1}$$

In Equation 1;
f_m: Compressive strength, MPa
P: Maximum breaking load, N
A: Surface area of the sample, mm^2

The 28-day compressive strengths of the cement mortar samples were approximately determined to be 50 MPa (Bang et al., 2017).

In the literature reviews conducted, bending tests have also been applied to prismatic-shaped samples of cement mortar. The bending property previously sought in Turkish standards is no longer included in the current testing standards. Therefore, the requirement to calculate the bending-tensile values of the mortar samples has been eliminated. According to the latest Turkish standards, while obtaining bending strength is not mandatory, tests are still conducted on prismatic samples for compressive strength. In examining American standards, compressive strength tests are performed on cube samples measuring 50×50×50 mm. In this context, less material is used when preparing cube samples compared to prismatic molds. Consequently, the BS EN 196-1 standard was employed in this study, and only compressive tests were conducted on cube samples, with no need for bending-tensile tests.

3.4. Mortar Ratio and Saturation Degree in Semi-Rigid Mixtures

In semi-rigid pavements, the mortar ratio, saturation degree, and the remaining air voids in porous asphalt mixtures after being filled with mortar are three critical parameters related to performance and durability under traffic loads and climatic conditions. Due to the potential flow of the asphalt binder at high temperatures, approximately 4-8% air voids are required in asphalt mixtures(Arabani et al., 2017). In contrast, in semi-rigid pavements, the mortar materials with sufficient coverage over the components of the asphalt mixture prevent the flow of the asphalt binder. Therefore, studies have indicated that semi-rigid pavements should have remaining air voids ranging from 3% to 6%.

After filling the voids in porous asphalt mixtures, the parameters of mortar saturation degree and mortar ratio, as well as the remaining porosity in semi-rigid pavements, are calculated. The saturation degree of the mortar materials (Sg) is used to calculate the amount of mortar materials in the porous asphalt mixtures and is determined using Equation 2 (Luo et al., 2020).

$$S_g = \frac{(m_2 - m_1)}{\rho \times V \times V_a} \times 100 \tag{2}$$

In Equation 2;
Sg: The degree of saturation of mortar materials (%)
m_1: Weight of the specimen before filling with mortar (g)
m_2: Weight of the specimen after filling with mortar (g)
ρ : Cement density (g/cm^3)
V: Sample volume (cm^3)
Va: Air void of porous asphalt mixtures (%)

The proportion of mortar mix is generally the ratio of the volume of mortar material to the target air space. Equation 3 is used for the calculation(Abedini et al., 2017).

$$G_r = \frac{m_0 - m_1}{\rho V_a} \tag{3}$$

In Equation 3;
Gr: Proportion of mortar material in porous asphalt mixtures (%)
m_1: Weight of the sample before filling the mortar mix (g)
m_2: Weight of the specimen after filling the mortar mixture (g)
ρ : Cement density (g/cm^3)
Va: Air void of porous asphalt mixtures (%)

One of the most important parameters that can affect the performance of semi-rigid pavements exposed to heavy traffic loads and bad weather conditions is the degree of saturation. According to Chinese standards, the degree of saturation of mortar should be ≥92% (Corradini et al., 2017).

3.5. Preparation of Porous Asphalt Mixture Samples

Porous asphalt Marshall specimens were prepared after determining the aggregate gradation and optimum bitumen content. Porous asphalt specimens prepared using Marshall mix design were obtained by mixing 1100 g of aggregate with 4% pure bitumen (Figure 10).

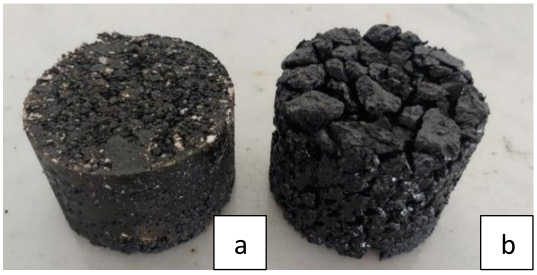

Figure 10. (a) Conventional asphalt mix and (b) Porous asphalt mix marshall specimens

For the basalt aggregate mixtures, 50 strokes were applied on both surfaces in the Marshall compaction device. For the limestone aggregate mixtures, impact compaction on both surfaces was found to cause severe crushing of the limestone aggregate in specimens formed by the standard forming method (Figure 11). This type of crushing is not consistent with real engineering. Therefore, the Marshall impact number of limestone aggregate mixtures should be reduced.

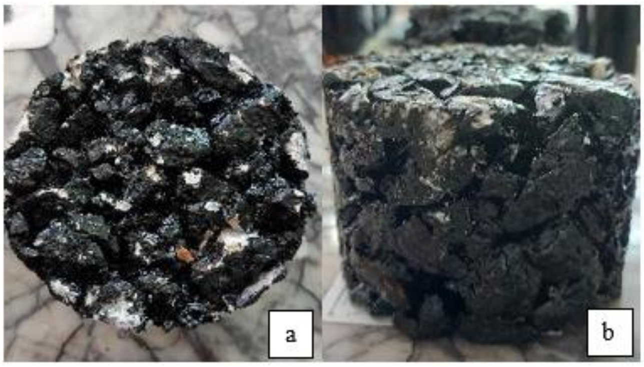

Figure 11. (a) Crushing of limestone mixed specimen with 50 strokes on both surfaces and (b) specimen without sufficient void ratio

In their study, Xu et al. performed compaction by selecting 36 impacts on both surfaces of the specimen to ensure that the void ratio of limestone aggregate mixtures reaches the targeted void value in the specimens. They suggested that the number of impacts in the compaction of Marshall specimens should be adjusted by considering the targeted void ratio of porous asphalt mix specimens(Xu et al., 2021).
Based on these studies, porous asphalt with limestone aggregate was compacted on Marshall specimens with 35 impacts on each side (Figure 12).

Figure 12. Porous asphalt specimens with limestone aggregate compacted to 35 impacts on both surfaces

The voids in the prepared porous asphalt mixture specimens were filled with cement mortar and semi-rigid pavement mixtures were obtained to determine the degree of saturation (Figure 13).

Figure 13. Porous asphalt and semi-rigid mix specimens

4. Results and Discussion

Within the scope of the study, the results of fluidity, compressive strength and degree of mortar saturation of cement mortar mixtures are given under headings.

4.1. Results of the Fluidity Experiment

Within the scope of the study, the mixture ratios used in the literature were taken as references for the mixture ratios of the cement mortar injected into the porous asphalt mixture specimens to obtain semi-rigid pavement specimens. As a result, it was deemed appropriate to use two different w/c ratios in the cement mortar Accordingly, the first mix used a 0.50 w/c ratio, 26.8% aggregate and 48.8% cement, while the second mix used a 0.55 w/c ratio, 24.4% aggregate and 48.8% cement. For each type of mixture, both control samples and mortar mixtures with superplasticizers added at 2%, 1% and 0.8% were tested separately for flowability and compressive strength. CEM I 42.5 N Portland cement was used in the mixtures. Figure 14 shows the flow times of the mixture types prepared with basalt aggregate and limestone aggregate.

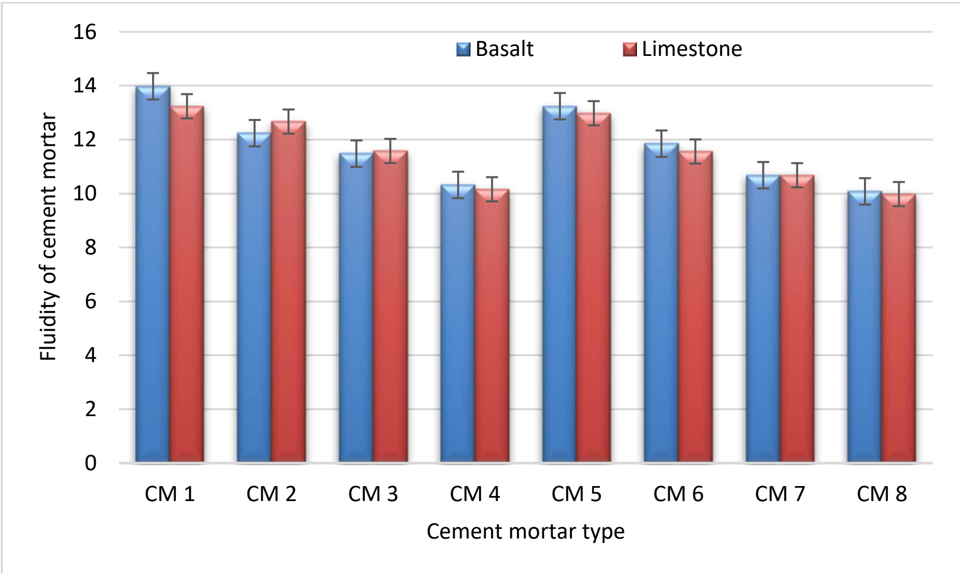

Figure 14. Fluidity times of mortar mixtures prepared with basalt and limestone aggregate

When the fluidity times of the cement mortar types were examined, the fluidity time of the control sample with a w/c ratio of 0.50 without additives in the mortar mixtures of basalt aggregate was determined as 13.98 seconds. Likewise, the fluidity time of the control sample prepared with limestone aggregate without additives was determined to be 13.24 seconds. The viscosity times of the mortar mixtures with 2%, 1% and 0.8% superplasticizer additives were determined to be suitable since they were within the viscosity time determined as 10-14 seconds. Since the cement mortar injected into the voids in the porous asphalt was required to be very fluid, CM 4 cement mortar mixtures with an additive content of 2%, a w/c ratio of 0.50 and viscosity times of 10.32 and 10.16 s, respectively, were selected.

High fluidity (short flow time) can lead to poor mechanical properties of hardened cement mortar materials. In addition, high fluidity increases the likelihood of the cement mortar flowing out at the bottom or sides when injected into the porous asphalt mix. Low viscosity (long flow time), on the other hand, makes it difficult for the grouting materials to penetrate into the porous asphalt mix specimens, which may affect the injection rate and injection time. The flow time selected for the study was in the range of 10-14 seconds. The majority of the mixtures produced had the specified flow times.

4.2. Compression Test Results

In the compressive strength test, 50×50×50 cm cube specimens were used. Cement mortars were prepared separately for limestone and basalt aggregates. Two different w/c ratios and three different proportions of additives were added to the mixtures and compressive strength tests were performed on the combined specimens. The compressive strength test results are given in Table 9 for basalt aggregate and Table 10 for limestone aggregate.

Table 9. Compressive strength values of cement mortar mixtures prepared with basalt aggregate

Basalt Mix	Additive Ratio	W/C ratio	Fluidity Time (sn)	7-day Compressive Strength (MPa)	28-day Compressive Strength (MPa)
CM 1	-	0.50	13.98	42.75	51.24
CM 2	0.8%		12.24	34.52	48.71
CM 3	1%		11.48	40.66	49.99
CM 4	2%		10.32	37.48	50.28
CM 5	-	0.55	13.24	25.1	35.1
CM 6	0.8%		11.85	34.61	46.67
CM 7	1%		10.68	32.63	48.17
CM 8	2%		10.08	31.89	46.36

Table 10. Compressive strength values of cement mortar mixtures prepared with limestone aggregate

Limestone Mix	Additive Ratio	W/C ratio	Fluidity Time (sn)	7-day Compressive Strength (MPa)	28-day Compressive Strength (MPa)
CM 1	-	0.50	13.24	39.18	46.21
CM 2	0.8%		12.67	51.62	56.99
CM 3	1%		11.58	33.84	45.34
CM 4	2%		10.16	28.8	41.94
CM 5	-	0.55	12.98	27.06	38.45
CM 6	0.8%		11.56	33.2	38.81
CM 7	1%		10.68	27.49	38.64
CM 8	2%		9.98	30.2	31.84

The comparison of the 7-day and 28-day compressive strengths of the mortar mixtures according to the types of mixtures is presented separately in Figures 15-18.

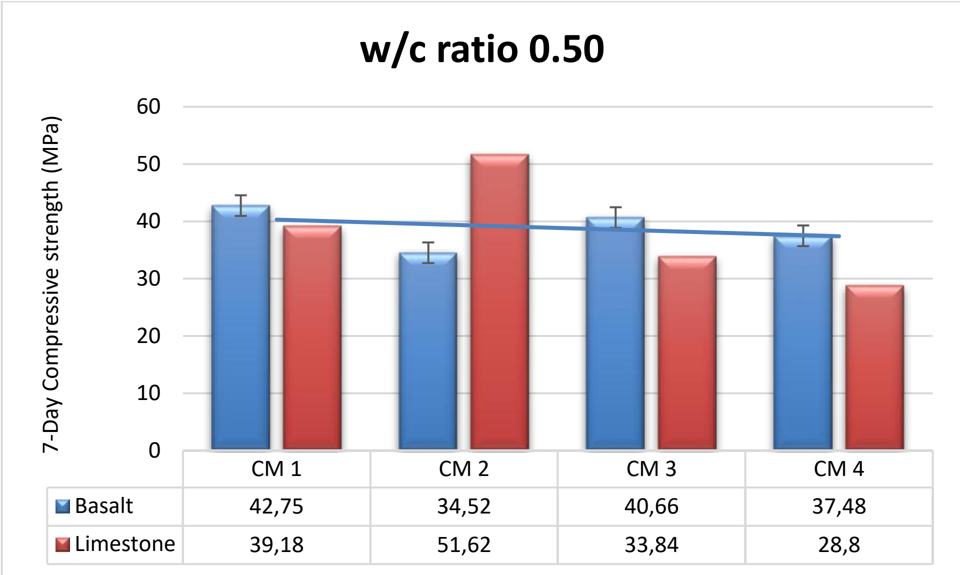

Figure 15. 7-day compressive strengths of mortar mixtures prepared with basalt and limestone aggregates with a w/c ratio of 0.50 and according to additive ratios

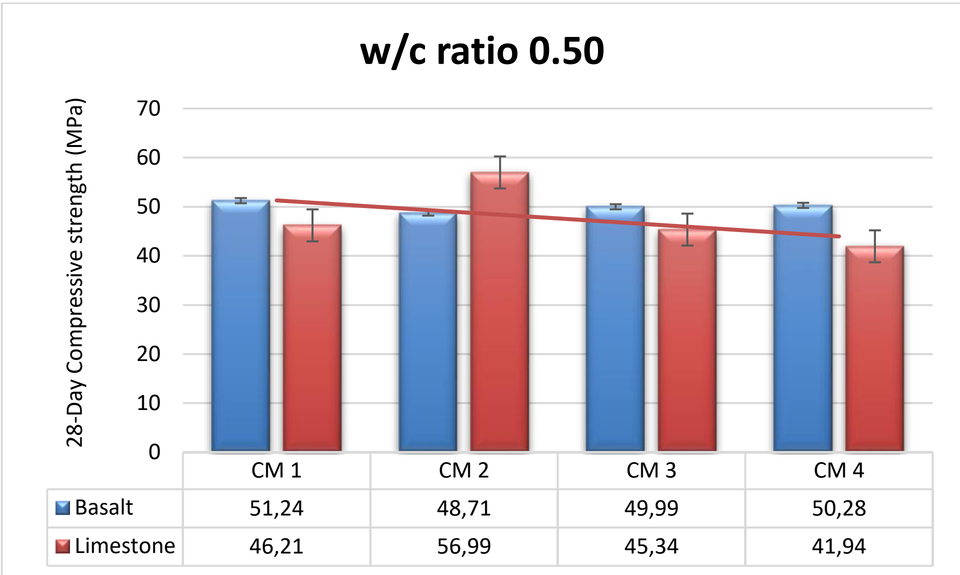

Figure 16. 28-day compressive strengths of mortar mixtures prepared with basalt and limestone aggregates with a w/c ratio of 0.50 and according to additive ratios

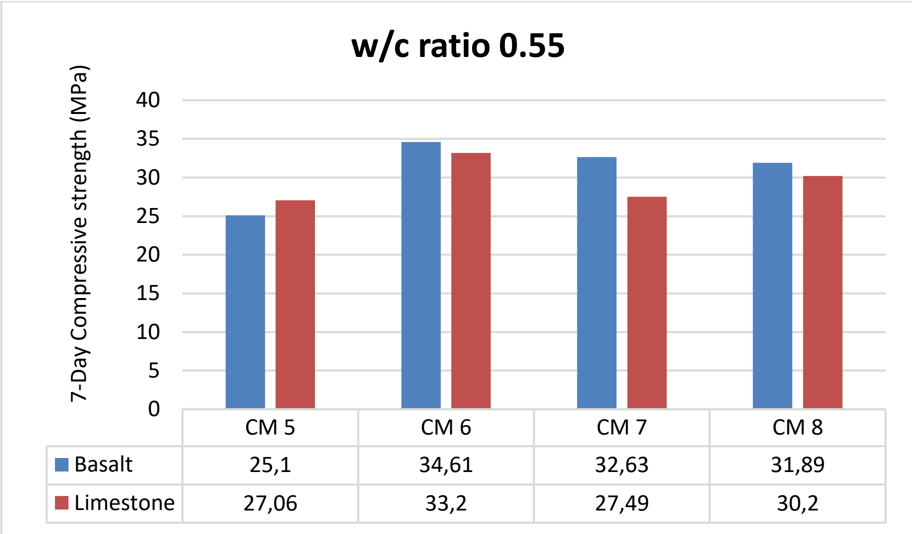

Figure 17. 7-day compressive strengths of mortar mixtures prepared with basalt and limestone aggregates with a w/c ratio of 0.55 and according to additive ratios

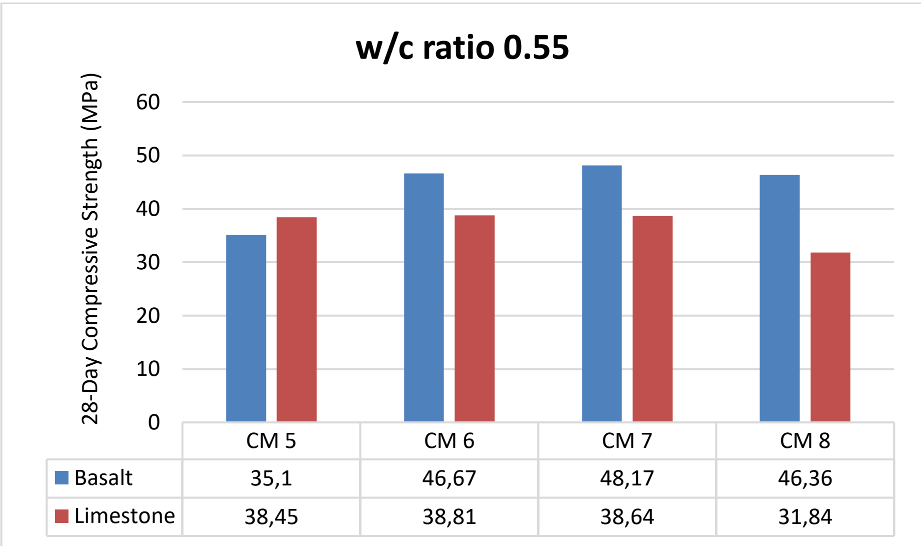

Figure 18. 28-day compressive strengths of mortar mixtures prepared with basalt and limestone aggregates with a w/c ratio of 0.55 and according to additive ratios

When the results were examined, it was found that as the curing time of the cement mortar increased, the compressive strengths showed an increase in each mixture. In the cement mortar prepared with basalt aggregate, the mixture with a w/c ratio of 0.50 exhibited the highest compressive strength in the control sample named CM1, with a 7-day compressive strength of 42.75 MPa and a 28-day compressive strength of 51.24 MPa. Since the cement mortar injected into the porous asphalt was desired to be fluid, the ideal mixture in terms of fluidity and compressive strength was the one with a w/c ratio of 0.50 and 2% additive material, which had a fluidity time of 10.32 and a 28-day compressive strength of 50.28 MPa. This CM4 basalt aggregate mortar mixture was used to obtain semi-rigid mixture samples.

Looking at the results of the mortar mixtures prepared with limestone aggregate, the control sample CM1 with a w/c ratio of 0.50 had a 28-day compressive strength of 46.21 MPa, while the control sample with a w/c ratio of 0.55 had a 28-day compressive strength of 38.45 MPa. To select the ideal mixture type in terms of fluidity and compressive strength, the CM4 limestone aggregate mortar mixture with a w/c ratio of 0.50, containing 2% additive material and a 28-day compressive strength of 41.94 MPa, was used to obtain semi-rigid samples. Since a high amount of superplasticizer can cause separation in the mixture, literature sources indicate that the superplasticizer content in cement mortar should be a maximum of 2%. Therefore, in this study, the superplasticizer ratio was selected as a maximum of 2%.

When the results of the experiment were analyzed comprehensively, when the compressive strengths based on the additive ratios used in the cement mortar are examined, the mixture prepared with basalt aggregate at a w/c ratio of 0.50 with 2% additive material had a 7-day compressive strength of 37.48 MPa. The mixture with 1% additive material achieved a 7-day compressive strength of 40.66 MPa, while the mixture with 0.8% additive material had a compressive strength of 34.25 MPa. For mixtures with a w/c ratio of 0.55, the 7-day compressive strength of the mixture with 2% additive material was determined to be 31.89 MPa, the mixture with 1% additive material was 32.63 MPa, and the mixture with 0.8% additive material was 34.61 MPa.

In the mortar mixtures prepared with limestone aggregate, the 7-day compressive strengths for the mixtures with a w/c ratio of 0.50 and with 2%, 1%, and 0.8% additive materials were found to be 28.8 MPa, 33.84 MPa, and 51.62 MPa, respectively. For the mixtures with a w/c ratio of 0.55 and with 2%, 1%, and 0.8% additive materials, the 7-day compressive strengths were obtained as 30.2 MPa, 27.49 MPa, and 33.2 MPa, respectively.

To select the most suitable mixture among the mortar combinations, the flowability time and compressive strengths of the mortar were generally examined. The cement mortar injected into the porous asphalt mixture samples was prepared by injecting each aggregate type with its corresponding mortar mixture, resulting in semi-rigid mixture samples. Since flowability is the most important factor in the mortar mixtures prepared with basalt and limestone aggregates, the CM4 mortar mixtures with a w/c ratio of 0.50 and 2% additive material were used to obtain the semi-rigid mixture samples.

Due to the lack of a standard for semi-rigid pavement design in our country, the experimental results were evaluated based on data collected from literature reviews. Accordingly, for the production of semi-rigid pavement samples, the flowability time of the cement mortar should be selected between 10 and 14 seconds, with 7-day compressive strengths ranging from 10 to 30 MPa and 28-day compressive strengths between 20 and 50 MPa. Additionally, according to Chinese standards, the flowability time of the mortar should also be within the range of 10 and 14 seconds, with compressive strengths of at least 15 MPa for 7 days and at least 30 MPa for 28 days.

4.3. Mortar Ratio and Saturation Degree

In semi-rigid pavement design, the mortar ratio and saturation degree represent the connections between the voids within the mixture. According to the literature, the saturation degree of the mortar should exceed 90%. This ensures uniform penetration within the mixture, eliminating the gaps between the interconnections. In this study, the saturation values of the mortar within the porous asphalt samples are presented in Table 11.

Table 11. The saturation degree values for the semi-rigid mixtures prepared with basalt aggregate

Type of Aggregate	M1 (g)	M2 (g)	ρ (g/cm^3)	V (cm^3)	Va (%)	Sg (%)
Basalt	1129.4	1379.4	1.92	528.62	27.2	90.5579
Limestone	1132.63	1382.63	1.92	512.35	27.2	93.4336

When examining the experimental results, the saturation degrees of the semi-rigid mixtures prepared with limestone aggregate were found to be higher than those prepared with basalt aggregate. This is attributed to the smoother surface of the limestone aggregate compared to the basalt aggregate. The saturation degrees of the prepared mixtures exceeded the threshold values.

5. Conclusion

In the study, the material properties and mixture formulations used in the production of semi-rigid pavements were presented. Flowability and compressive strength tests were conducted on the cement mortar mixtures, leading to the proposal of the most suitable mixture design. In this work, porous asphalt samples were prepared, and the selected optimal cement mortar mixture was injected into the voids to determine the saturation degrees for the semi-rigid mixtures. The results obtained from the study are as follows:

• One of the most important parameters for semi-rigid pavement layers is the cement mortar. The better the flowability of the cement mortar, the better it will penetrate the voids within the porous asphalt and connect the spaces between them.

• When examining the flowability times of the cement mortar mixtures, it was determined that the mixtures containing 2%, 1%, and 0.8% superplasticizer additives remained within the established flowability time of 10-14 seconds. Therefore, all mortar mixtures were deemed suitable. Since the cement mortar injected into the voids of the porous asphalt needs to be very fluid, it is appropriate to use CM4 cement mortar mixtures with a 2% additive amount, a w/c ratio of 0.50, and flowability times of 10.32 and 10.16 seconds, respectively.

• According to the experimental results, the compressive strengths of the cement mortars with different additive ratios showed very high values for both basalt and limestone aggregate mixtures. The mortar mixtures for both aggregate types are quite suitable for semi-rigid superstructure mixtures. However, since flowability is more important than compressive strength, better results can be achieved by using mixtures with a 2% additive ratio and a w/c ratio of 0.50.

• Additionally, it was determined that selecting lower w/c ratios in the cement mortar mixtures positively affects their strength.

• In future studies, it is suggested to investigate many factors of the cement mortar, such as curing time, rheological properties, shear strength, elastic modulus, segregation rate, and adhesion strength. Furthermore, cement production causes carbon dioxide emissions both directly and indirectly. Therefore, research can be conducted to develop durable, sustainable, and cost-effective cement mortars for semi-rigid pavement surfaces by using a significant percentage of municipal/industrial waste.

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Conflict of Interest

No conflict of interest was declared by the authors.

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