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Effect of Filler to Bitumen Weight Ratio on Low-temperature Cracking Performance of Asphalt Mixture

Sajad Rezaei [1]***, Mohammad Mehdi Khabiri***[2]*****, Behzad Pezeshki*** [3]***,***
Mojtaba Bagheri Movahed [4]***, Amir Hossain Khakbazan*** [5]

[1] *Department of Civil Engineering, Yazd University, Yazd, Iran. E-Mail: sajadrezaei@yazd.ac.ir*
[2] *Department of Civil Engineering, Yazd University, Yazd. Iran. E-Mail: mkhabiri@yazd.ac.ir*
[3] *Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Iran. E-Mail: behzad.pezeshki@srbiau.ac.ir*
[4] *Development and Civil Organization of Qom Municipality, Qom, Iran. E-Mail: mbmovahed@qom.ir*
[5] *Development and Civil Organization of Qom Municipality, Qom, Iran. E-Mail: akhakbazan@qom.ir*

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ABSTRACT

The effect of mineral filler weight ratio on the low-temperature performance of hot asphalt mixtures with continuous gradation has been a subject of significant interest in the field of pavement engineering. This study focused on testing mastic, which is a bitumen mixture with mineral filler passing through a No. 200 sieve, using various tests, such as the bending beam rheometer test (BBR), direct tensile (DT) test, Infrared spectroscopy test (FTIR), X-ray diffraction (XRD) test, and semi-circular bending (SCB) test. Different weight ratios of mineral filler to useful bitumen ranging from 0.4 to 1.6 were investigated for PG 70-16 bitumen. According to the SHRP-A-407 standard, the weight ratio of mineral filler to useful bitumen plays a crucial role in determining the low-temperature performance of asphalt mixtures. The research findings confirm this fact, indicating that the weight ratio of mineral filler to bitumen plays a crucial role in determining the low-temperature performance of asphalt mixtures. As the filler-to-bitumen ratio increased, the stiffness of the bituminous mastic increased, leading to reduced fracture strain and decreased low-temperature cracking life. The optimal filler-to-bitumen ratio was recommended to be a maximum of 0.8 to balance performance and control low-temperature behavior. The results of this study underscore the importance of considering the rheological properties of bitumen mastic in addition to bitumen and asphalt mix when evaluating low-temperature performance.

Keywords: Asphalt mixing, Filler-to-bitumen ratio, Cracking performance, Low-temperature, cracking.

INTRODUCTION

The pursuit of asphalt pavements capable of excelling in low-temperature conditions while exhibiting sufficient resistance to stresses imposed by heavy vehicle traffic has long captivated the interest of researchers and industry professionals alike (Hamedi et al., 2019). The amalgamation of bitumen and mineral filler, commonly referred to as mastic, plays a pivotal role in enhancing the performance and durability of asphalt mixtures. Mineral fillers are instrumental in bolstering the stability of asphalt mixes by diminishing voids and augmenting hardness (Barra et al., 2014, Chen et al., 2022). Topini et al. (2018) explored the application of such sustainable filler materials as recycled glass powder and waste foundry sand, in asphalt mixtures. The study evaluated the effect of these alternative fillers on the low-temperature cracking performance of asphalt mixtures, considering the filler-to-bitumen ratio as a critical parameter. The findings suggested that the incorporation of these sustainable fillers, when optimized with respect to the filler to bitumen ratio, can contribute to the enhancement of low-temperature cracking resistance while promoting the circular economy principles in the construction industry (Topini et al., 2018). A review by Li et al. (2024) provided a comprehensive synthesis of the current knowledge on the influence of filler to bitumen ratio on the low-temperature performance of asphalt mixtures. The authors critically analyzed the existing literature, identified knowledge gaps, and proposed future research directions to further advance the understanding of this complex relationship. The review underscored the importance of considering the filler to bitumen ratio as a key design parameter in the development of resilient and sustainable asphalt pavements. Hence, experts have dedicated considerable attention to determining the optimal weight ratio between filler and effective bitumen (Steineder et al., 2022; Rezaei et al., 2023; Guo et al., 2020). In a study, a range of laboratory tests, including indirect tensile strength (ITS) test and thermal stress restrained specimen (TSRST) test, were used to evaluate the performance of asphalt mixtures with different filler/bitumen (F/B) ratios. Findings showed that there is an optimal F/B ratio, where cracking resistance is maximized at low temperatures, and deviation from this optimal ratio can lead to performance deterioration (Asmael, 2020). Also, another study used a comprehensive approach, including the bending beam rheometer (BBR) test and the disc-shaped compressive stress (DCT) test to evaluate the low-temperature performance of asphalt mixtures with different F/B ratios. The results confirmed the findings of the previous study and showed that the F/B ratio is an important parameter in determining the low-temperature cracking resistance of asphalt mixtures (Boz & Jhony, 2021). As per the specifications outlined in the Strategic Highway Research Program (SHRP)-A-407, this ratio is recommended to fall within the range from 0.6 to 1.2. Several international organizations and research bodies have developed guidelines and standards to address the appropriate mineral filler to bitumen weight ratio in asphalt mixtures. The American Society for Testing Materials (ASTM) Standard D3515-96, according to this standard, recommends a mineral filler to bitumen weight ratio range from 0.6 to 1.2 for hot-mix asphalt (HMA) mixtures; and the European Standard (EN) 13108-1:2016 suggests an F/B ratio from 0.6 to 1.2 for asphalt concrete mixtures (ASTM D3515, 2016; EN 13108-1, 2016). This prescribed range reflects the intricate balance required to achieve an asphalt mixture that delivers exceptional performance across a spectrum of environmental and load conditions. By meticulously considering the composition and proportions of mastic components, engineers and researchers are able to fine-tune asphalt mixtures to meet the stringent demands of modern infrastructure projects and ensure the longevity and reliability of pavement systems.

In a separate research endeavor, the importance of the weight ratio of filler to useful bitumen in achieving optimal low-temperature performance was underscored by Chen and He (2008). Building upon this insight, the primary objective of the present study is to assess the weight ratio of mineral filler to useful bitumen in accordance with SHRP-A-407 standard, focusing on the low-temperature performance of asphalt mixtures. The aim is to gain a comprehensive understanding of how this ratio influences the low-temperature performance of hot asphalt mixtures with continuous gradation, enabling adjustments in the asphalt mixing design to enhance the expected performance outcomes. To achieve this goal, a series of tests were conducted on bituminous mastic and asphalt mixture samples with varying weight ratios of mineral filler to useful bitumen (ranging from 0.4 to 1.6) using Performance Grade (PG) 70-16 bitumen. These tests included the BBR test (AASHTO T 313), the DT test (AASHTO T 314), the FTIR test (ASTM E168, ASTM E1252), and the X-ray diffraction test (XRD) for bituminous mastic samples, as well as the SCB test (AASHTO TP 105-13) for assessing low-temperature performance in asphalt mixture samples. The existing body of research underscores the critical role of the F/B ratio in determining the low-temperature cracking performance of asphalt mixtures. The studies highlighted in this essay have contributed to a deeper understanding of the underlying mechanisms and provided practical insights into the design and construction of resilient and durable asphalt pavements. As the industry continues to prioritize sustainable and climate-resilient infrastructure, the optimization of the F/B ratio will remain a pivotal consideration in the development of next-generation asphalt mixtures. By meticulously examining the impact of different weight ratios on various performance parameters, this study aims to provide valuable insights into optimizing the design and composition of asphalt mixtures to enhance their low-temperature performance characteristics.

MATERIALS AND RESEARCH METHODOLOGY

Materials

The performance grade of bitumen PEN60/70 or PG70-16 from asphalt plant no. 2 (Aman) of Qom Municipality, which is the most consumed type of bitumen, was evaluated through various tests to determine its adequacy and quality. The results of these tests can be found in Table 1.

Table 1. Bitumen properties and test results

Experiment	Experiment results	The approved range of regulations	Quality
Specific gravity at 25 °C	1.018	-	OK
Penetration degree at 25 °C (0.1 mm)	60	60-70	OK
Soft point (°C)	51	49-56	OK
Degree of ignition (°C)	306	Minimum 232	OK
Ductility at 25 °C (cm)	100	Minimum 100	OK
Solubility in trichloroethane (%)	99.8	Minimum 99	OK
G*/sinδ in shear dynamic rheometer (Pa) at 70 °C on the unaged pitch with the frequency of 10 rad/s	1060	Minimum 1000	OK
G*/sinδ in shear dynamic rheometer (Pa) at 70 °C on the aged pitch RTFO with the frequency of 10 rad/s	2380	Minimum 2200	OK
Creep stiffness in bending beam rheometer (MPa) at -6 °C	80	Maximum 300	OK
The amount of m in bending beam rheometer at -6 °C	0.342	Minimum 0.3	OK
*Based on 1 to 3, the performance grade of used pitch is PG 70-16			

The research utilized dolomite limestone aggregates sourced from Kahak mine of asphalt plant no. 2 in Qom municipality, comprising 0-19 types, including medium gravel, fine gravel, and sand from the hot silo. The filler was obtained from the asphalt plant dust collection system. Tests to evaluate the adequacy and quality of the filler and aggregate are shown in Table 2.

Table 2. Filler and aggregate properties

Dimensions and size of aggregates	Tests		Test results	The approved range of regulations	Conforming to the specifications
Filler Aggregates	Atterberg Limits (AASHTO T89, 90)	Plasticity Index (PI)	NP	Maximum 4	OK
	Specific gravity at 25 °C (gr/cm^3) (AASHTO T100)		2.633	-	OK
Coarse-grained Aggregates (Gravel)	Fracture Aggregates (ASTM D5821)	One Side	100%	At least 95%	OK
		Two Side	98%	At least 90%	OK
	Weight loss *versus* sodium sulfate (AASHTO T104)		0.3%	Maximum 8%	OK
	Percentage of broad and long aggregates (ASTM D4791)		7%	Maximum 15%	OK
	Los Angeles weight loss against abrasion (AASHTO T96)		18%	Maximum 25%	OK
	Water absorption		1.3%	Maximum 2.5%	OK
	Specific weight (gr/cm^3) (AASHTO T85)	Apparent density	2.709	-	OK
		Bulk density	2.620	-	OK

The comparison between the final grading from mixing and the proposed grading of SHRP A407 standard is presented in Table (3) for reference and analysis.

Table 3. Particle- size distribution of aggregate mixture

Sieve size	SHRP A-407		The average passing percentage of each sieve	Compliance with the range of standards
	Min.	Max.		
¾”	100	100	100	OK
½ ”	90	100	94	OK
#4	-	-	62	OK
#8	28	58	42	OK
#50	-	-	13	OK
#200	2	10	5	OK

Sample Preparation

Sample preparation in the realm of asphalt technology is a critical process that demands precision and adherence to specific temperatures and mixing guidelines. The viscosity of bitumen, when combined with aggregates to create asphalt mixtures, plays a pivotal role in determining the overall quality and performance of the final product. It is imperative that the mixing temperature is carefully controlled to ensure that the viscosity falls within the range from 170 ± 20 to 280 ± 30 centistokes (CST). For the mixing of bitumen and aggregate (as Table 4), temperatures between 149°C and 155ºC are recommended, while the compaction of the asphalt mixture should occur within the range from 139°C to 143°C. To create bitumen mastic samples, the bitumen is initially heated to 155°C and then mixed with filler gradually in a mechanical mixer for 15 minutes to achieve a homogeneous mixture.

Table 4. The matrix of the experimental design of the mixture of bituminous mastic

Sample Code	Composition of Various Materials	Weight Ratio (%)
S1.0	Filler/Bitumen Ratio 0	0
S2.6	Filler/Bitumen Ratio 0.6	60
S3.8	Filler/Bitumen Ratio 0.8	80
S4.10	Filler/Bitumen Ratio 1.0	100
S5.12	Filler/Bitumen Ratio 1.2	120
S6.14	Filler/Bitumen Ratio 1.4	140
S7.16	Filler/Bitumen Ratio 1.6	160

The preparation of asphalt samples involves a meticulous process, where the weight ratio of mineral filler to bitumen is varied to study its impact on the final mix. Standardized methods, such as the Marshall method (AASHTO T245) and the modified Marshall method (ASTM D5581) are employed for mix design and quality control purposes, depending on the characteristics of the aggregates used. The use of these methods allows for the fabrication of test specimens that undergo rigorous testing to assess properties, such as stability, flow, and void content. Test methods, like the BBR test, are employed to evaluate the rheological properties of the asphalt samples, providing crucial insights into their performance under different conditions. By following established protocols and conducting thorough testing, researchers and engineers can gain valuable insights into the behavior and characteristics of asphalt mixtures, ultimately contributing to the advancement of asphalt technology. In the process of designing asphalt mixes for the creation of asphalt samples with varying weight ratios of mineral filler to useful bitumen, a series of standardized methods were employed. Table 5 shows the theoretical maximum specific gravity for different bitumen percentages.

Table 5. Theoretical maximum specific gravity for different percentages of bitumen

Theoretical maximum specific gravity (gr/cm^3)	Percentage of bitumen
2.465	4.0
2.447	4.5
2.429	5.0
2.411	5.5
2.394	6.0
2.377	6.5

The Marshall method (AASHTO T245) was utilized for both mix design and asphalt operation control for aggregates with a maximum size of 25 mm and a dense, continuous gradation. For aggregates with a maximum size of 50 mm and 15 cm molds, the modified Marshall method (ASTM D5581) was employed. The modified Marshall method was specifically utilized for the design and production of SCB test specimens (AASHTO TP 105-13) with a 15 cm diameter. Asphalt mix samples were prepared with varying percentages of bitumen at specified temperatures and compacted using a specific number of blows as per the respective method requirements. In the mix design, the aim is to maintain the average void content of the specimens at 4% throughout. The theoretical maximum specific gravity of the asphalt mixtures for different bitumen percentages was determined using the Rice test in accordance with the American Association of State Highway and Transportation Office (AASHTO) T209 standard. Additionally, the absolute specific gravity of compacted asphalt mixture (G_{mb}) samples was determined following the AASHTO T166 standard, while the stability and flow characteristics were assessed based on the AASHTO T245 standard method for the different bitumen percentages. Furthermore, calculations for void content percentages of dense asphalt mixture (Air Void), void content percentages of the aggregate mixture (VMA), and void content percentages of the aggregate mixture filled with bitumen (VFA) were performed as per the relations outlined in the MS-2 Journal of the Asphalt Institute.

Test Methods

The BBR test, conducted in accordance with ASTM D2872 and ASTM D6521 standards, involves subjecting the samples to a controlled temperature creep load in the middle of a beam. The midpoint bend is recorded at specific time intervals to determine creep softness using mathematical equations (Ghuzlan et al., 2021). The stiffness, along with maximum bending stress and bending strain, are key parameters evaluated in this test. The BBR test is essential for assessing bitumen properties at low temperatures (Das et al., 2017; Ho et al., 2011). The DT test, following AASHTO T 314 standard, focuses on determining fracture properties under direct tensile force for aged Rolling Thin-Film Oven and Pressure Aging Vessel (RTFO + PAV) bitumen. The test procedure involves mounting the sample on a loading mold, zeroing the strain, and applying tension until reaching a specific load value. Fracture strain is then calculated based on the increase in length at the fracture moment relative to the sample's effective length. These tests play a crucial role in evaluating the performance and quality of bitumen for various applications, especially in low-temperature conditions (Figure 1).

Figure (1): A) Bitumen mastic bending beam samples for the BBR test and B) Molded samples of bitumen mastic for the DT test

Fourier-Transform Infrared and X-Ray Diffraction Analyses

FTIR testing using Fourier transform based on ASTM E168 and ASTM E1252 standards is a widely utilized method for analyzing polymers and their additives. This technique relies on the correspondence between the electromagnetic radiation frequency in the infrared region and the natural vibration frequency of atoms within a molecule. Upon absorption of infrared waves, molecules undergo a series of vibrational motions, with flexural and tensile movements being the simplest types. The FTIR device, employing Fourier mathematical conversion, offers numerous advantages over traditional IR devices, including rapid data collection and improved signal-to-noise ratio. For this study, FTIR spectra were acquired using a JASCO 4100 series spectrometer from Japan, analyzing bituminous mastic samples with a 5% weight-to-volume concentration in tetrahydrofuran solvent. Spectra were recorded from 4000 cm^{-1} to 400 cm^{-1} with an accuracy of 2 cm^{-1}.

XRD testing is a prevalent method for determining material structures by examining the location, shape, and intensity of XRD ray reflections. In this research, XRD was conducted using a PHILIPS PW1730 device from the Netherlands, analyzing bituminous mastic samples with X-ray Cu radiation (wavelength of 1.54056 angstrom) and a step size of 0.05 degree. Each step lasted 1 second, with the goniometric angle ranging from 5 degrees to 80 degrees, a voltage of 40 kV, and a current of 40 mA. The scattering intensity results were reported for goniometric angles between 5 degrees and 80 degrees. These analytical techniques provide valuable insights into the molecular structures and properties of the materials under investigation.

Semi-circular Bending Test

An SCB test was conducted in accordance with the AASHTO TP 105-13 standard at the UTM Device Technical and Soil Mechanics Laboratory of Tehran Ministry of Roads and Urban Development. The test involved seven different combinations of asphalt samples, with six samples tested per combination, totaling 42 samples. All samples were tested at a temperature of -10° C and were found to be unsaturated. Using the UTM device, load values were measured against the linear displacement of SCB specimens, enabling the determination of the resistance to failure at low temperatures based on the area under the load-displacement diagram. The asphalt samples were prepared using the modified Marshall method (ASTM D5581) and were characterized by a 150-mm diameter, a 100-mm height, and a 4% void content. SCB samples with specific dimensions and a central crack were then created for the test. The testing procedure involved applying incremental loads at specified rates until failure occurred, with load values and displacement data recorded throughout the test. The results included a cumulative permanent vertical strain diagram and the identification of the maximum tolerable force and loading cycle leading to sample failure. The positioning of SCB samples in the UTM device loading cell was illustrated in Figure 2.

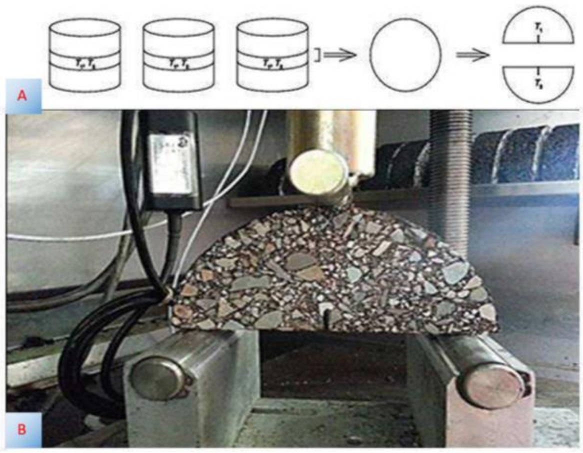

Figure (2): A) Preparing of SCB samples and B) Placement of samples and molds in the semi-circular bending test apparatus

RESULTS AND DISCUSSION

Mix-design Properties

The maximum specific gravity of asphalt mixture theory for different percentages of bitumen was determined using the AASHTO T209 standard as outlined in Table 5. The curve depicting changes in particle density quantities of dense asphalt mixture (G_{mb}) samples, as well as stability and flow of Marshall samples, percentage of dense asphalt mixture void content (Air Void), percentage of aggregate void content (VMA), and percentage of void content of aggregate mixture filled with bitumen (VFA) were analyzed. This analysis was crucial in determining the optimal bitumen percentage for the main design. The VMA graph in

Figure (3) suggests that as the percentage of asphalt binder in the mixture increases, the void space between the compacted aggregate particles decreases. This phenomenon can be attributed to the fact that with higher asphalt binder content, the individual aggregate particles become more thoroughly coated and the overall volume of the mixture becomes more compact, reducing the void space. The bulk specific gravity or unit weight of the asphalt mixture initially shows an increase, followed by a subsequent decrease. This behavior can be explained by the interplay between the specific gravities of the asphalt binder and the aggregates. At lower asphalt binder contents, the increase in G_{mb} is primarily due to the higher specific gravity of the asphalt binder compared to the aggregates. However, as the asphalt binder content continues to rise, the overall specific gravity of the mixture begins to decrease due to the lower specific gravity of the asphalt binder, resulting in the observed downward trend in the G_{mb} graph. As the asphalt binder content in the mixture increases, the Marshall flow value also increases. This relationship can be attributed to the lubricating and softening effects of the asphalt binder. With higher asphalt binder content, the mixture becomes more pliable and susceptible to plastic deformation, leading to a larger flow value during the Marshall test.

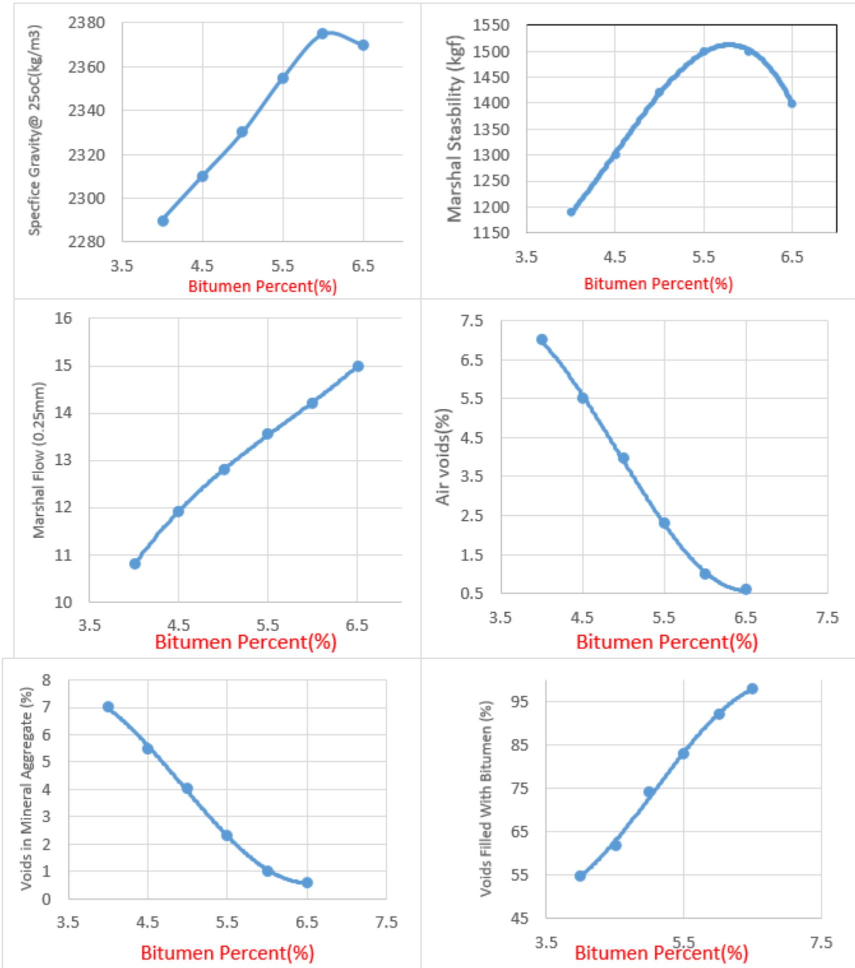

Figure (3): The variations in bitumen percentage and its effects on various parameters, top-to-bottom, right-to-left sequence: specific gravity, Marshal stability, Marshal flow, Air voids, Voids in mineral aggregate and voids filled with bitumen

The MS-2 Journal outlines that for a 4% void content, the optimal bitumen percentage for asphalt design is 5%, with 3.9% effectively absorbed by the aggregate surface. It is important to note that all other quantities within the asphalt mixture were controlled to align with this specified bitumen percentage and fall within the acceptable range of standard specifications. Following the SHRP-A-407 standard, the filler weight ratio to useful bitumen for the asphalt mixture containing 5% bitumen was calculated to be 1.08, a value that falls within the prescribed range from 0.6 to 1.2 as per the regulations. The filler weight ratio of 1.08 ensures optimal asphalt performance, complies with standards, and supports the formulation's integrity. Various asphalt mixing designs were investigated for different weight ratios of filler to useful bitumen, ranging from 0.4 to 1.6. The specific mixing design mentioned above was selected based on a ratio of 1.0. To explore additional designs, the 1.0 ratio of filler to useful bitumen served as a reference point, and the values of filler and bitumen were modified through iterative trial and error methods.

Bending Beam Rheometer Test

In the realm of pavement engineering, the BBR test holds significance in assessing the behavior of asphalt mixtures under varying temperatures. As temperatures drop, asphalt mixtures at the surface tend to contract, leading to the development of tensile stresses. These stresses can result in low-temperature cracks when the asphalt's tensile resistance is surpassed due to restricted movement caused by friction with the pavement substrate. The test involves subjecting a bitumen beam sample to a small creep to determine its creep stiffness. Excessive creep stiffness indicates brittleness in the bitumen, which increases the risk of low-temperature cracking. The critical cracking temperature of bitumen through the BBR test at varying temperatures was assessed. For aged RTFO+PAV bitumen, it is recommended that the values of S and m at the test temperature should be below 300 kPa and above 0.3, respectively. Figures (4) and (5) illustrate the values of S and m from the BBR-test results for various samples of aged bituminous mastic RTFO+PAV at temperatures of 0ºC, -6 ºC, and -12ºC. The selection of temperature values for the Bending Beam Rheometer (BBR) test is crucial for evaluating the low-temperature performance of asphalt mixtures. These temperatures represent a range that is critical for understanding the material's behavior as it transitions from a more ductile state at higher temperatures to a brittle state under colder conditions.

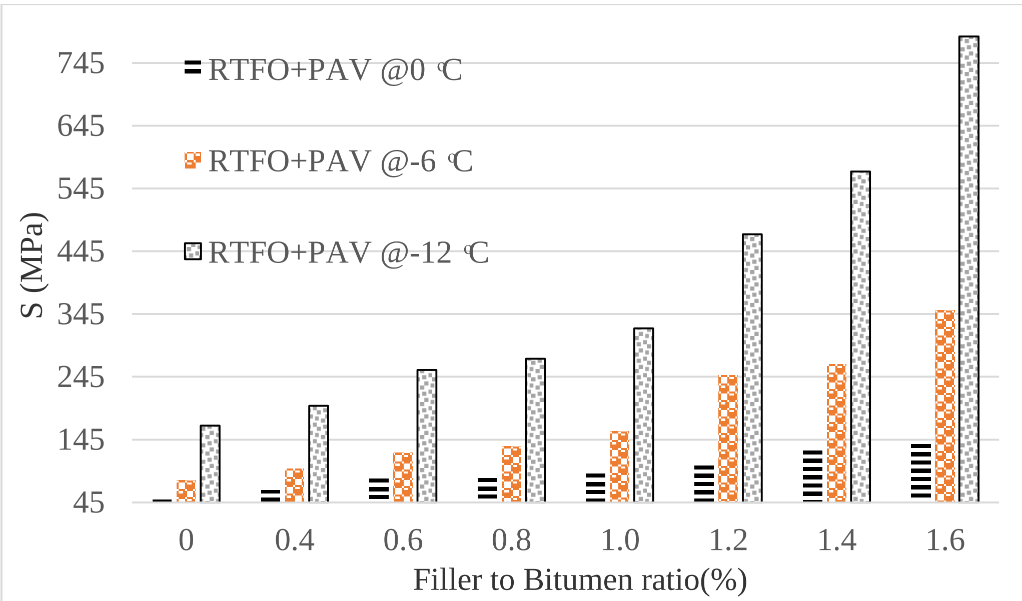

Figure (4): Effects of temperature and F/B ratio on creep stiffness in aged RTFO+PAV samples

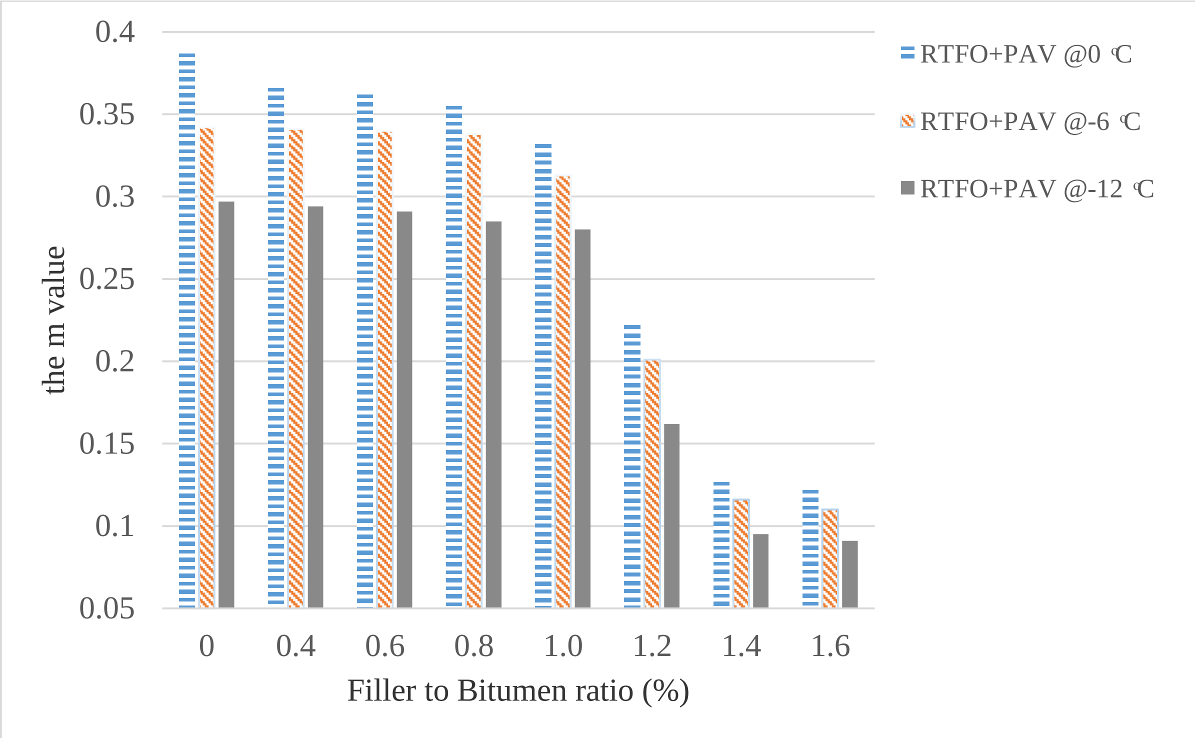

Figure (5): Influence of F/B ratio on the creep stiffness at different temperatures in the aged situation of RTFO+PAV

As depicted in Figures (4) and (5), the relationship between F/B ratio and the values of S and m is evident. With an increase in the F/B ratio, the value of S tends to rise, while the value of m decreases. This phenomenon can be attributed to the stiffening effect and reduced elasticity of bituminous mastic as the filler's proportion increases. Figure 6 illustrates that at a temperature of -6°C, corresponding to a low-temperature performance evaluation of -16°C based on the performance grade of the base bitumen, all ratios except for the ratio of 1.6 exhibit creep stiffness values below 300 MPa, meeting the requirements outlined in the MS-4 guidelines. However, as per Figure 10 at the same temperature, only ratios equal to or less than 0.1 exhibit m values exceeding 0.3, thereby fulfilling the relevant criteria. Consequently, it can be inferred that to mitigate low-temperature cracking in asphalt mixtures, the maximum filler to useful bitumen weight ratio should not exceed 0.1. To account for a higher safety margin and achieve a performance grade lower than -16°C, such as a functional grade of -22°C (equivalent to a test temperature of -12°C), the filler to useful bitumen weight ratio should be maintained below 0.8. According to Li et al. (2022), the compliance of the S value with the stipulated standards indicates that a filler to useful bitumen weight ratio below 0.8 is necessary for effective control of low-temperature cracking and overall enhancement of low-temperature performance. Therefore, as the filler content increases, the resistance to low-temperature cracking diminishes, potentially due to the decreased elasticity of bitumen mastic in comparison to its viscosity.

Direct Tensile Test

To assess the low-temperature performance, the DT test was conducted (Cao et al., 2021; Xu et al., 2021). It is expected that the fracture strain percentage for aged RTFO+PAV bitumen samples at test temperature exceeds 1%. Figure (6) displays the fracture strain percentage results from the DT test on various samples of aged bituminous mastic RTFO+PAV at temperatures of 0ºC, -6ºC, and -12ºC.

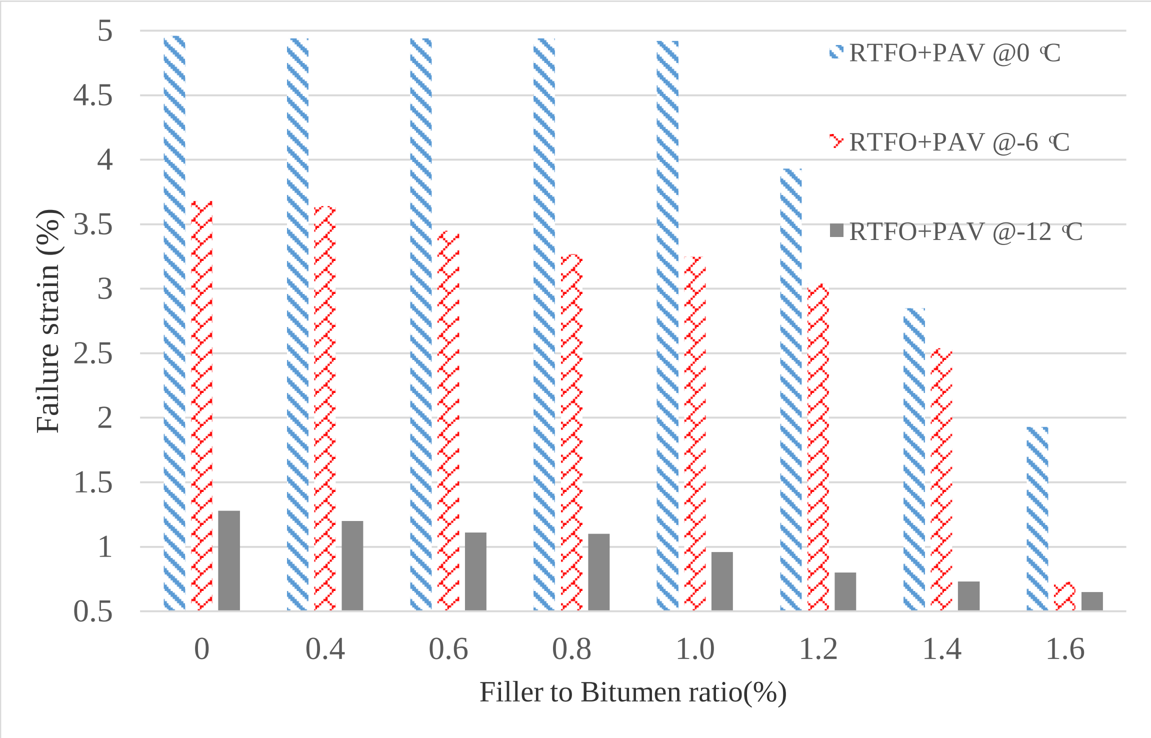

Figure (6): Fracture strain values for different filler to bitumen ratios at 0°C, -6°C and -12°C in the aged state of RTFO+PAV

As illustrated in Figure 8, the relationship between the F/B ratio and fracture strain becomes apparent as the ratio increases. This decrease in fracture strain could be attributed to the augmented stiffness and diminished elasticity of the bitumen mastic as the filler proportion rises. At a testing temperature of -6°C, which corresponds to a low-temperature performance evaluation of -16°C based on the performance grade of the base bitumen, all ratios, with the exception of the 1.6 ratio, exhibit a fracture strain exceeding 1%. Consequently, it can be inferred that to mitigate low-temperature cracking in asphalt mixtures, the optimal weight ratio of filler to effective bitumen should not exceed 1.4. However, for enhanced safety considerations and to achieve a performance grade lower than -16°C, such as the functional grade of -22°C, equating to a test temperature of -12°C, weight ratios of filler to bitumen below 0.8 display fracture strains meeting the required standards. Thus, to effectively combat low-temperature cracking and enhance the overall low-temperature performance, it is imperative to adhere to a filler to useful bitumen weight ratio below 0.8. Consequently, as the filler content increases, the ability to withstand cracking at low temperatures diminishes, potentially due to the weakening of bitumen mastic elasticity in comparison to viscosity (Al-Mohammedawi et al., 2020; Ishaq et al., 2022).

Fourier-Transform Infrared and X-Ray Diffraction Analyses

The FTIR spectrum for various F/B ratios compared to pure bitumen is depicted in Figure (7).

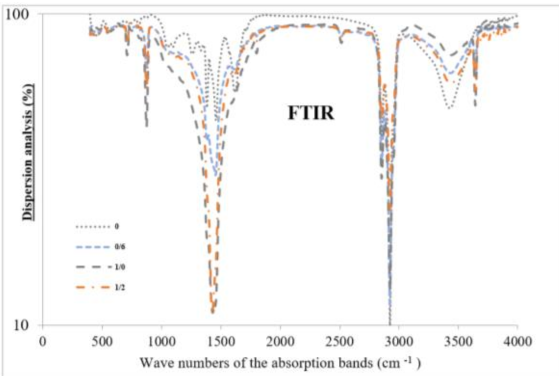

Figure (7): **Results of FTIR test**

In Figure (7), the FTIR spectra depict various bituminous mastic compounds exhibiting a consistent pattern within the wavelength range below 400cm^{-1} and above 1500cm^{-1}, while showcasing changes in the wavelength range spanning from 400 cm^{-1} to 1500 cm^{-1}. This particular range corresponds to the bending absorption region, commonly referred to as the fingerprint region, in the operation of an infrared spectrometer. The bending peaks observed in this fingerprint region play a crucial role in analyzing the performance of materials at medium and low temperatures, aiding in their qualitative identification. Researchers have highlighted the significance of an increased number of bending peaks in this region for bitumen materials, indicating enhanced performance at medium and low temperatures (Khordehbinan & Kaymanesh, 2020). Notably, in Figure 8, it is evident that the base bitumen and a filler to bitumen ratio of 0.6 exhibit the highest bending peaks in the wavelength range from 400 cm^{-1}to 1500 cm^{-1}, suggesting superior performance in medium and low temperatures compared to other compounds. Consequently, the findings suggest that augmenting the F/B ratio may potentially compromise the performance of materials at medium and low temperatures, a trend that aligns with the outcomes of fatigue performance tests and assessments of low-temperature behavior in bitumen and asphalt mixtures. The pattern in the wavelength range below 400cm^{-1} and above 1500 cm^{-1} indicates characteristic functional groups or molecular structures in bituminous mastic compounds. The most important observations are in the range from 400 cm^{-1} to 1500 cm^{-1}, known as the "fingerprint" region. Bending absorption peaks in this region are vital for analyzing material performance at medium and low temperatures. More bending peaks in this region suggest better performance at medium and low temperatures for base bitumen and the compound with an F/B ratio of 0.6 compared to other compositions. XRD analysis of various ratios of filler to useful bitumen is depicted in Figure (8). The results show a consistent pattern across different compounds, where the peak axis and level remain largely uniform while the peak intensity varies. As previously discussed, XRD offers a means to chemically analyze bitumen samples by examining peak axis, peak level, and peak intensity. The peak intensity serves as an indicator of the relative resistance of dispersion. Lower peak intensity suggests reduced dispersion resistance, leading to improved consistency of the bitumen material, but potentially weaker low-temperature performance (Khordehbinan & Kaymanesh, 2020). This phenomenon may be attributed to the increased hardness of bitumen resulting from filler addition, which enhances material stiffness by reinforcing cohesive forces between fine filler particles and the bitumen mastic.

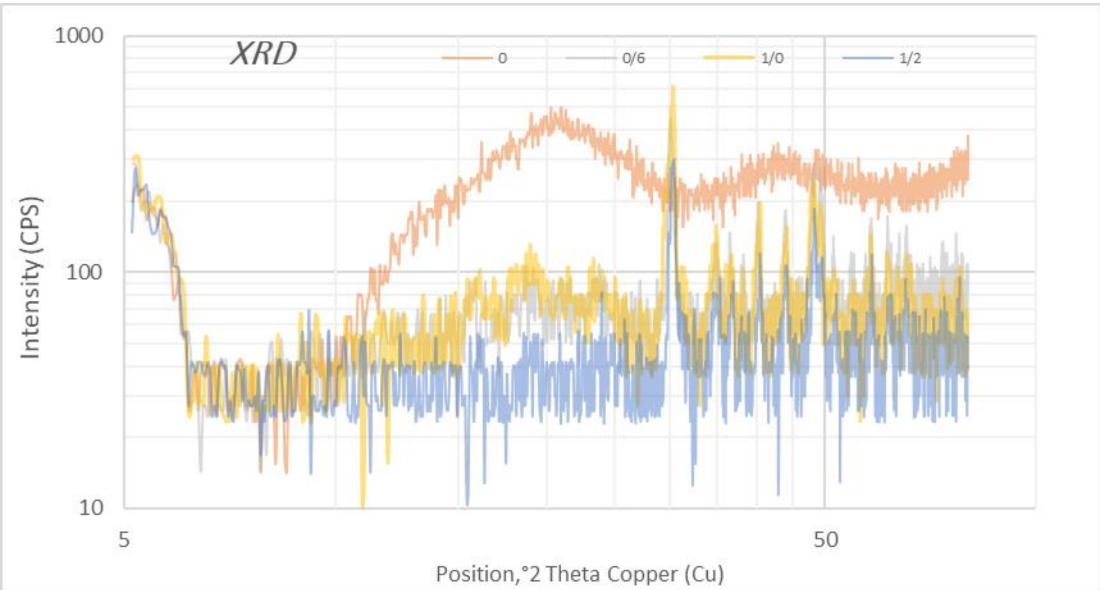

Figure (8): XRD-test results of bituminous mastic samples

Semi-circular Bending Test

The assessment of low-temperature performance in materials is crucial for ensuring the durability and reliability of infrastructure in cold climates. One commonly employed method for evaluating this aspect is the SCB test, which adheres to the specifications outlined in the AASHTO TP 105-13 standard (Ziari et al., 2023). By subjecting samples to controlled loading conditions at a test temperature of -10°C, researchers can observe the cumulative permanent vertical strain and maximum fracture capability of the material over time. Figures (9) and (10) present the results of these tests, illustrating the relationship between load time (in seconds) and the corresponding performance metrics. The use of a linear displacement rate of 0.005 mm/s until the sample reaches failure provides valuable insights into the behavior of materials, particularly when considering factors, such as the operating grade of base bitumen (e.g. PG70-16) and the extreme temperatures experienced in real-world conditions.

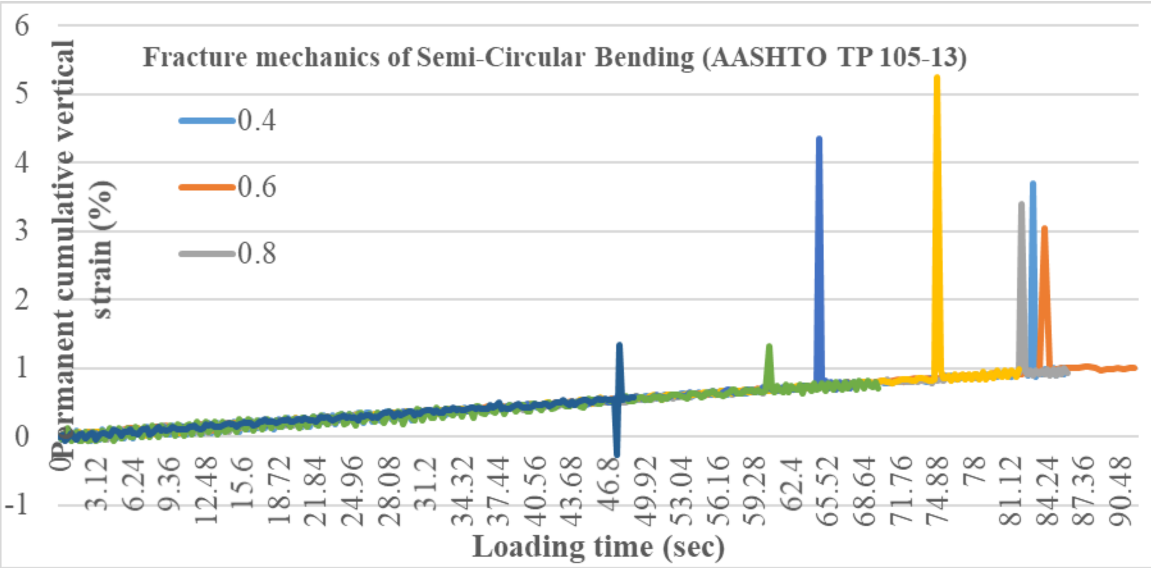

Figure (9): Cumulative permanent vertical strain of asphalt mixtures with different filler to useful bitumen ratios in the SCB test

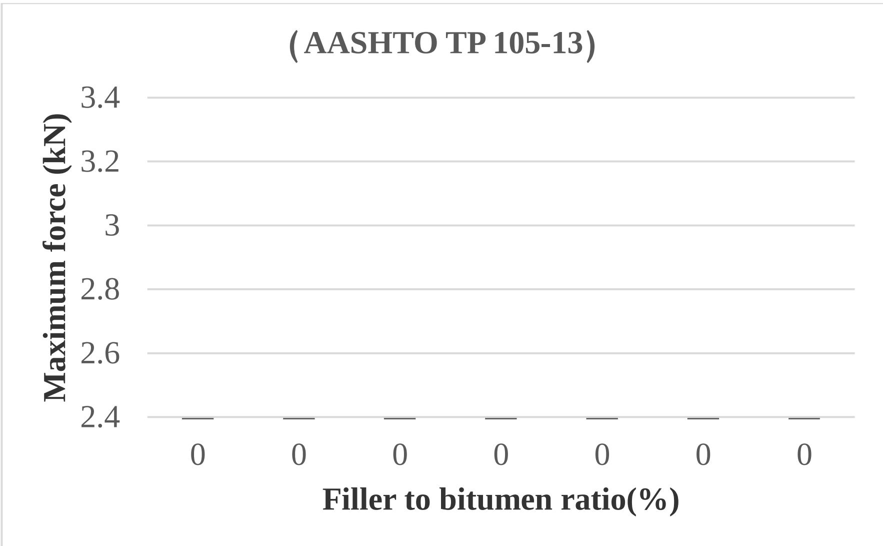

Figure (10): Maximum fracture resistance of asphalt mixtures with different filler to useful bitumen ratios in the SCB test

In Figure 10, distinct groups of behavior are evident in the cumulative permanent strain changes of the SCB test across various F/B ratios. These groups are categorized based on specific ratios: 1.6, 1.2 and 1.4, 0.1, and 0.4, 0.6, and 0.8. The first group, represented by the ratio of 1.6, exhibits poor resistance, reaching a strain of 7% at the 50^{th} second. The subsequent groups reach the same strain at different time intervals, with the second group displaying weak resistance at 65 seconds, the third group showing medium resistance at 75 seconds, and the fourth group demonstrating high resistance at 80-85 seconds. Furthermore, these groups can be further classified based on their maximum breakable force, with corresponding fracture resistances of 2.5 kN, around 3 kN, and approximately 3.4 kN. Notably, to enhance the low-temperature performance of asphalt mixtures, it is advisable to maintain the F/B ratio at a maximum of 0.6. The increase in this ratio leads to a decrease in the time taken to reach fracture strain and subsequently reduces the low-temperature cracking life, possibly due to the heightened stiffness and decreased bitumen mastic elasticity resulting from a higher filler share. Other researchers have also highlighted this point (Fusco et al., 2020; Zhang et al., 2021). Comparing the low-temperature cracking life at a filler to useful bitumen ratio of 0.4 to that of 0.1 reveals a significant improvement of over 10% and more than 80% compared to the ratio of 1.6. Consequently, the ratios of 0.4 and 0.6 emerge as the optimal designs for enhancing the low-temperature performance of asphalt mixtures among the analyzed options. These findings align with the parameters observed in the BBR test, as well as the outcomes of the DT and FTIR tests.

As evidenced by the provided justifications, the relationship between the F/B ratio and the pavement's low-temperature performance is well-documented. With an increase in the filler proportion, the value of stiffness (S) tends to rise, while the value of (m) decreases. This phenomenon can be attributed to the stiffening effect and reduced elasticity of the bituminous mastic as the filler's proportion increases. At a low-temperature evaluation of -16°C, based on the performance grade of the base bitumen, the data reveals that all ratios except the 1.6 ratio exhibit creep-stiffness values below the 300 MPa threshold, as stipulated in the MS-4 guidelines. However, when considering the m-value criterion, which requires a minimum value of 0.3 to mitigate low-temperature cracking, only ratios equal to or less than 0.1 meet this requirement. To account for a higher safety margin and achieve a performance grade lower than -16°C, such as a functional grade of -22°C (equivalent to a test temperature of -12°C), the F/B ratio should be maintained below 0.8. This recommendation is further supported by the observed relationship between the F/B ratio and fracture strain, which decreases as the ratio increases. At the -16°C low-temperature performance evaluation, all ratios except the 1.6 ratio exhibit a fracture strain exceeding 1%, meeting the required standards. However, to enhance safety considerations and achieve the desired -22°C performance grade, weight ratios of F/B ratio below 0.8 display fracture strains that comply with the necessary requirements. In conclusion, the presented justifications clearly demonstrate the critical importance of adhering to a filler-to-useful bitumen weight ratio below 0.8 to effectively combat low-temperature cracking and optimize the overall low-temperature performance of asphalt pavements.

CONCLUSIONS

The study examined the impact of mineral filler weight ratio on the low-temperature performance of hot asphalt mixtures with continuous gradation. Various tests, including BBR, DT, FTIR, XRD, and SCB tests, were conducted on mastic samples containing PG 70-16 bitumen and mineral filler. The findings revealed that the weight ratio of mineral filler to useful bitumen is a critical factor in determining the low-temperature performance of the asphalt mixture, as per SHRP-A-407 standard.

1- Firstly, in the BBR test, it was observed that as the F/B ratio increased, the value of S increased, while the value of m decreased. Additionally, the DT-test results indicated a decrease in fracture strain with increasing filler content, likely due to the increased stiffness and reduced elasticity of the bituminous mastic.
2- Furthermore, findings from the FTIR test revealed that an F/B ratio of 0.6 exhibited the highest bending peaks in the wavelength range from 400 cm^{-1} to 1500cm^{-1}, suggesting improved performance at medium and low temperatures compared to other ratios. Conversely, the XRD test demonstrated a decrease in peak intensity with higher filler ratios, leading to poorer temperature performance.
3- The SCB- test results highlighted that increasing the F/B ratio reduced the time to reach fracture strain, thereby diminishing low-temperature cracking life. Overall, the study emphasized the importance of balancing filler and bitumen ratios to achieve optimal asphalt mixture performance, with a recommended maximum ratio of 0.8 for controlling and enhancing low-temperature performance.

4- Additionally, it was suggested that evaluating bitumen rheology behavior and bitumen mastic rheology across different F/B ratios is crucial for effectively managing asphalt performance based on specific expectations and requirements. This comprehensive analysis underscores the significance of considering various factors in optimizing asphalt mixture performance and durability.

Data Availability

No data, models or codes were generated or used during the study.

Conflict of Interests

In conducting this study, the authors wish to disclose that there is no conflict of interests that could potentially bias the results or interpretation of the findings.

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