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Effectiveness of Weight Ratio of Mineral Filler to Effective Bitumen in the Asphalt-mixture Fatigue Performance

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ABSTRACT

The effectiveness of weight ratio of mineral filler to effective bitumen in the fatigue performance of asphalt mixture with integral granules was investigated based on experiments on bitumen mastic (mixture of bitumen and mineral filler passed through sieve grade 200). The experiments included a dynamic shear rheometer, elastic recovery, linear amplitude sweep tests and other performance tests on asphalt mixture, such as fatigue of indirect tensile and resilient modulus test for assessing the medium temperature with various mineral filler-to- bitumen ratios of: 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 for bitumen 70-16 PG. Based on this project, the weight ratio of mineral filler to effective bitumen according to Iran Management and Planning Organization (IMPO-234) and SHRP-A407 standard and based on fatigue performance of asphalt mixture was separated and modified. So, to control and modify the medium temperature, the maximum weight ratio of filler to effective bitumen should be considered, which is equal to 0.8. The results of this research showed that for controlling the fatigue performance, the rheological behavior of bitumen mastic should be considered beside the asphalt mixture performance and the bitumen rheological behavior.

KEYWORDS: Asphalt mixture, Bitumen mastic, Ratio of filler to bitumen, Performance, Fatigue.

INTRODUCTION

Asphalt mixtures are complicated materials that are comprised of mineral sand, bitumen, mineral filler and voids. The asphalt mixture is an excellent and first-level pavement material that is used in road construction. For enhancing the performance, we can add additives to asphalt or bitumen. Recognition of effectiveness of exclusive elements from this mixture for better design of asphalt mixtures is vital for achieving the appropriate structural and surface requirements (Almusawi, Sengoz and Topal, 2021; Sukhija, Wagh and Saboo, 2021; Hamedi, Sohrabi and Sakanlou, 2019; Pan et al., 2015, Bennert et al., 2010; Delgadilho and Bahia, 2008).

Significant regions of Iran due to the existence of the two vast mountains of Alborz and Zagros have a cold-temperate climate and on the other hand, in these regions, several asphalt roads with heavy and super-heavy traffic exist. For this, achieving asphalt pavements that have a good performance at middle

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temperatures and show sufficient resistance under the stress of the wheels of heavy vehicles has always been the focus of researchers.

The mixture of bitumen and mineral filler is usually called bitumen mastic. It is expected that mineral fillers improve the stability of the asphalt mixture by reducing voids and increasing stiffness. Mastic has an important role in enhancing the performance of asphalt mixtures; however, it has a low percentage related to the volume and weight of the whole asphalt mixture (Mukhtar et al., 2021; Antunes et al., 2015). In various standards and instructions, mastic has been given serious attention.

The shares of bitumen and filler can change the bitumen mastic nature and make a significant effect on the performance of the whole asphalt mixture. For this reason, researchers have given serious attention to the ratio of filler to bitumen. Based on Iran Management and Planning Organization (IMPO-234) and SHRP-A407 standards, the mentioned ratio should be between 0.6 and 1.2.

International research has shown that the ratio of filler to effective bitumen affects the different performance characteristics of the asphalt mixture and it is essential to determine the effectiveness of this ratio in different performances at high, medium and low temperatures of the asphalt mixture. Based on the desired performance, the mentioned ratio can be adjusted in asphalt mixtures. Recent research all over the world has shown that adding mineral filler in asphalt mixture is essential. Using mineral filler not only improves the mastic viscosity, but also prevents the separation of bitumen from aggregates during mixing, transportation, distribution and compaction (Kuity and Jayaprakasan, 2014; Barra et al., 2014; Kutuk-Sert and Kutuk, 2013; Gedik, Selcuk and Lav, 2021; Chen et al., 2011). For this reason, mineral filler is considered one of the vital elements in an asphalt mixture. Although mineral filler is widely used in asphalt mixtures, asphalt mixtures should be analyzed based on the reaction of filler and bitumen. More research on this subject is essential for the logical application of mineral fillers. The filler amount has not a sensitive effect on increasing the viscosity of bitumen mastic and preventing separation in the mixture (Kuciel et al., 2014; Wu et al., 2011). Brittle behavior starts with two kinds of fracture; one is the adhesion of bitumen mastic so that the bitumen mastic fractures from the surface of coarse-aggregate materials and separates, while the other is the fracture of integrity and bitumen mastic adhesion itself so that the bitumen mastic cracks under tensile or shear load. The mentioned two kinds of fracture are normal in low-temperature performance (Wang et al., 2021; Mo et al., 2011). From internal damage of asphalt mixture, two indices of bitumen mastic strength have existed; adhesion strength and strength of integrity (Zhang et al., 2016; Lyne et al., 2013). Rheology experiment of bending beam in the assessment of rheology effect of bitumen and bitumen mastic is important (Ho and Romero, 2011). Research has shown that the amount and meso-scopic properties of mineral filler have effects on the ratio of absorbed bitumen – free bitumen in bitumen mastic. Hence, analyzing the relation of bitumen and filler in terms of these two factors is essential. Results have shown that meso-properties of mineral filler can affect asphalt performance significantly. This study has used the adhesion strength of bitumen mastic as a critical-failure control index and the rate of change in bending creep strength at low temperatures as a fatigue-failure control index (Zheng et al., 2018). Physical and chemical interactions of bitumen and mineral filler can affect the aging of bitumen mastic. Aging commonly happens because of oxidation and vaporization of unstable parts and light parts of bitumen (Huang et al., 2002) and can induce a decrease in elastic response of bitumen mastic, which can make bitumen mastic crack, especially in middle-temperature conditions (Khordehbinan and Kaymanesh, 2020; Lackner et al., 2005). Based on research in analyzing the middle-temperature performance in hot asphalt mixtures with fibers, it is proposed that the ratio of filler to bitumen should not be more than 1.5, because the strength modulus of bitumen mastic is significantly increased (Upadhya, Thakur and Sihag, 2022). Another research has shown that for obtaining the middle-temperature performance (controlling the fatigue failure), the ratio of filler to effective bitumen should be between 0.8 and 1.2 and this ratio should not be above 1.2 (Qiu et al., 2013).

Hence, the main subject of the present project is assessing the ratio of mineral filler to effective bitumen based on IMPO-234 and SHRP-A407 standards and based on the fatigue performance of the asphalt mixture. Also, we try to have a logical perception of the influence of this ratio on different performances of middle-temperature hot-asphalt mixtures with integral granules to adjust the desirable mentioned ratio in the asphalt-mixture scheme. For this reason, the dynamic shear rheometer test (ASTM D7175), elastic recovery test (ASTM 18-D6084M) and linear amplitude sweep test (AASHTO TP 101-12) were conducted on bitumen mastic samples and indirect tensile fatigue test (BS EN 12697-24:2004) and resilience module test (ASTM D4123) were conducted for analyzing the middle-temperature performance of asphalt-mixture samples with different mineral filler to effective bitumen ratios; 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 and PG70-16 bitumen.

RESEARCH METHODS AND EXPERIMENTS

Materials

Bitumen plays a fundamental role in the performance of asphalt mixture and its viscosity behavior. Bitumen 60/70 with a performance grade of PG70-16 was obtained as a widely used bitumen in Iran from number 2 asphalt company (Aman) of Qom municipality, Figure 1. The experiments for analyzing the quality of this type of bitumen are given in Table 1.

Table 1. Properties of used bitumen quality

Characteristic	Value	Acceptable values according to standards	Conforming to the specifications
Specific gravity at 25 °C	1.018	-	Ok
Penetration at 25 °C (0.1 mm)	60	60-70	Ok
Softening point (°C)	51	49-56	Ok
Flash point (°C)	306	Minimum 232	Ok
Ductility at 25 °C (cm)	100	Minimum 100	Ok
Solubility of asphalt materials in trichloroethylene (%)	99.8	Minimum 99	Ok
Kinematic viscosity (Pa.S) at 135 °C	0.375	Maximum 3	Ok
Loss on heating 5 hours at 163 °C (%)	0.2	Maximum 0.8	Ok
G*/sinδ in dynamic shear rheometer (Pa) at 70 °C on the unaged bitumen with the frequency of 10 rad/s	1060	Minimum 1000	Ok
G*/sinδ in dynamic shear rheometer (Pa) at 70 °C on the aged bitumen 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
Bitumen using rolling thin-film rheometr (RTFO) at -6 °C	0.342	Minimum 0.3	Ok
The performance grade of used bitumen is PG 70-16.			

Figure (1): Preparation of bitumen from bitumen flask in asphalt plant

Although the filler has a filling role in bituminous mastic, its quantity and type affect the strength and performance of the asphalt mixture. The used filler in this research is mineral filler obtained from dolomite limestone from Kahak mine; belonging to number 2 asphalt factory (Aman), Qom municipality. The filler was obtained from the asphalt-plant dust system, Figure 2. The experiments are given in Table 2 for assessing the quality of the filler.

Figure (2): Filler preparation from the asphalt-plant dust system

Table 2. Properties of filler quality test

Test	Test result	The amount of instructions 234	Conforming to the specifications
Atterberg limits of plasticity index (PI) (AASHTO T89, 90)	NP	Maximum 4	Yes
Specific gravity at 25°C (gr/cm^3) (AASHTO T100)	2.633	-	Yes

Aggregates constitute usually 90% of the asphalt mixture and their physical and mechanical characteristics are effective on the performance of the pavement. Sand and aggregate in this experiment were obtained from dolomite limestone materials from Kahak mine, belonging to number 2 asphalt factory (Aman), Qom municipality. The aggregate material had a size of 0-19 mm with three kinds of medium, fine and coarse sand, based on Figure 3, that were obtained from a hot silo of an asphalt plant. The properties of the used aggregates are shown in Table 3.

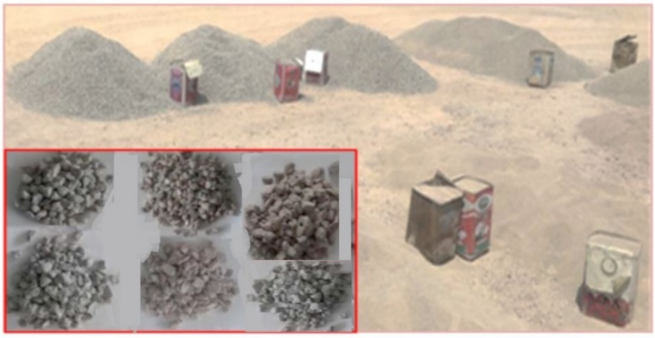

Figure (3): Preparation of fine aggregate and natural sand from hot-asphalt plant

Table 3. Properties of the used aggregates

Dimensions and sizes of aggregates	Tests		Test result	The amount of instructions 234	Conforming to the specifications
Coarse-grained aggregates (gravel)	Fracture aggregates (ASTM D5821)	One Side	100%	At least 95%	Yes
		Two Side	98%	At least 90%	Yes
	Weight loss *versus* sodium sulfate (AASHTO T104)		0.3%	Maximum 8%	Yes
	Percentage of broad and long aggregates (ASTM D4791)		7%	Maximum 15%	Yes
	Los Angeles weight loss against abrasion (AASHTO T96)		18%	Maximum 25%	Yes
	Water absorption		1.3%	Maximum 2.5%	Yes
	Specific weight (gr/cm^3) (AASHTO T85)	Apparent density	2.709	-	Yes
		Bulk density	2.620	-	Yes
Fine-grained aggregates	Atterberg limits (AASHTO T89, 90)	Plasticity Index (PI)	NP	Maximum 4	Yes
	Weight loss *versus* sodium sulfate (AASHTO T104)		0.7%	12	Yes
	Determining the angularity of fine-grained aggregate materials in terms of percentage of empty space (ASTM C1252)		44.5	At least 45	Yes
	The value of fine-grained sand (AASHTO T176)		72%	At least 50%	Yes
	Water absorption (%)		2.3%	Maximum 2.5%	Yes
	Specific weight (gr/cm^3) (AASHTO T85)	Apparent density	2.704	-	Yes
		Bulk density	2.549	-	Yes
Percentage of bitumen coated to aggregates after the effect of boiling water on asphalt mixtures (ASTM D3625)			More than 95	-	Yes

The final aggregate gradation of the mixture and its comparison with the proposed gradations in IMPO-234 and SHRP-A407 standards are given in Table 4 and Figure 4.

Table 4. Test gradation of aggregates

Sieve number (or inch)	IMPO-234	SHRP-A407	The percentage through the following sieve size / %	Conforming to the specifications
$\frac{3}{4}''$	100	100	100	Yes
$\frac{1}{2}''$	100-90	100-90	94	Yes
#4	74-44	-	62	Yes
#8	58-28	58-28	42	Yes
#50	21-5	-	13	Yes
#200	10-2	10-2	5	Yes

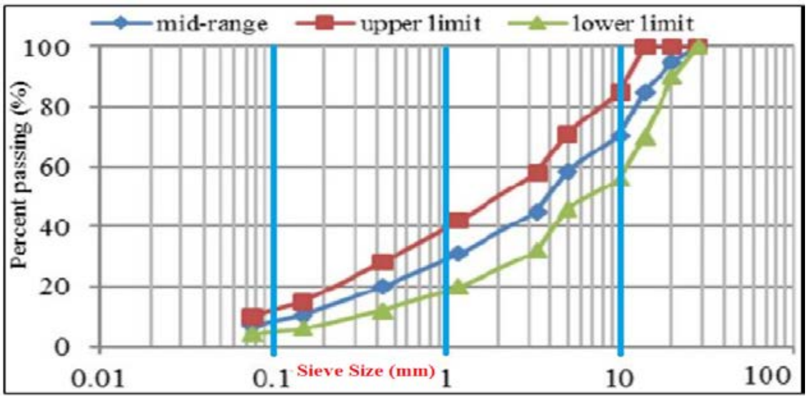

Figure (4): The gradation plot of used aggregates

Preparation of Samples

The mixing temperature of bitumen with aggregate materials and the compaction should be at temperatures so that the viscosity in the kinematic viscosity test of bitumen and aggregate materials is 170±20 and 280±30, respectively (IMPO-234, 2011). The mixing temperature of bitumen and aggregate materials is between 149 and 155°C and the compaction temperature range is defined to be between 139 and 143°C. So, to prepare bitumen mastic samples, first, the bitumen was heated to 155°C. Then, this temperature was kept and the filler was added slightly while a mechanical stirrer (due to its facile and high-performance mixing) mixed the bitumen and the filler completely. This operation was done for 15 minutes to mix the mixture completely (IMPO-234, 2011). Naming the bitumen mastic samples and the material ratios are given in Table 5.

Table 5. Different compounds for bitumen mastic samples

Pavement sample coding	Naming compounds	Amount of material composition per 1 kg of bitumen mastic
FB0.0	Filler/Bitumen Ratio 0	1 kg Bitumen
FB0.6	Filler/Bitumen Ratio 0.6	0.625 kg Bitumen + 0.375 kg Filler
FB0.8	Filler/Bitumen Ratio 0.8	0.556 kg Bitumen + 0.444 kg Filler
FB1.0	Filler/Bitumen Ratio 1.0	0.500 kg Bitumen + 0.500 kg Filler
FB1.2	Filler/Bitumen Ratio 1.2	0.454 kg Bitumen + 0.545 kg Filler
FB1.4	Filler/Bitumen Ratio 1.4	0.417 kg Bitumen + 0.583 kg Filler
FB1.6	Filler/Bitumen Ratio 1.6	0.385 kg Bitumen + 0.615 kg Filler

In the scheme of asphalt mixtures for the preparation of asphalt samples, the weight ratios of mineral filler to effective bitumen were 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6, according to Table 5, where the Marshall method was used (AASHTO T245). This method is useful for both mixture scheme preparation and controlling the asphalt operation for aggregates with a maximum size of 25mm and compacted and integral granules. The asphalt-mixture samples with various percentages of bitumen (4, 4.5, 5, 5.5, 6 and 6.5 weight ratio of asphalt mixture) were mixed at 155°C and compacted at 140°C, by applying 75 impacts for the Marshall method (AASHTO T245) using molds with 10-cm diameter. Samples have 4 percent voids according to the test method. The highest specific weight of the asphalt mixture with various percentages of bitumen is defined based on the Rice experiment according to AASHTO T209 standard.

The bulk density specific weight of compacted asphalt-mixture samples (G_{mb}) based on AASHTO T166 standard as well as the strength and flow of samples based on AASHTO T245 standard for different percentages of bitumen. air-void percentage (air void) of compacted asphalt-mixture samples, void percentage of aggregate materials (VMA) and void percentage of aggregate materials filled with bitumen (VFA) were calculated based on equations specified by MS-2

Asphalt Institute (Equations 1-7):

$$G_{sb} = \frac{p_1+p_2+p_3}{\frac{p_1}{G_1}+\frac{p_2}{G_2}+\frac{p_3}{G_3}} \quad (1)$$

$$G_{se} = \frac{100-p_b}{\frac{100}{G_{mm}}-\frac{p_b}{G_b}} \quad (2)$$

$$p_{ba} = 100 \times \frac{G_{se}-G_{sb}}{G_{se} \times G_{sb}} \times G_b \quad (3)$$

$$p_{be} = p_b - \frac{p_{ba}}{100} \times p_s \quad (4)$$

$$VMA = 100 - \frac{G_{mb}}{G_{sb}} \times p_s \quad (5)$$

$$p_a = 100 \times \frac{G_{mm}-G_{mb}}{G_{mm}} \quad (6)$$

$$VFA = 100 \times \frac{VMA-p_a}{VMA} \quad (7)$$

P_1, P_2 and P_3= the big, small and filler percentage in the aggregate material.

G_1, G_2 and G_3= the bulk density specific weight of coarse and fine aggregate materials and filler.

G_{sb}= the bulk density specific weight of aggregate materials.

P_b= the weight ratio of bitumen to the weight of asphalt mixture.

G_b= the bulk density specific weight of bitumen.

G_{mm}= the maximum theory specific weight of the asphalt mixture.

G_{se}= the bulk density specific weight of useful aggregate materials.

P_{ba}= the percentage of absorbed bitumen in aggregate materials.

Ps= the weight percentage of aggregate materials to the asphalt-mixture weight.

P_{be}= the percentage of effective bitumen to the weight of asphalt mixture.

G_{mb}= the bulk density specific weight of the asphalt mixture.

VMA= the void percentage of aggregate materials.

P_a= the void percentage of the asphalt mixture.

VFA= the void percentage of aggregate materials filled with bitumen.

Experimental Methods

For analyzing the rheologic behavior at middle temperatures in bitumen mastic, the dynamic shear rheometer experiment was used based on standard ASTM D7175. At middle temperatures, the most important damage in the pavement is fatigue destruction. This phenomenon can be considered as both a constant stress phenomenon (for thick layers) and a constant strain phenomenon (for thin layers). Since the fatigue phenomenon is more effective when the asphalt pavement is thin, the fatigue phenomenon can be studied as a constant-strain event. By considering the mentioned contents, the work loss in every loading period is shown based on Equation 8 (Anderson et al., 1994):

$$W_c = \pi \times \delta \times\times \varepsilon_0 \times Sin\delta. \quad (8)$$

In this equation, ε_0 is the constant shear strain magnitude, which is related with stress based on Equation 9:

$$\sigma = \varepsilon_0 \times G^*. \quad (9)$$

By substituting Equation 9 into Equation 8, the prominent fatigue potential is obtained according to Equation 10 (Anderson et al., 1994):

$$W_i = \pi \times \varepsilon_{0i}^2 (G^* \times Sin\delta). \quad (10)$$

In this equation, W_i is the lost energy in the loading period of i, ε_{0i} is the constant shear strain in the loading period of i, G* is the mixing module and δ is the phase difference.

The lost work in every loading period at middle temperatures expresses itself in the form of cracking or crack propagation based on the rheologic properties of bitumen. Hence, for decreasing the cracks or their growth, the best approach is decreasing $G^*.sin\delta$. Based on this, it can be said that as softness is more, the viscosity loss is less (elastic property is more) and the strength to fatigue phenomenon will be higher. In other words, it can be said that decreasing $G^*.sin\delta$ increases strength potential in fatigue of bitumen (Anderson et al., 1994). This parameter is used for analyzing the middle-temperature performance of bitumen mastic.

For confirming the bitumen in the experiment at the given temperature, $G^*.sin\delta$ should be lower than 5000 MPa for aged bitumen RTFO+PAV based on ASTM D2872 and ASTM D6521 standards. This means that it is appropriate to decrease [G*] content (more softness) and δ (decrease in viscosity loss) (IMPO-234, 2011). In this research, the upper and lower functional levels in the PG method are 70 and -16°C, respectively. By choosing 31°C as a middle temperature, the temperatures of 28, 31 and 34°C were chosen as experiment temperatures. Choosing functional experiment temperatures is based on the functional grade of base bitumen PG70-16 and IMPO-234 recommendations and SHRP-A407 about middle-temperature functions. The amount of $G^{*}.sin\delta$ for bitumen-mastic samples in constant frequency (10 rad/s) is defined as 1.59 Hz. The maximum $G^{*}.sin\delta$ parameter for controlling the fatigue potential of bitumen was used for gaining assurance in bitumen-mastic samples. Figure 5 shows a picture of sample preparation for DSR and linear amplitude sweep (LAS) experiments.

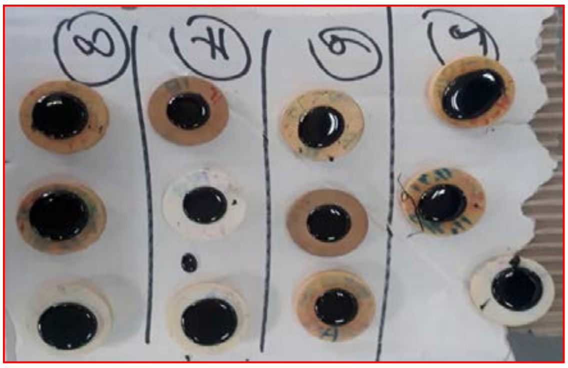

Figure (5): Some of the prepared bitumen-mastic samples for DSR and LAS experiments

The linear amplitude sweep test (LAS) is performed on PTFO+PAV aged samples based on D2872 and ASTM D6521 standards by using a dynamic shear rheometer (DSR) based on AASHTO TP 101-12 standard (Figure 5). This test is made by two experiments: frequency sweep test and linear amplitude sweep test. The goal of this experiment is to define the relation of fatigue for assessing the fatigue strength so that the viscoelastic continuum damage (VECD) meaning is used for determining the fatigue life in every stage of strain. In this research, the upper and lower functional degrees in the PG method are 70 and -16°C, respectively. By considering 31°C as a middle temperature, 31°C was chosen as the experiment temperature. Choosing functional experiment temperatures is based on the functional grade of base bitumen PG70-16 and IMPO-234 recommendations and SHRP-A407 about middle-temperature functions. The linear amplitude sweep at a constant frequency of 10 Hz is obtained by increasing the shear strain from 0% to 30% in 300 seconds.

The elastic recovery is performed based on the ASTM D6084M-18 standard. In this experiment, first, the mold is prepared on the main sheet. For preventing zone heating, the bitumen sample is heated to become completely fluid and then it is poured into the mold. After overall stirring, bitumen is poured into the mold and it should be confirmed that no voids are trapped. Then, the mold and its parts are allowed to cool at room temperature. Then, samples are kept in the water bath. The experiment is conducted at room temperature. Water in the tank of the testing device should cover the upper and lower parts of the sample. The clamp was attached to the rivets of the testing device. The clamps pull the specimen at a speed of 5cm per minute until the mold's length increases to 20 cm. After increasing the length to 20cm, after 5 minutes, the specimens were separated from the center with a pair of scissors and the specimens were allowed to remain intact in the flexometer for 1 hour (Figure 6). Finally, the amount of sample shrinkage was measured by a flexometer indicator. The elastic recovery percentage of bitumen materials was calculated by Equation 11:

$$\text{Elastic recovery} = \frac{20-X}{20} \times 100 \qquad (11)$$

X= the final parameter for the testing device after taking two separated ends of the sample in cm.

Figure (6): The elastic recovery experiment of bitumen-mastic samples

The indirect tensile fatigue test was defined based on standard (BS-EN-12697-24:2004) by using a UTM device from Tehran Laboratory of Soil Engineering and Soil Mechanics, Ministry of Roads and Urban Development. Considering that seven different asphalt samples are needed and for every experiment three samples are averaged; hence, in this stage, the number of samples is 21. The prepared asphalt samples for the resilience modulus and indirect tensile fatigue tests are made by the Marshall method. The modulus test is non-destructive; therefore, a sample was made for both tests and first, the resistance test was performed according to ASTM D4123 standard. Asphalt samples with a diameter of 100 mm and a height of 63 mm were made with a void percentage of 4%. The load string for samples with a diameter of 100mm is 13 mm. The samples were kept in the UTM device for 4 hours for the isotherm situation. All samples were tested at 20°C. The samples are unsaturated (Figure 7).

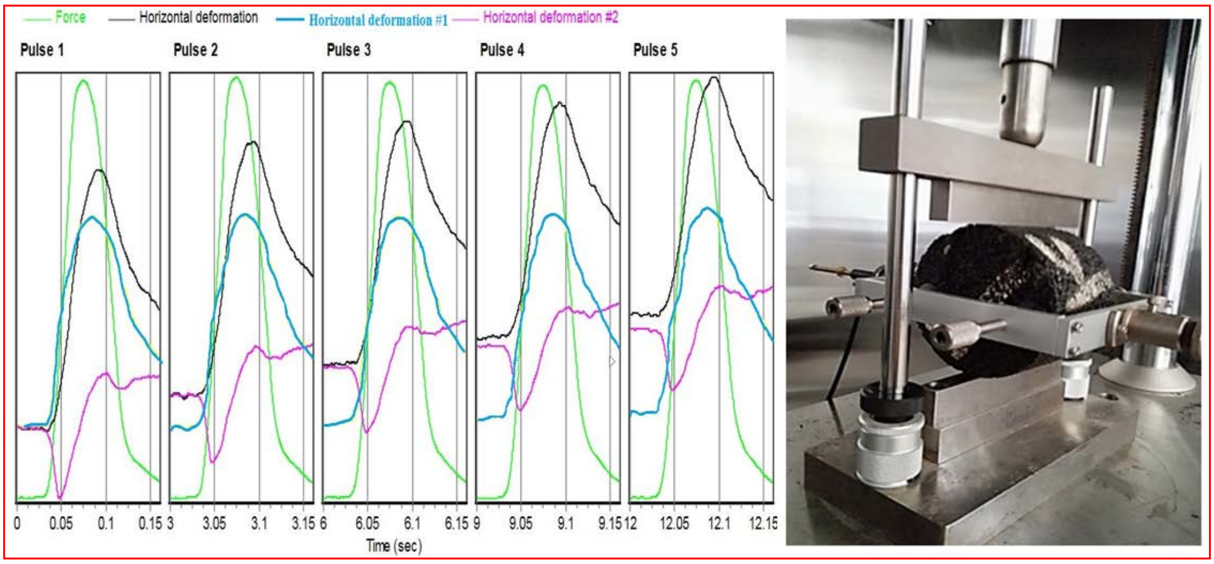

Figure (7): The state of keeping the samples, molds, LVDTs and load curves in resilient modulus and indirect tensile fatigue tests

The experiment was started with the loading amplitude of 250 kPa. Semi-sinus loading with 0.2 amplitude and 0.8 second resting was considered. Since the deformation shown on the monitor at the stress level of 250 kPa was out of range (100 to 400 micro-strain) for the first 10 loads, the test was stopped immediately and the load level was adjusted again. Accordingly, a stress level of 500 kPa was chosen in this experiment. During the test, the cumulative permanent stresses were recorded against a pre-determined number of load cycles. When the sample reached a cumulative permanent strain of 7%, the experiment was stopped. The failure life is equal to the number of loads, which causes a permanent cumulative strain of 7%.

The resilient modulus test was carried out based on ASTM D4123 standard. Each specimen was tested two times. First, the first section was performed and then, the sample was kept in the temperature-control storage. Then, the sample was turned by 90 degrees in the second section and the experiment was carried out for the second time. For the resilient modulus test, semi-sinus loading with 1 Hz frequency and 1 second loading cycle for 0.1 second loading time and resting time of 0.9 second and with Poisson's ratio of 0.35 was considered. After the repetitive deformation of the sample was fixed, during at least three loading cycles, the average of reversible horizontal and vertical deformations was determined using Equations 12-15.

$$E_{RI} = \frac{P(\vartheta_{RI}+0.27)}{t \times \Delta H_I} \tag{12}$$

$$E_{RT} = \frac{P(\vartheta_{RT}+0.27)}{t \times \Delta H_I} \tag{13}$$

$$\vartheta_{RI} = 3.59\left(\frac{\Delta H_I}{\Delta V_I}\right) - 0.27 \tag{14}$$

$$\vartheta_{RT} = 3.59\left(\frac{\Delta H_T}{\Delta V_T}\right) - 0.27 \tag{15}$$

In these equations:

E_{RI}= instantaneous elastic resilient modulus (MPa).
E_{RT} = total elastic resilient modulus (MPa).
υ_{RI} = instantaneous Poisson's ratio.

υ_{RT} = total Poisson's ratio.
P = repetitive loading (N).
t = sample thickness (mm).
Δ_{HI} = instantaneous reversible shape deformation of the samples in the horizontal axis direction (mm).
Δ_{VI} = instantaneous reversible shape deformation of the samples in the vertical axis direction (mm).
Δ_{HT} = total reversible shape deformation of samples in the horizontal axis (mm).
Δ_{VT} = total reversible shape deformation of the samples in the vertical axis direction (mm).

RESULTS AND DISCUSSION

The apparent theoretical specific weight of asphalt mixture was defined for various percentages of bitumen with Ray experiment based on AASHTO T209 standard according to Table 6.

Table 6. The apparent density (specific gravity) of asphalt mixture (G_{mm}) for various bitumen percentages

Percentage of bitumen	Maximum specific gravity of asphalt mix (apparent density)
4.0	2.465
4.5	2.447
5.0	2.429
5.5	2.411
6.0	2.394
6.5	2.377

The plots of apparent specific-weight variation for compacted asphalt mixtures (G_{mb}) as well as strength and flow of Marshall samples, void percentage of compacted asphalt mixtures (air void), void percentage of aggregate materials (VMA) and void percentage of aggregate materials filled with bitumen (VFA) were defined based on the previous section for determining the effective bitumen percentage of the main scheme.

Based on IMPO-234 standard and the recommendations of MS-2 Asphalt Institute Journal and considering a bitumen void percentage of 4.0%, the optimal bitumen percentage of the scheme is defined as 5.0 percent of asphalt-mixture weight. In this regard, the percent of absorbed bitumen in aggregate materials is calculated at 0.39%. It should be mentioned that other parameters of the asphalt mixture are controlled based on this bitumen percentage and they are in the IMPO-234 standard range. Based on IMPO-234 and SHRP-A407 standards, the weight ratio of filler to effective bitumen for asphalt mixture with 5% bitumen is defined to be equal to 1.08 which is in the 0.6-1.2 range of the mentioned standards.

Since the asphalt-mixture scheme for the weight ratio of filler to effective bitumen is 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6, the above-mentioned scheme was considered for a ratio equal to 1.0. To find other schemes, the weight ratio of filler to effective bitumen equal to 1.0 was considered as the basis and the other schemes were adjusted by trial and error using Equations 1-4.

Dynamic Shear Rheometer Experiment

With an increasing number of passing traffic over the pavement, the most important failure at middle temperatures is fatigue. The quality of bitumen in the asphalt mixture plays an important role in the creation and propagation of fatigue cracks. The G*.sinδ parameter defines a criterion for fatigue cracks. As this parameter is higher, the resistance of the asphalt mixture to the phenomenon of fatigue and cracking at medium temperatures is lower. The value of G*.sinδ for aged RTFO+PAV bitumen at a constant frequency of 10 rad/s and the test temperature, should be less than 5000 kPa (IMPO-234, 2011). This criterion was used to analyze bitumen-mastic samples. Therefore, a dynamic-shear rheometer test was performed at 28, 31 and 34°C with a constant frequency of 10 rad/s on aged RFTO+PAV samples using a DSR device and the results are shown in Fig. 8.

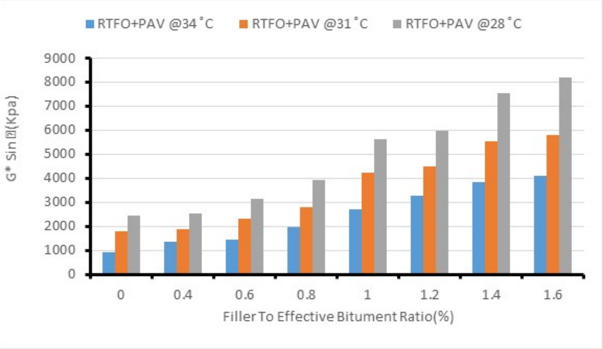

Figure (8): The amount of G*. sinδ for various filler-to-bitumen ratios at 28, 31 and 34°C in the aged state

As shown in Figure 8, at filler-to-bitumen weight ratios of less than 0.8 at all three temperatures of 28, 31 and 34°C, the values of G*.sinδ are lower than the IMPO-234 requirements and since the performance grade of the base bitumen was PG70-16 and according to SHARP-A407, the average operating temperature is 31°C, so it can be concluded that to control fatigue and improve the middle-temperature performance, it is necessary to consider the weight ratio of filler to effective bitumen less than 1.2 . But, according to the result obtained for the temperature of 28°C, which has more critical conditions for the middle state, it can be concluded that to control maximum fatigue and completely improve the middle-temperature performance, it is necessary to consider the weight ratio of filler to bitumen to be less than 0.8.

As the results of this project show, by increasing the filler content, the strength potential to fatigue is decreased and this is due to weakness in the elastic property of bitumen mastic due to viscosity property.

Linear Amplitude Sweep Experiment

For a more accurate analysis of middle-temperature performance, the results of linear amplitude sweep (LAS) test were considered. The results of the shear stress and shear strain at 31°C for differently aged RTFO+PAV samples are given in Figure 9 based on the LAS experiment.

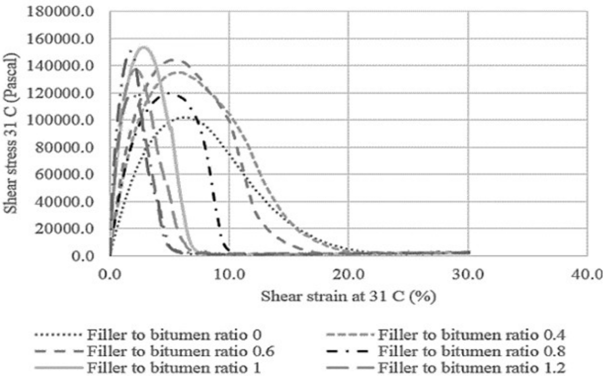

Figure (9): The results of LAS experiment for differently aged RTFO+PAV mixtures at 31°C

As can be seen from Figure 9, by adding filler at 0.6 ratio, both shear stress and shear strain are increased in comparison with those of the control sample and after the ratio of 0.8, shear strain decreases. This decrease is significant for the ratio of 1 and more, which means that the formability of materials in stress is decreased and the middle-temperature performance has weakened. Also, the area under plot (A, toughness) is the highest for the ratios of 0.4 and 0.6 and after that, it decreases and this decrease is significant for 1 and more ratios. According to the area under the plot, the toughness for the ratio of 1 is more than 34% and for 1.6 ratio, it has a 59% decrease in comparison with the control sample. Hence, for improving the middle-temperature performance, a lower ratio of filler to bitumen until 0.8 should be used. The results of this experiment are according to the results of DSR for 28°C temperature.

Elastic Recovery Experiment

The results of the elastic recovery experiment based on the ASTM D6084M-18 standard for different filler to bitumen ratios are given in Figure 10.

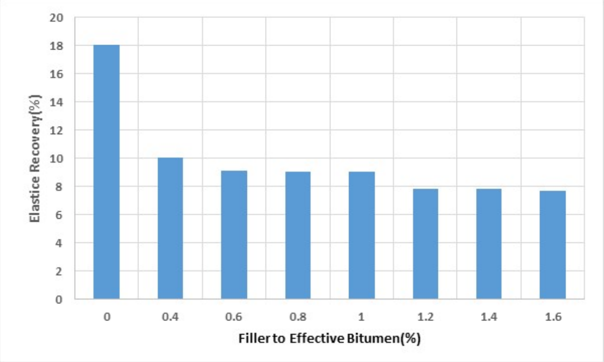

Figure (10): The elastic-recovery amount for different filler to bitumen ratios at 20°C

According to Figure 10, the results of elastic recovery at 20°C show that with increasing the ratio of filler weight to bitumen, the percentage of elastic recovery decreases, which means that the elastic ductility of the material decreases and the middle-temperature performance has weakened. This experiment confirms the results of DSR and LAS tests and shows that for improving the middle-temperature performance, lower filler to bitumen ratios should be used. Hence, according to the results of DSR, LAS and elastic-recovery tests, it can be concluded that for controlling and improving the middle-temperature performance of asphalt mixtures, the maximum filler-to-bitumen ratio is considered to be 0.8. Based on this research, among the studied ratios, 0.4 is the best weight ratio of filler to effective bitumen for controlling and improving the middle-temperature performance.

Resilient Modulus Test

To determine the resilience performance, the resilient modulus test according to the ASTM D4123 standard was used. The values of the overall elastic modulus in MPa in asphalt samples with different filler to bitumen ratios are shown in Figure 11.

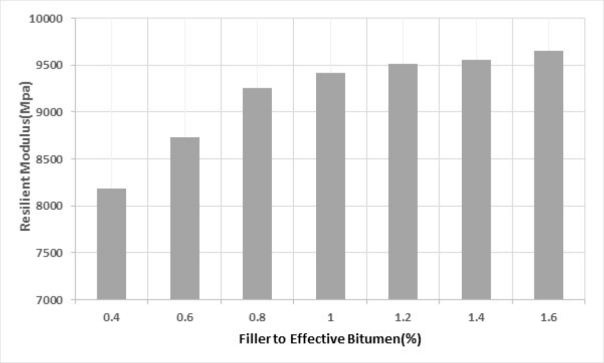

Figure (11): Overall elastic resilient modulus in asphalt mixtures at 20°C

As can be seen from Figure 11, the resilient modulus in asphalt mixtures increases with increasing filler to bitumen ratio. Regarding the improvement of the resilient modulus, this can be due to the creation of three-dimensional networks in the bitumen mastic due to higher adhesion forces between fine filler particles and bitumen due to the high specific surface area of filler particles and increasing filler content. Hence, these adhesion bonds increase the strength and integrity of bitumen mastic in asphalt mixtures and finally, the resilient modulus increases.

Based on this research, resilient modulus in asphalt samples with filler to effective bitumen weight ratios of 1.2, 1.4 and 1.6 is higher than for other ratios and they are approximately equal to each other. Resilience modulus of these ratios is increased by more than 30% compared to the weight ratio of filler to effective bitumen of 0.4 and by more than 5% compared to the ratio of 1.0.

Indirect Tensile Fatigue Test

To determine the middle-temperature performance, indirect tensile fatigue test according to BS-EN-12697-24: 2004 standard was used (Khalid, Al-Khateeb and Khader, 2021). The results of cumulative permanent strain against loading time from an indirect fatigue test are shown in Figure 12 and the fatigue life (rupture time) for a stress level of 500 kPa and a test temperature of 20°C is shown in Figure 13.

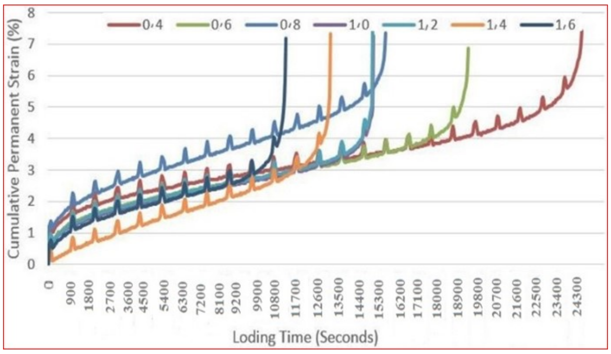

Figure (12): The results of cumulative permanent strain against loading time in indirect tensile fatigue test for different filler to effective bitumen ratios (BS EN 12697-24:2004)

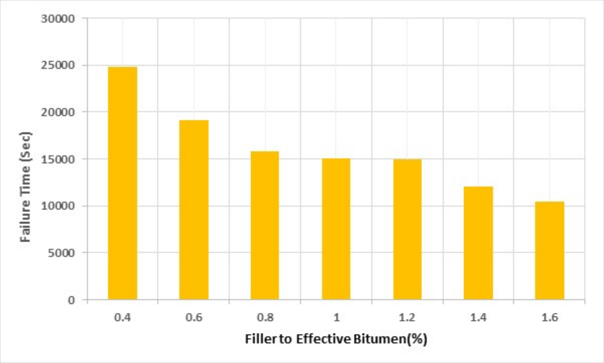

Figure (13): The fatigue life in indirect tensile fatigue test for different filler to effective bitumen ratios

As can be seen in Figure 12, three different behaviors can be distinguished in the cumulative permanent strain changes from the indirect tensile fatigue test for different filler to bitumen ratios. One group of similar behavior includes ratios of 1.6 and 1.4 and another similar-behavior group includes ratios of 1.2, 1.0 and 0.8 and the last group includes ratios of 0.6 and 0.4. In this regard, the first group at a stress level of 500 kPa and a temperature of 20°C in the loading cycle of 11000 to 13000 reaches a strain of 7% and therefore it does not have a high fatigue resistance. The second group reaches a strain of 7% in the loading cycle of 15,000 to 16,000 and the third group reaches a strain of 7% in the loading cycle of 20,000 to 24,000; hence, the second group has a medium fatigue resistance and the third group has a high fatigue resistance. The mentioned categorization can be clearly seen in Figure 13.

Considering Figures 12 and 13, by increasing the filler to effective bitumen ratio, the times to reach strain failure and fatigue life decrease. This is due to an increase in stiffness and a decrease in elastic property of bitumen mastic with higher-filler contents.

Based on Figure 13, the fatigue life of the filler to effective bitumen weight ratio of 0.4 compared to that of the ratio of 1.0 is more than 160%, which has been chosen as the asphalt mixture scheme of Qom municipality number 2 factory based on IMPO-234 requirements; this fatigue life is more than 220% compared to that of the ratio of 1.6. Accordingly, the ratios of filler to effective bitumen equal to 0.4 and 0.6 represent the best scheme in terms of middle-temperature performance among the studied designs; hence, to improve the middle-temperature performance of the asphalt mixture and increase its fatigue life, it can be concluded that the required filler to bitumen ratio should be 0.6 at maximum. These results are under the values of the G*×sinδ parameter in the DSR test, the results of the LAS test and the results of the elastic-recovery test.

CONCLUSIONS

Based on the dynamic shear rheometer test, by increasing the amount of filler, the resistance potential for fatigue decreases, which can be due to the weakness of the elastic property of bitumen mastic against the viscosity property. According to the LAS test, by increasing the filler to a ratio of 0.6, both values of shear stress and strain and the area below the graph (A, toughness) increased compared to the control sample and decreased for a ratio of 0.8. The results of elastic-recovery test showed that with increasing the weight ratio of filler to bitumen, the elastic recovery percentage decreases. According to the resilient modulus test of the asphalt-mixture samples, the resilient modulus increases with increasing the ratio of filler to effective bitumen. Regarding the improvement of the resilient modulus, this can be due to the creation of three-dimensional networks in bitumen mastic due to higher adhesion forces between fine filler particles and bitumen due to the high specific surface area of filler particles and increasing filler content. Hence, these adhesion bonds increase the strength and the integrity of bitumen mastic in the asphalt mixture and finally the resilient modulus increases. Based on the indirect tensile fatigue test, by increasing the weight ratio of filler to effective bitumen, the time to reach the fracture strain and consequently the fatigue life is decreased. This can be due to the increase in stiffness and decrease in the elastic property of bitumen mastic with increasing filler content. Also, the results show that the addition of mineral filler to bitumen causes the bitumen mastic to become harder and by increasing its amount, the middle-temperature performance is weakened; hence, to adjust the weight ratio of filler to effective bitumen, the expected performance of the asphalt mixture should be considered. According to this study, to control and improve fatigue performance, the maximum weight ratio of filler to effective bitumen should be considered equal to 0.8. These findings from this study showed that to control the fatigue performance, besides investigating the bitumen rheology behavior and the asphalt mixture performance, the behavior of bitumen mastic rheology at different ratios of filler to bitumen should also be investigated. According to this study, the weight ratio of filler to effective bitumen according to IMPO-234 and SHRP-A407 requirements should be modified based on the expected performance of the asphalt mixture.

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