The effect of lignin on mechanical and dynamical properties of asphalt mixtures

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Abstract

The present article has studied the mechanical and dynamic properties of asphalt mixtures containing lignin. At first, the Fatigue Life (FL) and Resilient Modulus (RM) tests performed on the samples, and then the Marshall Stability (MS) test carried out on them. Lignin was added to asphalt mixtures with 3, 6, 9, and 12%. The RM test performed at a frequency of 1 Hz, with a haversine load at 5, 25, and 40 °C. In addition, the Fatigue test performed at three levels of tensile stress (250, 350, and 450 kPa) at 20 °C with a haversine load and a loading time of 250 ms with a rest period of 1250 ms. The results indicated that by using lignin up to 6%, the performance properties of asphalt, in particular, MS, RM, and its FL, would improve. Also, as the percentage of additives in the mixture increased, the samples' thermal sensitivity decreased. On the other hand, the economic analysis results indicated that adding lignin to 6% would make the asphalt mixture economical. Finally, the results of the two-factor statistical analysis of the RM and FL indicate that a combination of temperature–lignin and lignin–stress affects the RM and FL.

Keywords Lignin · Marshall stability · Fatigue life · Resilient modulus · Economic analysis · Statistical analysis

1 Introduction

Researchers have used a modification of the technical properties of the asphalt mix with the additive [1–3]. Several attempts have been made by researchers to improve the properties of asphalt mixtures. Temperature variations may change the behavior of asphalt mixtures; this may be related to bitumen's viscoelastic behavior. The Resilient Modulus (RM) is a crucial variable in mechanical design approaches for pavement structures. The RM is the elastic modulus based on a recoverable strain under repeated load [3]. Also, Fatigue damages of asphalt mixtures are one of the most critical stages of crack formation. By studying the fatigue behavior of modified asphalt mixtures, crack propagation in asphalt mixture can be controlled. For modified asphalt mixtures, various additives such as nano-materials, fiber materials, and polymers have been

proposed to improve the mechanical and dynamical properties of asphalt mixtures. Nano-materials are among emerging additives. If this additive is used correctly, it can be used to modify the properties of bitumen and asphalt due to its inherent and unique properties. Black nano-carbon, carbon nanotube, nano-clay, etcetera, are among these types of additives. Researchers have investigated the effect of these additives on asphalt mixtures, and the results suggested that these additives possess a positive effect on the asphalt mixtures [4–9]. Also, fibrous materials are considered as compatible additives for modifying the asphalt mix's technical characteristics. Carbon fibers, polyester fibers, glass fibers, etcetera, are considered among these types of additives, which have used in the asphalt mix [10–20].

Lignin is considered as one of the polymer materials, which has been used to strengthen the mechanical and

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dynamic properties of the asphalt mix [3]. The researchers have provided various definitions of this additive. By definition, lignin refers to a heterogeneous biopolymer with a complex structure composed of phenylpropanoid groups, which include regular and stable carbon–carbon bonds with aryl/alkyl connections (phenyl rings) [21]. Nevertheless, the elements and units of the main structures of lignin have mostly determined. Lignin in plants and wood is formed by polymerization of three propanoic monomers. These monomers are as follows [22]:

- 3-(4-Hydroxyphenyl)-2-propan-1-ol. (Paracoumaryl Alcohol)
- 3-(Methoxy-4-hydroxy-phenyl)-2-propan-1-ol. (Coniferyl Alcohol)
- 3-(3,5-Dimethoxy-4-hydroxyphenyl)-2-propan-1-ol. (Sinapyl Alcohol)

Lignin is a heterogeneous copolymer of phenyl propane units connected to each other by carbon–carbon and ether bonds, which is considered as a waste in the paper industry. Hence, this material is a member of the polymer family; using this natural polymer (like other used polymers) improves the asphalt mix's mechanical properties. Due to its special bonds, lignin creates a three-dimensional network in the bituminous matrix, which results in improving the bitumen performance at elevated temperatures, and it plays the role of an antioxidant in bitumen [23].

Pan (2012) was the first to study the antioxidant effect of lignin on the bitumen obtained from crude oil (pure bitumen) by using physic and chemistry rules. This research evaluated the samples composed of bitumen and lignin, which were obtained from wood, by X-ray photoelectron spectrometry. The results indicated that lignin could be used as an antioxidant in bitumen. The lignin is not oxidized, and lignin oxidation usually occurs at temperatures above 130 °C; therefore, the lignin oxidation temperature should be considered when the lignin is added to bitumen [23].

Wood et al. [24] examined the effect of lignin on the epoxy–kenaf composite. They added different ratios (0.5, 1, 2, and 5% by weight) to the epoxy–kenaf composite and examined its effect on the composite's mechanical properties. Their results indicated that adding lignin to the epoxy–kenaf composite increases its mechanical properties, such as impact resistance, tensile strength, etcetera. In addition, Scanning Electron Microscopy (SEM) images taken from the sample fracture section showed that there is better compatibility between epoxy, kenaf, and lignin in the sample with 2.5 wt% [24].

Using liquid waste containing lignin in the asphalt mix to determine the RM has been observed in Pérez's et al. [25] research. The results showed that by adding 20%

lignin to asphalt mix, the RM increases at 30 °C. Xu et al. [26] investigated the rheological properties and anti-aging performance of asphalt binders modified with wood lignin. The result indicates that the lignin increases rutting resistance significantly, but it has a negative effect on the fatigue cracking of the asphalt mix [26].

The purpose of this research is as follows:

1. Investigating the effect of lignin on the mechanical properties of asphalt mixture (Marshall Stability and Flow);
2. Investigating the effect of lignin on the dynamic properties of asphalt mixture (RM and FL);
3. Performing statistical analysis of two factors to investigate the effect of additives on modulus and fatigue;
4. Economic analysis of the effect of lignin on asphalt mixtures.

2 Materials and methods

2.1 Materials

The materials used in this research include bitumen, aggregates, and lignin. The aggregates used in making the laboratory sample have prepared from the Ghazanchi asphalt factory in Kermanshah. The mixing ratios of the aggregates in the asphalt mix for the surface layer are according to Table 1. The curves presented in Fig. 1, correspond to the lower limit, average limit, and upper limit of the gradation. In this research, the aggregates were prepared according to the average curve (i.e., the middle one in Fig. 1). The bitumen used in this research is a 60–70 binder made in Isfahan refinery (Table 2).

The lignin used in this research was gross, and this powder, which contains high amounts of lignin, passes through sieve mesh 30 after it was milled. In order to achieve the desired mixture, bitumen and lignin were stirred homogeneously with a high-shear mixer rotating at a speed of 5000 rpm and a constant temperature (155 °C) for 30 min [27]. Finally, the lignin, which was passed through the sieve mesh 30, added to bitumen in various weight ratios (3, 6,

Table 1 Mixing ratios of the aggregates

Mixing percentage	Particle size	Aggregates properties
Medium sand	4.75–25 mm	8
Tiny sand	0–19 mm	23
Sand	0–6 mm	68
Filler	Micron	1

Fig. 1 Grading curve of asphalt mixture (Topeka layer)

9, and 12%). Some of the properties of modified bitumen with lignin are given in Table 3.

2.2 Lignin

The compounds in the used lignin are shown in Table 4, according to the manufacturer report.

2.3 Test methods

2.3.1 Marshall test

In this research, at first, the optimum bitumen content for controlled samples (samples with pure bitumen without any additive) obtained based on Marshall Mix design. Then the samples were constructed using lignin additives based on the selected optimum bitumen content. The method of designing the asphalt mixture performed according to the standard method of ASTM-D1559. The controlled asphalt mixture was composed of three main parts: (i) limestone aggregate with nominal maximum aggregate size of 12.5 mm (according to the Iranian paving standard code-234), (ii) base bitumen with penetration grade of 85/100, and (iii) 4% air void. After making samples, RM and FL tests conducted on the samples. Finally, the samples were broken with Jack Marshall to gain Stability and Flow.

2.3.2 Resilient modulus test

The RM test has used to evaluate the performance of the asphalt mixture according to the standard method of (ASTM D-4123). For this purpose, for evaluating the effect of temperature on the RM of asphalt mixture, this test was carried out at three temperatures (5, 25, and 40 °C) with

Table 2 Test results on bitumen

Pure bitumen test	Test result	ASTM result	Standard specifications pure bitumen (70–60)	
			Min	Max
Specific gravity at 25 °C	D70	1.019	–	–
Degree of penetration at 25 °C (100 g—5 s)	D5	58	60	70
Softness point (ball-ring) in Celsius	D36	47.5	49	56
Stretching amount at 25 cm	D113	122	100	–
Solubility in tertiary chloride	D2042	99.23	99	–
Frasse Breakpoint (Celsius)—UK standard IP80	*	– 14	–	–
Degree of ignition (open-angle) Celsius	D92	300	232	–
Kinematic viscosity at 120 °C (CStux)	D2170	587	–	–
Kinematic viscosity at 135 °C (CStux)	D2170	355	–	–
Kinematic viscosity at 160 °C (CStux)	D2170	146	–	–
Thick bitumen glaze (163–5 h)	D1754			
Heat loss percentage		0.8	0.029	0.8
Degree of penetration after heat loss tests		–	39	–
Percentage of the degree of penetration after testing to the degree of primary penetration		–	63.33	–
The amount of stretch of bitumen after thermal loss test at 25 cm		–	+ 50	–
Bitumen thermal sensitivity:				
PI—(in terms of degree of penetration at 25 °C and softness point of bitumen)		–	– 0.89	–
PVN—(per degree of penetration of 25 cm and Viscosity in Cstux at 135 °C)		–	– 0.943	–

Table 3 Bitumen modified with lignin

Pure bitumen test	Percent of lignin (%)				
	0	3	6	9	12
Penetration grade	58	55.9	51.1	48.3	57.14
Softening point (°C)	47.5	48.7	49.2	55	56.2
Viscosity (C St)	355	380.1	410	440.2	475
Ductility (Cm)	122	59	38.1	30.1	17.7
Flash point (°C)	300	311	313	315	318

Table 4 Ingredients of consumable lignin [28]

Final decomposition	Soft wood lignin (dry matter percentage)
Carbon	62.17
Hydrogen	5.89
Nitrogen	0.15
Sulfur	0.06
Ash	0.62
Oxygen	31.11

five loading pulses by using the UTM14 apparatus. The RM of asphalt samples measured by performing a haversine loading with a frequency of 1 Hz and a loading time of 0.1 s (0.9 s of a rest period).

2.3.3 Fatigue test

The UTM14 apparatus was used to perform the fatigue test on the aged sample containing lignin by the indirect tensile method (ASTM D-4123). The test was performed at three levels of tensile stress (250, 350, and 450 kPa) and at 20 °C with a haversine load and a loading time of 250 ms and a rest period of 1250 ms. Until the full fracture of the asphalt mix, the number of cycles was defined as the FL of the asphalt mixture; therefore, to compare the FL of mixtures, the FL of each mixture is divided into the FL of the controlled sample.

3 Results and discussions

3.1 Results of the Marshall test

According to Fig. 2, by increasing the lignin content to 6%, the MS in the asphalt mixture increased compared to the controlled sample. It seems that this result is due to the decrease in penetration grade, stiffness, and more adhesion to bitumen corrected with lignin. In addition, as shown in Fig. 3, the asphalt mix flow is in a desirable range. The simultaneous increase in flow and stability is a

Fig. 2 Results of stability **Fig. 3** Results of flow

significant point in this section, which seems to be due to lignin's excellent effect on bitumen in the asphalt mix. By comparing this result with the results of previous research [3], the addition of lignin to asphalt mix is recommended.

3.2 The resilient modulus test result

According to Fig. 4, adding the lignin content leads to an increase in the RM of the samples at 5, 25, and 40 °C. At high temperatures, this is considered a positive point and a negative point at low temperatures. It seems that the increase in the RM is the change in the modified lignin bitumen's properties. Various reasons for this can be expressed. By adding lignin to bitumen, according to the results in the table, the bitumen becomes stiffer (because of an increase of viscosity [29]), and consequently, the asphalt mixture hardness increases. Chemically, lignin has been showing a high potential of anti-oxidation due to free radical scavenging activity and the polyphenolic structure in the lignin [26]. In terms of microstructure, researches showed that by increasing the lignin percentage in the mixture up to 6%, the intensity of the 1262 cm⁻¹ absorption band increases. Therefore, this indicates that the mixing of bitumen and lignin has improved [30, 31]. By

Fig. 4 Resilient modulus at 5 °C, 25 °C, and 40 °C **Table 5** Resilient modulus changes with temperature

LOG (RM)					
Tem- perature (°C)	0 L	3 L	6 L	9 L	12 L
5	4.100302	4.141694	4.179483	4.276393	4.214245
25	3.547775	3.589167	3.626956	3.693903	3.644636
40	2.817565	2.858958	2.896747	3.021685	3.118595

increasing the lignin content to 9%, the RM of the samples increases to 5 °C, and the RM has reduced. The highest of RM belongs to the sample containing 9% lignin, which has become 1.5 times more than the controlled sample.

The RM has increased in all samples (compared to the controlled sample) by adding the lignin to the asphalt mix. The largest RM is related to the sample containing 9% lignin, which its RM has become 1.4 times compared to the controlled sample. The low amount of lignin has little effect on the RM; on the other hand, the RM of the samples has decreased to more than 9% by increasing the lignin content.

The samples containing lignin have a more magnificent RM than the controlled sample, and the RM has increased at 40 °C by increasing the lignin content. The interesting point is that adding 12% lignin to the asphalt mix, unlike other temperatures (5 °C and 25 °C), the RM increased. It is observed that the RM of the asphalt mix at 40 °C has been changed more in greater amounts of lignin than the amounts below 6%. The highest of RM belongs to the sample prepared with 12% lignin (Table 5).

3.3 The thermal sensitivity (the trend of changes in RM with increasing temperature)

Due to changing weather conditions, engineers are trying to improve the performance characteristics of asphalt mixtures using additives. Researchers use these modifiers because bitumen may not perform well in all environmental and loading conditions. As stated in Fig. 5, the thermal sensitivity of asphalt mixes has decreased by increasing the lignin content to more than 9%; however, it is observed

Fig. 5 Resilient modulus changes with temperature

that the thermal sensitivity of asphalt mixes containing 3 and 6% lignin is same as the controlled sample. Besides, the thermal sensitivity of the sample containing 12% lignin (due to lower slope) has the lowest value. Therefore, it is generally concluded that the lignin additive improves the thermal sensitivity of the asphalt mixes (at 12%). Reducing the thermal sensitivity of the asphalt mixes improves its performance under different temperature conditions; this is more important at high temperatures because most transformations occur in asphalt mixes and rutting at high temperatures [32]. Since the RM's changes depending on the temperature changes, and the relative improvement in the specimens' thermal sensitivity, the reduction in the RM in the modified specimens is less than the base value.

3.4 The fatigue life test result

According to Fig. 6, adding the lignin content leads to an increase in the FL of the samples at 250, 350, and 450 kPa. According to Table 2, with increased viscosity of bitumen, the adhesion of the asphalt mixture has increased. It seems that this reason has increased the FL [33]. Increasing the FL of asphalt mixtures reinforced with lignin is due to that lignin forms a strong bond with bitumen, which increases the ability of bitumen to absorb and retain bitumen (Coating aggregate with bitumen); this eventually leads to the

Fig. 6 Fatigue life at a stress level of 250 kPa, 350 kPa, 450 kPa

adhesion of bitumen to aggregate. As adhesion increases, the displacement of the aggregates decreases relative to each other, and the resistance to shear displacement increases.

Figure 6 indicates that increasing lignin to 6% increases the FL of the asphalt mix, and then after, the FL of samples decreases by increasing the lignin content. It is observed that the FL of the mixes containing 9 and 12% of lignin has decreased compared to the controlled sample. Also, comparing the diagrams of Fig. 6, it was found that the asphalt mix constructed with 6% lignin, at a stress level of 250 kPa, tolerates the highest loading cycle until fracturing, i.e., it has the longest FL. According to Fig. 6, it can be seen that adding 3 and 6% of lignin to the asphalt mix, at a stress level of 350 kPa, increases the FL of the asphalt mix and the FL of the asphalt mix has decreased by increasing the lignin content. It is worth noting that the reduction in FL of the asphalt sample first increases and then decreases. In general, it can be said that increasing the lignin content in low increases, at stress levels of 350 kPa, has increased the FL, and lignin in high percent has decreased the FL.

The FL ratio of the sample containing different amounts of lignin to the controlled sample has shown in Fig. 6. It is observed that FL of samples increases by raising the lignin content to 6%, and the FL of samples reduces with increasing the lignin content to more than 6%. The interesting point is that the difference between the FL of the samples has reduced by increasing the stress level, and the FL imperceptibly increased in the mix with 9% lignin compared to the base state. As a whole, it can be said that

the FL has increased by raising the lignin content in all mixes except the mix containing 12% lignin compared to the base state.

3.4.1 The trend of changes in N_f with stress level

For all tested mixes, it was observed that the FL of samples reduces with increasing the inbound stress level. It was also noticed that the relationship between FL of samples is different from increasing the lignin content at different stress levels, i.e., the behavior of asphalt mixes containing lignin is not similar at all levels of stress. Thus, it can be concluded that N_f is related to σ . The well-known exponential Eq. (1) is used to illustrate the relationship between N_f and σ :

$$N_f = K_1(\sigma)^{k_2} \quad (1)$$

where N_f is fatigue life, σ is tensile stress, and K_1 and K_2 are Laboratory coefficients.

Equation (1) in the logarithmic set has represented a linear relationship with Eq. (2), where k_2 , is an indication of the slope of the line.

$$\log(N_f) = \beta_0 + \beta_1 \log(\sigma) \quad (2)$$

In this equation, β_0 and β_1 are the coefficients obtained from the secondary equations (see Table 6).

In Fig. 7, the line $\log(N_f) - \log(\sigma)$ has drawn by the Ordinary Least Square Estimation (OLSE) method (simple fit) for

Table 6 Parameters of fatigue equation in logarithmic scale

Specifications of asphalt mixtures	$\log(N_f) = \beta_0 + \beta_1 \log(\sigma) \quad N_f = K_1(\sigma)^{k_2}$				Log (N_f)		
					Log (stress)		
	β_0	β_1	k_1	k_2	2.398	2.544	2.653
0L	13.34	−3.85	2.20E+13	−3.85	4.117	3.468	3.141
3L	13.48	−3.87	3.02E+13	−3.87	4.214	3.558	3.233
6L	13.71	−3.94	5.20E+13	−3.94	4.266	3.605	3.266
9L	12.97	−3.72	9.30E+13	−3.72	4.089	3.460	3.150
12L	12.667	−3.61	4.70E+12	−3.61	4.033	3.429	3.119

Fig. 7 Changes in fatigue life with stress level with OLSE method

all the used asphalt mixes. The amounts of k_1 , k_2 , β_0 , β_1 and has also calculated and have given in tables.

4 Statistical analysis

Two-way analysis of variance with one observation has been used to analyze the results of the RM and fatigue tests. The present article considers RM as a function of lignin percentage–temperature and FL as a function of lignin percentage–stress level, and for this reason, a two-way ANOVA has been used. Moreover, ANOVA with one observation is used because the RM and fatigue tests are done at each temperature and percent of lignin (stress level and percent of lignin for fatigue) on a sample. The mathematical model of this method is following Eq. (3) [29]:

$$Y_{ij} = \mu + P_i + T_j + E_{ij} \quad (3)$$

where Y_{ij} = Total RM or Fatigue Test; μ = Total Average; P_i = The Effect of Lignin Percent ($i = 1, 2, 3, 4$); T_j = The Effect of Temperature ($j = 1, 2, 3$); E_{ij} = Error.

The research on the normality of the results obtained from the RM and FL of the asphalt mixes by using the Kolmogorov–Smirnov test.

4.1 The results of the resilient modulus test

The results of the Ln (RM) ANOVA test are presented in Table 7 and Figs. 8 and 9. The results indicate that both factors of temperature and lignin percent affect the RM since the significance level (P value) of both variables is less than 0.05; however, the effect of temperature changes

Table 7 Results of variance analysis

Source	DF	Adj SS	Adj MS	F value	P value
Lignin (%)	4	0.3864	0.0966	7.45	0.008
Temp (°C)	2	20.444	10.222	787.78	0.000
Error	8	0.1038	0.0130	–	–
Total	14	20.9343	–	–	–

Fig. 8 Graph of influence factors for Ln (RM)

Fig. 9 Graph of influence factors for Ln (RM)

on the RM is more significant. According to the results, it is observed that adding the lignin content has increased the RM of the asphalt mixture; it is also worth mentioning that temperature has had a significant effect on the RM so that the RM is reduced by increasing the temperature. It is also observed that the effect of lignin is higher at temperatures above 25 °C.

4.2 The results of the fatigue test

The ANOVA results of the FL test are presented in Table 8 and Fig. 10. The two-way ANOVA of the normalized fatigue results indicates that both lignin and stress levels affect the sample's fatigue. However, the effect of stress level is

Table 8 Results of variance analysis

Source	DF	Adj SS	Adj MS	F value	P value
Lignin (%)	4	0.3798	0.09495	56.87	0.000
stress (KP)	2	12.7108	6.35538	3806.72	0.000
Error	8	0.0134	0.00167		
Total	14	13.1039

Fig. 10 Graph of influence factors for Ln (NF) **Fig. 11** Graph of influence factors for Ln (NF)

more significant than changes in lignin percent. According to Fig. 11, it can be observed that the factors under study (Lignin percentage–stress) are not related to the fatigue parameter since there is no collision between their graphs at any levels of stress. Results show that asphalt mix fatigue is affected by lignin percent and inbound stress levels.

Table 9 Design result

Additive%	Marshall stability (pound)	a_1	D_i
0 L	1966	0.425	$D_0 = 4.6353$
3 L	2270	0.46	4.2826
6 L	2694	0.465	4.2366
9 L	2447	0.462	4.2640
12 L	2414	0.460	4.2730

Table 10 Economical result

Additive%	Benefit	Cost	Benefit-cost	Result
0 L	0	0	0	–
3 L	23,012	2589	+ 20,424	Economical
6 L	26,017	5122	+ 20,895	Economical
9 L	24,222	7733	+ 16,489	Economical
12 L	– 11,065	10,333	– 21,398	Uneconomical

5 Economic analysis

In this research, the economic analysis of adding additive (lignin) to asphalt mix was evaluated [3, 8, 10, 34]. In this section, the costs and benefits of adding lignin were evaluated. For this purpose, the construction of a 6-line road (each direction 3 lines) for 1 km was evaluated. The particular weight of asphalt was considered $\gamma = 2.3 \text{ ton/m}^3$, and the price of each ton of asphalt and lignin (per kg) was considered 51\$ and 0.25\$, respectively. Finally, the benefit and cost of adding lignin into mixtures were calculated using the following formula:

$$\text{Benefit} = 1000 \times 6 \times 3.65 \times \frac{D_i \times 2.54}{100} \times \gamma \times \text{asphalt price} - 1000 \times 6 \times 3.65 \times \frac{D_0 \times 2.54}{100} \times \gamma \times \text{asphalt price} \quad (4)$$

$$\text{Cost} = 1000 \times 6 \times 3.65 \times \frac{D_i \times 2.54}{100} \times \gamma \times 1000 \times \frac{62.4}{1000} \times \text{additive percent} \times \text{Lignin price} \quad (5)$$

Tables 9 and 10 show the results of design and economic analysis, respectively. According to Table 10, the mixes 6L, 3L, and 9L have the best (benefit-cost) and are economical. With the addition of lignin to the asphalt mix, Marshall's resistance increased, so the difference between D_i and D_0 increase, eventually leading to an economical design. It is worth noting that by adding 3% and 6% of lignin to the asphalt mixtures, 20424 and 20895 economic benefits were observed, respectively.

This amount of benefit was obtained for a road with a length of 6 km and 6 lanes. Assuming the use of this additive in the amount of 6% (according to the technical discussion), and its application in a road with a length of 100 km, the financial benefit is more than 2 million dollars. Therefore, adding lignin on a large scale would be recommended when taking into account the technical, economic, and environmental benefits.

6 Conclusion

This paper examines the effect of lignin on some asphalt mix properties, such as Marshall Stability (MS), Resilient Modulus (RM), and Fatigue Life (FL). The summary results of this research presented as follows:

- The overall results of the Marshall test showed that the presence of lignin, in addition to increasing the MS, also reduced flow; As a result, Marshall's ratio can be expected to increase, which improves rutting performance.
- The Lignin increases the RM of the asphalt mix at all temperatures. However, as the temperature increased, the RM decreased. Also, the effect of lignin on MR at 40 °C was more significant than at other temperatures; this was due to the well mixing of lignin and bitumen at higher temperatures.
- Lignin in the amounts of 3 and 6% does not affect on the thermal sensitivity of the asphalt mix, but it reduces the thermal sensitivity in high amounts.
- The FL results show that the FL of asphalt mix positively affected by adding lignin. Adding 3 to 6% of lignin to the asphalt mixture increased the fatigue life, and by increasing the amount of lignin to 9%, the fatigue life was reduced.
- Examining the statistical analysis of the RM results that temperature and lignin affect the resilient modulus. Moreover, the statistical analysis of the fatigue results showed that both lignin percent and stress levels in the two-factor test were effective on the asphalt fatigue.
- The economic analysis results showed that the project's profitability depends on the increase in the mixture's stability. According to financial results, lignin recommended with 3, 6, and 9%.
- According to the discussions and conclusions, the optimum amount of using lignin was determined equal to 6%.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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