Research Article

Experimental determination of the optimum percentage of asphalt mixtures reinforced with Lignin

Mohsen Zahedi[1] · Ali Zarei[1] · Mohammad Zarei[2] · Omid Janmohammadi[3]

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Abstract

This article has used lignin additive to improve the bitumen properties as well as the asphalt mixture performance. Therefore, Lignin added to the bitumen 60/70 in various weight percentage (3, 6, 9 and 12 percent). Then, its effect on various properties of bitumen, including penetration grade, softening point, ductility, viscosity, weight loss percent, permeability index, flash point, and Frass breaking point were compared. Then, Asphalt mixtures were made. The results of experiments show that, by adding lignin to bitumen, the penetration grade, softening point, permeability index, kinematic viscosity and flash point of bitumen were increased, but its ductility and Frass breaking point were reduced by increasing the lignin content. Also, the weight loss test revealed that lignin reduces the oxidation of bitumen at high temperatures and in the short term. The results of mechanical asphalt experiments also showed that the performance properties of the asphalt, in particular its Marshall stability would improve by using lignin up to 6%. Finally, Economic analysis was evaluated for a 3-way road. After observing the findings and summarizing the results (technical and economic), the optimal amount of lignin was determined equal to 6 percent.

Keywords Lignin · Bitumen · Asphalt mixtures · Rheology · Marshall

1 Introduction

Road maintenance has been faced with many problems due to increasing the road traffic and the damages caused by it. In recent years, the upward trend in repair and reconstruction costs for airport and road pavements, which is caused by the increase in the amount and repetition of inbound traffic loads on pavements, has led to a comprehensive study on increasing the capacity of asphalt pavements against dynamic loads. Moreover, due to the fact that bitumen in the asphalt mix plays the most important role in interlocking the aggregates, improving the rheological properties of bitumen can be importance. Improving the rheological properties of bitumen and the mechanical and dynamic properties of asphalt mix can be achieved with suitable additives [1–8]. Many researchers have always looked for reasons to justify the use of additives to modify the properties of bitumen. These additives have been added to asphalt mixtures in various forms, such as nanomaterial, fibers and polymers [9–12].

One of the important polymer is lignin. Lignin was used as an additive to improve the properties of bitumen and asphalt. Several definitions and characteristics have been proposed over time to define this additive.

Lignin in plants and wood is formed by polymerization of three propanoid monomers [13]. These monomers are as follows:

- 3-(4-hydroxyphenyl)-2-propan-1-ol. (Paracoumaryl Alcohol)

✉ Ali Zarei, eng.ali.zarei69@gmail.com; Mohammad Zarei, mohammadzarei959@yahoo.com | [1]Department of Civil Engineering, Razi University, Kermanshah, Iran. [2]Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran. [3]Department of Civil Engineering, Central Tehran Branch, Azad University, Tehran, Iran.

- 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, which have connected to each other by carbon–carbon and ether bonds and it is among the wastes in the paper industry. On one hand, lignin strengthens wood and fiber cellulosic fibers and on the other hand, as a member of polymer families, the use of this natural polymer also improves the mechanical properties of the made asphalt as other used polymers. Due to its chemical structure in the bitumen matrix, lignin creates a three-dimensional network, which results in improving the bitumen performance at elevated temperatures and it also plays the role of antioxidant in bitumen [14].

The following studies have been done to investigate the effect of lignin on bitumen and asphalt properties.

The use of liquid waste containing lignin in asphalt mix, was investigated by Pérez's et al. [15] The results indicated that by adding 20%, the resilient modulus increased at 30 °C. Also, as the percentage of industrial waste increased, the thermal susceptibility of the mixture also increased.

The effect of lignin on bitumen was investigated by Batista et al. [16] the result show that by adding content of 4 wt.% of lignin to bitumen, thermal stability of bitumen increased after the Rolling Thin Film Oven Test (RTFOT). Also, the asphalt resistance to thermal cracking was improved by Lignin at temperatures up to 12 °C.

Norgbey et al. [17] investigated the use lignin as a modifier for bitumen. The results indicate that the cohesion and stiffening of the bitumen are improved by adding of lignin to bitumen. Also, adding 10% lignin has little effect on the performance and compaction characteristics of the asphalt mixtures.

Wang and Derewecki [18] pointed out the positive effect of lignin on Rheological Properties of Asphalt Binder. The result indicated that by adding of lignin into bitumen increased the viscosity of bitumen.

Xu et al. [19] investigated the effect of lignin on bitumen. The results show that Lignin increased rutting resistance but negatively effects on fatigue cracking of asphalt.

Wang et al. [20] investigated the rheological properties of wood-lignin-modified bitumen in a laboratory study. They combined two types of bitumen PG 64-22 and PG 76-22 with two percentage of lignin (5 and 10 weight percent) and evaluated the samples under Sharp experiments. The results of the dynamic shear rheometer (DSR) test showed that increasing the percentage of wood lignin improves the resistance to the wheel effect phenomenon. They stated that lignin is not just as a filler, but it is chemically reactive with bitumen. Also, the results of the bending beam rheometer (BBR) test indicated that lignin does not have much effect on controlling the thermal cracks development.

Zarei et al. [21] investigated the mechanical properties of asphalt mixtures containing lignin-glass fiber. Their results showed that Marshall Stability was dependent on fiber length. Also, Flow and void in total mixture (VTM) increased and unit weight and voids in the mineral aggregate (VMA) decreased.

Wood et al. [22] examined the effect of lignin as a simulator in the epoxy-kenaf composite. They added different amounts of lignin (0.5, 1, 2, 5 weight percent) to the epoxy-kenaf composite and examined its two effects on the mechanical properties of the composite. They showed that adding lignin to the epoxy-kenaf composite increases its mechanical properties, such as impact resistance, tensile strength and flexural strength. However, the tensile and flexural strength and its modulus had been reduced by adding excessive lignin content (5 weight percent) due to poor mixing and increased viscosity of the resin so that the properties of the elastic modulus and UTS at 2.5 weight percent of lignin had the optimum value. Also, by increasing the amount of lignin, its impact resistance has also increased so that its maximum value was observed at 5 weight percent of it. SEM images taken from the sample fracture section showed that there is a better compatibility between epoxy, kenaf and lignin in the sample with 2.5 weigh percent.

This research is similar to Zahedi et al. [9] Research with two following advantages:

1. The effect of lignin on the following three cases was investigated.
    - (A) The weight loss percent of the bitumen by heating,
    - (B) Results of thin-film oven test on bitumen (bitumen oxidation) and
    - (C) Bitumen performance at low temperatures (frass breaking point)
2. The results of the economic analysis indicate that the use of lignin is superior and better.

As can be seen, a few studies have been conducted about the effect of lignin on bitumen on asphalt mixture. But, the lack of a research to consider the technical–economic effect of lignin on properties of bitumen and asphalt mixture, was felt. So, the main objective of this article is technical–economic effect of lignin on properties of asphalt mixtures and bitumen.

2 Consumable materials properties

2.1 Aggregate gradation

The aggregates used in making the laboratory sample have prepared from the Ghazanchi asphalt plant in Kermanshah and source of materials were constant at all stages of testing. The mixing ratios of the aggregates in the asphalt mixtures for the surface layer are determined as shown in Tables 1 and 2.

The grading curve resulting from mixing the required weight percent in comparison to the grading used in preparing the sample has drawn in Fig. 1.

2.2 Bitumen

The bitumen (60/70) used in this research have prepared from the Isfahan refinery (J-Oil Company). The classic bitumen tests were performed in the Marshall method on the sample bitumen (base state), and the results of these experiments are presented in Table 3.

2.3 Lignin

The lignin used in this research was gross, which was prepared from the paper mills wastewaters in Iran. The wastewater from the Iranchuka's paper mill, known as black liquor, is as liquid and contains large quantities of lightning and water; therefore, in order to use it in bitumen and asphalt as an additive, it should be indirectly heated (at a maximum temperature of 110 °C) till its water be evaporated and a black powder remains in the container. Then, this powder, which contains high amounts of lignin, passes through sieve mesh 30 after it was milled. Finally, the lignin, which was passed through the sieve mesh 30, was used as an additive (Table 4).

Table 1 Mixing ratios of the aggregates

Specifications of aggregate	Particle size (mm)	The percentage of the mixing of aggregate of layer surface
Medium sand	0–25	8
Tiny sand	0–19	23
Sand	0–6	68
Filler (limy)	Micron	1

Table 2 Asphalt mixture aggregate gradation

Gradation number	Iranian paving code 234 No. 4, NMAS: 12.5 mm	Grading of mixture
Sieve size	Passing percent (specification limits)	Passing percent
19	100	100
12.5	90–100	95
4.75	44–74	55
2.36	28–58	37
0.3	5–21	10
0.075	2–10	5

3 Sample preparation

In the present research, lignin was first added to bitumen in different percentages (3, 6, 9 and 12 bitumen weight percent) for all samples and after mixing bitumen and lignin, asphalt mixtures were made with the intended bitumen. The method of mixing bitumen and lignin was done in such a way that at first the bitumen was heated to 155 °C, after that, the lignin powder, which had passed through a sieve mesh 30, was gradually added to the bitumen. The desired asphalt mixture was stirred with a high-shear mixer rotating at a speed of 5000 rpm and a constant temperature for 30 min until the lignin and bitumen were well combined [23]. Then, for Marshall Test, samples was carried out according to the ASTM D-1559 standard. Finally, the economic analysis was done at the end. Also, the cost of adding lignin into mixtures is calculated using the following formula [24–26]:

$$\text{Benefit} = 1000 * 6 * 3.65 * \frac{D_i * 2.54}{100} * \gamma * \text{asphalt price} - 1000 * 6 * 3.65 * \frac{D_0 * 2.54}{100} * \gamma * \text{asphalt price} \quad (1)$$

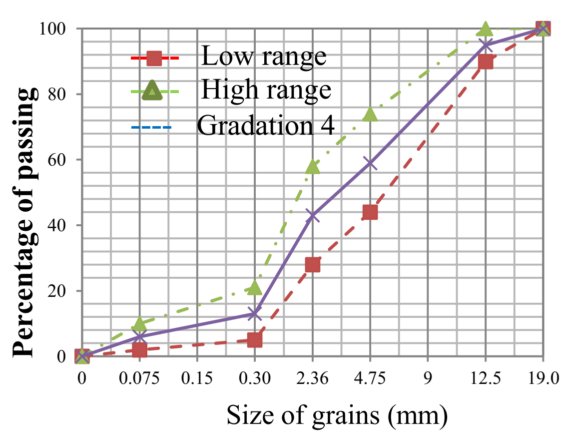

Fig. 1 Grading curve of asphalt mixture

Table 3 Test results on bitumen

Base bitumen test	Test result		ASTM result	Standard specifications base bitumen (60–70)	
	AASHTO	ASTM		Min	Max
Specific gravity at 25 °C	T228	D70	1.019	–	–
Degree of penetration at 25 °C (100 g-5 s)	T49	D5	60	60	70
Softness point (ball-ring) in Celsius	T53	D36	49.5	49	56
Stretching amount at 25 cm	T51	D113	125	100	–
Solubility in tertiary chloride	T44	D2042	99.23	99	–
Frass Breakpoint (Celsius)-UK standard IP80	*	*	– 14	–	–
Degree of ignition (open-angle) Celsius	T48	D92	300	232	–
Kinematic viscosity at 120 °C (CStux)	T201	D2170	587	–	–
Kinematic viscosity at 135 °C (CStux)	T201	D2170	354	–	–
Kinematic viscosity at 160 °C (CStux)	T201	D2170	146	–	–
Thick bitumen glaze (163-5 h)	T179	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 4 Ingredients of consumable lignin

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

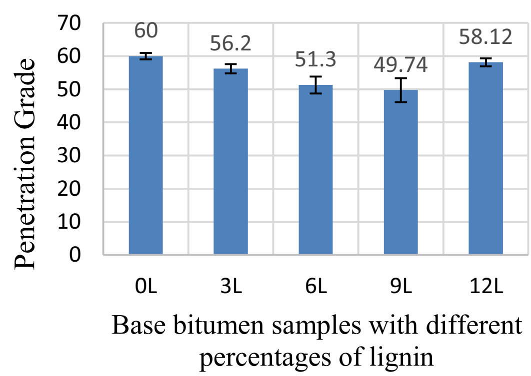

Fig. 2 Penetration test results for samples with different percentages of lignin

$$\text{Cost} = 1000 * 6 * 3.65 * \frac{D_i * 2.54}{100} * \gamma * 1000 * \frac{62.4}{1000} * \text{additive percent} * \text{Lignin price} \quad (2)$$

γ = unit weight $\left(\frac{\text{ton}}{\text{m3}}\right)$, D_i = Layer thickness (*Cm*)

4 Explaining and analyzing the results of bitumen tests modified with different percentages of Lignin

In order to evaluate the performance of bitumen, various tests were performed on it. Various properties of bitumen as physical, mechanical, morphological and rheological, etc. can be determined by using these tests, which here the effect of lignin additive on some fundamental properties of bitumen was evaluated in comparison to the pure bitumen.

4.1 Results and analysis of penetration grade test

The results of penetration grade test (at 25 °C) conducted on the bitumen samples containing lignin additive in various percentages have shown in Fig. 2. As the results indicate, adding lignin to bitumen result in decreases the penetration grade. According to Fig. 3, it can be

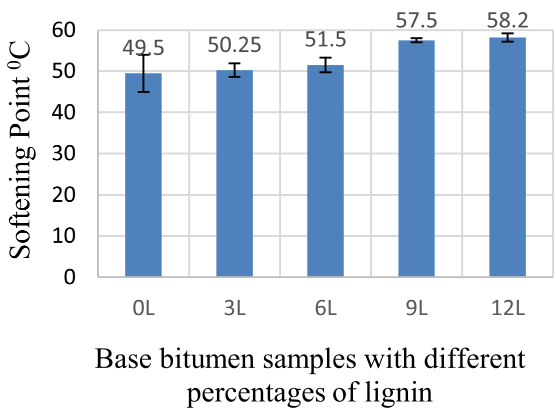

Fig. 3 Softening point results for samples with different percentages of lignin

seen that increasing the amount of lignin to more than 9% (bitumen weight percent) increases the penetration grade. This increase occurs when the penetration grade of the bitumen containing 12% lignin is higher than the base bitumen. The penetration grade reduction in the bitumen containing lignin in less than 12% can be found in the numerous polar bonds in lignin that arranges specific molecular arrangements in bituminous aromatic structures. Stronger bonds are created between bitumen and lignin particles by adding the lignin polymer content to bitumen, which increases the bitumen hardness, while the excessive addition of polymer to bitumen results in the loss of forces between bitumen molecules and the primary structure of the bitumen breaks down and it loses its original property [27]. This is pretty obvious in the bitumen containing 12% lignin.

4.2 Results and analysis of softening point test

The results obtained from the softening point test, which is conducted on the bitumen samples combined with lignin in different percentages have presented in Fig. 3. As it can be seen, the softening point increases with rising the lignin percentage so that the softening point has increased by 8 °C with a 9% increase in lignin. The increasing trend of the softening point in the low percentages of lignin (3%) is minor and it differs little from the base bitumen. This reason can be justified in a way that bitumen viscosity decreases as the temperature rises and the polymer moves more freely and the intermolecular forces become important among them. By increasing the amount of polymer, stronger forces form between its molecules, which results in improving the bitumen performance against temperature rise [28].

4.3 The effect of lignin on the ductility property of bitumen

The results of the ductility test were performed on the base bitumen sample with different percentages of lignin at 25 °C and the results have shown in Fig. 4. According to the results, it was found that adding lignin to bitumen even in small amounts also significantly reduces the ductility of the bitumen. The bitumen ductility trend was more sensitive at lower percentages of lignin and the trend changes with a milder gradient at the higher percentages. This can be explained by the fact that adding lignin polymer and creating three-dimensional polymer blocks in bitumen increase the bitumen hardness and bitumen loses its original essence and thus, the bitumen ductility is reduced.

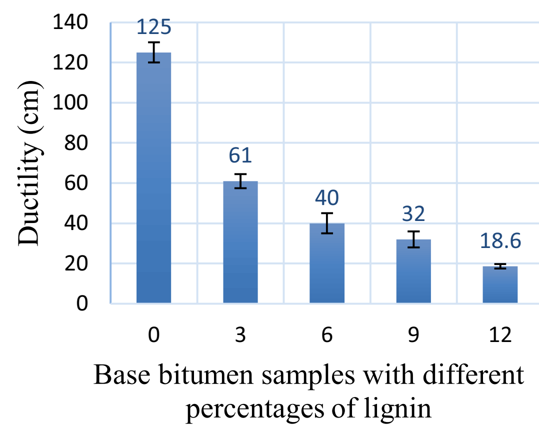

Fig. 4 Effect of adding lignin on bitumen ductility

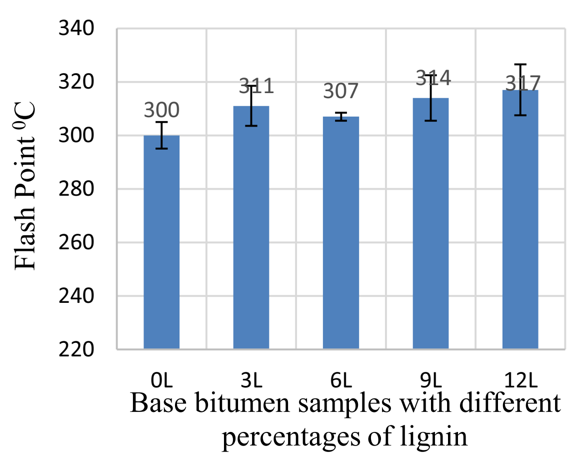

Fig. 5 Test results for the degree of ignition for samples with different percentages of lignin

4.4 The effect of Lignin on the bitumen flash point

Referring to the results of tests conducted on the bitumen with different percentages of lignin, which have shown in Fig. 5, it was found that adding lignin to bitumen increases the bitumen flash point. The flash point slightly reduces with increasing lignin from 3% to 6%; however, it is still higher than the base bitumen flash point. By adding the amount of lignin, the flash point increases in more than 6%. Bitumen flash point is of great importance in executive safety for heating and whatever its amount is higher it is better, since the bitumen flares at higher temperatures.

4.5 The effect of Lignin on the bitumen viscosity

The kinematic viscosity of the base bitumen and the modified bitumen with different percentages of lignin was calculated in various weight percentages at 135 °C, which have shown in Fig. 6. According to Fig. 6, the kinematic viscosity of bitumen increases by adding lignin to it. Such a result was observed in the research of Wang et al. [18]. This increase may be due to the fact that the molecular structure of lignin, regarding its aromatic nature, has aromatic interactions with aromatic structures of bitumen. Moreover, the etheric, phenolic and polar groups of its structure also make it possible to have strong interactions, even covalent, with polar structures and bitumen heteroatoms such as bitumen resins and asphaltenes. In other words, lignin, as a linking factor, can create abundant cross links between heavy structures of bitumen and it makes the bitumen structure more coherence and strength. The structure of the lignin makes a three-dimensional and a networked structure of the bitumen. This has shown schematically in Fig. 7 [14].

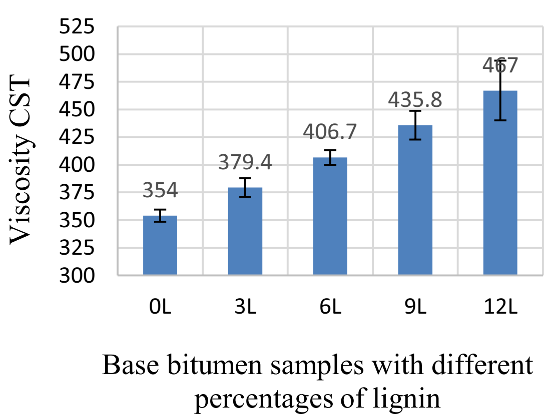

Fig. 6 The effect of lignin on the viscosity of bitumen at 135 °C

4.6 The effect of Lignin on the thermal sensitivity of the bitumen

The resulting changes in the concentration of bitumen (penetration grade or viscosity), which is caused by a change in its thermal conditions, are called the thermal sensitivity of the bitumen, which varies for different bitumen. The thermal sensitivity of the bitumen can be expressed by two parameters of the permeability index (PI) and the penetration viscosity number (PVN). In general, the more the proposed parameters are closer to + 1, the bitumen thermal sensitivity is lower and the bitumen is in more ideal condition. The calculations of PI and PVN have presented in Table 5. Changes of PI and PVN in the modified and unmodified bitumen with lignin in various weight percentages have shown in Figs. 8 and 9, respectively. According to the results in Table 5, it is seen that the parameters PI and PVN get closer to + 1 by increasing the lignin. Therefore, it can be concluded that increasing the amount of lignin decreases bitumen sensitivity to temperature changes. This suggests that bitumen, which modified with lignin, has more favorable properties in areas with a high thermal difference.

4.7 The effect of Lignin on the weight loss percent of the bitumen by heating

In order to test the weight loss of each bitumen, two samples have provided and the average results of the test have presented in Fig. 10. In this test, a 0.001 precision digital scale was used to weigh the samples before and after testing. As can be seen, the weight loss has increased at 163 °C by raising the lignin content. This increase in sample weight loss can be due to the oxidation of lignin at this temperature, since lignin loses its weight at temperatures above 130 °C [14]. Emitting the intense odor of lignin in the laboratory environment during the testing process can be due to this phenomenon. Also, after calculating the weight loss on the samples, ductility test was performed on them, which its results have presented in Table 6.

4.8 The effect of Lignin on the results of thin-film oven test on bitumen (bitumen oxidation)

Thin-film oven test to determine the hardening of the bitumen indicates the effect of heat generated by different stages of using bitumen to produce asphalt. The oils in the bitumen are evaporated by heating and the bitumen is oxidized and in other words, the bitumen gets into the short term aging. The bitumen that is aged does not have the ability to carry a high load and it's not suitable for use in road construction process since its resistance to the fatigue phenomenon is low. In general,

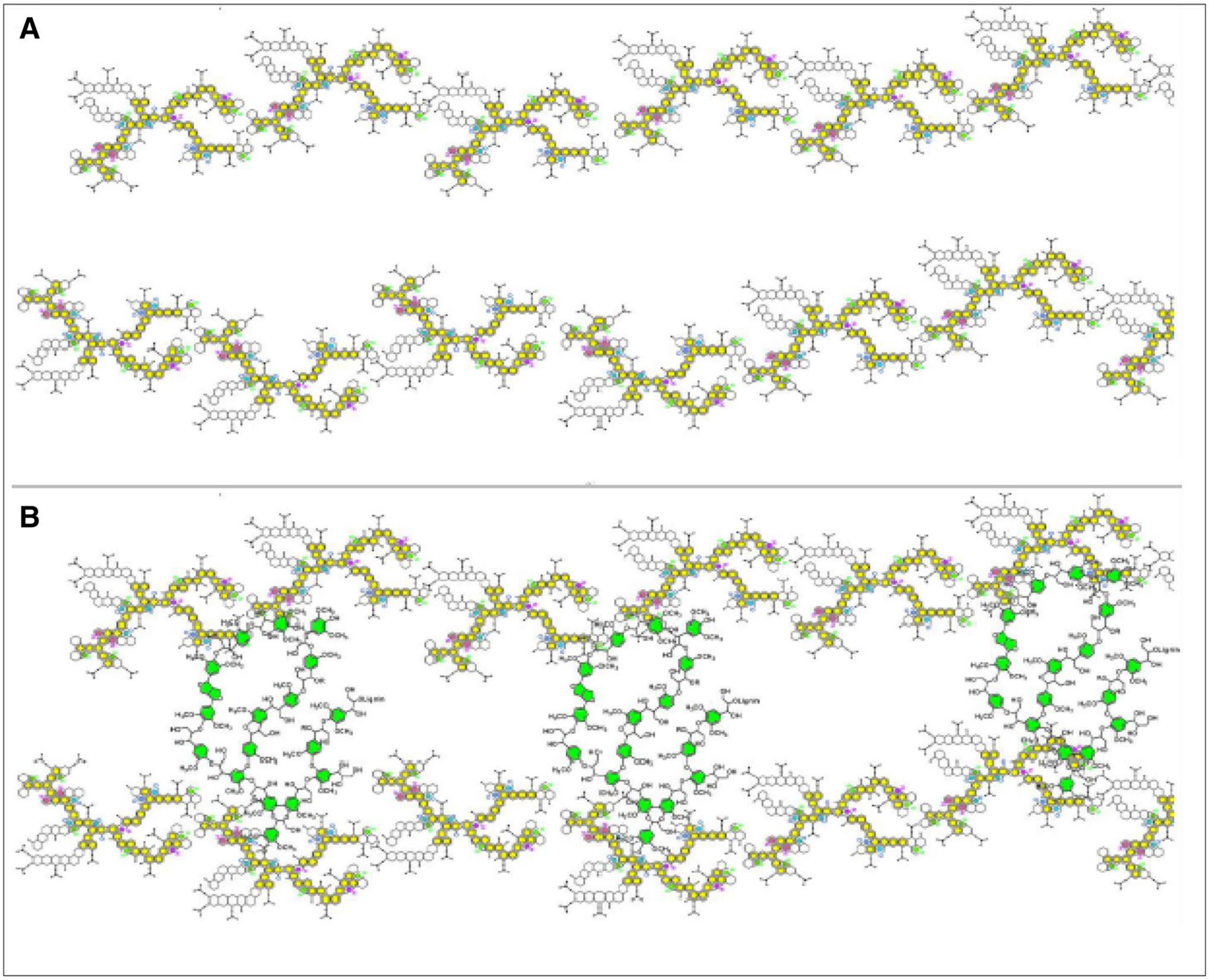

Fig. 7 Lignin effect on bituminous Structure [19]

Table 5 Calculate PI and PVN

Sample type	Lignin percent	L*	M**	A***	PI****	PVN*****
0 L	0	2.841	2.377	0.046	− 0.897	− 0.943
3 L	3	2.846	2.394	0.046	− 0.864	− 0.909
6 L	6	2.896	2.418	0.045	− 0.772	− 0.899
9 L	9	2.906	2.426	0.037	0.504	− 0.834
12 L	12	2.852	2.385	0.034	1.050	− 0.587

*$L = 4.25800 - 0.7967 \times \log(\text{P.G})$

**$M = 3.46289 - 0.61094 \times \log(\text{P.G})$

***$A = \frac{\log 800 - \log(Pen\ at\ 25^{\circ}\text{C})}{T_{R\&B} - 25^{\circ}\text{C}}$

****$PI = \frac{20 - 500A}{1 + 50A}$

*****$PVN = \frac{-1.5 \times [-\log(Viscosity\,135^{\circ}\text{C})]}{L - M}$

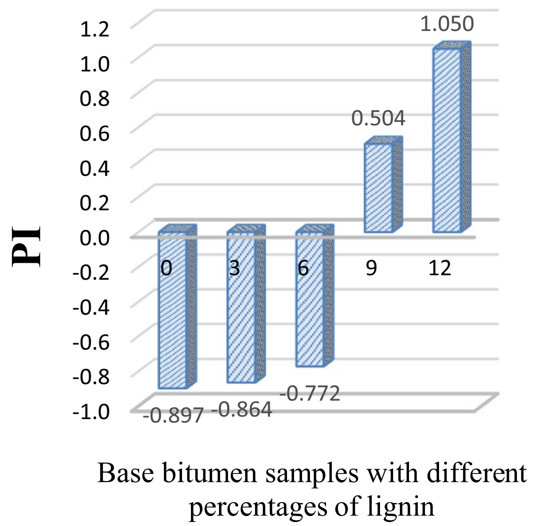

Fig. 8 Effect of lignin on bitumen permeability index

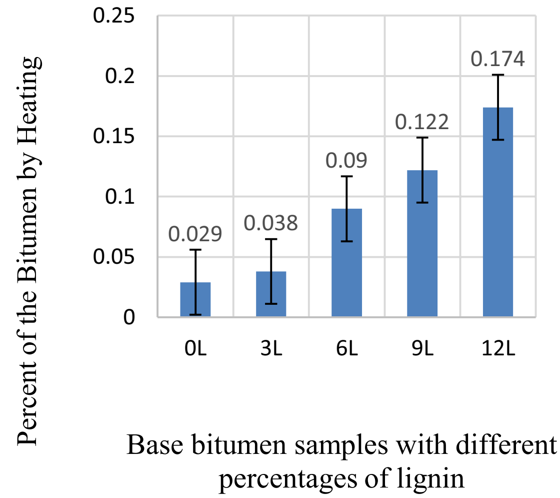

Fig. 10 Effect of lignin on weight loss

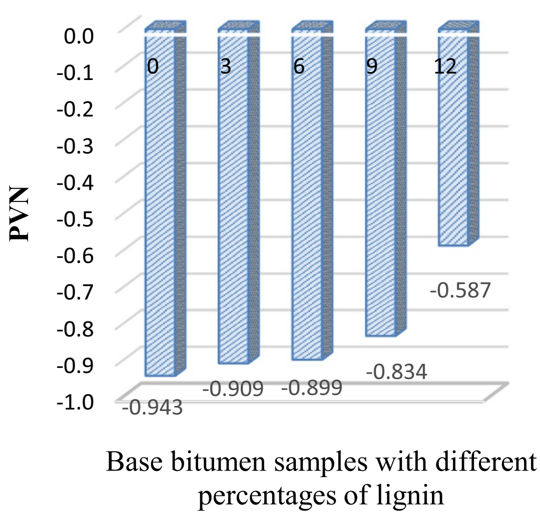

Fig. 9 Effect of Lignin on penetration viscosity number

Table 6 Ductility of a sample of Bitumen containing lignin before and after thermal loss test

Sample type	Lignin percent	Ductility before weight loss test	Ductility after weight loss test
0 L	0	125	95
3 L	3	61	43
6 L	6	40	37.2
9 L	9	32	28.5
12 L	12	18.6	13

Table 7 Penetration degree before and after testing of bitumen glaze for samples containing lignin with different percentages

Sample type	Lignin percent	Degree of penetration before the thin-film oven test	Degree of penetration after the thin-film oven test
0 L	0	60	38
3 L	3	56.2	36.8
6 L	6	51.3	33.9
9 L	9	49.74	37.7
12 L	12	58.12	28

whatever the penetration grade reduction after thin-film oven test is lower, the bitumen is less hardened and it has a good resistance to oxidation and the intended bitumen is more favorable. This test was carried out on the base bitumen and the bitumen samples containing lignin with different percentages, the results of which are in accordance with Table 7. Also, the percentage of the bitumen penetration grade before and after testing has also shown in Fig. 11. It should be noted that the test is repeated twice for each sample and the declared results are the number average of the two tests. According to Fig. 11, the ratio of penetration grade in the thin-film oven test has increased by raising the lignin content and this means that bitumen is less hardened. Based on the results, lignin, as an antioxidant substance, has prevented bitumen oxidation. It is also observed that the ratio of penetration grade is even lower than that of the base in high levels of lignin content (12%) and bitumen with this level of lignin content has been further oxidized. Therefore, it can be stated that lignin decreases hardening of bitumen in low percentages up to 9%, but the excessive addition has the opposite result. This is due to the fact that the structure of bitumen is crumbled by adding lignin to bitumen at levels higher than 12% and

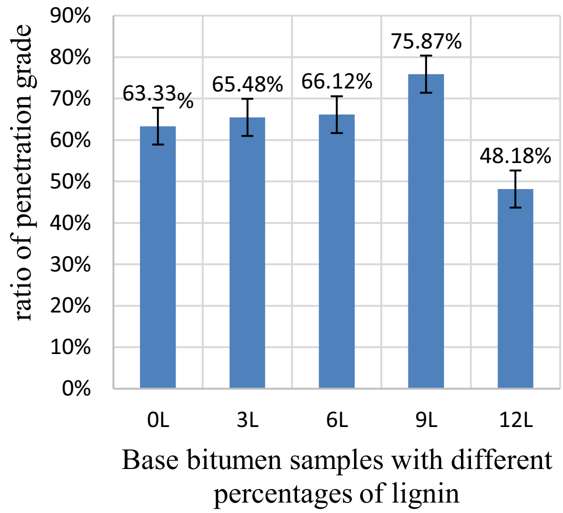

Fig. 11 Ratio of penetration grade of bitumen containing lignin

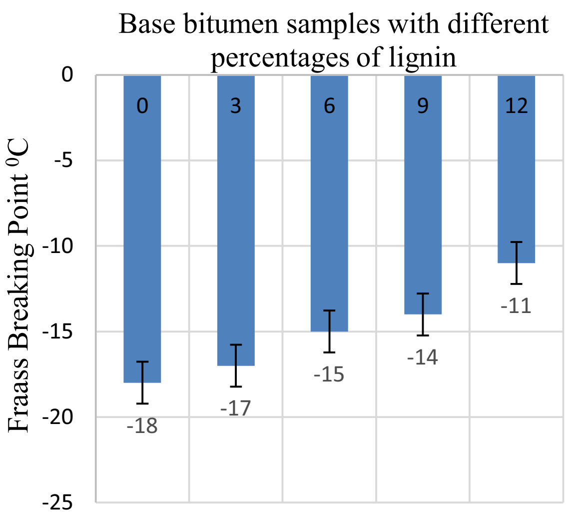

Fig. 12 Effect of lignin on bitumen performance at low temperatures

its resistance properties are reduced and it gets more easily oxidized [29].

4.9 The effect of Lignin on bitumen performance at low temperatures (frass breaking point)

The Frass breaking point is considered as one of the most important experiments to describe the behavior of bitumen at low temperatures. As shown in Fig. 12, the Frass breaking point decreases with increasing the lignin polymer percentage (it becomes more positive). This suggests that adding lignin polymer to bitumen leads to inappropriate behavior of bitumen at low temperature (below zero degrees Celsius). In other words, adding lignin increases bitumen hardness at lower temperatures and reduces bitumen elasticity. However, this reduction is negligible and can be ignored. In the low percentage of lignin (up to 6%), the difference in the Frass breaking point of the bitumen containing the additive and the base bitumen is negligible, but the improper performance of the bitumen at low temperatures than the base state can be seen by increasing the lignin content from 6% to 12% so that with a 12% increase in lignin to the bitumen, its Frass breaking point is reduced by 7°. This phenomenon can have a significant effect on creating and expanding fatigue cracks at low temperatures.

5 Marshall tests

The test was carried out according to the ASTM D-1559 standard. To dry the aggregates, the aggregates were placed in the oven (at 170° C for 24 h).

The mixing temperature of aggregates and bitumen was 160 °C. Also, the compaction was carried out at 150 °C. For all samples, the optimum bitumen was 5.5% (with 3 replicates). Also, for all samples, the design air void content was 4%.

5.1 The results of Marshall test

By conducting Marshall Tests on the asphalt concrete samples made of lignin, the present study has attempted to determine the physical properties and volumetric parameters of the asphalt mix, such as Marshall Stability, Marshall Flow, unit weight, voids in the mineral aggregate, void in total mixture, voids filled with asphalt binder.

According to the diagrams in Fig. 13, adding lignin to asphalt mix increases the Marshall stability. The trend of increasing Marshall Stability is ascended by increasing lignin content to 6% and then it is descended. In other words, adding lignin in amounts exceeding 6%, not only does not increase the Marshall stability, but also reduces it. Based on the test results, adding only 6% of lignin to asphalt mix has increased the mix Marshall Stability to 36.5% compared to the base state. This factor can be attributed to the reduction of bitumen penetration grade, more hardening and adhesion of the bitumen modified with lignin. Moreover, decreasing Marshall Stability for contents more than 6% may also be due to the lack of suitable sample density followed by increased bitumen viscosity. By comparing this result with the results of Zarei et al. [21], it can be concluded that lignin has a positive effect on asphalt.

Flow refers to the maximum deformation of the asphalt sample for loading prior to the sample breaking. Figure 13 has presented the Flow of all the asphalt samples, which

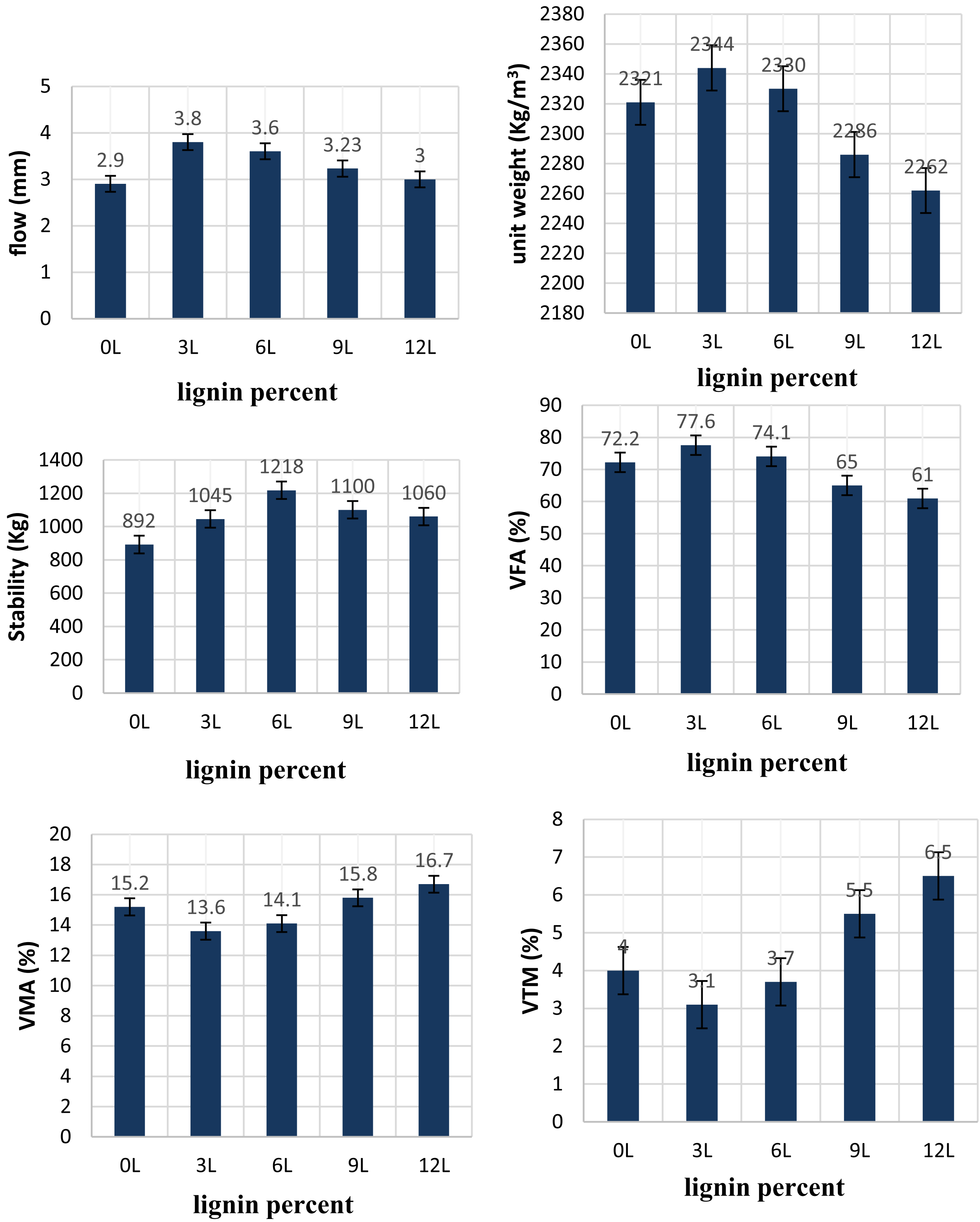

Fig. 13 Marshall results

are made with different additive percentage. As it is obvious, the Flow at first has increased and then it has reduced. This result is similar to Zarei et al. [21].

Due to the insignificant amount of additives, the unit weight of the made samples cannot be changed significantly. According to the Fig. 13, it can be seen that the unit weight of lignin samples has increased by 3 and 6 percent compared with the control sample and other samples have lost the unit weight. By comparing this result with the results of Zarei et al. [21], it can be concluded that lignin has a positive effect on unit weight of asphalt.

By comparing the diagrams shown in Fig. 13, it can be observed that the most amount of VMA is related to the common use of 12% lignin. Also, the lowest amount of VMA is related to the mix containing 3% lignin. As it can be seen, the low amounts of lignin have reduced VWA to 6% and adding it in amounts greater than 9% has increased the VMA.

According to Fig. 13, adding lignin to asphalt mix in levels of 3 and 6% has increased the voids filled with asphalt binder (VFA) value of asphalt mix compared to the control sample.

The VTM decreases a slight by adding lignin in the amounts of 3 and 6% to the asphalt mix.

According to Fig. 14, adding lignin in low percentage (3%) has reduced the Marshall ratio of the asphalt mix as compared to the control sample; but, increasing the lignin content has increased the Marshall ratio and the asphalt mix resistance to rutting.

The Marshall ratio is an empirical parameter that some road administrations in the world, such as the UK's TRRL, has regarded it as a criterion for the phenomenon of rutting. Marshall Ratio is the Marshall Stability ratio in kg to the sample Flow in mm. Empirical studies have shown that the higher the Marshall ratio, the greater the asphalt mix resistance to rutting. Figure 14 has indicated the Marshall Ratio of all samples tested in this research.

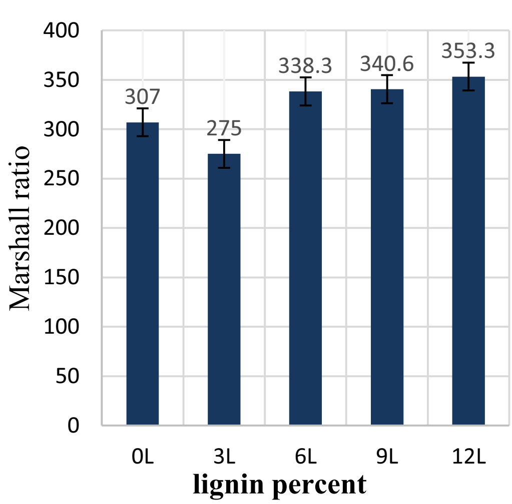

Fig. 14 Marshall ratio

6 Economic analysis

In this research, based on previous results, the economic analysis of adding lignin to asphalt mixtures was evaluated [24–26]. In this section, the costs and benefits from adding Lignin was evaluated. For this purpose, construction of a 6-line road (each direction 3 lines) for 1 km was evaluated. The special weight of asphalt was considered $\gamma = 2.3$ ton/m3 and the price of each ton of asphalt and lignin (per kg) were considered about 51$, 0.25$, respectively.

Tables 8 and 9 show the results of design and economic analysis respectively:

According to the Table 9 and after performing the economic analysis, adding lignin to the asphalt mixes makes the project economical. According to Table 9, the mixes 6 L, 3 L and 9 L have the best benefit-cost. This result ensures the use of additives on a large scale.

So, according to technical and economic considerations, adding 6% lignin to the asphalt mixture seems appropriate.

7 Conclusion

Providing a solution to achieve a pavement with better performance and resistance properties than ordinary pavements is the main objective of the present research

Table 8 Design result

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

Table 9 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

because asphalt pavements are considered as a national capital and every year, a large amount of the country's development budget is spent on the road pavement. The summary results of this research are presented as follows:

Adding lignin to bitumen in less than 3 percent has no significant effect on the bitumen performance properties and increasing its content by more than 3% has led to reduce the penetration grade and to increase the softening point and the bitumen viscosity.

The use of lignin in less than 6% has no significant effect on the bitumen performance at temperatures below zero degrees; however, the Frass breaking point has been significantly reduced by increasing its value to more than 6%.

The permeability index (PI) and the penetration viscosity number (PVN) have increased to + 1 by adding the lignin content.

Considering that the ratio of penetration grade increases by adding lignin to bitumen before and after thin-film oven test, it can be concluded that lignin prevents the oxidation of bitumen at high temperatures during producing asphalt. Yet, this is not true for the values of 12% or more than it.

The use of lignin has caused an overall increase in the Marshall stability in asphalt mix. The trend of changes in Marshall Stability is ascended by increasing lignin content to 6% and then it is descended.

Generally, the use of lignin in asphalt mix increases the Flow compared to the base state. However, the process of changes in flow decreases with increasing lignin content and reaches a minimum of 12%.

Marshall Ratio increases by adding the lignin content in asphalt mixtures and it reaches the maximum level among all the mixes at 12%.

Lignin has no effect on the thermal sensitivity of the asphalt mix in the amounts of 3 and 6%, but it has reduced the thermal sensitivity in high amounts, which it increases the desirability of using lignin.

Due to the fact that the lignin used in the present study was obtained from the paper mill's wastewater, thus, in addition to improving the properties of the made asphalt, its use also reduces environmental pollution.

The results of the economic analysis indicate that mixtures containing 6, 3 and 9 percent lignin, are economic.

After observing the findings and summarizing the results, the optimal amount of lignin was determined equal to 6 percent.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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