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Technical-economic studies about the effect of Nano-carbon black on asphalt mixtures

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ABSTRACT: Nanomaterial have been considered one of the new additives by researchers for use in asphalt pavement. In this study, first, mechanical properties such as marshall stability and marshall flow as well as volumetric properties of asphalt mixture such as voids in the total mix (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) were investigated. Then, the rutting resistance of the asphalt mixture, which is a measure of resistance to permanent deformation, was evaluated. Finally, economic analysis of the effect of different percentages of Nano-carbon black on a 1 km long road was evaluated. The results showed that adding Nano carbon black to the asphalt mixture in low percentages reduced the marshall stability due to the lack of proper bonding between bitumen and Nano carbon black. By increasing the amount of Nano carbon black in the asphalt mixture, marshall stability increased. Also, Nano carbon black has clearly shown potential for improving the permanent deformation resistance of the modified asphalt mixture. During the Marshall Quotient (MQ) test, more than two times increase in rutting resistance was observed by adding more than 10% Nano carbon black to the asphalt mixture. On the other hand, the results of the economic analysis showed that the addition of 15, 17.5, 13, and 20% of Nano carbon black, respectively, has made the project economical. Due to the positive effect of adding Nano carbon black on the mechanical properties of asphalt mixtures, it is recommended to use Nano carbon black extensively in areas where the pavement suffers from a lack of load-bearing capacity.

Keywords: *Nano carbon black, marshall stability, rutting resistance, economic analysis.*

1 INTRODUCTION

Additives are used as an effective solution to strengthen the asphalt mixture. These materials include nanomaterial, fibers, plastics, elastic materials, and sulfur (Li et al., 2017; Zahedi et al., 2017a; Zhao et al., 2014). Among these materials, nanomaterial have been used due to their inherent properties, especially in asphalt mixtures. Improvements in mechanical properties such as fatigue strength, rutting depth, elastic modulus, and other engineering properties are among these results (Rafi et al., 2018; Barati et al., 2020; Zahedi et al., 2017b; Zahedi and Zarei, 2016; Zahedi et al., 2017b; Zarei et al., 2020a; Zahedi et al., 2020a). Nano carbon black is one of the nanomaterial that has recently been considered in the pavement industry. In addition to improving the mentioned features, using these materials in the pavement industry is suitable when it is economically viable (Cong and Chen, 2014; Abdi et al., 2020; Akhtari et al., 2022; Zahedi et al., 2020; Zarei and Zahedi 2016; Ahmad et al., 2018; ASTM D1559, 1997). Therefore, the lack of a study examining the effect of these materials on asphalt pavement encouraged the authors to evaluate the economic impact of this additive on asphalt pavement.

1.1 Literature Review

Vallerga and Gridley (1980) declared that black carbon (Filler) leads to the high durability of asphalt and reduces the sensitivity of viscosity-temperature. Also, abrasion resistance results showed that asphalt mixtures containing carbon black have significantly less abrasion than conventional asphalt (Vallerga and Gridley, 1980).

Khalid (2017) investigated the effects of carbon black on bitumen. Two types of carbon black including Raven-350 and n-220 were used to strengthen bitumen of 60/70 types. The results of the rheology test showed that the addition of these two additives reduces the penetration grade and increases the softening point (Khalid, 2013).

Sheng Zhao et al. (2014) declared that the addition of Nano carbon black has a good effect on marshall tests (Sheng Zhao et al., 2014).

Park & Lovell (1996) studied the effect of different percentages of pyrolyzed carbon black (PCB) from wasted tires on the mechanical properties of asphalt mixtures made with two types of bitumen, including AC-10 and AC-20. The results showed that marshall stability increased at high carbon black content; however, marshall flow decreased Park & Lovell, 1996).

A review of previous studies shows that the carbon black (with and without Nano scale) has acceptable effect as an additive material on mechanical features of asphalt mixtures. On the other hand, the lack of scientific study on the economic impact of this material on the asphalt mixture was one of the reasons for evaluating the effect of this nanomaterial on the asphalt mixture. The results of this research are expected to give designers and engineers a deep understanding of the amount and manner of using this additive in asphalt pavement.

2 MATERIALS AND METHODOLOGY

2.1 Bitumen

In order to evaluate the effect of Nano carbon black on asphalt mixtures' mechanical properties, bitumen with type 85/100 obtained from the Kermanshah refinery was prepared based on the specifications of Table 1.

Table 1. Specifications of bitumen

Type of test	Standard number	Results	Standard value
Specific weight at 25 °C	T228	1.012	-
Penetration grade at 25°C	T49	98	85-100
Softening point (ring and ball, °C)	D36	45	45 -52

2.2 Aggregates

The grading curve obtained from mixing the required weight percentages compared with grading used in the preparation of samples has been illustrated in Figure 1.

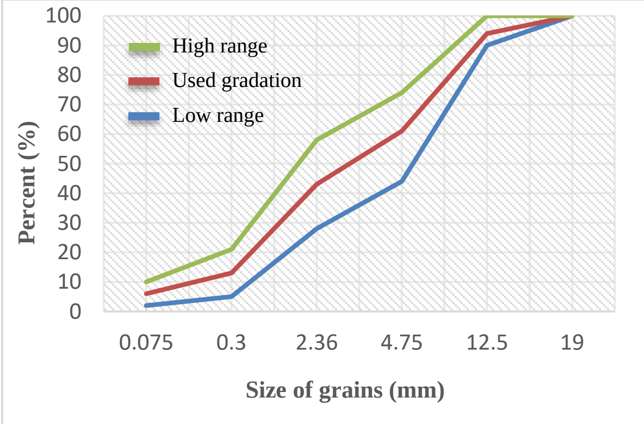

Figure 1. Stone materials granulation of asphalt mixture of Topeka layer 0-19 mm

2.3 Nano Carbon Black

Nano carbon black, known as a pure substance, is produced by burning hydrocarbons in the presence of limited air. This soft, fine material, sometimes made in nanoparticles, is about 100-1,000 Å, 88-99.5% carbon, 3-11% oxygen, and 0.1-1% hydrogen. Figure 2 shows a scanning electron microscope (SEM) image of Nano-Carbon black. Also, Table 2 presents some technical properties of Nano carbon black.

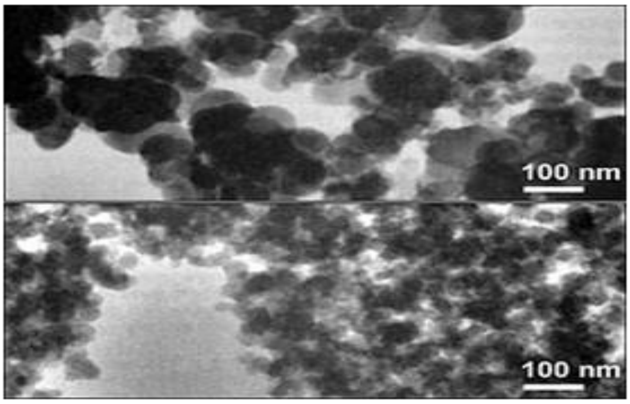

Figure 2. Scanning electron microscope (SEM) image of Nano carbon black (Zarei and Zahedi, 2016)

Table 2. Characteristics of Nano-carbon black

Size used (nm)	Size (nm)	Surface area (m^2/g)	Density bulk (g/cm^3)	Classification
42	15-300	80	0.21	CAS no. 1333-86-4

2.4 Mixing design and preparation of samples

The method of construction and design of asphalt mixture was performed based on ASTM-D 1559 standard (ASTM D1559, 1997). The optimal bitumen content (OBC) for all samples in this study was 5%. A total of sex different mixtures containing 5, 10, 13, 15, 17.5, and 20% Nano carbon black were made. These percentages were added to bitumen relative to the weight percentage of OBC. To mix Nano carbon black with bitumen, first, bitumen was heated to 155 °C, then Nano carbon black was slowly added to the bitumen (wet method). For complete mixing of bitumen and Nano carbon black, the mixture was stirred with a high shear mixer with a speed of 5000 rpm and a constant temperature for 30 minutes. Nano carbon black-modified bitumen was mixed with preheated aggregates and compacted with a marshall hammer (75 blows on each side). Figure 3 shows the steps of making asphalt samples.

Figure 3. Steps of making asphalt samples

3. TEST RESULTS

3.1Analysis of Marshall Stability results

As shown in Figure 4, the addition of 5% Nano carbon black to the asphalt mixture reduced the marshall stability. In terms of volumetric properties, the decrease in marshall stability may be related to the increase in VTM (Figure 7) and VMA (Figure 8) (an increase in these two indices means a decrease in the cohesion of the asphalt mixtures). Hence, when the sample was loaded, the stability of the sample decreased. In terms of chemical properties, it can be said that the addition of 5% Nano carbon black has reduced the covalent bond; hence, the asphalt mixture experienced a decrease in stability (Park and Lovell, 1996). On the other hand, Nano carbon black affects two bonds cohesion (bond between bituminous tissues) and adhesion (bond between bitumen and aggregates). Accordingly, the addition of 10% or more of the Nano carbon black additive has increased the cohesion of the asphalt mixture by increasing the viscosity. In addition, Nano carbon black has increased adhesion to increase bitumen-coating coverage and increased stability (Khalid, 2013). According to Figure 4, samples containing 15% Nano carbon black are about 71% more marshall stability.

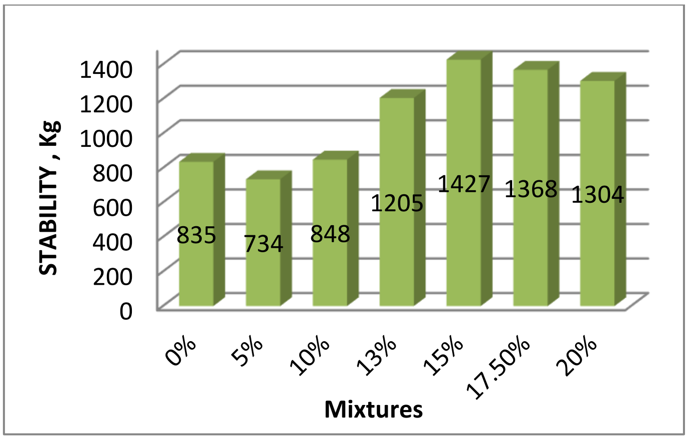

Figure 4. Effect of Nano carbon black on marshall stability

3.2 Analysis of the results of unit weight

As shown in Figure 5, at a higher amount of Nano carbon black, the unit weight of the asphalt mixture increased. Therefore, it can be said that Nano carbon black in higher percentages increased cohesion and decreased voids. As bitumen cohesion increases, aggregates are better covered; therefore, the desired mixture will be denser. However, at a lower percentage, unit weight decreased due to increased VTM and VMA (see Figures 7 and 8).

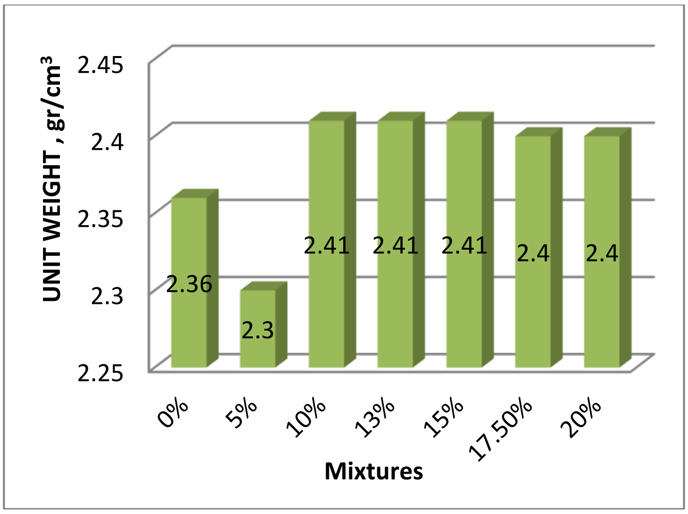

Figure 5. Effect of different percentages of Nano carbon black on Special Weight

3.3 Analysis of the flow results of Marshall

As shown in Figure 6, the addition of Nano carbon black increased the flow of the asphalt mixture. Nano carbon black is a hydrocarbon that has carbon in its chemical structure. At higher percentages of Nano carbon black, with increasing carbon content, the hardness or viscosity of the bitumen increases (Rafi et al., 2018). Therefore, the stiffness and flow of the mixture increase and decrease, respectively. This result shows that the use of higher percentages of Nano carbon black increases the hardness of the mixture and ultimately increases the cracking potential of the asphalt mixture.

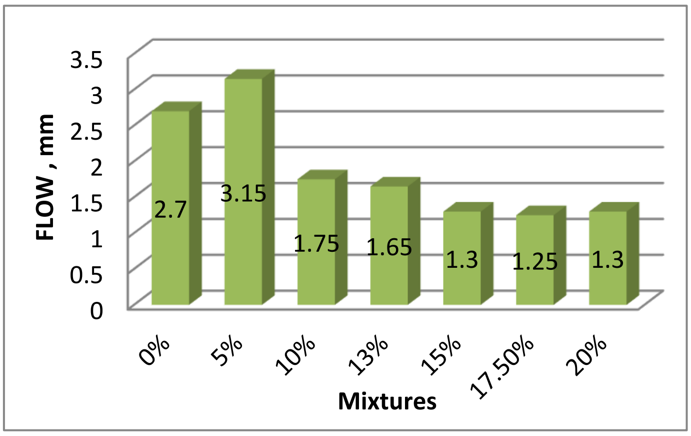

Figure 6. Effect of Nano carbon black on marshall flow

3.4 Analysis of the results of VTM

As discussed earlier, the cohesion of bitumen increases as the percentage of Nano carbon black in the asphalt mix increases. Subsequently, the interlocking of the aggregates increased due to their complete coverage, and consequently, the total volume decreased (Figure 7). However, the results showed that adding 5% Nano carbon black to the asphalt mixture increased the amount of VTM. As mentioned in the previous sections, at lower percentages of Nano carbon black, the amount of adhesion and cohesion of the asphalt mixture is decreased due to reduced viscosity; hence, the bond between bitumen and stone materials reduces, and eventually, the amount of VTM increases.

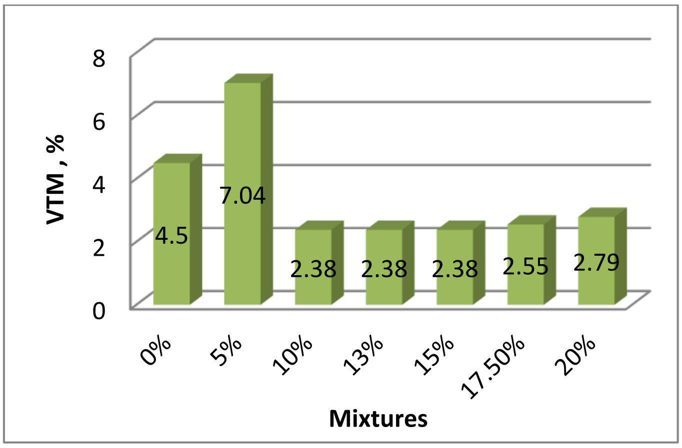

Figure 7. Effect of different percentages of Nano carbon black on VTM

3.5 Analyzing the VMA results

As the percentage of Nano carbon black in the asphalt mix increased, the cohesion of the bitumen increased. Also, the adhesion between the bitumen-aggregates is enhanced, which in turn reduces the VMA (Figure 8).

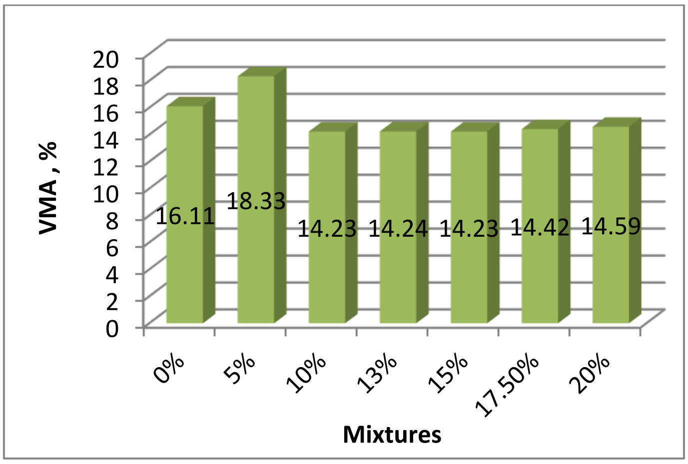

Figure 8. Effect of different percentages of Nano carbon black on the specific weight of asphalt mixture

3.6 Analysis of the results of VFA

As shown in Figure 9, VFA was initially reduced and increased by adding different percentages of Nano carbon black to the asphalt mixture. According to the results, increasing the cohesion and adhesion of the asphalt mixture caused the covering of stone materials, which led to an increase in VFA in higher percentages.

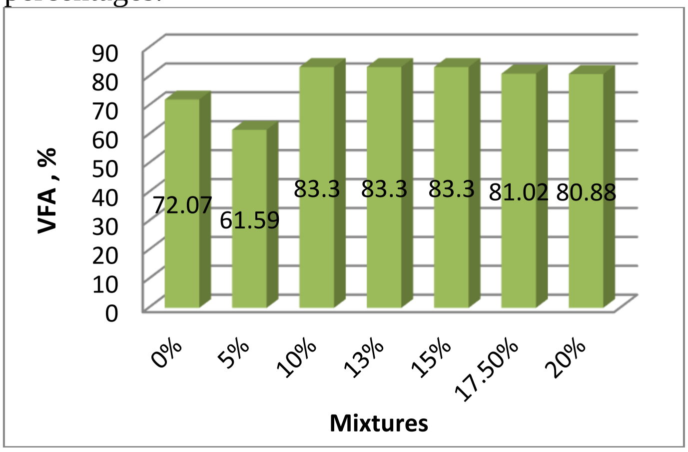

Figure 9. Effect of different percentages of Nano carbon black on VFA

3.7 Analysis of the results of Marshall Quotient

Marshall Quotient (MQ) is an experimental parameter that some organizations, such as UK's TRRL, have used as a benchmark for measuring rutting. MQ is the marshall stability to flow ratio (in kilograms per millimeter). Previous studies have shown that the higher the MQ, the higher the rutting resistance of the asphalt mixture (Zarei et al., 2019; Zarei et al., 2020b; Zarei et al., 2021a; Zarei et al., 2021b; Janmohammadi et al., 2020; Sodeyfi et al., 2021). Figure 10 shows the MQ results of samples with and without Nano carbon black. According to the results, adding 10, 13, 15, 17.5, and 20% Nano carbon black to the asphalt mixture increased the rutting resistance by 60, 200, 255, 240, and 225%, respectively. Lee et al. concluded that nanoparticles affected the interaction within bitumen by increasing the surface area of bitumen, leading to higher resistance to rutting (Li et al., 2017). In a study, Zhao et al. examined the rutting resistance of asphalt mixtures containing Nano carbon black when the samples were under 8000 loading cycles. The results showed that the modified asphalt mixture had better rutting resistance than the base mixture (Zhao, 2014). As can be seen, the results of previous studies are consistent with the results of this study.

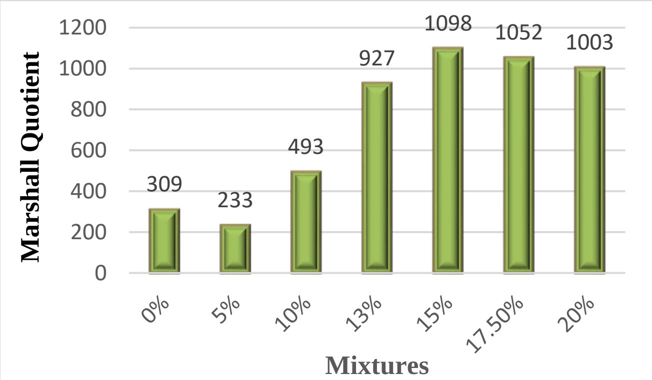

Figure 10. Effect of different percentages of Nano carbon black on the Marshall Quotient

4 ECONOMIC ANALYSIS

4.1. Adding Nano carbon black to asphalt mixture

In this study, the economic analysis of the effect of Nano carbon black on asphalt mix was evaluated. For this purpose, the Marshall results were converted into pounds (Figure 11). The reason for this conversion was due to the units of Figures 12 and 13.

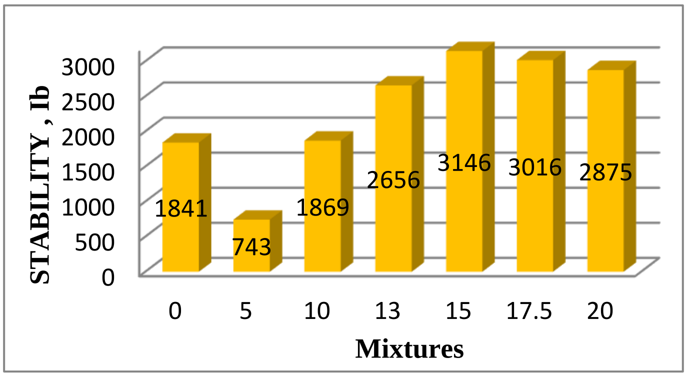

Figure 11. New samples of marshall stability used in the economic analysis

4.2. Asphalt mixture design

4.2.1. Sample problem

The problem of sample 11 of Huang's pavement book was used in order to asphalt mixture (Huang, 2004). In this problem, the value of SN_0 is obtained at 1.97 for the asphalt layer. Given that the value of SN0 depends on the underlying layers of the asphalt layer, this parameter is constant during this study (with different resistances and additive values). Therefore, the value of D_1 is obtained from relation 1:

$$D_i = \frac{SN_i}{a_1} \quad (1)$$

In this relation thickness of the asphalt layer is obtained (in inches). Also, the graph in Figures 12 and 13 will be used in order to get a_1.

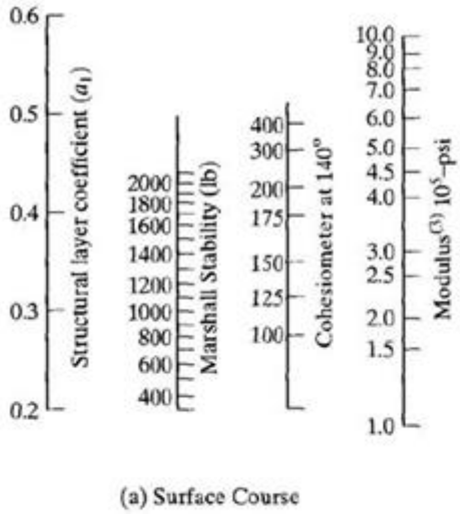

Figure 12. Determining of resilient module (Huang, 2004)

As shown in Figure 12, the value of a1 is not achievable at high stability. On the other hand, the AASHTO standard (AASHTO T 96-02., 2019) limits the coefficient a1 to 0.44. However, Tim and Priest (2006) proposed an extrapolation method to determine the value of a1. They attributed this value to 0.54 for high stability (Figure 12) (Timm and Priest, 2009). Table 3 shows values of these coefficients for different values:

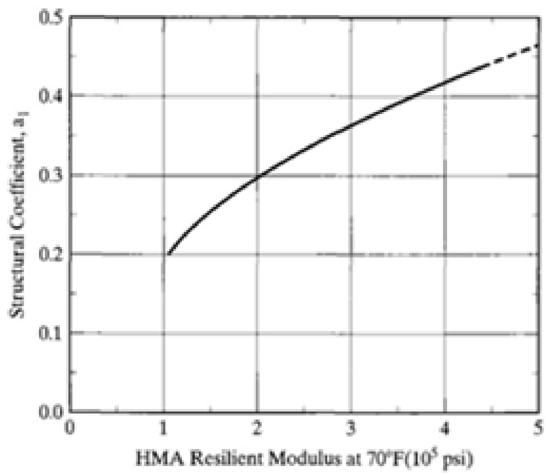

Figure 13. Chart for estimating layer coefficient of asphalt concrete based on resilient modulus (Huang, 2004)

Table 3. Design Result

Marshall stability (Pound)	Resilient coefficient $*(10^5 - psi)$	a_1	D_i
1841	4	0.41	D_0=4.8
743	1.5	0.285	6.912
1869	4.2	0.41	4.8
2656	4.3	0.49	4.02
3146	4.4	0.53	3.71
3016	4.7	0.52	3.79
2875	4.9	0.51	3.86

4.3. Economic analysis

In this part, costs and benefits from adding Nano carbon black were calculated. In this method, a 6-lane road (3 lanes in each direction) with a length of 1 km (Zarei et al., 2022; Zahedi et al., 2020b; Rassafi et al., 2021; Zarei et al., 2021c) was evaluated. It should be noted that the unit weight of asphalt mixture is approximately $\gamma = 2.3\ \frac{\text{ton}}{\text{m}^3}$. Also, the price of each ton of asphalt mixture and the cost of each kilogram of Nano carbon black are respectively about 51$ and 0.55 $.

4.3.1. Benefit for per kilometer

As mentioned, in order to calculate the benefit of adding different percentages of Nano carbon black to the asphalt mixture, a 6-lane road with a length of 1 km and a width of 3.65 m was considered according to Formula 2:

$$Benefit=1000 \times 6 \times 3.65 \times \frac{(D_o - D_i) \times 2.54}{100} \times \gamma \times asphalt\ price \qquad (2)$$

In this formula, ɣ is unit weight and other parameters are explained in the text.

4.3.2. Cost for per kilometer

Value of spent cost for one kilometer asphalt is obtained according to formula 3:

$$Cost=1000 \times 6 \times 3.65 \times \frac{D_i * 2.54}{100} \times \gamma \times 1000 \times \frac{63}{1000} \times additive\ (\%) \times Nano\ carbon\ black\ price \qquad (3)$$

In this formula, $\frac{63}{1000}$ is the amount of bitumen used (per kg), and other parameters are explained in the previous sections.

4.3.3. Economic analysis results

In the economic analysis of the effect of this additive on the asphalt mixture, it was found that the addition of 15, 17.5, 13, and 20% of Nano carbon black, respectively, made the project economical. The reason for this result is that the D_i coefficient for these mixtures was significantly different from the sample without additives (Table 3). It should be noted that the addition of 15% Nano carbon black increased the technical properties such as marshall stability and rutting resistance by about 71 and 255 percent, respectively. Therefore, the use of this additive in road construction projects is recommended. Table 4 expresses the results of calculating benefit and cost in the previous parts.

Table 4. The results of the economic analysis of the effect of Nano carbon to the mixtures

Additive	Benefit	Cost	Benefit - Cost	$\frac{\text{Benefit}}{\text{cost}}$	Result
5	-137506*	15321	-148848	-12.0	uneconomical
10	3777	21043	-17266	0.18	uneconomical
13	51186	23169	+28016	2.21	**economical**
15	70984	24716	+46267	2.87	**economical**
17.5	66320	29390	+36929	2.26	**economical**
20	61473	34247	+27225	1.79	**economical**

* The reason for the negative benefit was the lower Marshall stability for the mixture containing 5% compared to the base mixture.

Figures 14 and 15 show the correlation between benefit and cost for different percentages of Nano carbon black additive, respectively (in the presented analysis, the effect of the mixture containing 5% Nano carbon black was neglected due to the Marshall stability less than the base sample). As shown in Figure 14, there was a moderate correlation between benefit and cost (R^2 = 0.60). On the other hand, by eliminating the effect of the mixture containing 10% Nano carbon black on the results, a high correlation with a value of R^2 = 0.87 was obtained between the benefit and cost for all mixtures (as shown in Figure 15). This was due to the relatively equal marshall stability for samples containing 10% Nano carbon black and the base sample, which resulted in a relatively close benefit (shown in Figure 14 with a blue line). Also, since the coefficient x in the R-squared value was less than 1, therefore, the tendency of the fit chart was towards the benefit axis. As a result, it can be concluded that marshall stability, which directly affected the outcome of the benefit, played a significant role in the economics of the project (see Figure 16).

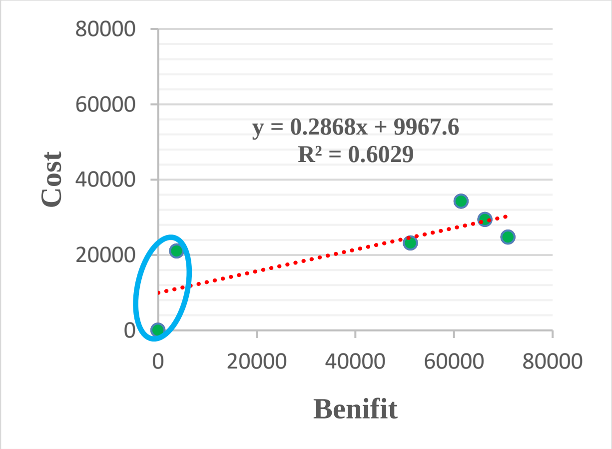

Figure 14. Correlation between benefit and cost for all mixtures

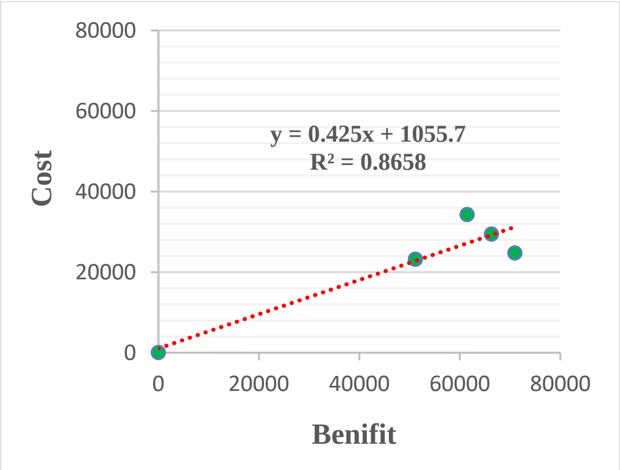

Figure 15. Correlation between benefit and cost with the exception of the mixture containing 10% additive

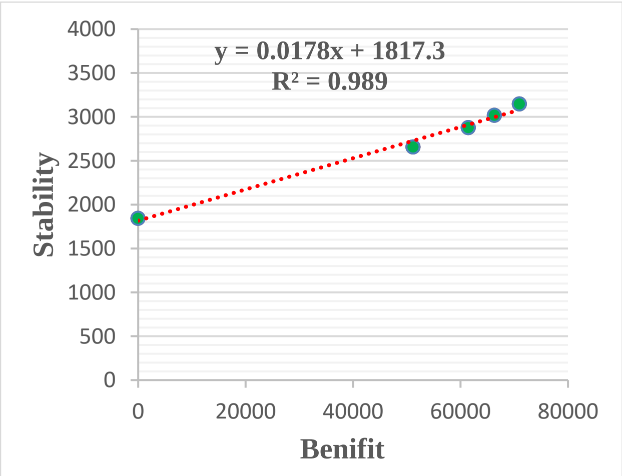

Figure 16. Correlation between benefit and stability with the exception of the mixture containing 5% additive

5 CONCLOSIONS

In this research, Nano carbon black additive was used as an additive to investigate the mechanical and economic properties of asphalt mixtures. For this purpose, a total of 6 mixtures containing different percentages of Nano carbon black were made. By comparing obtained experimental results in this study with the results of Park and Lovell's experiments is concluded that the effect of Nano carbon black in lower percentages decreases marshall stability. Increasing Nano percentage increases the resistance of marshall stability. Note that the excessive addition of Nano declines flow which is not desirable. A summary of the results is as follows:

- In the making of the sample, at the first, the Nano carbon black has compounded to the ratio of weight percentage of bitumen, and then preheated aggregates were added to it. Nano carbon black increased the marshall stability by changing the behavior of bitumen. Adding 10, 13, 15, 17.5, and 20% Nano carbon to the asphalt mixtures increased the marshall stability by about 2, 44, 71, 64, and 56%, respectively, compared to the base sample.

- The unit weight results showed that the addition of Nano carbon black first reduced the unit weight by about 2.5%, and then with the increase of Nano carbon black in the mixture, the unit weight increased by about 2%.
- Because Nano carbon black is small and Nano-sized, adding it to the mixture up to 5% increased the marshall flow by about 17%. However, as the percentage of Nano carbon black in the asphalt mix increased, the amount of carbon in the bitumen phase increased, resulting in about a 52% reduction in marshal flow.
- The results showed that the addition of higher percentages of Nano carbon black reduced the VTM of the asphalt mixture by about 47% due to the increase in bitumen cohesion. On the other hand, a decrease of about 12% for VMA is due to increased adhesion (bitumen-aggregate bond).
- Nano carbon black has clearly shown potential for improving the permanent deformation resistance of the modified asphalt mixture. During the MQ test, more than two times increase in rutting resistance was observed by adding more than 10% Nano carbon black to the asphalt mixture. The improvement in rutting resistance is because Nano carbon black-modified asphalt mixture has higher stiffness and a better ability to bond with the aggregates.
- In economic analysis, the results showed that marshall stability played an important role in making the project economical. Marshall stability increased the benefit of the project by increasing the difference between D_0 and D_i, and ultimately made the project more economical.
- The economic analysis results showed that the addition of 15, 17.5, 13, and 20% Nano carbon black to the asphalt mixture resulted in a benefit-

to-cost ratio of 2.87, 2.26, 2.21, and 1.79. This result shows that adding this additive to the project is technically and economically justifiable. However, due to the reduction of marshall flow, the mixture containing 15% and 13% of Nano carbon black is preferred.

Finally, according to mechanical and economic discussions, it was concluded that the modified asphalt mixtures with Nano carbon black were a mixtures with desirable mechanical-economic properties. Therefore, adding 15, 13, and 17.5% Nano carbon black to the asphalt mixture can be widely used (due to project economics) in areas under heavy traffic load (due to higher marshall stability).

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