Improving Local Asphalt Pavement with Nano-$CaCO_3$

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Abstract. During the last two decades, a significant increase in the number of vehicles in Baghdad city related to uncontrolled axle loading, hot climate summer, lack of asphalt pavement maintenance, and heavy traffic has combined and led to severe consequences in the paved road. Therefore, asphalt cement enhancement and improvement is the first key to solving and correcting these issues. Recently, nanomaterial has gained considerable recognition in asphalt technology as the new modifier due to the homogeneity, dispersion, and large surface area in contact with asphalt particles. This paper investigates the effect of adding nano $CaCO_3$ into asphalt cement. The laboratory experiment included 40-50 penetration grades prepared with different content 1, 3,5, and 7% to quantify the potential benefit of a physical test of Asphalt, Marshall properties, and tensile strength of hot mix asphalt. The testing result indicated that nano-$CaCO_3$ modified asphalt with a 5% improved penetration grade and softening point. On the other hand, Marshall Stability increased to 14.38 kN. Furthermore, tensile strength increased to 1121 KPa due to the stuffing effect, increased adhesion that increased the resistance of asphalt mixture towards permanent deformation during the hot summer climate in Iraq.

Keywords: Asphalt; nanomaterial; $CaCO_3$; Marshall; tensile strength.

1. INTRODUCTION

Overall evaluation of nano-$CaCO_3$ influence on bitumen and asphalt mixtures and identifying their rheological and mechanical behavior required more research. Nano-$CaCO_3$ is a solid white powder with an average of 10 to 100 nm particle sizes and calcium Carbonate of about 98.5%; it increases the quality of base asphalt and asphalt mixtures, and the combination of nano-$CaCO_3$ with asphalt generates a consistent and stable system that enhances asphalt temperature susceptibility at high temperatures. The nano material have wide applications in improving the engineering properties of construction materials [1-3]. A study by Hao [4] found that adding 6% nano-$CaCO_3$ to asphalt concrete enhanced the dynamic and residual stability, indicating that asphalt concrete's high-temperature and water stability have improved. In light of these findings, Raufi [5] assesses the rheological, physical, and performance of hot mix asphalt modified with 3,6 and 9% nano-$CaCO_3$, showing that as nano content increases, it slightly softer the penetration, increases softening and viscosity, which improves sensitivity towards permanent deformation and has good anti-aging performance as indicated by a higher penetration index value. On the other hand, with the inclusion of 6% nano-$CaCO_3$, the mixture performed well against moisture damage excellent, attributed to the better adhesion performance and cohesion that inhibit displacement of the aggregate particle efficiently from displacing by the effect of water.

A combination study done by [6] on Nano-TiO_2/$CaCO_3$-modified bitumen shows that increasing nano-TiO_2/$CaCO_3$ by up to 5% would significantly improve the mechanical properties of bituminous materials in terms of reducing penetration and ductility and showing an increasing trend for softening point and viscosity which reduce bituminous sensitivity. Nejad studied the dynamic behavior of Asphalt concrete mixture emerging tensile strength proprieties [7] and suggested that nano-$CaCO_3$ promoted the rutting of asphalt mixtures acquiring less sensitivity to higher temperatures and increased fatigue life by 41.4 and 55.8% for 2 and 4% nano-$CaCO_3$, respectively. An attempt was made by Zhai [8] to investigate SBR polymer with nano-$CaCO_3$ modified asphalt, implying a significant impact on rutting resistance within 5% due to higher surface area that promotes both viscosity and adhesion and expanding micromechanical property through adhesion, dissipated energy, and anti-cracking resistance compared to stand-alone SBS-modified Asphalt. This mechanism was studied by Xing [9], who described most diminutive particle size indicates the lesser average distance between the particles, which better the yield stress of the modified asphalt by the Orowan mechanism. On the other hand, the atomic arrangement is irregular, and the phase contact prevents the modified asphalt from deforming plastically according to the Hall–Petch reinforcement mechanism. The literature above shows that Nano-$CaCO_3$ can increase the higher temperature of asphalt performance, moisture susceptibility, good anti-cracking fatigue resistance, aging, adhesion, and dispersion in asphalt binder.

2. MATERIALS

2.1 Nano Material

Nano- $CaCO_3$ was used in this study; this material was brought from USA SkySpring inc. their physical properties are listed in Table 1 and Figures 1 and 2.

2.2 Asphalt Cement

40-50 penetration grade, widely used in Iraq for the paving industry, was brought Al-Doura refinery in the southwest of Baghdad Province. Table 2 lists its main properties.

2.3 Aggregate and Mineral Filler

Crushed coarse and fine aggregates were gathered and obtained from Al-Nabiee Quarry North of Baghdad. Aggregates batched in the Job mix formula were followed SCRB/R9 wearing layer with 19.0 mm maximum size aggregate. Table 3 presents the main physical properties of Al-Nabiee aggregate and showing in Figure 3. Limestone was added as filler brought from Karbala.

Table 1: Physical properties of Nano-$CaCO_3$ (*supplied with datasheet).

Property	Nano-$CaCO_3$
Color	white powder
Morphology	hexagonal
Specific Surface area (m^2/g)	30~60
Bulk density (g/cm^3)	2.93
Purity	99.9%
Solubility	Insoluble
Molecular Weight. (g/mol)	100.08

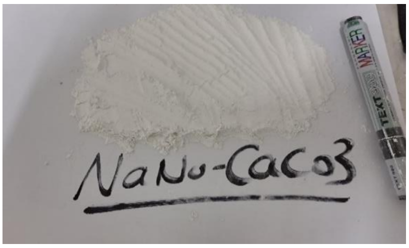

Figure 1: Photograph Nano- $CaCO_3$ particles.

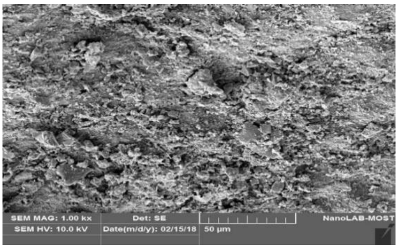

Figure 2: Photograph Nano-$CaCO_3$ particles.

Table 2: 40-50 Asphalt Cement physical testing property.

Property	Testing Standard	Units	Result	SCRB/R9 Requirement
Penetration at 25 °C, 100gm,5 sec	AASHTO T 49	0.1 mm	45	40-50
Softening point	AASHTO T 53	°C	43	----
Specific gravity at 25 °C	ASTM-D70	----	1.03	----
Flash point	AASHTO T 48	°C	274	Min.232
Ductility	AASHTO T 51	cm	108	≥ 100
Residue from thin-film oven test AASHTO T 179				
Retained penetration,% of original	AASHTO T 49	0.1mm	60	>55
Ductility at 25 °C, 5cm/min	AASHTO T 51	cm	87	>25

Table 3: Physical properties of Al-Nibee coarse and fine aggregate.

Property	Designation	Result		Specification
		Coarse aggregate	Fine Aggregate	
Bulk Specific gravity, (g/cm^3)	ASTM C127	2.627	2.545	--------
Apparent Specific gravity (g/cm^3)		2.674	2.656	
Percent water absorption, %		0.66	1.647	
Percent Fractured Face	ASTM D5821	93	----	Min.90
Consensus Properties				
Coarse Aggregate Angularity, %	ASTM D5821	97		Min. (95/90)
Fine Aggregate Angularity, %	ASTM D1252	60	49	Min. 45
Sand Equivalent, %	ASTM D2419	78	53	Max. 45
Flat and elongated particles percentage, %	ASTM D4791	1.2		Max. 10
Source Properties				
Percent wear by Los-Angeles Abrasion %	ASTM C131	21		Max .30
Soundness,%	ASTM C 88	3.71		Max .12
Clay Lumps,%	ASTM C 124	0.57		Max.3
Deleterious. materials, %	ASTM C142	0.58	0.92	Max .10

Figure 3: Aggregate used for wearing course asphalt mixture.

3. METHODS

3.1 Nano-Modified Asphalt

The high shear mixer device (HSMd), shown in Figure 4, serves as a laboratory stirrer for good mixing via the dispersion of nanoparticles by creating a centrifugal force that helps asphalt and enforces nanoparticles to attract in a homogeneity blend [10]. The mixing procedure concludes by heating 200 gm of asphalt to 155°C in a metallic can. Then, a continuous increase of nano-$CaCO_3$ was gradually added at a rate of 4 gm per minute at a mixing rate of 6000 revolutions/minute until the complete addition of nanoparticles, HSMd, was stirred to 45 minutes to gain blended modified asphalt. Hence 1, 3, 5, and 7% were added to neat asphalt. The mixing of nano $CaCO_3$ with asphalt procedure is exhibited in Figure 4.

Figure 4: Mixing neat asphalt with nanomaterial using HSMd.

3.2 Asphalt physical test

Routine physical testing presented in Figure 5 was established to assess the impact of various nano-modified asphalt concentrations, including a penetration test to measure the consistency of asphalt based on AASHTO T49. At the same time, the softening point is conducted based on AASHTO T53. Furthermore, AASHTO T51 accurately measures the tensile property of asphalt by a ductility test. The penetration and the softening point result were later used to compute the penetration Index (PI) presented in Eq.1 to quantify asphalt temperature sensitivity [11].

$$\mathrm{PI} = \frac{1952 - 500\log_{10}\mathrm{P25} - 20\mathrm{SP}}{50\log_{10}\mathrm{P25} - \mathrm{SP} - 120} \tag{1}$$

Figure 5: Physical testing of nano-$CaCO_3$-modified asphalt.

3.3 Marshall Testing

Standard practices for preparing the Marshall mix design method followed ASTM D6926; prior to testing, the batch aggregate was combined following the job mix formula within SCRB/R9 ranges for wearing the 19.0 mm course layer exhibited in Figure 6. The produced samples weighted 1200gm were compacted using an automatic compactor with 75 blows on each side and cured for 24 hours at room temperature. Neat and nano-modified asphalt with different percentages was heated in the oven alongside coarse and fine aggregate. Replicate specimens were prepared for wearing course at asphalt content ranging from 4 to 6% by weight of mix at an increasing range of 0.3% to obtain optimum asphalt content. Based on the Marshall approach, design asphalt content at 4% air void content was chosen. Since the binder content was maintained constant, the effect of the nano-$CaCO_3$ content was held constant to quantify the impact on Marshall Stability and Plastic flow of compacted mix following ASTM D6927. Figure 7 presents Marshall samples and testing devices.

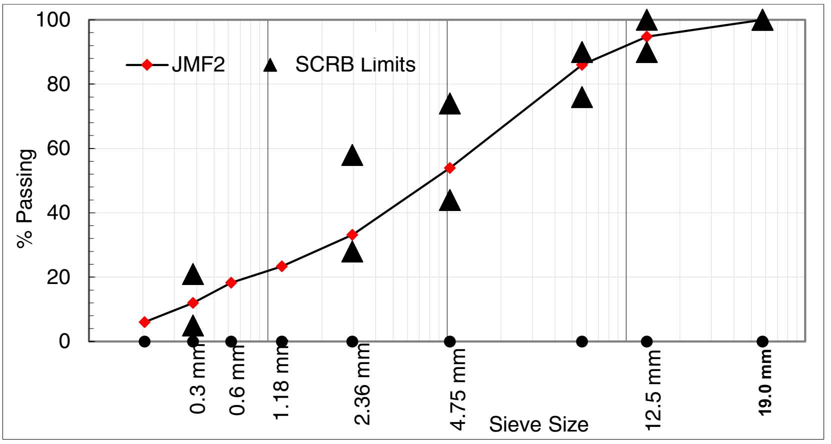

Figure 6: Ranges for wearing the 19.0 mm course layer.


Figure 7: Marshall Sample preparation and testing.

3.4 Tensile strength properties and Moisture Damage

Using AASHTO T283, the moisture susceptibility of asphalt concrete mixtures was assessed. These test results are the tensile strength ratio (TSR) and indirect tensile strength (ITS). In this test, specimens were made for each mix per the Marshall protocol and compacted to 7 % target air voids. The set consists of six specimens split into two subgroups; the control set was tested at 25°C, while the conditioned set was tested at 25 °C after undergoing one cycle of freezing and thawing. The test consisted of passing a series of 13 mm broad steel strips curved at the specimen interface with a compressive force at a rate of (50.8 mm/min) acting parallel to and along the vertical diametrical plane. These specimens split along the vertical diameter before failing. According to Eq. (2), the indirect tensile strength was computed; the tensile strength ratio (TSR), which is given in Eq. (3), was obtained by dividing the conditioned specimens ($ITS_{,cond.}$) by the unconditioned specimens ($ITS_{,uncon}$). The ITS device and the failed specimen are shown in Figure 8.

$$\text{Tensile Strength} = \frac{2P}{\pi t D} \tag{2}$$

$$\text{TSR} = \frac{ITS_{,cond}}{ITS_{,uncond}} \tag{3}$$

Since, t = thickness of sample, D= diameter, P= load.

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Figure 8: Indirect Tensile test of neat and nano-modified asphalt mixture.

4. TESTING RESULT

4.1 Effects of Nanc-$CaCO_3$ on Physical Properties of Asphalt

The effect of adding different content of nan-$CaCO_3$ into 40-50 neat asphalt physical properties can be seen in Figure 9. First, the penetration value exhibits a lower value than neat asphalt, up to 7%, showing a decrease in penetration value by about 4.4, 13.4, and 17.8%, respectively. This increase reduces to 15.3% when nano content increases to 7% in asphalt. On the other hand, the same trend was noted for softening point that exhibit an increasing value by 2.2, 8.5, 17.3%, and 15.6% for nano content from 1 to 7%, respectively. A decreased penetration value and a higher softening point indicate higher specimen stiffness and lower temperature susceptibility, which signifies improved resistance to rutting at high temperatures [12]. Besides, the addition of nano-$CaCO_3$ is to an extant degree since the excessive amount of nano-$CaCO_3$ will decrease asphalt penetration, and the softening point would change the homogeneity of the asphalt binder. Meanwhile, the ductility value of nano-modified asphalt does not affect the increase of nano content since 7% nano $CaCO_3$ yields a reduction to 97 cm compared to neat asphalt with 108 cm. Penetration index values grew steadily as the amounts of nano-$CaCO_3$ increased, praising the improvement of the modified binder's heat stability.

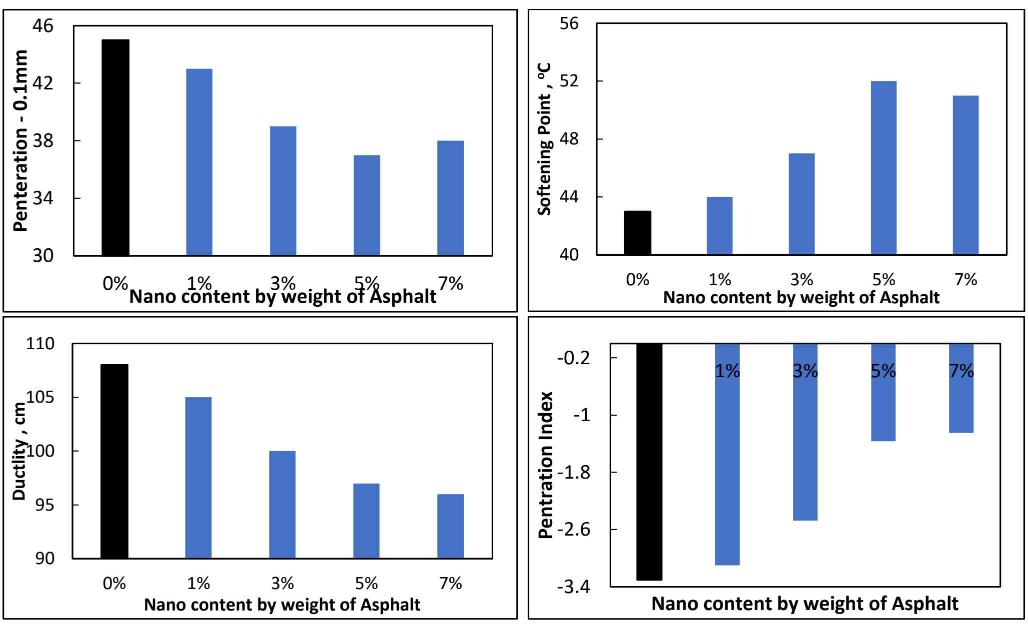

Figure 9: Physical testing results of neat and different Nano content on asphalt.

4.2 Effects of Nano-$CaCO_3$ on the Marshall Test

Figure 10 depicts the variation in Marshall Stability as a function of nano-$CaCO_3$ content. As shown, the amount of nano-$CaCO_3$ enhances the Marshall stability; for this, the stability value increased to 10.23, 11.80, 12.37, and 12.87 kN as compared to neat asphalt mixture; experiencing an increasing trend by about 7.7, 15, 23.7% and 26.6% when nano content increased from 1 to 7%; this may be to the higher surface area of the nano-$CaCO_3$ particles, and their interaction with the binder by enhancing asphalt absorption and making it stiffer can be attributed to the increase in stiffness of asphalt concrete by nano-$CaCO_3$ modification [4]. The Iraqi Highways

Code [13] stipulates a minimum Marshall stability of 8 kN for application on highways with heavy traffic. The flow of the mixes with various content of nano is depicted in Figure 11. Nano-modified asphalt mixes with 5 to 7% present lower flow values of 2.75 and 2.5 mm, respectively, which makes the mixture susceptible to cracking. Compared to the neat asphalt mixture, all the mixtures made with nano-modified asphalt binder had lower optimum binder contents, as shown in Table 4. Due to its nature as a filler, nano-$CaCO_3$ may reduce overall air voids, reducing the amount of asphalt binder needed to make asphalt mixtures with the necessary characteristics. The reduction in VMA% and VFA% is also clearly seen in Figures 12 and 13 when the filler content is increased. The improvement resulting from nano $CaCO_3$-modified asphalt can enhance Marshall properties up to 5% and increase the asphalt mixture resistance to hot summer temperatures and pavement distress with permanent deformation due to the unique property of nano- $CaCO_3$ to improve the stability at higher temperatures of modified asphalt binder through a reinforcement mechanism to stand for a long time via dispersion ability.

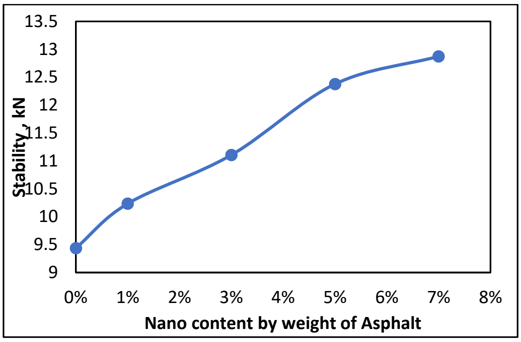

Figure 10: Stability value of Marshall test with different nano content.

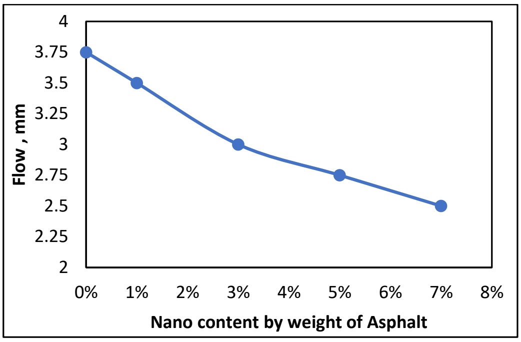

Figure 11: Flow value of Marshall test with different nano content.

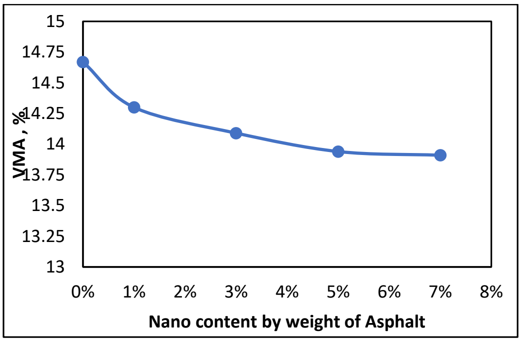

Figure 12: Voids in the mineral aggregate value of Marshall test with different nano content.

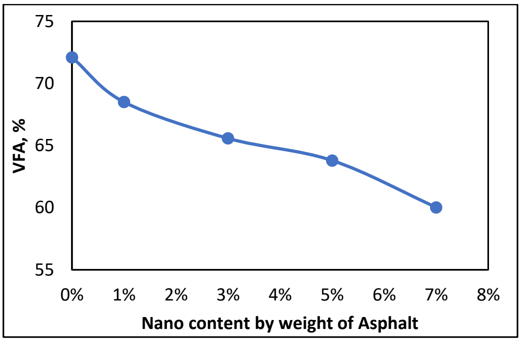

Figure 13: Voids filled with asphalt value of Marshall test with different nano content.

Table 4: Marshall volumetric properties of neat and nano-modified asphalt.

$CaCO_3$ content %	0%	1%	3%	5%	7%	SCRB/R9 Requirement
Marshall Stability, kN	9.43	11.23	13.80	14.37	13.8	Min.8
Marshall Flow, mm	3.75	3.5	3.0	2.75	2.5	2-4
Voids in Mineral Aggregate (VMA), %	14.67	14.30	14.09	13.94	13.91	Min.14
Voids Filled with Asphalt (VFA), %	72.11	68.51	65.58	63.80	60.03	60-80
Air Voids (VA), %	4.01	4.13	4.08	4.59	4.77	3-5
Density, gm/cm^3	2.333	2.331	2.328	2.316	2.309	---
Optimum Asphalt Content (OAC), %	5.0	4.9	4.9	4.7	4.6	4-6

4.3 Effects of Nanc-$CaCO_3$ on Tensile Strength Properties and Moisture

The tensile strength of hot mix asphalt can be considered an important parameter related to fatigue and thermal cracking since fatigue cracking occurs at intermediate temperatures. Figure 14 describes the effect of different nano-$CaCO_3$ content on tensile strength for conditioned and unconditioned specimens. The result indicated an increasing tensile strength value with increasing nano content for both conditions. Hence, the tensile value highlights promoted the unconditioned sample better than condition one; this was anticipated since water reduces the adhesion between the asphalt and the aggregate, lowering the strength of the sample's asphalt mixture under loading. For example, the average tensile value shows an increase of 7.70%, 17.54%, 36.81%, and 36.61% for increasing nano-$CaCO_3$ range from 1 to 7%. At the same, this improvement keeps growing with less effect for a conditioned sample showing an average value of 5.21%, 11.60%, 28.63 and 27.53 % for the same nano content. This behavior offers excellent resistance toward fatigue cracking.

Figure 15 confirmed that Nano-$CaCO_3$ could significantly increase the TSR value up to 90% with the inclusion of 5 to 7% nano content since the nano can increase the stiffness of asphalt binder, which in turn makes it harder or take a long time to peel the aggregate particles from stiffer asphalt in the matrix. Besides, the aggregate type used in this study is from the Al-Nibiee quarry. This type has an electric charge with its surface or polar aggregate surface [7]. When nano-modified asphalt (primarily made up of high molecular weight hydrocarbons) comes in contact, the binding between aggregate and asphalt forms mainly due to low dispersion forces. Furthermore, moisture damage in HMA is reduced by adding 5 to 7% nano-caco3 due to enhanced binder-aggregate adhesion and developing a solid nano network structure. As a result, the TSR values of the nano-$CaCO_3$ mixes are all significantly higher than 70%. Adding nano from 1 to 7% increased TSR by 3.3, 7.51, 12.51, and 13.24% compared to the neat asphalt mixture.

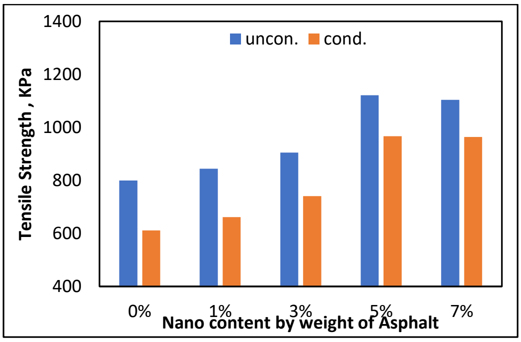

Figure 14: The tensile strength value of neat and nano-modified asphalt.

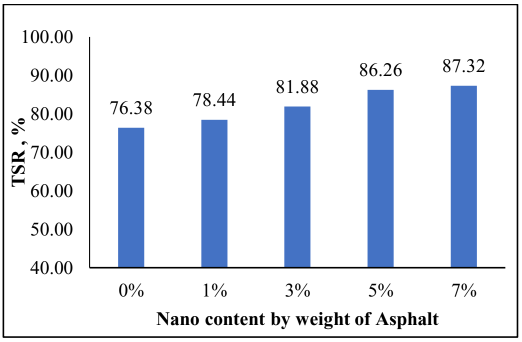

Figure 15: TSR value of neat and nano-modified asphalt.

5. CONCLUSIONS

In this study, widely used asphalt cement with 40-50 penetration grades was modified with different nano $CaCO_3$ at a rate of 1, 3, 5, and 7% to investigate the potential effect of adding these nano types on asphalt physical properties and prepared to evaluate Marshall Properties, tensile strength, and moisture damage. The following conclusion is proposed:

- Nano- $CaCO_3$ can improve asphalt cement physical properties since its decreased penetration value and higher softening indicated higher stiffness and lower temperature susceptibility, up to 5%, since excessive amounts would change the homogeneity of asphalt.
- Modifying neat asphalt with 5% nano- $CaCO_3$ improves Marshall Stability value resulting in increases in the asphalt mixture resistance to hot summer temperatures and pavement distress with permanent deformation.
- Increasing nano – $CaCO_3$ in asphalt mixture shows excellent resistance toward fatigue cracking through increasing tensile strength that exhibits better value at 5% growing to 36.8 and 28.6 for both condition and unconditioned sample.
- Moisture damage in hot mix asphalt is reduced by adding 5 to 7% nano-$CaCO_3$ due to enhanced binder-aggregate adhesion; as a result, the TSR values of the nano-$CaCO_3$ mixes are all significantly increased by 12.51 %higher than neat asphalt mixture.
- Using 5% nano-$CaCO_3$ to modify local asphalt cement will enhance its physical properties and improve asphalt mixture resistance against fatigue and permanent deformation.

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