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Investigation of the Rheological Behavior and Properties of Modified Asphalt Binder with Nano Hydrated Lime

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ABSTRACT: The common types of pavement distresses include: fatigue cracking and rutting. Some of the typical causes of pavement deterioration include: traffic loading; environment or climate influences; drainage deficiencies; materials quality problems; construction deficiencies; and external contributors, such as utility cuts. The most common method for decreasing these types of distress in asphalt mixtures is using suitable additives. Nanomaterials, in recent years, have been widely used to improve rheological properties of asphalt binder. This study is aimed to investigate the effect of nano hydrated lime, which is prepared from hydrated lime in a low-cost method using a planetary ball mill, on rheological behavior of asphalt binder. Therefore, in this research, the dynamic shear rheometer (DSR) test was used to determine the characteristics of control and modified asphalt binder at moderate and high temperatures. The bending beam rheometer (BBR) test was also used to determine their characteristics at low temperatures. The results indicated that the use of nano hydrated lime, especially in the amount of 10% (by weight of asphalt binder), increases the resistance to rutting fatigue cracking. Also, Modified asphalt binder at low temperatures based on the two creep stiffness parameter and m-value has a better performance than control asphalt binder.

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1- Introduction

The rheological and viscoelastic properties of asphalt binder as one of asphalt mixture components affect its mechanical properties. The science of rheology indicates the amount of deformation of material due to stress and the effect of time on this deformation [1, 2]. Since asphalt binder has viscoelastic behavior, its rheological parameters change with time and temperature, which changes their physical properties, such as rutting and fatigue cracking [3, 4].

Increasing traffic and axial load of vehicles in recent years, cause more forces on the pavement and asphalt systems, and reduce the useful life of the pavement. The high costs of construction, repair, and maintenance of asphalt pavements make the researchers look for solutions to increase the durability and stability of asphalt pavements. The use of high-quality materials, asphalt binder modification, grading modification, the use of suitable fillers and the use of various additives over the past years have been considered by various researchers, each with its own advantages and disadvantages [5, 6]. One of the common and successful methods in recent years to achieve this goal was to modify asphalt binder using nanomaterials. Due to their good physical properties and high specific surface area, nanoparticles mainly improve the properties of asphalt binders and eventually asphalt mixtures.

A lot of research has been carried out to improve and modify asphalt binders with different materials such as polymers [7], ashes [8], oils [9], and nanomaterials. Shi et al. [10] investigated the rheological performance of asphalt binders containing nano-silica. In this research, 8% of the weight percent of asphalt binder from Nano SiO_2 additive was used for viscosity, DSR and BBR tests. The results showed that the addition of Nano SiO_2 has increased the resistance to rutting and cracking. Also, in a study by Mubaraki et al. [11], the rheological properties of aluminum nano oxide modified asphalt binder were investigated in 3, 5 and 7 wt.% of asphalt binder. The results showed that the use of the modifier yields a rutting resistance, which has been shown by the hardness factor. In another study, different types of nanoparticles such as TiO_2, Al_2O_3, Fe_2O_3 and ZnO in different percentages were added to the base asphalt binder in order to decrease the rutting potential of HMA. Results of this study showed that using the nanoparticles improved the behavioral properties of the asphalt binder and decreased rutting in asphalt mix samples [12]. In addition, Ziari et al. [13] assessed the effect of nano-carbon tubes on asphalt binder function. The results showed that the use of this additive improves the classical properties (such as softening point, penetration grade, etc.) and functionalities (such as complex modulus, phase angle, fatigue and rutting

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factors). In this research, the effect of nano hydrated lime on rheological parameters of asphalt binder such as complex modulus (G*) and phase angle (δ) obtained from DSR and related properties such as fatigue parameters (G*sinδ) and the rutting (G*/sinδ) is evaluated at moderate and high temperatures, respectively. Also, the effect of nano hydrated lime on the creep stiffness parameter of the asphalt binder at low temperature is investigated by the BBR. Nazari et al. [14] modified asphalt binders using SiO_2, TiO_2, and $CaCO_3$ nanoparticles. Then, rheological and thermal properties of the modified binders were investigated. The results suggested that the addition of these nanoparticles increases glass transition temperature and the low-temperature stiffness of asphalt binder. Furthermore, the increase in complex shear modulus and decrease in phase angle values were observed at intermediate temperatures. In another research, the characteristics of the hot mixed asphalt modified by 2, 4, 6, and 8% nanosilica by weight of binder was investigated. Results showed that nanosilica can improve Marshall stability, resilient modulus, indirect tensile strength, and fatigue life compared to unmodified mixtures [15]. Hamedi and Esmaeili [16] investigated the effects of two nano anti-stripping additives called nano iron oxide (Fe_2O_3) and nano aluminum oxide (Al_2O_3) on the moisture susceptibility HMA mixtures containing crushed glass. The results showed that the addition of nanomaterials improved the adhesive force between asphalt binders and aggregates (crushed glass and aggregates with acidic properties) by reducing the acidic and increasing the basic properties of the modified asphalt binder. You et al. [17] assessed the dispersal of nano hydrated lime (NHL) particles in the asphalt using a scanning electron microscopy (SEM) test, and to evaluate the physical properties of NHL modified water-foamed asphalt (NMFA). The presence of NHL reinforcement in the water-foamed asphalt stiffens the asphalt, consequently decreasing the rutting potential. In another study, Cai et al. [18] proposed an asphalt mixture modified by nano-silica, rock asphalt, and SBS. The results of this study show that nano-silica/rock asphalt/SBS modified asphalt mixture had higher temperature stability, low-temperature cracking resistance, moisture susceptibility, and durability than 5% SBS modified asphalt except the similar fatigue life.

2- Materials

In this research, asphalt binder with the penetration grade of 60/70 from the Pasargad Oil Refinery Company of Tehran has been used and conventional experiments have been carried out to describe the properties of pure asphalt binder, the results of which are given in Table 1.

In order to produce hydrated lime nanoparticles, a planetary ball mill has been used. In this type of mill, four parameters of rotational speed, rotational time, the ratio of bullet to hydrated lime high-quality and process control agent (PCA) are the process variables of milling. Process control agent refers to a group of additives that are used in the milling process. These materials keep the balance between breaking the bonds of materials and re-connecting them in the milling process and create a stable structure, ultimately [19]. In this study, isopropanol was used as PCA. Isopropanol is a member of the family of alcohols, and by repelling between particles of nano hydrated lime prevents them from sticking together. The milling operation was also performed by applying PCA as 5% by weight of hydrated lime. Also, the chemical characteristics of nano hydrated lime used in this study are determined using X-ray fluorescence analysis and are shown in Table 2. Also, the physical properties of nano hydrated lime are given in Table 3.

Table 1. Results of the experiments conducted on neat asphalt cement

Test		Standard	Neat asphalt cement (AC) (60/70)	Modified asphalt cement		
				5 % nano-HL	10 % nano-HL	15 % nano-HL
Penetration (100 g, 5 s, 25 ºC), 0.1 mm		ASTM D5-73	68	65	60	58
Ductility (25 ºC, 5 cm/min), cm		ASTM D113-79	114	126	>150	>150
Softening point, ºC		ASTM D36-76	51	53	57	59
Flash point, ºC		ASTM D92-78	265	271	282	285
Viscosity, MPas	115 ºC	ASTM D2171-07	0.729	0.735	0.754	0.763
	135 ºC		0.311	0.323	0.337	0.344
	150 ºC		0.156	0.169	0.183	0.188

Table 1. Results of the experiments conducted on neat asphalt cement

Properties	Silicon dioxide, SiO_2 (%)	R_2O_3 (Al_2O_3+Fe_2O_3) (%)	Aluminum oxide, Al_2O_3 (%)	Ferric oxide, Fe_2O_3 (%)	Magnesium oxide, MgO (%)	Calcium oxide, CaO (%)
Value	0.936	0.560	0.245	0.315	0.537	76.42

Table 3. Properties of nano- Hydrated lime used in this study

Specification	Result
SSA (m^2/g)	10-45
Color	White
Particle size (nm)	20
Bulk density (g/cm3)	0.46
Purity (%)	+99
Morphology	Spherical

3- Experimental design

In this research, a high shear mixer was used to mix the control asphalt binder with nano hydrated lime. According to previous studies, the circulation speed of 3500 rpm, mixing temperature of 160 °C and mixing time of 40 minutes were chosen for the mixing of nano hydrated lime with asphalt binder [5].

In this regard, in order to investigate the appearance of nanoparticles and their mixing method inside a ‘nanoparticle distributor’ device, scanning electron microscopy (SEM) was used. This image was obtained from scanning the sample by the concentrated loads of the electron. As can be seen in Figure 1, the image was taken with the magnification of 500X and 30 kV voltage. The appearance of these nanoparticles was nearly spherical and the following image demonstrated the validity of the size and appearance of these nanoparticles.

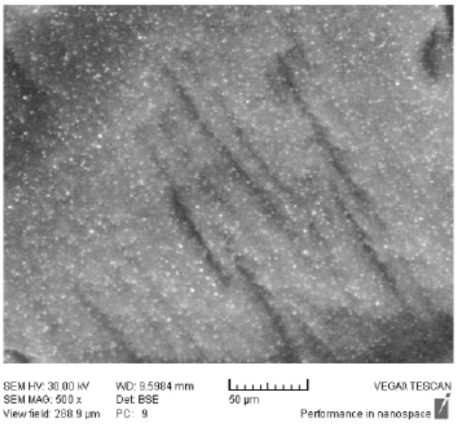

Figure 1. Nano hydrated lime particles mixed in the asphalt binder

A central theme of the Superpave binder specification is its reliance on testing asphalt binders in conditions that simulate critical stages during the binder’s life. The three most critical stages are:

- During transport, storage, and handling,
- During mix production and construction, and
- After long periods in a pavement

Tests performed on unaged asphalt represent the first stage of transport, storage, and handling.

Aging the binder in a rolling thin film oven (RTFO) simulates the second stage, during mix production and construction. The RTFO aging technique was developed by the California Highway Department and is detailed in AASHTO T-240 (ASTM D 2872). This test exposes films of binder to heat and air and approximates the exposure of asphalt to these elements during hot mixing and handling.

The third stage of binder aging occurs after a long period in a pavement. This stage is simulated by use of a pressure aging vessel (PAV). This test exposes binder samples to heat and pressure in order to simulate, in a matter of hours, years of in-service aging in a pavement. It is important to note that for specification purposes, binder samples aged in the PAV have already been aged in the RTFO. Consequently, PAV residue represents a binder that has been exposed to all the conditions to which binders are subjected during production and in-service.

3- 1- Rolling thin film oven (RTFO)

In this research, asphalt binder samples with and without nano hydrated lime were tested in terms of short term aging under the effect of heat and air on a thin movable layer of asphalt binder (RTFO) at 163 °C with an aging time of 75 minutes in accordance with AASHTO T240 standard (T240 2015).

3- 2- Pressure aging vessel (PAV)

Long term aging is carried out using an under pressure aging chamber (PAV) on aged samples with RTFO according to AASHTO R28 standard (R28 2015). The samples are placed in an apparatus under the pressure of 2060 kPa and at a temperature of 110 °C for 20 hours and are prepared to rheological experiments.

3- 3- Dynamic Shear Rheometer

DSR experiment is used to measure the viscoelastic dynamic properties of asphalt binder (G^*, δ) at moderate and high temperatures in accordance with AASHTO T315 standard (T315 2015). In this study, for samples aged with RTFO, parallel plates with a diameter of 25 mm and a sample thickness of 1 mm, and for samples aged with PAV, parallel plates with a diameter of 8 mm and a sample thickness of 2 mms were used. Also, this test was performed for samples aged with RTFO and PAV at 58 to 76 °C and 16 to 22 °C, respectively.

3- 4- Bending Beam Rheometer (BBR)

The BBR test is used to measure the stiffness of asphalts at very low temperatures. The test uses engineering beam theory to measure the stiffness of a small asphalt beam sample under a creep load. A creep load is used to simulate the stresses that gradually build up in a pavement when temperature drops. Two parameters are evaluated with the BBR. Creep stiffness is a measure of how the asphalt resists constant loading and the m-value is a measure of how the asphalt stiffness changes as loads are applied. Also, rheological properties of asphalt binder with and without nano hydrated lime at low temperature are evaluated by the BBR according to AASHTO T313 standard (T313 2015).

4- Results and discussions

4- 1- The results of DSR test

According to the AASHTO specification, the amount of rutting factor (G*/sinδ) should be at least 1 and 2.2 kPa for the non-aged and aged asphalt binder with RTFO, respectively. As shown in Figures 2 and 3, the modified asphalt binder, in comparison with the control asphalt binder has a larger rutting factor at all temperatures (58 to 76 °C). The larger values of the rutting factor indicate that the modified asphalt binder exhibit less sensitivity to rutting or permanent deformation.

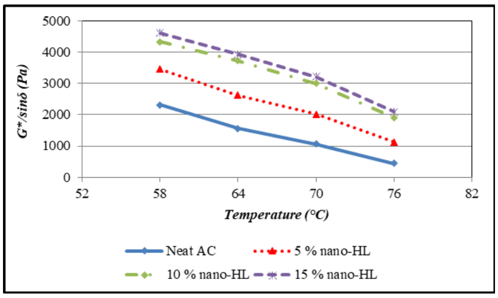

Figure 2. G*/sin(δ) of un-aged asphalt cement

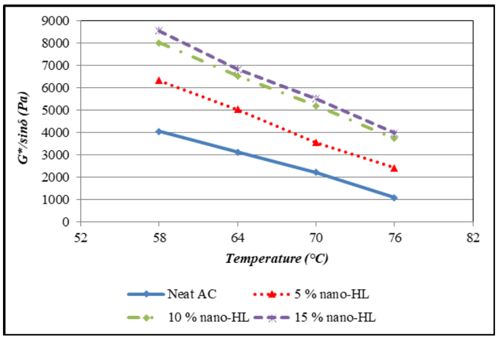

Figure 3. G*/sin(δ) of RTFO aged asphalt cement

Also, when the results of the DSR experiment for asphalt binder samples aging with PAV are examined, (G*sinδ) is introduced as a fatigue factor, which should be at most 5000 kPa according to the AASHTO specification. From the viewpoint of resistance to fatigue cracking, lower values of fatigue factor are more favorable. In this study, the fatigue factor values were measured at the temperatures of 16, 19 and 22 °C and the results are represented in Figure 4. The nano hydrated lime modified asphalt binder has lower fatigue factors in all three values (5, 10 and 15 wt% of asphalt binder) compared to control asphalt binder. As a result, it can be expected that asphalt mixtures containing nano hydrated lime modified asphalt binder have a longer fatigue life compared to control mixtures. Also, as can be seen, using the amounts of 10 and 15% of nano hydrated lime at a temperature of 16 °C has been able to improve one grade the asphalt binder performance.

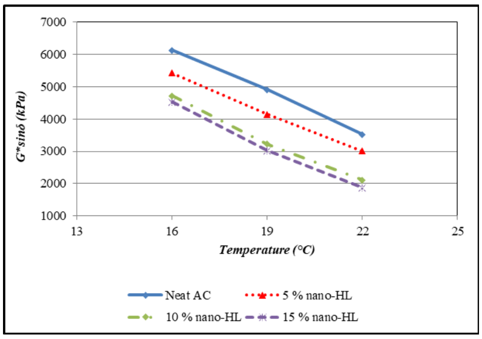

Figure 4. G*sin(δ) of PAV aged asphalt cement

4- 2- The results of BBR test

In this research, the BBR experiment has been carried out at temperatures -6 to -18 °C and the results were presented in Figures 5 and 6. According to the AASHTO specification, the maximum acceptable creep stiffness at low temperatures for a specific kind of asphalt binder is 300 MPa.

As shown in Figure 5, this condition is provided to a temperature of -12 °C for the control asphalt binder hence based on the creep stiffness factor, the asphalt binder functional temperature is above -22 °C. However, for modified asphalt binder with 10 and 15 percent of nano hydrated lime, the amount of creep stiffness at the temperature of -18 °C is still less than 300 MPa, which indicates an increase in the functional temperature of the asphalt binder to -28 °C. In Addition, modified asphalt binder at all temperatures has a creep stiffness factor less than that of the control asphalt binder.

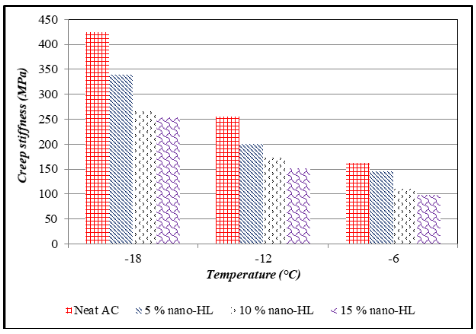

Figure 5. Stiffness Results vs Temperature

Another parameter that is important in the BBR experiment is the m-value. The m-value represents the change rate of creep stiffness (S (t)) with loading time. According to the AASHTO specification, the m-value, when measured in 60 seconds, should be greater than or equal to 0.3, otherwise the creep stiffness will change rapidly with changes in the temperature. These rapid changes in creep hardness can cause accumulation of stresses in the asphalt binder, which ends in the thermal cracks. As shown in Figure 6, the modified asphalt binder, in comparison with the control asphalt binder, show grater m-values. In general, the results show that nano hydrated lime has been able to improve desirable asphalt binder performance at lower temperatures.

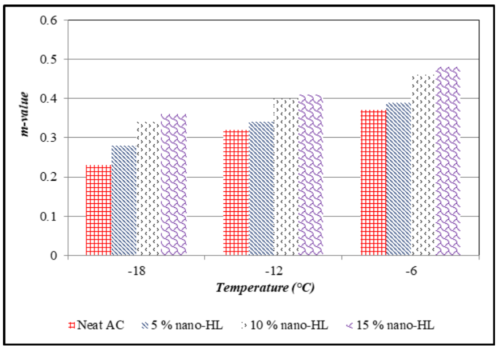

Figure 6. m-value Results vs Temperature

5- Conclusions

This research was carried out to investigate the effect of nano hydrated lime additive on viscoelastic properties of asphalt binder and to evaluate rutting and fatigue behavior by DSR as well as to evaluate their behavior at low temperatures by using BBR.

The most important results obtained from this research are:

- Modified asphalt binder has a higher softening point, a better ductility and a lower penetration grade compared to control asphalt binder.
- The use of nano hydrated lime increases the rutting factor in modified asphalt binder, which can reduce the potential of the rutting of asphalt mixings containing these asphalt binder at high temperatures. For example, at 58 °C and for samples containing 5, 10 and 15 % nano hydrated lime, the rutting factor improve by 56.9, 98.7 and 111.8%, respectively.
- Nano hydrated lime additive improves the fatigue properties of modified asphalt binder, resulting in being late the premature fatigue cracks in mixes containing modified asphalt binder. For example, at 19 °C and for samples containing 5, 10 and 15 % nano hydrated lime, the fatigue factor improve by 15.8, 34.5 and 38.6%, respectively.
- Modified asphalt binder at low temperatures based on the two creep stiffness parameter and m-value has a better performance than control asphalt binder.

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