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Research Paper

Evaluating the Effect of Nano-Al_2O_3 on the Fatigue Resistance of Rubberized Asphalt Mixtures

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Abstract

Due to the traffic structure in Iran and the excessive occurrence of loads to the surface of the pavement and then to the lower layers, the need to implement a resistant layer against to traffic loads in different weather conditions is quite obvious. In recent years, the upward trend in repair and maintenance costs for pavements has been increasing due to the increase in the amount and frequency of traffic loads on pavements, has led to an increase in the tendency to use modified asphalt mixtures, especially in areas with high traffics. Many studies have been done to identify the appropriate additive for use to improve the behavior of bitumen and mixtures. The efficiency and effect of Nano Al_2O_3 as additive in bitumen and rubberized asphalt mixtures in order to improve their performance against external loads and environmental factors was evaluated in this study. In order to achieve the objectives of this study, bitumen with different percentages of Nano Al_2O_3 (0, 0.5, 1.0 and 1.5%) was combined and subjected to physical and rheological tests. Also, for evaluating the functional properties of nano modified samples, various experiments were carried out including 4point bending fatigue test and wheel track. The results of this study show that improving the bitumen behavior in moderate and high temperatures can be led to decrease of fatigue and rutting failure in asphalt mixtures. Evaluation on the results showed that using of 20% rubber powder and 1.5% Al_2O_3 has the best effects on the rheological behavior of bitumen. Also using of this bitumen can improve the asphalt mixture fatigue behavior.

Keyword: Asphalt Mixtures, Bitumen, Fatigue, Rubber Powder, Nano Al_2O

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1. Introduction

Today, the growth of the urban population, the development of industry, and the increase in traffic in and around cities have made the need for buildings and road construction apparent more than ever. Meanwhile, road construction is of particular importance in different countries of the world, especially in developing countries. Road pavement is one of the most important parts of road construction, which is typically influenced by various factors affecting their life and durability. Since a road passes through different areas where the volume of traffic, type of traffic, geographical conditions and rainfall of these areas are different from each other, various defects and shortcomings occur in different parts of a road. If not addressed, evaluated, and repaired, it will lead to rapid road failure. The failure rate of asphalt pavements varies according to fatigue due to repeated loading and weather conditions. Fatigue is the fracture phenomenon due to load repetition, the stress created by this load maybe even much smaller than the ultimate strength of the material. Over time and due to loading, the pavement surface becomes rougher due to cracking (fig. 1), deformation, and crushing.

Figure 1. Growth of fatigue cracks caused by applied traffic load on asphalt pavement

Conducted studies show that although pavement failure is commensurate with their life, this proportion is not linear so that in the early life of the pavement, the intensity of failures is low and increases over time. In general, pavement failure can be classified into two major types, which include structural failure and surface or functional failure [Fakhri and Farrokhi, 2007].

Structural failure is a type of failure in which the pavement structure does not have sufficient load-bearing capacity against applied loads. The structure of this type of pavement cannot bear any load without increasing damage. Whereas functional failure occurs when the pavement system structurally retains its load-bearing capacity, but its serviceability encounters problems and difficulty due to excessive roughness of the surface. Also, the useful life of a pavement includes three phases:

- The consolidation phase is the first phase of the pavement useful life, during which different layers are consolidated due to the passage of traffic loads. This phase is relatively short and depends on the amount of compaction obtained for different layers during the fabrication operation.
- The elastic phase occurs immediately after consolidation, and during this phase, elastic deformations occur in the pavement structure, and the load due to the passage of vehicles causes a definite and transient deformation in the pavement, which disappears with the passage of vehicle and the pavement returns to its initial state.
- The fatigue phase is the final phase of a pavement life. Elastic deformations (deflections) caused by traffic loads produce tensile stresses on the asphalt surfacing and after a period of time, pavement loses its structural capability and strength due to fatigue.

Fatigue failure starts with longitudinal cracks in the pavement structure and after a short time, transverse cracks appear and allow water penetrate into the pavement structure. It is noteworthy that fatigue cracks occur only where the asphalt is under repeated traffic load, such as the wheel paths. Cracking is directly related to the increase in tensile strains at the bottom of the asphalt layer and starts when the strain increases above the threshold. Despite the efforts, determining the amount of this threshold has not been successful [Saburi et al., 2014]. The bitumen obtained from crude oil or natural bitumen, which has been used for many years mainly as a binder in road construction or other paving applications, has never had a series of completely satisfactory physical and mechanical properties. Meanwhile, the modification of bitumen properties and the use of modified asphalt mixtures with the use of new additives such as nano-Al_2O_3 can play a decisive role in correcting defects and improving the chemical and physical properties of asphalt mixtures against phenomena such as fatigue. The study and evaluation of this effect is one of the main objectives of this research.

The use of additives in bitumen and asphalt mixtures with the aim of improving their performance against loads and environmental conditions is the main topic of many researches that has been done in recent years in the field of pavement engineering. The purpose of using these additives can be one or all of the items such as improving asphalt conditions, reducing the thickness of asphalt pavement and as a result economic savings, environmental issues, etc. In recent years, the use of nanomaterial technology in various sciences has led to dramatic advances. Various industries, such as textile, automotive, medical, etc., have been able to achieve incredible goals by using the latent capabilities of nanoscience. The higher surface-to-volume ratio at the nanoscale is one of the mainstays on which nanotechnology is based. Due to the positive effects of using nanomaterials in various sciences, engineers and researchers in the field of asphalt pavement have decided to evaluate the feasibility of their use in asphalt. As a result, nano-additives are among the newest and most up-to-date additives that researchers have used to find solutions for improving the behavior of asphalt mixtures. The review of researches in recent years has shown the high impact of the use of nanomaterials on the behavior of asphalt mixtures, and the results of these researches have shown that the high capabilities of nanotechnology can improve the various parameters of asphalt mixtures.

2. Review of Previous Studies

To date, many studies have been conducted on evaluating the impact of additives on extending the service life of asphalt mixtures. Nanotechnology is one of the additive types that has been one of the main topics of pavement engineer researches in recent years.

Shafabakhsh and Chelovian in a study investigated the effect of nano-Al_2O_3 additive on the mechanical properties of coarse-aggregate mastic asphalt mixtures. The results of their study showed that the use of 0.6% nano-Al_2O_3 can significantly improve the life of asphalt mixtures as well as their rutting modulus. However, they stated that the feasibility study of using nano-Al_2O_3 in asphalt needs further studies and more comprehensive researches [Shafabakhsh & Chelovian, 2017].

Alberka et al. evaluated different percentages of nano-Al_2O_3 on the viscosity and rheological properties of bitumen. The results of their research showed that the use of nano-Al_2O_3 improves the viscosity and shear modulus of bitumen and thus improves its resistance against fatigue [Alberka et al., 2015].

Kordi and Shafabakhsh investigated the effect of nano Fe_2O_3 additive on the mechanical properties of stone mastic asphalt mixtures. They first added different percentages of nano-Fe_2O_3 to bitumen 70-60 by using wet method and used the modified bitumen to construct stone mastic asphalt mixtures. The results of their research showed that the use of 0.9% nano-Fe_2O_3 can significantly improve the life of asphalt mixtures as well as their stiffness modulus. Another result of their research was a significant reduction in the rate of permanent deformation of stone mastic asphalt mixtures due to the addition of different percentages of nano-Fe_2O_3 [Kordi and Shafabakhsh, 2017].

Shabakhsh et al. in another study by adding different percentages (1, 3 and 5% by weight of asphalt mixture) of nano-TiO_2 to bitumen and asphalt mixtures (by using the wet method) with a diameter and height of 40 and 100 mm and using indirect tensile fatigue test method at different temperatures and stresses on them, they found that nano TiO_2 prevents tensile and vertical cracks from being easily generated by tensile stresses and also prevents them from propagating. The results of this study showed that the replacement of 5% by weight of asphalt mixtures with nano-TiO_2 is an optimum content of this material, and improves the fatigue performance of asphalt mixtures even at high temperatures and stresses [Shafabakhsh et al., 2014].

Arabani et al. evaluated the effect of nano zinc oxide on the physical properties of bitumen. In this research, they first mixed bitumen with nano zinc oxide using dry method and then performed experiments on modified bitumens, such as viscosity, penetration grade and softening point and elasticity. The research results showed that the addition of nano zinc oxide can improve the parameters of penetration grade, softening point and elasticity of bitumen [Arabani et al., 2013].

Moghadas Nejad et al. examined the results of bitumen and dynamic creep tests of asphalt samples. They stated that nanoclay with the modified bitumen has a positive effect on the creep performance of asphalt mixtures. Also, the results of direct tensile tests on bitumen samples showed that the use of nanoparticles increases the tensile strength of bitumen. In this research, they utilized a wet method to add nanoclay to bitumen [Moghadas Nejad et al., 2014].

Ghaffarpour and Khodaii studied the effect of nanoclay on the properties of bitumen. They concluded that increasing the percentage of clay to bitumen improves the rheological properties of bitumen. To achieve this result, they applied common bitumen tests (softening point, penetration test, etc.) as well as dynamic shear rheometer tests. In their research, they examined both methods of adding nano to bitumen (dry and wet) and concluded that the wet method is more suitable [Ghafarpour and Khodaie, 2009].

Zhanping et al. employed a dry method to investigate the addition of nanoclays on the performance of asphalt mixtures. After using nanoclays in asphalt mixtures, they concluded that the use of these materials will increase the dynamic modulus of asphalt mixtures [Zhanping et al., 2011].

Sadeghpoor et al. concluded that the addition of nanoclay using a wet method improves the stability of polymer-modified bitumen [Sadeghpoor et al., 2010].

Taherkhani et al. concluded that by adding nanoclay to bitumen, the phase angle is reduced which can lead to the improvement of bitumen elastic behavior. Also, with the increase of nanoclay to bitumen, the mixed shear modulus of bitumen increases, which indicates the effect of nanoclay on bitumen stiffness. The method of adding nanoclay to bitumen has been a wet technique in this research [Taherkhani et al., 2013].

In a research, the rheological properties of bitumens modified with nano-additives have been investigated. These additives are impure nanoclay and polymer-modified nanoclay that have been added to PG 58-34 bitumen at 2 to 4% by the weight of bitumen. The method of adding nanomaterials to bitumen in this research is both dry and wet methods. According to the conducted experiments, the rotational viscosity and mixed shear modulus of bitumen significantly have increased with the addition of impure nanoclay and slightly decreased with the addition of polymer-modified nanoclay. In addition, the resistance properties of bitumen against fatigue and creep loads in bitumen modified with impure nanoclay have increased compared to the bitumen modified with polymer-modified nanoclay [Jahromi et al., 2009].

Baharvand et al. concluded that nanoclays have a high filler role and improve the adhesion between materials and bitumen. Moreover, the addition of nanoclay also increases the thickness of the bitumenious membrane around the aggregates and the volume of bitumen [Baharvand et al. 2014].

Faramarzi et al. evaluated the effect of using carbon nanotubes on the properties of asphalt mixtures. The results of experiments performed on bitumen and asphalt mixtures showed that the modification of asphalt with carbon nanotubes increases the fatigue resistance of asphalt mixtures, especially at low temperatures. The method of adding nano to bitumen in this study was both wet and dry. Researchers in this study concluded that adding nano to bitumen using wet method will create a more uniform combination [Faramarzi et al., 2014].

Shirakawa et al. studied the composition of carbon nanotubes using a solvent. The experimental results showed that the use of carbon nanotubes improves the penetration of bitumen [Shirakawa et al., 2012].

2.1. Research Objective

Examination of the results of studies conducted in this section shows that, if nanomaterials are properly and correctly added to bitumen and asphalt mixtures, will have a high potential to improve many of their properties. In most studies, researchers have used the wet method to add nanomaterial to bitumen and concluded that this method of addition will create a more uniform bond between the constituents of bitumen and nanomaterial. Various nanomaterials such as nanoclay, iron nanoxide, titanium nanoxide, silica nanoxide, etc. have been evaluated so far and the results of previous research showed that their use due to the high potential of nanomaterials improves the behavior of bitumen and asphalt mixtures against different environmental conditions and traffic loads. In this research, in order to complete the research background and evaluate the impact of nanomaterials on the performance of bitumen and asphalt mixture, one of the nanomaterials that has been less considered by researchers in the field of pavement is discussed. As mentioned before, this study aims to investigate the effect of adding different percentages of aluminum nanoxide on the performance of rubberized asphalt mixtures against the fatigue phenomenon by using the experiences of previous studies in this field.

3. Materials and Methods

3.1. Used Materials

The gradation of the stone materials used in this research is the average grain size proposed in Code 234 (Iranian Asphalt Pavement Criteria) with a maximum nominal aggregate size of 19 mm for the Topka layer. The limits of these gradations are presented in Table 1. The granulation test of stone materials was performed according to AASHTO-T27 standard and also by washing method for fine-aggregate stone materials.

Table 1. Gradation of stone materials according to the proposal of code 234 for Topeka layer with a nominal size of 19 mm

Sieve size	Allowed values of the Code 234		Percent Passing
	Maximum	Minimum	
19 mm	100	100	100
12.5 mm	100	90	95
4.75 mm	74	44	59
2.36 mm	58	28	43
0.3 mm	21	5	13
0.075 mm	10	2	6

Experiments of true specific gravity, apparent specific gravity and water absorption percentage for the mixture of stone materials retained on the No. 8 sieve were performed according to the AASHTO-T85 standard and, materials passing through the No.8 sieve and retained on the No. 200 sieve were performed according to the AASHTO-T84 standard. The results of these experiments for stone materials are demonstrated in Table 2.

Table 2. True and apparent specific gravity and water absorption percentage of stone materials

Specification	Specific gravity (Kg/m^3)		Water absorption percentage
	Particle	Bulk	
Retained on the No. 8 sieve	2.534	2.672	2.20
Passing through the No. 8 sieve and retained on the No.200 sieve	2.502	2.697	2.90
Passing through the No. 200 sieve	2.668		-

Bitumen in the asphalt concrete mixture acts as an adhesive material that binds the aggregates in a continuous volume. Bitumen is a viscoelastoplastic material whose resistance and physical behavioral properties depend on temperature. The bitumen used is 85-100 bitumen in the Pasargad oil refinery in Tehran, I.R.Iran. Its specifications are listed in Table 3.

Table 3. Specifications of 85-100 bitumen used in this research

Specifications	Value	Allowed limit	Test Method
Specific gravity at 25 °C	1.013	-	ASTM D70
Penetration grade at 25 °C (0.1 mm)	91	85-100	ASTM D5
Softening point (°C)	46	45-52	ASTM D36
Ductility at 25°C	102	>100	ASTM D113
Flash point	308	>232	ASTM D92
Percent purity with Trichloroethylene (%)	99.6	>99	ASTM D2042

Waste rubber can be used extensively and with spending low cost. By using this material, which is disposable and non-degradable, in addition to providing the cheap required modifier and improving the properties of asphalt, it also helps to preserve the environment. Currently, the ASTM D6114 standard specifies the characteristics that an improved asphalt mix should have with waste rubber (crumb rubber). Numerous patents have been developed to further improve this process, and numerous technologies are currently being used to produce it. The biggest problem that these production units face is the separation of rubber and asphalt phases, which can create a great challenge for all the advantages of rubberized asphalt. When storing normal asphalt, the separation of phases is about 2 to 4%, which is 25% for rubberized asphalt. This problem can be solved and reduced (from 25% to 7%) by creating chemical bonds between bitumen and aggregate. In this research, to further reinforcing this bond, nanotechnology and specifically nano-Al_2O_3 are used.

In accordance with the ASTM D6114 standard, rubber powder passing through the (No.8) 2.36 mm sieve should be used for the production of rubber bitumens. No non-ferrous metal particles should be seen in the rubber powder, and also the percentage of ferrous particles should be limited to 0.01 wt% of the rubber powder. The maximum allowed moisture content of rubber powder should be about 0.075 wt%, and the density of rubber powder should be approximately 1.1-1.2.

In this research, based on previous studies, a constant amount of 20% rubber powder (by the weight of bitumen) with the mesh 80 is employed in all bitumen specimens. A view of the rubber powder used in this study is illustrated in Figure 2.

The properties of nano-Al_2O_3 used in this research are shown in Table 4. The specifications of the table are based on the information provided by the nano seller company. The nano used in this research has been prepared from Neutrino Company located in Tehran. Images of nanomaterials can also be seen in Figure 3.

Table 4. Basic properties of nano-Al_2O_3 used in this study

Specifications	Value	Specifications	Value
Chemical formula	Al_2O_3	Particle size Nm	60
Bulk specific gravity g/cc	0.9	Color	White
Specific surface M^2/g	160	Water absorption %	0.2<
Morphology	Quasi-spherical	Percent purity %	99.9

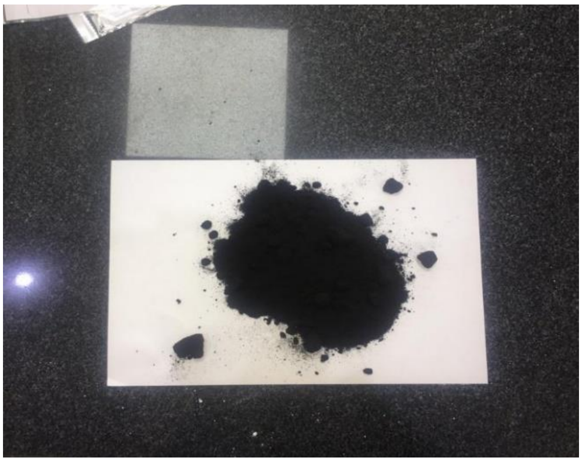

Figure 2. Rubber powder used in this research

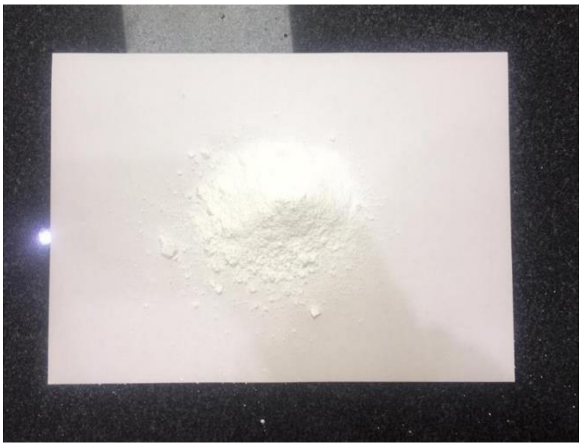

Figure 3. Nano-Al2O3 used in this research

3.2. Mixing Rubber Bitumen and Nano-Al2O3

In the mixing process, the nanomaterials are firstly dispersed in the kerosene solvent using a high shear mixer. In this research, several specimens of kerosene-nanomaterial solutions were made at different mixing times and different mixing periods. Comparisons between different specimens were performed based on the stability of nanomaterials in the solvent and their deposition over a given period of time. Comparison between different specimens studied showed that the best dispersion of nanomaterials in the solvent is to use this method that, first, the kerosene solvent is mixed with each of the nanomaterials in the high shear mixer with different rotation speeds and for different times so that the nanomaterials are well dispersed in the solvent. This method provides the energy needed to open the masses of nanomaterials without damaging them.

In order to examine the proper dispersion and stability of the solution after mixing, each of the compounds was poured into graduated glass cylinders and kept stationary for two weeks. In the end, the results were that mixing for 30 minutes at 2500 rpm had the best results. As a result, it can be assumed that due to the proper mixing process, the masses of nanomaterials are separated from each other and the nanomaterials can remain stable in the solvent in a separate form and therefore lighter and do not settle.

In many studies, the percentage of nanomaterials used in bitumen has varied between 0 and 1.5% by the weight of bitumen, because using more than this amount makes the design uneconomical. Thus, based on the existing experiences from previous researches, in this research, different percentages of nano Al_2O_3 (0, 0.5, 1.0 and 1.5% by weight of bitumen) have been employed. In order to perform the final mixing, first the rubber bitumen was heated to 150 ° C and during half an hour at regular intervals, the nanoparticle-solvent compound was slowly poured into the mixer and the mixing process was continued at 4000 rpm until forming a homogeneous mixture of bitumen and nanoparticles. The selection of the most suitable homogeneous composition was based on physical experiments performed on original bitumen and modified with different nanoparticles. At the end of the mixing process, the modified bitumens are as shown in Table 5.

Table 5. Properties of modified bitumens in this research

Normal bitumen	Rubber bitumen	Nano bitumen (modified with nano-Al_2O_3)
Bitumen 85-100 (C)	Bitumen 85-100 modified with 20% rubber powder (20% R)	Rubberized bitumen + 0.5% nano-Al_2O_3 (20% R + 0.5% N)
		Rubberized bitumen + 1.0% nano-Al_2O_3 (20% R + 1.0% N)
		Rubberized bitumen + 1.5% nano-Al_2O_3 (20% R + 1.5% N)

3.3. Research Method

In determining the properties of bitumen, penetration tests (ASTM D5), softening point (ASTM D36), ductility (ASTM D113), kinematic viscosity (ASTM D2170), dynamic shear rheometer (ASTM D7175) and bending beam rheometer (ASTM D6) were used. Furthermore, for determining the properties of asphalt mixtures, first the optimal bitumen content of asphalt mixtures was determined using Marshall Test (ASTM D1559). Then, asphalt mixtures were constructed using different bitumens to determine their performance against the fatigue phenomenon in the beam test (AASHTO T321).

3.4. Four-Point Bending Fatigue Test Method

After determining the gradation curve and the optimal content of bitumen, asphalt slabs are constructed. The asphalt slab is compacted by a kneading compactor. The operation of the kneading compaction device is mechanical and the necessary pressure for compression is provided by a hydraulic jack. During each load application, the load is slowly increased and for a few seconds kept constant and then the loading operation was performed. Slabs were cut according to standard dimensions to achieve the desired dimensions for fatigue test using waterjet cold cutting.

Bending fatigue test was performed by a device manufactured by IPC9 Australia. This device can apply repetitive bending loads to asphalt specimens and calculate the load and deformation created. Fatigue test was performed by placing the asphalt beam under repeated four-point loading at a certain strain level. In general, the fatigue beam test is performed in two methods: constant stress and constant strain. In the case of constant strain, the strain remains constant and stress is allowed to change, and in the case of constant stress, the load remains constant and the strain is allowed to change. Figure 4 displays how to perform this test.

In the case of the constant stress, the test is continued until the specimen is actually ruptured and broken. However, in the case of a constant strain, it is difficult to determine and define the failure. The reason for this is that in order to keep the strain constant, the applied stress is repeatedly reduced, in which case the actual fracture of the beam never occurs. Therefore, in the case of a constant strain, the failure is defined at the point where the stiffness reaches a predetermined value, which is typically considered to be 50%. For this research, the constant strain method was used. The experimental temperatures were 15 and 20 ° C, the load waveform was semi-sinusoidal and strain levels 600 and 1000 microstrain. Moreover, in order to reduce the error, three specimens were tested for each laboratory condition, which the final result is the average of three specimens.

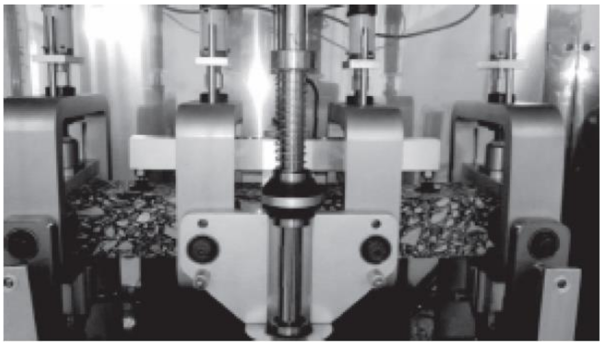

Figure 4. Conducting a fatigue test under four-point loading

4. Results and Analyses

4.1. Results of Bitumen Physical Tests

In the first step, in order to initially investigate the effects of nanomaterials on bitumen, penetration grade, softening point, ductility properties and kinematic viscosity tests have been performed. The results of these experiments are shown in Figures 5 to 8. The purpose of the softening point test is to evaluate the temperature sensitivity of bitumen. The higher the softening point of bitumen is, the lower the temperature sensitivity is. As can be seen from the results, normal bitumen has a low softening point, and as a result, a lower temperature is required for the ball to pass through the ring in the softening point test.

By adding different amounts of nanomaterials, the temperature balance of bitumen changes, and since the thermal sensitivity of nanomaterials to temperature changes is lower, these particles increase the temperature required to soften the bitumen by heat exchange. The increase in softening point is due to the fact that nanomaterials prevent breaking of bonds between bitumen layers by absorbing heat bitumen and therefore the softening point of bitumen is shown less change than thermal changes. Hence, percentages due to the increase in the amount of nanoparticles, the distances between the constituent particles of bitumen increase, which reduces the strength of the bitumen.

The results of the softening point test in this study show that the addition of nano-AL_2O_3 can significantly improve the softening point of bitumen so that the addition of 1.5% nano increases the value of softening point by 13% compared to control bitumen and 8% compared to rubber bitumen. Consequently, this value can be considered an improvement for the bitumen temperature sensitivity.

Figure 6 demonstrates the results of the penetration test by adding different contents of nano-Al_2O_3. As can be seen from the results, with the addition of nanomaterials, bitumen has hardened due to the formation of stronger bonds between bitumen compounds.

Asphaltene (bitumen structural skeleton) prevents the separation of bitumen particles by forming bonds with nanoparticles, in addition to creating a stronger bond and consequently, bitumen is formed with better properties. In the modified bitumen with 20% rubber powder and 1.5% nano-Al_2O_3, the results are much better and the value of penetration is reached close to 84, although the excessive reduction of penetration grade can be a negative parameter in cold weather.

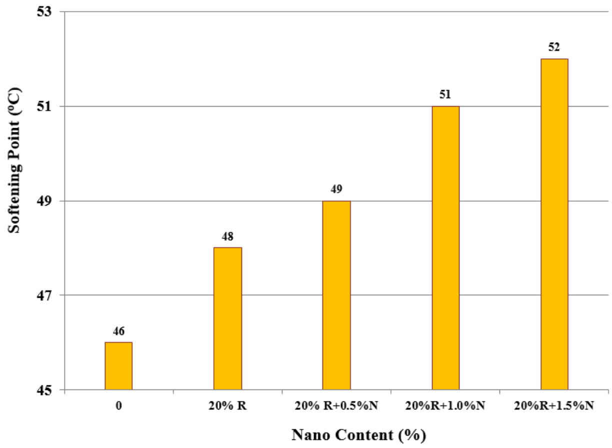

Figure 5. Results of softening point test based on different content of nano-Al_2O_3

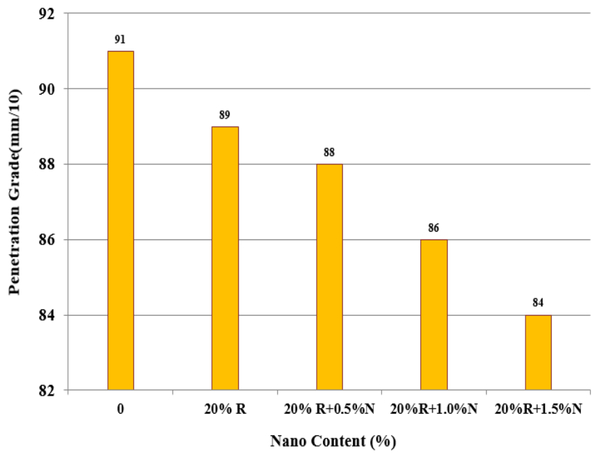

Figure 6. Results of penetration test based on different content of nano-Al_2O_3

In the ductility test, the bitumen specimen is subjected to tensile force, which in most bitumens in Iran, this number is above 100 cm. The upper and lower threads of the thin layer of bitumen in this experiment are under tension and pressure due to the centrifugal force due to the movement of this layer in the device bath.

Figure 7 illustrates the results of this experiment on specimens without nanoparticles and modified with different percentages of nanomaterials. The results indicate an increase in elasticity in bitumen specimens with the addition of nanoparticles. The reason for this increase can be attributed to the placement of nanoparticles between the bitumen particles, which leads to stronger bonds between them, and these stronger bonds prevent the rupture of the modified bitumen. The results of this experiment show that the increase in elasticity in bitumen increases with increasing percentage of nano-Al_2O_3.

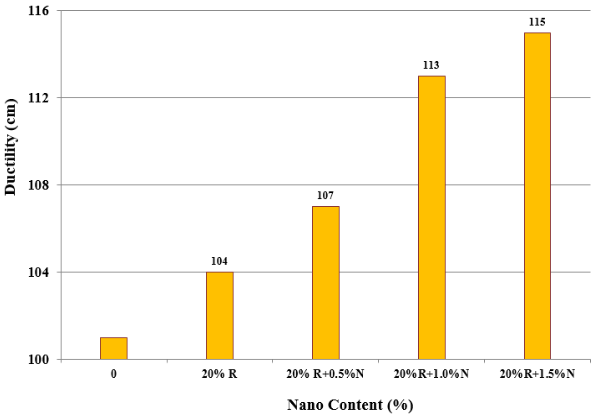

Figure 7. Results of ductility test based on different content of nano-Al_2O_3

The results of this test indicate that rubber bitumen containing 1.5% nano-Al_2O_3 can withstand the maximum amount of tensile force without breaking, which is about 14 and 11% more than the amount of tensile force that the control bitumen (without additive) and rubber bitumen can withstand. This increase in tensile resistance, especially in hot days of the year, can help to withstand the tensile stresses caused by temperature in asphalt mixtures.

The viscosity of bitumen plays an important role in covering aggregates and preventing the moisture infiltration into the destruction of the bond between aggregate and bitumen. The results of the kinematic viscosity test for temperatures of 135 and 150 °C are shown in Figure 8. The results show that with the addition of nanomaterials, the viscosity of bitumen increases at both temperatures. This increase continues at both 135 and 150 °C with the addition of 1.5% nano-Al_2O_3 to bitumen.

On the other hand, the effect of temperature on the process of changes in kinematic viscosity is quite obvious. As can be seen in each of the forms, the process of improving the kinematic viscosity decreases due to the addition of nanomaterials with increasing temperature from 135 to 150°C. The reason for this can be the thermal sensitivity of bitumen. However, with increasing temperature, the trend of increasing the kinematic viscosity of bitumen continues and only the increasing slope decreases, which indicates the high impact of nanomaterials on improving the resistance of bitumen against flowing.

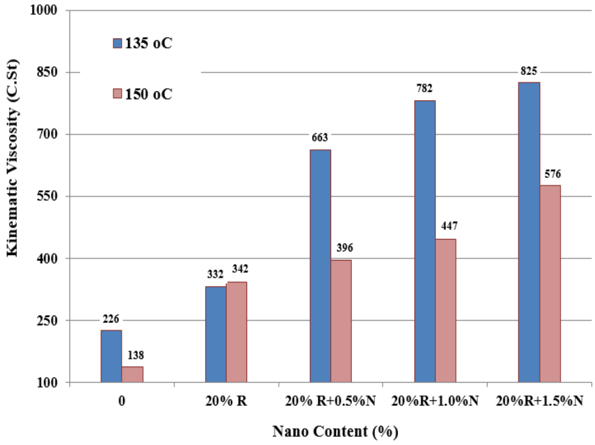

Figure 8. Results of kinematic viscosity test based on different content of nano-Al_2O_3

As it is clear from the results, if 20% rubber powder and 1.5% nano-Al_2O_3 are employed to improve the performance of bitumen, the rate of viscosity increase is higher. Nanoparticles increase the durability and concentration of bitumen by strengthening the bonds between asphaltene and maltin, and play an important role in better bonding of aggregates and bitumen.

4.2. Results of Dynamic Shear Rheometer Test

This test is performed in three states of normal bitumen and short-term aged bitumen (RTFO) at 58, 64 and 70°C and long-term aged bitumen

(PAV) at 20°C. First and foremost, the shear modulus (G*), which is one of the main outputs of this experiment, is presented for the different bitumens discussed in this study (control bitumen, rubber bitumen, and bitumen modified with rubber and nano-Al_2O_3) at different temperatures and in non-aged state. As the results indicate, the addition of different percentages of nano-Al_2O_3 has been able to improve the shear modulus of bitumen at all temperatures. One of the reasons for increasing the shear modulus is that adding different percentages of nanomaterials to bitumen increases its viscosity, and this high viscosity leads to a higher resistance of bitumen against applied shear forces. It is predicted that this higher viscosity will lead to a thicker crust of bitumen around the aggregates, which the adhesion between the bitumen and the aggregates will increase.

The figure 9 demonstrates the high effect of temperature on the bitumen performance. As it is clear from the results, the amount of shear modulus at 58°C and in the amount of 20% rubber powder and 1.5% of nano-Al_2O_3 is about 3.8 times of its amount at 70°C. This is due to the high sensitivity of bitumen to temperature. Higher temperatures cause the bitumen to dilute and reduce its adhesion properties and resistance against the shear force applied in this experiment.

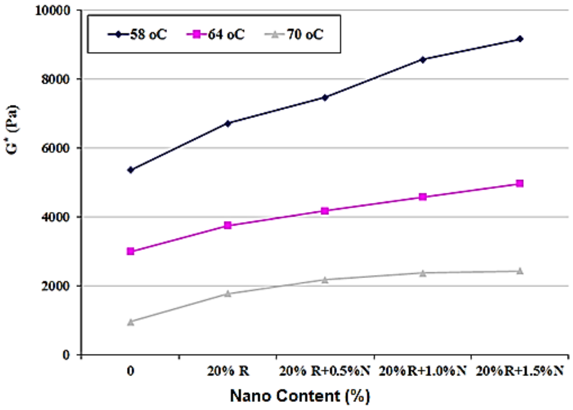

Figure 9. Shear modulus of bitumens modified with different percentages of nano Al_2O_3 in the state of non-aged bitumen

Moreover, increasing the temperature causes decrease in the increasing slope of the shear modulus in bituminous specimens with different percentages of nanomaterials, so that at 58°C, the effect of nanomaterial percentages has been much greater than temperatures of 60 and 70°C. This can be explained by the fact that at low temperatures bitumen has a certain adhesion and viscosity, which is improved by the addition of nanomaterials, while when the temperature rises, the bitumen properties are greatly reduced and the bitumen is diluted and this is no longer improved by the addition of nanomaterials.

As the results indicate, in bitumen specimens containing 20% rubber powder and 1.5% nano-Al_2O_3, the amount of shear modulus has reached its maximum. For example, at a temperature of 58°C, its value has increased by about 70 and 40% compared to control bitumen and rubber bitumen (containing 20% rubber powder and without nano). In fact, nano-Al_2O_3 particles in this situation have helped the bitumen reinforcement process and viscosity improvement to achieve this improvement.

In order to evaluate the effect of nano-Al_2O_3 on the rutting resistance of bitumen, the dynamic shear rheometer test is conducted at temperatures of 58, 64 and 70°C on control bitumen, rubber bitumen (modified with 20% rubber powder) and rubber bitumen modified with different percentages of nano-Al_2O_3. The results are shown in Figures 10 and 11 in two states of non-aged and short-term aged bitumen. The SHRP research group, after extensive researches, has proposed a minimum value of $G^*/Sin\delta$=1kPa for non-aged bitumens and 2.2kPa for short-term aged bitumens.

The results show that in the state of normal (non-aged) bitumen at all temperatures the value of $G^*/Sin\delta$ is more than 1 kPa determined by the Sharp and this is only the temperature of 70°C where the value of $G^*/Sin\delta$ is less than 1. This is because the bitumen used in this research is 85-100 bitumen, which is functionally equivalent to 64-22 bitumen and will have a drop in performance at temperatures above 64°C. However, the results show that by adding rubber and nano-Al_2O_3 to bitumen at 70°C, the value of G*/Sinδ at this temperature is also higher than the minimum value of 1 kPa in the non-aged state, which is why it is important that the results of this study could improve the serviceability temperature of bitumen.

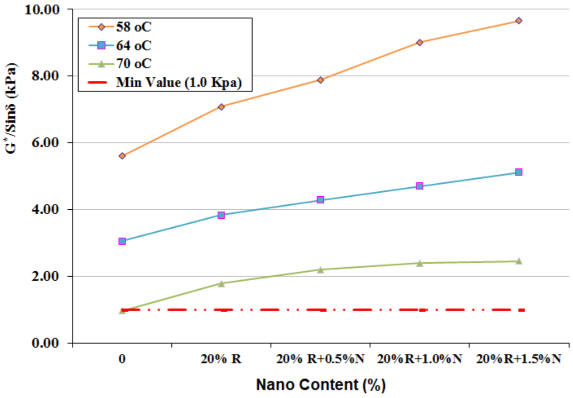

Figure 10. G*/ Sinδ of modified bitumens with different percentages of nano-Al_2O_3 in non-aged state

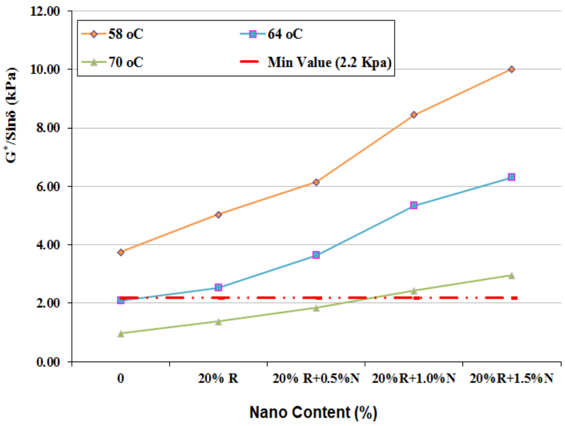

Figure 11. G*/ Sinδ of modified bitumens with different percentages of nano-Al_2O_3 in short-term aged state

As the results indicate, the 85-100 bitumen used in this research at temperatures of 64 and 70°C and in RTFO condition has had a value of G*/Sinδ less than the minimum value of the regulations (2.2kPa). However, the results show that in bitumen modified with nano-Al_2O_3 at all temperatures, this amount is more than the minimum value of the Sharp Institute, and this amount is increased by adding different percentages of nano-Al_2O_3, which can be a good sign for improvement of the bitumen performance against rutting phenomenon and permanent deformations. As Figure 10 displays, at 58°C, the value of G*/Sinδ in bitumen modified with 1.5% nano-Al_2O_3 is about 2.7 and 2.0 times that of control bitumen and rubber bitumen. This increase rate indicates the high impact of nano-Al_2O_3 on improving the rheological behavior of bitumen. However, with increasing temperature, the effect of nano-Al_2O_3 on it decreases due to the high temperature sensitivity of bitumen.

The high effect of nano-TiO_2 additive is at 70°C, where the value of G*/Sinδ has significantly decreased due to the increase in temperature and has become less than the standard value of 2.2, and by adding different percentages of this nano, the value of G*/Sinδ has been promoted and the rheological performance of this bitumen against the rutting phenomenon has been improved.

Like rutting, G* and δ are used in superpave bitumen materials to help control fatigue cracks in asphalt pavements. Since fatigue cracks usually occur at low to medium pavement temperatures, after the pavement was subjected to loading for some time, to determine fatigue, a dynamic shear rheometer test was performed at 20°C on aged bitumens in RTFO and PAV. The control factor for fatigue cracks is G*/sinδ. The Sharp Institute considers a maximum value of 5 kPa for G*/sinδ. Low values for G* and δ can be suitable in terms of resistance against fatigue cracks. Therefore, Sharp experiments recommend the use of elastic bitumens (aged in the PAV machine) to control the mixture against fatigue cracks. The values of G*.sinδ for modified bitumens with different percentages of nano-Al_2O_3 are shown in Figure 12. As the results show, adding different percentages of nano-Al_2O_3 has been able to improve the bitumen performance against fatigue.

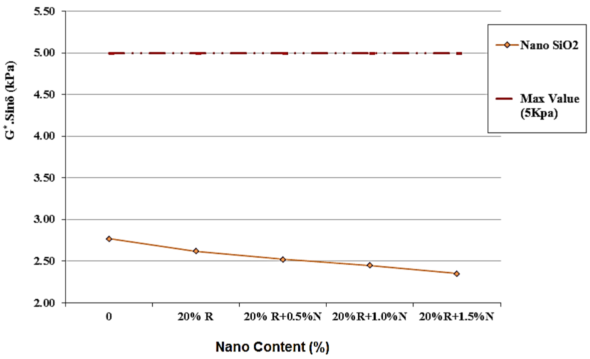

Figure 12. G*/sinδ of bitumens modified with different contents of nano-Al2O3 in the long-term aged state

4.3. Four-Point Bending Fatigue Test Method

After reviewing the results of bitumen tests and before entering the fatigue test, it is necessary to determine the optimal content of bitumen. Comparison of the results of control bitumen and rubber bitumen tests shows that the performance of rubber bitumen in all tests was better than the performance of control bitumen (without additive). As a result, by proving this case based on the results of bitumen tests, in the asphalt mixture testing section, only asphalt specimens were constructed with rubber bitumen (bitumen modified with 20% rubber powder) and rubber bitumen modified with the optimal amount of nano-Al_2O_3 (1.5% by weight of rubber bitumen). According to the results of Marshall Tests, the optimal values of bitumen (OBC) for rubberized asphalt specimens and modified with nano-Al_2O_3 are presented in Table 6.

Table 6. OBC in rubberized asphalt specimens and containing nano-Al_2O_3

Additive Material	Additive Material Content (%)	OBC (%)
Rubber Powder	20	5.0
Rubber Powder + Nano Al2O3	20+ 1.5	5.5

Fatigue is one of the common weaknesses of asphalt mixtures and its intensity varies due to the repetition of loading and its intensity and weather conditions. The onset of fatigue in an asphalt mixture is the onset of cracking that are hierarchically connected, and with continued loading may cover a large portion of the pavement, greatly reduce the bearing capacity of the pavement and reduce driving safety. As a result, finding a way to increase the resistance of asphalt mix against this phenomenon is one of the tasks of pavement researchers.

In this research, in order to improve the quality and performance of rubberized asphalt mixtures against fatigue phenomenon, four-point fatigue test method was used. As a result, after determining the granulation curve and the optimal percentage of bitumen, an asphalt slab was constructed, which was compacted by kneading compactor. The operation of the kneading compactor is mechanical and the necessary pressure for compaction is provided by a hydraulic jack. During each load application, the load is slowly increased and held constant for a few seconds, and then the loading operation is performed. Slabs were cut according to standard dimensions to achieve the desired dimensions for fatigue testing using waterjet cold cutting. This test was performed at two temperatures of 15 and 20°C as a control strain at levels of 600 and 1000 microstrains. Figure 13 shows the fatigue life of normal and modified rubberized asphalt mixtures with 1.5% nano-Al_2O_3 at different temperatures. Fatigue life in a 4-point bending beam test is defined as the number of tolerable cycles of an asphalt sample in which the sample stiffness reaches a predetermined value, usually considered to be 50%. As a result, the following figure illustrates this number of cycles.

As the results display, the number of tolerable loading cycles of asphalt samples at 15°C is higher than 20°C. For example, the ratio of the number of tolerable cycles of control specimens (without nanoparticles) at 15°C to 20°C was equal to 1.18, which indicates the high effect of temperature on the fatigue life of asphalt mixtures, and in fact a lower temperature equal to the longer lifespans of asphalt mixtures. In addition, the results show that the more the specimens are allowed more strain, definitely, the greater the number of tolerable cycles is. However, the above two parameters (temperature and strain) cannot be changed by road construction and transportation engineers. What is achievable is to find a way that even at higher temperatures can prevent excessive reduction of the mixtures lifetime. The results of this study suggest the use of nanotechnology for this purpose. The results indicate that the use of 1.5% nano-Al_2O_3 at both temperatures increases the number of tolerable cycles for asphalt mixtures.

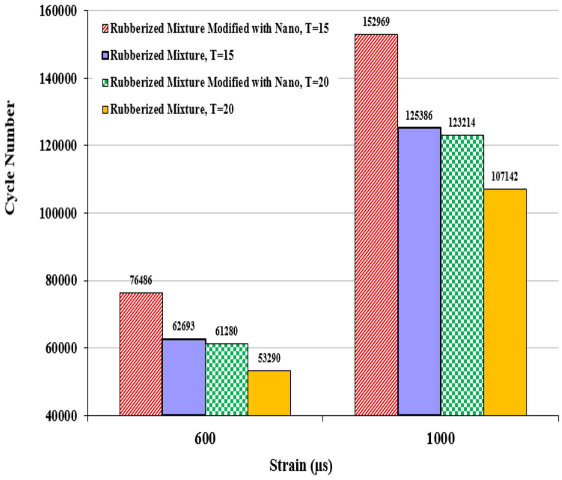

Figure 13. Fatigue life of normal and modified rubberized asphalt specimens

The results indicate that at different temperatures and strains, the number of tolerable cycles of modified mixtures with 1.5% nano-Al_2O_3 is between 15 to 22% more than rubberized asphalt mixtures without nano. As a result, it can be expected that the probability of cracking and the onset of fatigue will be significantly lower in mixtures modified with 1.5% nano-Al_2O_3 to rubberized asphalt samples.

In the following laboratory model, the relationship between flexural strain at the bottom of the asphalt layer and the creation of cracks due to fatigue in that layer is shown. Figure 14 illustrates the results of estimating the parameters of the above model for asphalt mixtures of this research at different temperatures and stresses.

$$\varepsilon_f = K_1 (N_f)^{K_2} \quad (1)$$

In this equation:

N_f : The number of loading cycles that lead to fatigue failure.

K_1, K_2 : Constant values.

ε_f : Tensile strain due to bending at the bottom of the hot asphalt layer.

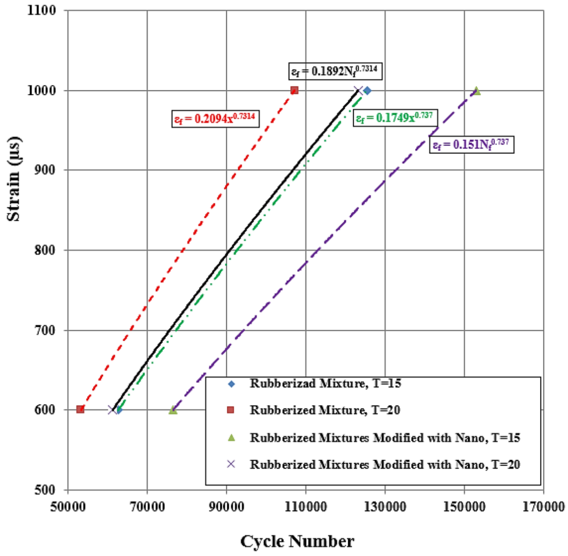

Figure 14. Estimation of fatigue model parameters for asphalt mixtures

5. Conclusion

In this study, the efficiency and effect of nano-Al_2O_3 as an additive on bitumen and rubberized asphalt mixtures to improve their performance against external loads and environmental factors were investigated. The most important results of this study are as follows:

- The results of physical tests of bitumen in this study indicate that the addition of nano-Al_2O_3 can significantly improve the physical properties of bitumen such as softening point, penetration, tensile strength and viscosity and the combination of 20% rubber powder and 1.5% nano-Al_2O_3 has the best performance.
- The results of dynamic shear rheometer test demonstrate that adding different percentages of nano-Al_2O_3 has been able to improve the shear modulus value of bitumen at all temperatures, so that in bitumen specimens containing 20% rubber powder and 1.5%

nano-Al_2O_3, the shear modulus value has reached its maximum value.

● The results indicate that in the state of normal (non-aged) bitumen at all temperatures, the value of G*/Sinδ is more than 1 kPa determined by the Sharp and this is only the temperature of 70 ° C where the value of G*/ Sinδ is less than 1. However, the results show that by adding rubber and nano-Al_2O_3 to bitumen at 70 °C, the value of G*/ Sinδ at this temperature is also reached higher than the minimum value of 1 kPa in the non-aged state.

● As the results indicate, in the case of non-aged, short-term aged and long-term aged bitumen due to the addition of different percentages of nano-Al_2O_3, the behavior of bitumen against failure due to fatigue and rutting is significantly improved and the best value is obtained by adding 1.5% nano.

● The results show that the use of 1.5% nano-Al_2O_3 increases the number of tolerable cycles of asphalt specimens and at different temperatures and strains, the number of tolerable cycles of mixtures modified with 1.5% nano-Al_2O_3 is between 15 to 22% more than asphalt rubber mixtures without nano. As a result, it can be expected that the probability of cracking and the onset of fatigue is significantly lower in mixtures modified with 1.5% nano-Al_2O_3 to rubberized asphalt specimens.

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