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Contribution of nano crumb-rubber to the rheological characteristics of modified buton rock asphalt

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ABSTRACT

The increasing number of overloaded vehicles on the highway is one of the factors causing damage to flexible pavements, especially at high temperatures. Therefore, investigating asphalt binders resistant to high temperatures is important. Many studies have been carried out on modifying asphalt with nanomaterials to increase the resistance of asphalt to rutting. One is research using nano crumb-rubber additive material as an asphalt binder variable. This research was carried out with different nano crumb-rubber content of 1.2%, 2.4%, 3.6%, and 4.8% added to pure asphalt binder pen 60/70 and Lawele Bitumen, resulting from extraction from the island of Buton. Rheological tests using the Dynamic Shear Rheometer were used to measure the value of the rutting factor (G*/sin δ) on pure asphalt binder and Asphalt Nano Crumb-Rubber Modified. The asphalt binder resistance to aging conditions can be seen from the aging index value. The results show that adding the percentage of nano crumb rubber to modified asphalt reduces the complex shear modulus (G*) value, the phase angle (δ), and the value of the aging index.

ABSTRAK

Peningkatan jumlah kendaraan yang melintas di jalan raya merupakan salah satu faktor yang menyebabkan kerusakan pada perkerasan lentur di negara dengan suhu tinggi. Penyelidikan terhadap pengikat aspal yang tahan terhadap suhu tinggi menjadi penting. Telah banyak penelitian yang memodifikasi aspal dengan bahan nano material untuk meningkatkan ketahanan aspal terhadap rutting. Penelitian ini menyelidiki penggunaan bahan aditif nano crumb-rubber sebagai peubah pengikat aspal potensial. Persentase nano crumb-rubber (NCR) yang berbeda yaitu 1,2%, 2,4%, 3,6% dan 4,8% ditambah ke pengikat aspal murni pen 60/70 dan Lawele Asphalt (LA) yang merupakan hasil ekstraksi aspal batuan dari pulau Buton, Indonesia. Pengaruh suhu tinggi dan viskositas di evaluasi. Tes reologi menggunakan Dynamic Shear Rheometer (DSR) bertujuan untuk mengukur nilai faktor rutting (G*/sin δ) pada pengikat aspal murni dan Asphalt Nano Crumb-Rubber Modified (ANCRM). Ketahanan pengikat aspal pada kondisi penuaan dilihat dari nilai aging index (AI). Hasil menunjukkan bahwa penambahan persentase NCR pada aspal modifikasi menurunkan nilai modulus geser kompleks (G*), nilai sudut fase (δ) dan nilai AI pada setiap persen campuran dan suhu tertentu.

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1. Introduction

Road infrastructure is built to meet the increasing number of vehicles every year. One of the factors causing damage to the flexible pavement in various countries, especially those with high-temperature climates, is the result of excessive traffic loads [1]. Early road damage is not only due to traffic loads but also the condition of the mixed pavement material. On road pavements, good structural performance will always be related to material properties, such as aggregate and binder material [2]. Therefore, selecting asphalt materials will be important to produce asphalt pavements with better performance. During the last few years, many researchers have researched the selection of suitable asphalt materials, especially asphalt binding materials [3]. Research continues to be carried out by modifying asphalt binder materials to replace the use of pure asphalt binder materials that are commonly used. Damage to flexible pavements that often occurs at high temperatures is rutting, which can cause the deformation of road pavements [4]. Improving the performance of road pavement materials includes adding additional materials to asphalt and aggregate. Increasing asphalt adhesion can be used with nanomaterials to minimize the formation of micro cracks. It can extend fatigue life and reduce permanent deformations in asphalt [5]. As a modified additive material, nano particles can increase the complex shear modulus's value, reducing the phase angle's value. They can improve the rheological performance of asphalt base binders [6]. Using modified asphalt in aggregate asphalt mixtures improves the performance of asphalt as resistance to load and temperature. Research on modifying old asphalt has been conducted in the last decade [7].

Asphalt modification with added materials, Nano Crumb-Rubber (NCR) material, can improve its mechanical properties. However, the instability in time and high temperatures still need to be resolved [8]. The higher the crumb-rubber (CR) content, the more viscosity and softening point values, while the penetration and ductility values decrease [9]. Future studies are expected to be able to compare the performance of hot mix asphalt with the dry process to improve rutting and fatigue resistance, stiffness, moisture susceptibility, and asphalt aging [10]. The characteristics of the particles, shape, and content of crumb-rubber (CR) significantly affect their rheological properties. The results of a study of adding nano silica and rock asphalt additives show that the addition of the optimal additive material high-temperature performance will be better and minor changes to low temperatures. Therefore, adding Nano Crumb-Rubber (NCR) as a modified asphalt mixture material will change asphalt's physical and rheological properties [4]. The results of a study of adding nano silica and rock asphalt additives show that the addition of the optimal additive material high-temperature performance will be better and minor changes to low temperatures. Therefore, adding Nano Crumb-Rubber (NCR) as a modified asphalt mixture material will change asphalt's physical and rheological properties.

This study using Nano Crumb-Rubber (NCR) aims to investigate the rheological characteristics of modified asphalt with the addition of NCR additive material in Original (Unaged) and Rolling Thin-Film Oven (RTFO) aged conditions. Data were analyzed from physical characteristics, viscosity, and Dynamic Shear Rheometer (DSR) tests.

2. Methodology

2.1. Base Asphalt

Asphalt is a visco-elastic material that acts as a binder for rock materials whose strength and physical properties are greatly affected by temperature [11]. In this study, the modified asphalt mixture consisted of asphalt, Lawele Granular Asphalt (LGA) bitumen, and nano crumb rubber additive. LGA bitumen is pure asphalt in the form of rock originating from an island in Indonesia called Buton Island, often called Asbuton. This asphalt is obtained from extraction [12]. The pure asphalt material used is penetration grade 60/70 bitumen binder material obtained from an oil company generally used for hot mix asphalt. This modified asphalt is called Asphalt Nano-Crumb Rubber (ANCR), a modification of pen 60/70 oil asphalt, extracted LGA bitumen, and nano-crumb rubber additive material.

2.2. Nano Crumb-Rubber

According to the Asphalt Institute, crumb-rubber is the result of repeated grinding of used tire rubber into 250 µm (60 Mesh) crumb-rubber nanoparticles, which is the maximum size rule allowed to perform rheology measurements with a dynamic shear rheometer (DSR) [8]. The nano crumb rubber material used from the tire factory and the nano crumb rubber content used in the research were 1.2%, 2.4%, 3.6%, and 4.8% by weight of asphalt.

2.3. Lawele Granular Asphalt (LGA)

LGA material is a type of Buton Rock Asphalt (BRA), Sulawesi, Indonesia. BRA is a blackish-brown granular asphalt material [12]. BRA has solid properties and room temperature, so when filtering BRA onto pure asphalt, it needs to be heated and stirred at temperatures between 160-170 °C [13] [14]. According to AASHTO T-315, the solid particles of the asphalt modifier must not exceed 0.25 mm to ensure that rock asphalt is filtered through a standard sieve of 0.15 mm [15].

a

b

Figure 1. materials (a) lawele granular asphalt; (b) nano crumb-rubber.

2.4. Sample Preparation

ANCRM is a modified asphalt composed of pure asphalt, Lawele bitumen, and Nano Crumb Rubber additive. LGA bitumen is obtained from rock asphalt extraction using tetrachlorethylene (TCE) solvent to obtain pure bitumen and determine the asphalt content in the rock asphalt Buton granules. In this study, the extraction results obtained asphalt content from rock asphalt as much as 27%. In this study, in 1000-gram Rock Asphalt using a centrifuge extractor (Figure.2), the time needed for extraction is around 1–1.5 hours. The extraction results were then dried in an oven at (110 ± 5) ℃ for 24 hours. This drying aims to remove the TCE liquid.

Furthermore, adding used oil softener to the modified mixed material melts pure LGA bitumen to mix homogeneously with nano crumb rubber. Previous research conducted experiments at speeds above 4000 rpm at a temperature range of 130 and 165°C for 15 minutes [16]. Then to mix evenly, the stirring speed is maintained at 6000 rpm for 45 minutes when the basic binder is mixed with nano-sized materials [17]. In this study, the primary binder that had been heated was then mixed with nano crumb-rubber material at a speed of 6000 rpm for 30 minutes, and the temperature was maintained at 165 °C.

2.5. Viscosity Test

The rotational viscometer test can determine workability during the asphalt mixing and compaction process. Asphalt viscosity is highly dependent on temperature, so asphalt viscosity tests are carried out with variations in temperature changes [18]. Inspection of asphalt viscosity using a Brookfield Thermosel can be carried out from 38 ℃ to 260 ℃. Asphalt viscosity examination was conducted regarding ASTM D 4402-95 Standard Test Method for Viscosity Determinations of Unfilled Asphalt Using the Brookfield Thermosel Apparatus. Asphalt viscosity is the ratio between shear stress and shear rate, which measures the material's relative resistance to spindle rotation in the test object tube. In this study, the temperature variations were 110°C to 200°C with a temperature difference of 15°C.

2.6. Dynamic Shear Rheometer Test

The viscoelastic characteristics of the asphalt binder at medium and high temperatures as measured by the complex shear modulus (G*) and phase angle (δ), the Dynamic Shear Rheometer (DSR) test was carried out [5]. The test temperature is from 32 °C to 80℃ with a range of 8℃ at a frequency of 10 rad/s. This study aimed to test the performance of modified asphalt at high temperatures. The G* value indicates that the asphalt binder determines its resistance to deformation. At the same time, δ reflects the ratio between the elastic viscous during the shearing process and indicates the relative index of recovery from the deformation value [4]. The rutting parameter indicates a permanent deformation failure from the value of G*/sin δ [19]. According to the Strategic Highway Research Program (SHRP), to minimize the rutting factor of asphalt binder in a pavement system, the G*/sin δ value for pure asphalt must be at least 1.0 kPa, and for asphalt binder left over from the RTFO aging process of at least 2.2 kPa. Therefore, a large G* value and a small δ value affect a better rutting factor [20][21].

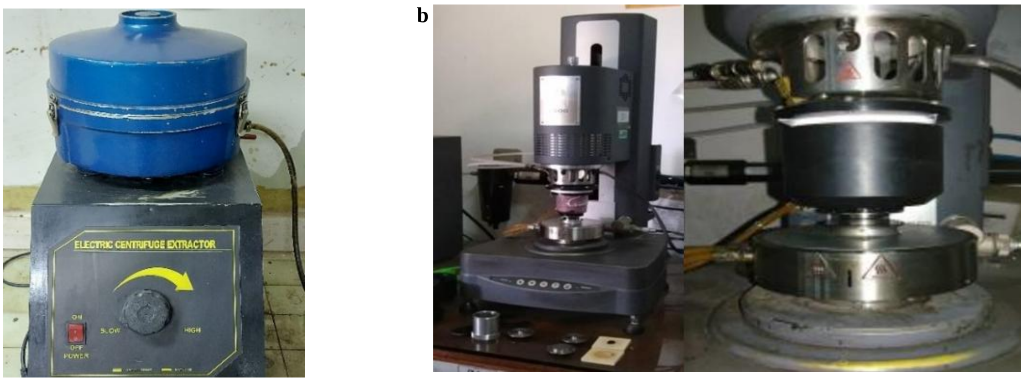

Figure 2. (a) Extractor centrifuge; (b) Dynamic Shear Rheometer.

3. Result and Discussion

3.1. Physical Properties Test Results

It can be seen in Table 1 that there was an increase in the penetration value with the addition of nano crumb-rubber 1.2% (ANCR-1), 2.4% (ANCR-2), 3.6% (ANCR-3), and 4.8% (ANCR-4). The increase in penetration shows the stiffness effect of the asphalt binder. The stiffness effect increases with the addition of nano crumb-rubber concentration. The softening point is also an indicator of asphalt's susceptibility to temperature. Adding nano crumb-rubber concentration to the mixture causes a decrease in the softening point value. The results of the ductility test showed a tendency to decrease after adding nano-rubber. The stiffening effect of the nano crumb rubber causes a decrease in the flexibility of the asphalt. The flash point of asphalt also shows a decrease in the addition of nano-crumb rubber material.

Table 1. Physical Properties

Asphalt Content	Penetration 25°C (mm/10)	Softening Point (°C)	Flash Point (°C)	Ductility 25°C (cm)
Virgin Asphalt	76.33	46	342	104
LGRA	32.67	54.5	218	51.1
ANCR-1	72.8	47	346	31.3
ANCR-2	78.86	43.5	316	29.26
ANCR-3	108.6	43	300	25.43
ANCR-4	140.67	42	288	23.7

3.2. Viscosity Test Results

A viscosity test was carried out with variations in temperature differences for pure and modified asphalt. Figure 3 shows the change in viscosity with the difference in temperature degrees with the addition of nano-rubber. This parameter indicates the efficiency level of the asphalt binder and the viscosity value of the asphalt mixture during the mixing procedure. The test results show that modifying pure asphalt binder and nano crumb rubber will increase viscosity. The increase in nano crumb rubber from 1.2% to 4.8% resulted in a higher viscosity value than pure asphalt. At 135 ℃, the viscosity value is higher than at 175 ℃, but it is still above the permissible performance characteristics for asphalt binder in the Superpave system, which is below 3 Pa.s [18].

3.3. Black Diagram

DSR testing in Original and RTFO conditions was carried out with temperatures in the range of 48°C to 80°C due to adjusting to temperatures in tropical countries. Whereas in PAV conditions, the selected temperature ranges from 16°C to 56°C. In the original (unaged) condition, the G* value for each addition of NCR decreased when the phase angle increased. This is shown in Figure 4. The addition of 2.4%, 3.6% and 4.8% NCR has a difference in the G* value at each phase angle (δ) value addition. With the addition of NCR, 1.2% and 2.4% distance changes did not significantly affect pure asphalt. However, when the NCR mixture is 3.6% and 4.8%, there is a large change gap to pure asphalt.

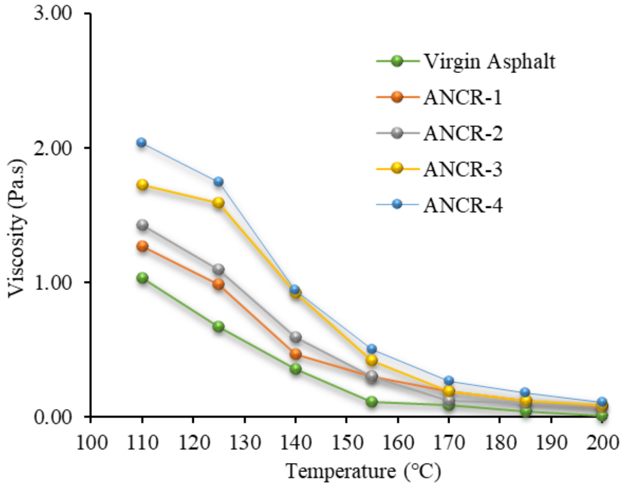

Figure 3. Viscosity Test Results

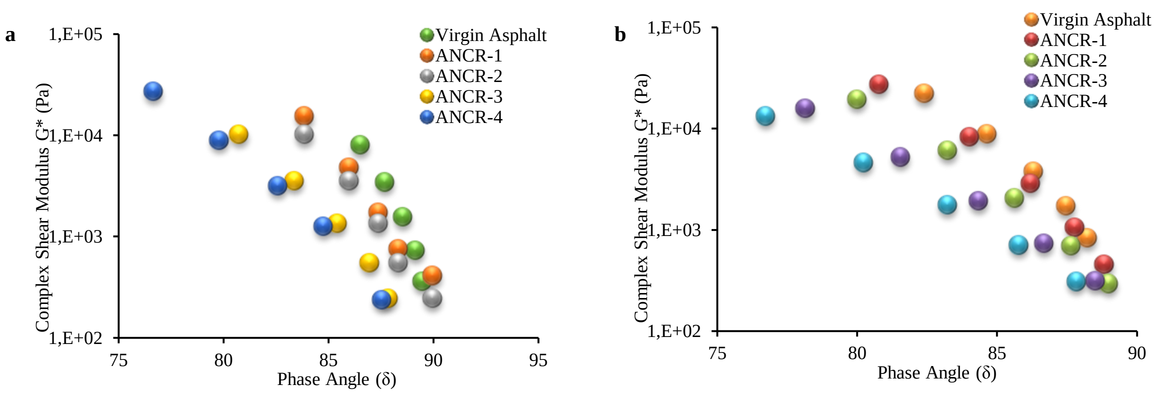

Figure 4. Black diagram G* and δ (a) Unaged condition; (b) RTFO condition.

The RTFO conditions carried out aim to simulate short-term aging conditions where asphalt is used during the production or mixing process. Similar to the original condition, the G* value decreases with increasing phase angle (δ) as shown in Figure 6. The addition of each percent of NCR on modified asphalt causes a decrease in the G* value with each increase in phase angle (δ).

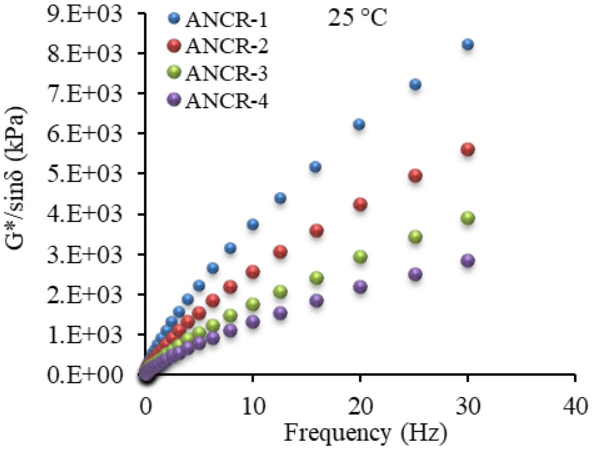

Figure 5. Frequency Sweep Curve at Temperature 25 °C Unaged Condition

3.4. Rutting Factor

At each addition of NCR to the value of G*/sin δ and frequency in the original condition (unaged) is shown in Fig. 5 – 6. Frequency sweep tests are carried out on binder samples with various frequencies for the rutting parameters. Test According to AASHTO, frequency sweep tests (used at a strain level of 0.1% to 30%) and amplitude sweeps are carried out at 10°C at a frequency of 10 Hz until the strain amplitude reaches 30% [22]. Frequency sweep tests were carried out at 25°C, 40°C, and 60°C.

In the original condition (unaged), when the test temperature was 25°C the value of G*/sin δ was higher than the test temperature of 40°C and 60°C. The value of G*/sin δ increases with increasing frequency. With an increase in the amount of NCR in the modified asphalt mixture, the minimum limit for the value of G*/sin δ at the original age condition is at least 1 kPa occurring in all NCR mixtures with a frequency of less than 10 Hz.

The aged RTFO condition is shown in Fig. 7 – 8. When the condition is RTFO aged, there is an increase in the G*/sin δ value for each percentage of the NCR mixture concerning its frequency value. The value of G*/sin δ under RTFO conditions with a minimum limit of 2.2 kPa occurs when the frequency is less than 5 Hz for a 1.2% NCR mixture at a test temperature of 25°C and 40°C, but at a test temperature of 60°C the frequency is more than 5 Hz. Meanwhile, for a mixture of 2.4%, 3.6%, and 4.8% NCR occurs close to the frequency value of 10 Hz at each test temperature.

a

b

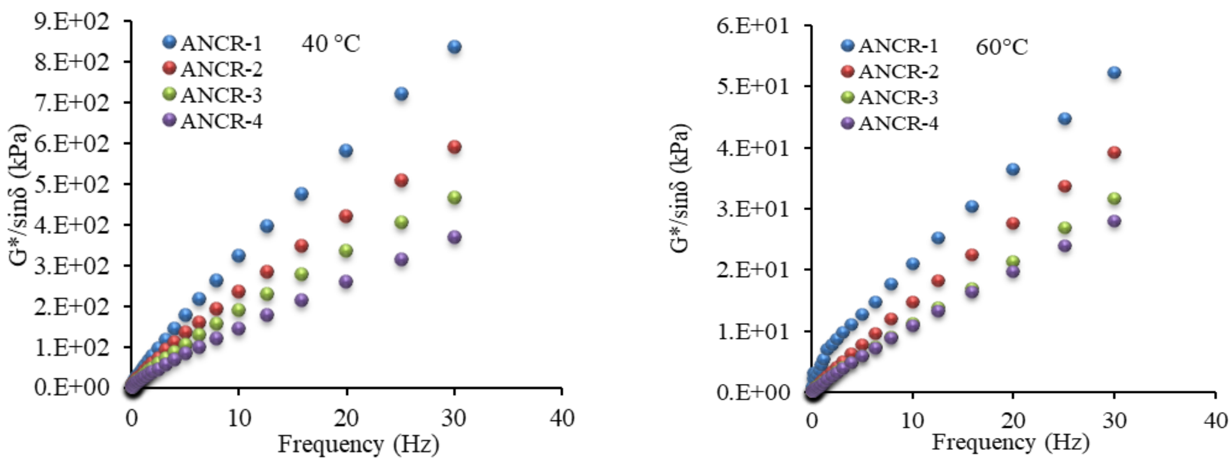

Figure 6. Frequency Sweep Curve Unaged Condition. (a) Temperature 40 °C; (b) Temperature 60 °C

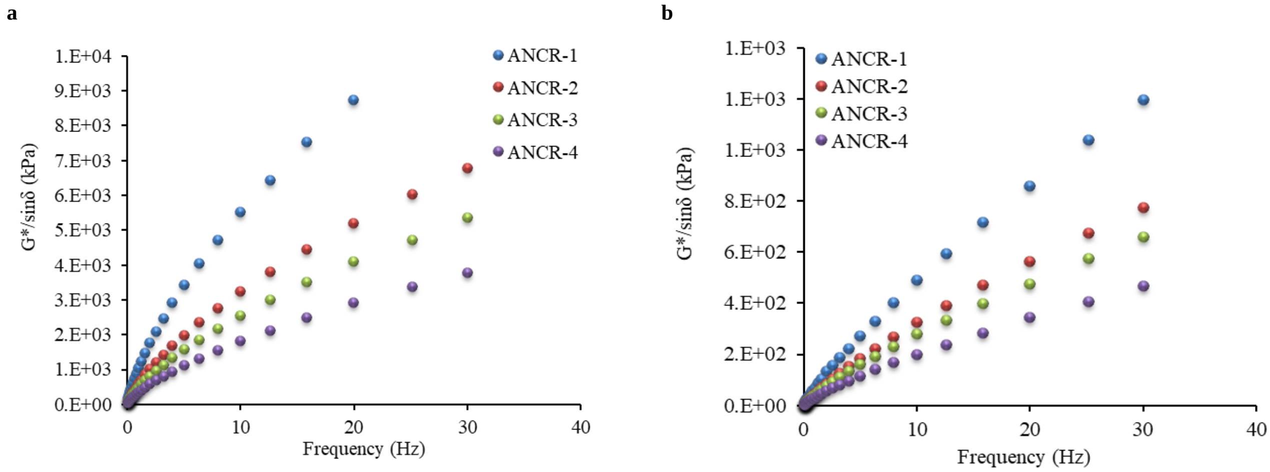

Figure 7. Frequency Sweep Curve RTFO Condition. (a) Temperature 25°C ; (b) Temperature 40°C

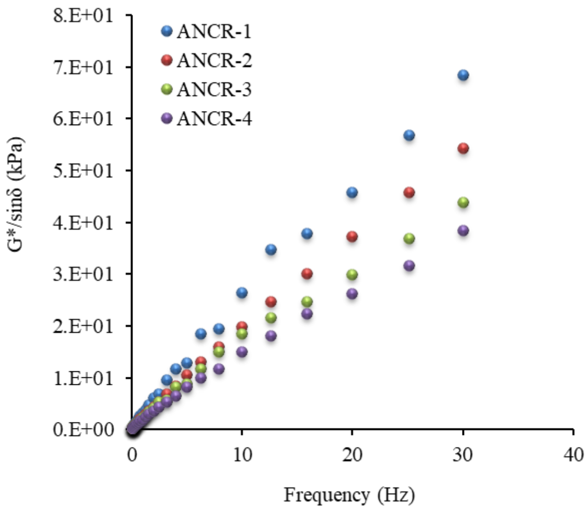

Figure 8. Frequency Sweep Curve at Temperature 60°C RTFO Condition

3.5. Fatigue Factor

The age condition of the PAV, which describes the condition when the pavement was used, is shown in Figure 9. Fatigue factor in terms of that the limit value of G*Sin δ is with a maximum limit of 5000 kPa [23]. For each NCR mixture with a percentage of 1.2%, the fatigue factor value occurs at 24°C. While the addition of 2.4% and 3.6% NCR decreased at temperatures less than 24°C. This temperature drop shows that any addition of NCR to modified asphalt will reduce its fatigue resistance.

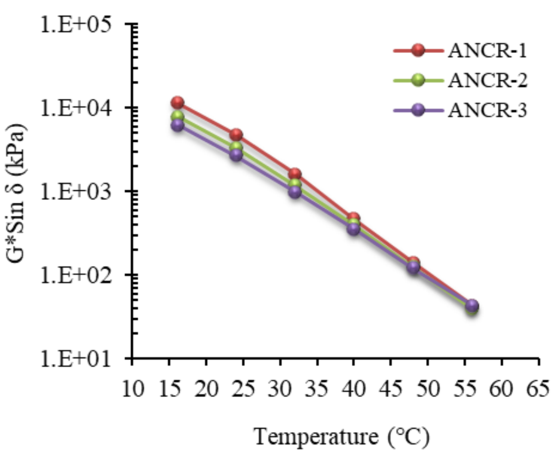

Figure 9. G*. Sin δ and Temperature PAV-aged Condition

3.6. Aging Index

Oxidative aging occurs in the asphalt binder during the mixing stage and its lifetime [24]. During the aging process, some of the components in the binder evaporate quickly, which causes the binder to experience damage to the pavement soon. In this study, the evaluation of the aging resistance of unmodified and modified asphalt binder was seen from the rheological aging index value. With formula 1 as follows:

$$AI = \left(\frac{\text{Aged rutting factor} - \text{Unaged rutting factor}}{\text{Unaged rutting factor}}\right) x100 \quad (1)$$

With AI: Aging Index.

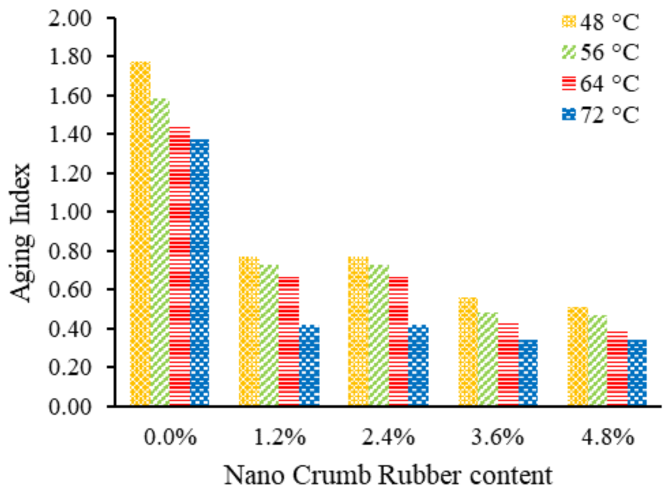

Figure 10. Aging Index of Modified Asphalt

Figure 10 shows the results of the aging index (AI) values obtained from comparing the G*/sin δ values of aged and non-aged asphalt used as short-term rutting factor parameters [3]. The results showed that, due to the addition of NCR, aged and unaged RTFO conditions significantly reduced the value of AI. Adding 1.2% and 2.4% NCR showed no change in AI values. At 80°C, there was an increase in the AI value for each percentage of the mixture. At the addition of 3.6% and 4.8%, the NCR decreased the AI value, the difference was relatively minor.

4. Conclusion

This research was conducted to develop NCR material-modified asphalt by evaluating the effect of temperature on the modified asphalt mixture. The resistance to deformation is evaluated using the rutting parameter. While resistance to aging is evaluated using the Aging Index (AI). Based on the results of the analysis, it can be concluded that:

1. The value of the complex shear modulus (G*) in the original condition (unaged) decreased with the addition of NCR but increased slightly with the addition of 1.2% NCR. Although, the G* value in the RTFO condition is lower than in the original condition, and the 1.2% NCR content produces a G* value that is almost the same as pure asphalt for temperatures < 56℃.
2. In the original condition (unaged), adding 1.2% NCR showed that the value of δ increased with increasing temperature up to 64℃ but then decreased. Under RTFO conditions, when the temperature is above 72 ℃, a decrease in δ value in pure asphalt and an increase in δ value occurs in a mixture of 1.2%, 2.4%, and 3.6% NCR. Decreasing the value of δ indicates that asphalt modification with NCR tends to be more elastic at high temperatures.
3. In the original conditions, the value of G*/sin δ > 1 kPa occurred in almost every combination of NCR mixtures (1.2%, 2.4%, 3.6%, and 4.8%) up to 64°C. Under RTFO aging conditions, the NCR mixture experienced an increase in the value of G*/sin δ > 2.2 kPa occurring in each mixture at variations in temperature changes between 16°C to 56°C. However, for a mixture of 1.2% NCR, the value of G*/sin δ at a temperature of less than 48°C is slightly higher than pure asphalt.
4. The addition of NCR significantly lowers the value of AI. Adding 1.2% and 2.4% NCR did not change the difference in AI values. At 80°C, there was an increase in the AI value for each percentage of the mixture. Adding 3.6% and 4.8% NCR decreased the AI value with a relatively minor difference.

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