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LABORATORY RESEARCH ON EVALUATING THE RUTTING RESISTANCE OF NATURAL ASPHALT CONCRETE MIXTURE

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Abstract. The road network in Iraq, particularly in the central and southern regions, suffers from frequent rutting due to harsh conditions, high temperatures, and the limited resistance of Regular Asphalt (RA) mixtures to repeated loading. These deformations reduce the service life of the pavement and increase maintenance costs. This study investigates the potential of improving asphalt mixture performance by incorporating Natural Asphalt (NA) sourced from the Abu Al-Jeer springs in Anbar Governorate. RA is the petroleum asphalt, which was obtained from the Dora oil refinery. The NA underwent two forms of treatment: thermal processing and blending with RA at varying ratios (20 %, 40 %, 60 %, and 80 %). Repeated load tests were performed on six different mixtures at 40 °C, with an applied pressure of 0.138 MPa for 6 000 loading cycles. The results showed that mixtures containing treated NA exhibited significantly greater resistance to permanent deformation and in the Resilient Modulus (M_r). Notably, the mix containing 80 % of NA showed a 72 % reduction in permanent microstrain compared to the mixes containing RA, indicating a significantly improved mechanical performance. These findings suggest that NA is a viable and eco-friendly alternative for improving asphalt mixture performance in hot climates such as Iraq.

Keywords: Sulphur spring, heat treatment, elemental analysis, resilient modulus.

1. Introduction

In general, the roads in Iraq are made of flexible pavement. However, they suffer from many harsh conditions, including repeated heavy vehicle loads, prolonged loading, and high summer temperatures, which affect the structural behaviour and serviceability of the asphalt pavement. Many trucks in Iraq, particularly those using major roads, are carrying loads that exceed legal and design limits. This overloading reduces the service life of the pavement. It also accelerates the occurrence of surface distress, such as rutting and cracking, which is clear even in the absence of a nationwide database that provides accurate figures on the actual number of heavy trucks or the percentage of overloaded vehicles [1]. In addition, population growth and increased commercial activity, particularly in the transportation of goods and commodities over the past two decades, have negatively impacted road performance [2]. Consequently, approximately 6.8 % of traffic accidents in Iraq were due to road failures and a lack of maintenance [3].

The most common distress that occurs in asphalt pavement in Iraq is rutting, which affects safety and maintenance costs. This distress causes fluctuating road levels due to vertical plastic deformation resulting from a repetitive vehicle load. Furthermore, it usually happens during hot seasons and leads to difficulties in manoeuvring, as well as rainwater collecting in the grooves. In addition to compromising comfort and driving safety, rutting can cause an uneven asphalt surface, and thus severely harm the stability and integrity of the structure of the road [4]. These are all factors that contribute to the occurrence of accidents. It leads increased maintenance and rehabilitation costs in the affected areas.

The asphalt binder has a significant impact on the stiffness of the asphalt mixture. In Europe, the binder is commonly referred to as bitumen, whereas in Iraq and North America, it is referred to as asphalt. Using a high-viscosity binder makes the mixture stiff and more resistant to long-term deformations such as rutting failure. Therefore, polymers are frequently added to asphalt to improve its rheological properties [5]. One of the innovative technologies in the road sector is using Natural Asphalt (NA) as a binder modifier or as a sole binder to improve the pavement performance, create environmentally friendly pavements, and reduce the dependency on petroleum asphalt [6]. This study was motivated by the fact that using natural materials is essential to encourage innovative methods in the production of road pavement. Additionally, this study focuses on assessing the resistance of a flexible pavement with NA to rutting distress.

Oil still accounts for about 30 % of global energy consumption, making it one of the most important natural resources used as a primary energy source today. Among other countries, Venezuela (17.5 %), Saudi Arabia (17.2 %), Canada (9.8 %), Iran (9.0 %), Iraq (8.4 %), and Russia (6.2 %) have the biggest discovered oil reserves [7]. Heavy oil and Natural Asphalts (NAs) have emerged as a significant source of raw materials to supply the increasing demand for fuels and petrochemical products due to the depletion of light and medium crudes [8]. NA is an alternative material with widespread industrial applications due to its comparatively low price and the abundance of NA mines around the world, such as Athabasca oil sands in Canada and Trinidad Lake Asphalt in the USA. Additionally, NAs have drawn much interest in the past decades due to their high compatibility with petroleum asphalt, allowing them to be utilised to modify binders and asphalt mixtures. For instance, modifying asphalt binder with gilsonite, a popular type of NA, may be less expensive than polymer-modified asphalt, which can experience phase separation failure due to chemical incompatibility and molecular differences between the asphalt and polymer, this leads to a reduction in the stability of the modified binder under high-temperature storage conditions. Polymers, such as polyethylene, polystyrene, and polypropylene, can partially separate from the asphalt binder, while NA blends are more uniform and ensure better thermal stability [9–11].

NA can be separated into two categories: soluble and pyrobitumens, which are solid natural hydrocarbon substances that differ from bitumen due to their infusibility and insoluble nature [12]. For example, paraffin and petroleum wax are solid NAs. White or colourless wax is made from petroleum and is consists of saturated hydrocarbons. It is primarily used to make candles, polishes, cosmetics, and electrical insulators. Other types of NAs include:

(1.) gilsonite or uintaite, which is a solid black organic material that forms when petroleum solidifies and has a carbon residue of 10–20 % by weight;

(2.) grahamite or anthraxolite, which is a bitumen-impregnated rock that is similar to gilsonite, though it has a higher fixed carbon value (35–55 %) and a higher melting point;

(3.) glance pitch or manjak, which is similar to gilsonite with a higher specific gravity and a higher carbon percentage (20–30 %) [13].

NAs' depositional origins, or variations in their chemical and mineralogical compositions, are the primary cause of variations in quality [14]. Bituminous springs are created if the NA reaches the ground surface. If it stays underground, it will oxidise and solidify over time to form mineral asphalt, which is a hard and solid material (such as asphaltites) [15].

NA is widely distributed throughout Iraq. Iraq has 8.4 % of the world's discovered oil reserves, placing it in the top five nations. One of the most available sources of NA in Iraq are sulphur springs. Asphalt springs can be found in many Iraqi provinces, such as Basra, Nasiriyah, Dhi-Qar, Karbala, Anbar, Nineveh, Dohuk, Erbil, and Sulaymaniyah. Most of the sulphur springs (NA deposits) are found in the northern region of Iraq [16]. These deposits are mined, thermally distilled, or chemically removed from the earth and are essential for the manufacturing of liquid asphalt and other petrochemical products [17]. To ensure the functionality and quality of NA, testing the asphalt is necessary. The tests are conducted to evaluate the physical and chemical characteristics of the asphalt during the extraction, refinement, and production stages. For example, Alkhafaji et al. [18] conducted an extensive biomarker analysis to identify the origin and characteristics of the NA collected from the Mishraq sulphur spring in northern Iraq, using gas chromatography and mass spectrometry. The results revealed that this bitumen was slightly affected by biodegradation and water washing, with partial removal of normal alkanes, while complex components such as terpanes and steranes remained intact. A deuterium isotope analysis indicated no significant abiotic oxidation, confirming that the asphalt retained its essential properties. Meanwhile, Farhan et al. [8] assessed the chemical composition of the saturated compounds of NA mined in western Iraq. The natural bitumen was divided into asphaltene (26.56 %) and maltene, with maltene then categorised into saturated (8.24 %), aromatic (55.67 %), and polar (9.93 %) fractions. The results of chemical characterisation analysis indicated a substantial presence of asphaltenes and aromatics, likely due to thermal maturation, while certain aliphatic hydrocarbons suggested possibilities for modifications as crude oil derivatives.

There have been a few recent research studies that have demonstrated numerous ways to treat NA and to enhance its chemical and physical characteristics. In their research, Mohammed et al. [19] combined NA from Abu-Jeer spring with petroleum asphalt in different proportions of 0, 20, 40, 60, and 80 %. The results indicated that Marshall Stability and resistance to moisture damage were enhanced for the asphalt mixture with 80 % NA. Another technique to improve NA characteristics is heat treatment. NA was heated to approximately 163 °C for several hours, and its chemical and physical characteristics were improved by increasing the asphaltene content, homogenising the binder, and removing moisture and impurities. This includes inducing minor chemical changes, improving the thermal stability and resistance to deformation without altering the asphalt's fundamental composition.

Additionally, Ahmed et al. [20] modified NA from Abu-Jeer spring by applying heat treatment for 5, 10, 15, 20, and 25 hours. Their research showed that after 20 hours of heat treatment, the NA qualities were enhanced to meet the Iraqi specifications for asphalt. Interestingly, the treated NA showed a considerable resistance to deformation since it was less susceptible to temperature. Additionally, as compared to a traditional mixture, mixtures containing treated NA exhibited improvements in stability, stiffness index, and moisture damage resistance of 17.6 %, 2.42 %, and 0.37 %, respectively. Furthermore, Mohsin and Latief [21] applied heat treatment to NA samples collected from five sulphur springs (Al-Mamora, Al-Jabal, Atatt, Al-Atffa, and Al-Askaree). According to the findings, the heat treatment significantly improves the properties of NA. Compared to the traditional mixture, the Al-Mamora-NA mixture had a substantial impact on the mechanical properties of the asphalt mixture, as its stability improved by 41.3 %. Meanwhile, the Al-Askaree-NA mixture offered a greater stiffness index and better resistance to water damage, making it more effective in preventing moisture damage and enhancing rutting resistance.

Nejres et al. [22] analysed the chemical composition of NA from Al-Qayyarah, Iraq, using SARA chromatography and infrared spectroscopy. They found it to have a SOL-type colloidal system with 28.6 % paraffins, 29.3 % aromatics, 19.9 % resins, and 20 % asphaltenes. In addition, the rheological properties of the NA were improved when treated with Eggshell Powder (ESP) and Low-Density Polyethylene (LDPE), as confirmed by testing its thermal and physical properties. In summary, adding 15 % EWP and 8 % LDPE to the NA achieved the best results to produce an eco-friendly and sustainable asphalt binder.

NA from sulphur springs in western Iraq was modified using Waste Engine Oil (WEO) [23]. WEO is added to NA in different percentages: 0 %, 2 %, 4 %, 6 %, and 8 %. Due to its similar hydrocarbon composition, WEO blended effectively with the asphalt, enhancing penetration, ductility, and viscosity. Spectral analyses (Ultraviolet (UV) and Fourier Transform Infrared Spectroscopy (FTIR)) confirmed that no chemical reactions occurred, and the modified asphalt met local requirements and ASTM standards, showing improved performance and an eco-friendly method for reusing WEO. Moreover, Albayati et al. [24] investigated the effect of WEO and Sugarcane Molasses (SM) on the performance of NA. Different amounts of SM and WEO, ranging from 10 % to 40 % of the total weight of NA, were used to partially replace 50 % of the NA in the modified blends. The findings indicated that fluidity was greatly enhanced by modified mixes with a high WEO concentration, which decreased rotational viscosity. The NA containing 40 % SM and 10 % WEO showed a 305 % increase in penetration value as compared to unmodified NA. According to the rheological tests results, the NA with 40 % SM content improved stiffness with a Performance Grade (PG) of 88 °C as compared to NA with 10 % SM.

To enhance the stiffness of NA, Mohsin and Latief [25] modified NA with Limestone Filler (LSF). The outcomes revealed that LSF is a suitable material as it increases the temperature resistance of NA and improves the dispersion of NA in a bitumen mixture. Additionally, a mixture containing modified NA from Al-Mamora sulphur spring achieved a 30.4 % higher stability than that of the control mixture. And the modified Al-Askaree sulphur spring NA mixture exhibited a tensile strength ratio and stiffness index that were 3.36 % and 45 % higher, respectively, than those of the control mixture.

While most previous research has focused on polymer modifiers and petroleum binders, the potential of Iraqi NA has not received much attention. There is a clear gap in evaluating the performance of locally sourced NA, both in its raw form and after thermal treatment as well as in its compatibility with petroleum bitumen at different blending ratios. The focus is on assessing the mixtures' resistance to Permanent Deformation (rutting) under repeated loading. The study compares the rutting performance of NA-modified mixes at different substitution ratios (20 %, 40 %, 60 %, and 80 %) with that of a control mix containing only petroleum asphalt. Two treatment techniques, thermal conditioning and proportional blending, were used to improve the NA characteristics. This research provides practical value to the Iraqi pavement sector by reducing the dependence on imported petroleum binders, lowering material costs, and offering better solutions suited to the country's high-temperature environment.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1. AGGREGATES

The crushed aggregates (fine and coarse) used in this investigation were obtained from the Al-Nibaie quarry. The fine aggregate was natural river sand and the coarse aggregate was crushed stone. Their physical properties conformed to the Iraq Standard Specification for Roads and Bridges [26]. The aggregates were sieved and blended in a field laboratory to produce a gradation that met local specification requirements. The limestone filler, sourced from a lime mill in Karbala (southeastern Iraq), was also used in the mix. Laboratory testing revealed that the filler had a specific gravity of 2.7, and over 95 % of its particles passed through a No. 200 sieve by weight. Figure 1 illustrates the selected design gradation along with the standard limits.

2.1.2. REGULAR ASPHALT

The petroleum asphalt used in this study, referred to as Regular Asphalt (RA) throughout this research, is produced at the Dora Refinery through the distillation of crude oil. According to the results presented in Table 1 and based on the specifications set by the Department of Roads and Bridges in Iraq [26], the RA is classified as AC with penetration grade 40–50, confirming its suitability for use in hot mix asphalt applications.

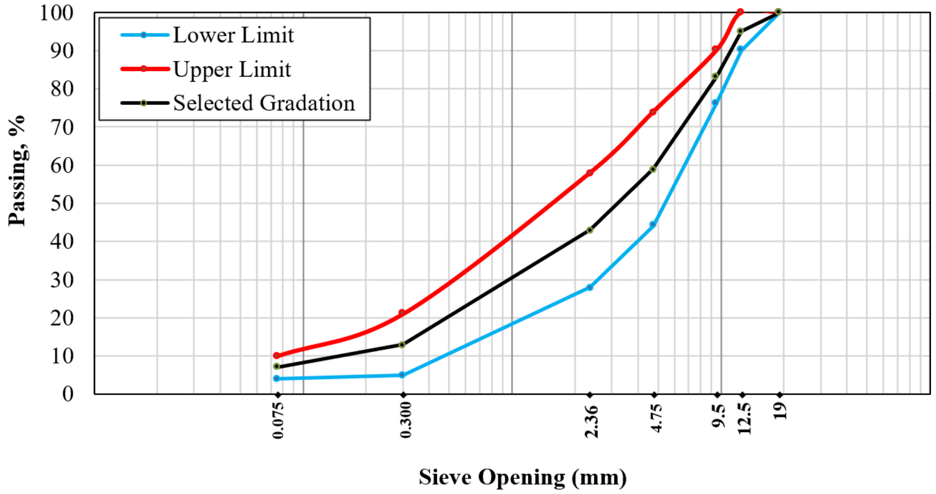

Figure 1. Aggregate gradation for wearing layer.

Binder property	Penetration at 25 °C	Ductility at 25 °C	Softening point	Specific gravity	Flash point
ASTM standard	D5 [27]	D113 [28]	D36 [29]	D70 [30]	D92 [31]
Unit	0.1 mm	cm	°C	-	°C
Test result	47	110	52	1.025	245
Specification limit [26]	40–50	≥ 100	Not limited	Not limited	≥ 232

Table 1. Regular asphalt properties.

2.1.3. Natural asphalt

Two types of NA, soft NA (SNA) and hard NA (HNA), were sourced from the Abu-Jeer region of the Al-Anbar province. Figure 2 shows the sulphur spring in the Abu-Jeer area. The SNA was collected from the Abu-Jeer spring at two separate times, approximately nine months apart. Figure 3 shows the HNA, SNA1, and SNA2 samples. Due to its high impurity content and unrefined composition, NA in its raw form is not directly suitable for pavement applications. Its physical properties differ significantly from those of RA produced in petroleum refineries. Therefore, pre-treatment and industrial processing are required in order to make NA viable for engineering applications.

2.2. Preparation and testing methods

2.2.1. NA treatment

Natural asphalt (NA) contains a significant amount of moisture, which must be removed prior to modification. To ensure effective water removal, the soft natural asphalt samples (SNA1 and SNA2) were first oxidised by stirring in 500 mL steel containers at 110 °C in an oven for two hours. Following the moisture removal, SNA underwent two different treatment processes:

- Treatment by mixing with RA: According to the method described by Erkuş et al. [32], the two types of NA (SNA1 and HNA) were blended in a mechanical mixer at a constant temperature of 170 °C for one hour at 1 000 revolutions per minute. Based on previous research [19], the optimal mixing ratio was determined to be 45 % SNA1 and 55 % HNA. The mixing setup included a thermostat-controlled heating plate connected via a conduit to the bitumen container. After finishing the mixing process, the resulting blend, referred to as HSNA, had a penetration grade that met the Iraqi specifications. This modified binder was then added to the RA at sub-

Figure 2. Abu-Jeer sulphur spring.


(a). SNA1. (b). SNA2. (c). HNA.

Figure 3. NAs samples.

Abbreviation	Description
NA	Natural asphalt
RA	Regular asphalt
SNA	Soft natural asphalt
SNA1	First sample of SNA extracted from sulfur spring in April
SNA2	Second sample of SNA extracted from sulfur spring in January, after SNA1 by 9 months
HNA	Hard natural asphalt
HSNA	Mix of HNA and SNA1
20NA	Bituminous mixture containing 20 % HSNA and 80 % RA
40NA	Bituminous mixture containing 40 % HSNA and 60 % RA
60NA	Bituminous mixture containing 60 % HSNA and 40 % RA
80NA	Bituminous mixture containing 80 % HSNA and 20 % RA
NA-20	SNA2 treated by heating for 20 hours

Table 2. Treated and untreated NA blends abbreviations.

stitution levels of 20 %, 40 %, 60 %, and 80 % by weight of bitumen.

- Heat treatment: The second treatment involved direct thermal processing of SNA2. It was heated at 163 °C for durations of 5, 10, 15, and 20 hours to improve its characteristics, ensuring they meet the specifications of the State Commission for Roads and Bridges [26] for use in bituminous base, binder, and surface layers in road construction. After 20 hours of thermal treatment at 163 °C, the properties of SNA2 closely resembled those of the RA, confirming its suitability for asphalt mixture applications. This improvement highlights the effectiveness of prolonged heat treatment in enhancing the NA quality. The sample legends for all treated and untreated NA samples used in this study are presented in Table 2.

2.3. Energy-dispersive X-ray spectroscopy

Energy Dispersive X-ray Spectroscopy (EDX) was used to determine the elemental composition of the bitumen samples. In this technique, the specimen is first placed inside the chamber of the Scanning Electron Microscope, where it is exposed to a focused electron beam. The interaction between the electrons and the atoms in the material causes the emission of characteristic X-rays from each element. These X-rays are then detected by an energy-sensitive detector, which records the energy peaks corresponding to different elements. The resulting spectrum displays the intensity of the detected signals versus their energy values, allowing for a qualitative and semi-quantitative identification of the elements present in the sample. The analysis was conducted in a vacuum, and the obtained data were used to compare the chemical composition of the assessed specimens.

2.4. Mix design

For mixture preparation, the aggregate blend and mineral filler were preheated at 150 °C for 6 hours to ensure uniform temperature. The asphalt binder was heated separately at 155 °C for 2 hours, then added to the preheated aggregate blend at the specified binder content. Mixing was performed at 155 °C for 2 minutes to achieve full homogeneity. The prepared mixture was then conditioned in an oven at a compaction temperature of 145 °C for 30 minutes prior to compaction. The mould assembly was placed on the compaction pedestal, and the top and bottom of the specimen were struck 75 times with a special compaction hammer with a sliding weight of 4.535 kg and 0.457 m free- fall height. The Marshall Mix Design method

Asphalt binder content [%]	Stability [kN]	Flow [mm]	Bulk specific gravity	AV [%]	VMA [%]	VFA [%]
4.0	7.13	2.12	2.252	6.95	18.09	61.58
4.5	9.11	2.95	2.301	5.35	16.57	67.71
5.0	10.52	3.18	2.340	4.10	15.69	73.87
5.5	9.67	3.65	2.314	3.54	15.59	77.29
6.0	8.34	4.02	2.271	3.25	15.70	79.30
Specification limit [26]	8.0 Min.	2.0–4.0	Not limited	3.0–5.0	14.0 Min.	60–75

Table 3. Marshall mix design results.

(ASTM D6927) [33] was employed to determine the Optimum Asphalt Cement Content (OAC). Asphalt binder contents of 4.0 %, 4.5 %, 5.0 %, 5.5 %, and 6.0 % by total mixture weight were evaluated. The OAC was selected based on achieving a target Air Void (AV) content of approximately 4 %, in accordance with Asphalt Institute recommendations. This ensures that all other key parameters, stability, flow, Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) met their respective specification limits.

As outlined in Table 3, the mixture containing 5.0 % of the asphalt binder achieved an air void content of 4.1 %, which was closest to the design target. At this binder content, all Marshall properties satisfied the required specification limits. Therefore, 5.0 % of asphalt binder was selected as the OAC for all mixtures to ensure that performance differences reflected the binder type rather than the binder content.

2.4.1. Uniaxial repeated load test

A uniaxial compressive test was conducted using the Pneumatic Repeated Load System (PRLS), as illustrated in Figure 4, with detailed specifications presented in Albayati [34]. Two series of tests were conducted: one at a controlled temperature of 40 °C to evaluate permanent deformation, and one at 20 °C to measure the resilient modulus (M_r) in the form of a rectangular wave at a constant frequency of 1 Hz, producing a compressive stress of 0.138 MPa for 0.1 seconds, followed by a 0.9-second rest period without load.

Figure 4. Pneumatic repeated load system apparatus.

Cylindrical specimens used in this study measured 100 mm in diameter and 200 mm in height. The aggregate fractions delivered from the mixing plant were divided into seven sizes, as retained on each of the following sieves: (19 mm, 12.5 mm, 9.5 mm, 4.75 mm, 2.36 mm, 0.300 mm, and 0.075 mm) using dry sieve analysis. According to the required gradations, mineral filler (limestone dust) has been added in a 7 % proportion (by mass) and the binder content was 5 %. Prior to mixing with the heated asphalt, the aggregate is blended into a batch of 3.8 kg in the mixing bowl and heated to the mixing temperatures. Until the asphalt had thoroughly coated the surface of the aggregates, the asphalt and aggregates were manually mixed in a mixing bowl on a hot plate for three minutes. The compaction mould was set up and heated to 100 °C. A 101.6 mm paper disk was then placed to cover the base plate of the mould, and the interior edge of the mould was greased with light oil by brush to facilitate the removal of the specimen. The first third of the asphalt mixture was poured into the heated mould, and then it was vigorously shovelled with a heated spatula 15 times around the outside and 10 times inside to spread the third of the mixture in the mould. The remaining two- thirds were then poured into the mould using the same procedure.

After conducting multiple trials, the compaction process and applied load value were used to determine the densities of specimens. These trials begin with altering the compaction efforts while fixing the weight of the asphalt mixture of the specimens. Four specimens were compacted for one minute using four different loading values (150, 160, 170, and 180 kN) applied to each face of the specimen. The compacted specimen densities were then calculated and plotted against the compaction efforts, as presented in Figure 5. This figure led to the following conclusion: 174 kN loads ap-

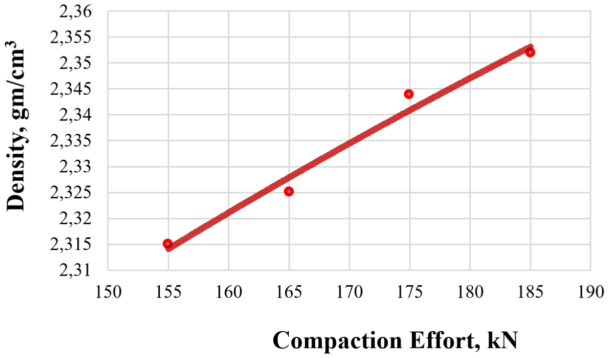

Figure 5. Density versus compaction effort.

plied to both ends of the cylindrical specimen for one minute would be sufficient to achieve the density and air voids required by the Marshall specimens, with values of 2.34 and 4.1, respectively.

The specimens were compacted using the double plunger method, and a maximum load of 174 kN was applied during the compaction using a hydraulic compression machine. A group of prepared specimens is illustrated in Figure 6.

To measure the displacement in the middle third of the test specimen in order to prevent end problems, a Linear Variable Displacement Transducer (LVDT) with an accuracy of 0.00001 mm was used. As displayed in Figure 7, the LVDT was mounted at the mid-height (in the middle of the one-third depth) of the specimen and connected to the data acquisition system, which recorded displacement readings for each loading cycle.

The permanent axial deformation (P_d) was measured throughout the test at (1, 2, 10, 50, 100, 500, 1 000, 2 000, 3 000, 4 000, 5 000, and 6 000) repetitions. The following formula was used to compute the permanent strain (ε_p):

$$\varepsilon_p = \frac{P_d \cdot 10^6}{h}, \tag{1}$$

where:

ε_p axial permanent micro strain,

P_d axial permanent deformation [mm],

h specimen height [mm].

For the resilient modulus test, the resilient deformation was measured between the 50th and 100th load repetitions. The following formulas were used to compute the resilient strain (ε_r) and resilient modulus (M_r):

$$\varepsilon_r = \frac{r_d \cdot 10^6}{h}, \tag{2}$$

where:

ε_r axial resilient microstrain,

r_d axial resilient deformation [mm],

h specimen height [mm],

Figure 6. Group of specimens after mould extraction.

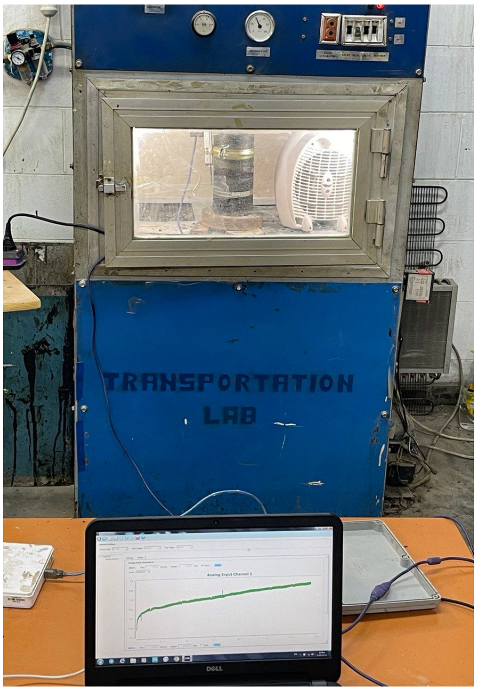

Figure 7. PRLS connected to LVDT.

$$M_r = \frac{\sigma}{\varepsilon_r}, \tag{3}$$

where:

M_r resilient modulus [N mm^{-2}],

σ repeated axial stress [N mm^{-2}].

3. Results and discussion

3.1. Conventional properties of asphalt cement

A series of conventional asphalt cement tests, including ductility, penetration, flash point, softening point, and specific gravity, were conducted for Regular Asphalt (RA), unmodified Natural Asphalt (NA), and

Asphalt type	Property				
	Penetration [$\frac{1}{10}$ mm]	Softening point [°C]	Ductility [cm]	Flash point [°C]	Specific gravity
RA	47	52	>150	245	1.020
SNA1	203	32	>150	175	0.980
SNA2	146	36	103	180	1.000
HNA	3	79	0	230	1.100
HSNA	43	56	93	210	1.060
NA-20	46	53	>150	250	1.036
20NA	46	52	139	245	1.027
40NA	45	53	132	240	1.032
60NA	45	54	111	235	1.040
80NA	44	55	102	230	1.045
Limits [26]	40–50	Not limited	100 (min.)	232 (min.)	Not limited
P-value	7.6×10^{-28}	1.05×10^{-21}	-	4.85×10^{-20}	4.85×10^{-15}

Table 4. Physical properties of asphalt samples.

modified NA samples. The results of these tests have been reported in previous studies [19, 20]. Table 4 presents some of the physical properties of all asphalt samples evaluated in this study.

Statistical analysis using one-way ANOVA confirmed that the differences among binder types were statistically significant for all measured properties ($p < 0.05$). Highly significant variations were observed for penetration ($p = 7.6 \times 10^{-28}$), softening point ($p = 1.05 \times 10^{-21}$), flash point ($p = 4.85 \times 10^{-20}$), and specific gravity ($p = 4.85 \times 10^{-15}$). This indicates that the observed property changes resulted from binder composition and treatment rather than random variation. For ductility, the test could not be meaningfully applied since several samples exceeded the upper measurement limit ("> 150 cm"), and exact values were not recorded. As outlined in Table 4, the properties of SNA1 and SNA2 vary significantly, indicating that NA requires periodic testing due to the variability in its composition. These differences arise from environmental exposure and aging, which cause the material to stiffen over time. The very high penetration values of SNA1 and SNA2 reflect their soft consistency. Their penetration level results also exceed the upper limit specified in [26], making them unsuitable for direct use in pavement construction as a substitute for RA. Conversely, HNA displays a very hard consistency, with a penetration value far below the acceptable range.

To produce a binder (HSNA) with a penetration grade that meets the standard specification [26], SNA1 was blended with HNA. After several trials, the optimal blend was determined to be 55 % HNA and 45 % SNA1. This HSNA binder was then incorporated into the RA at substitution levels of 20 %, 40 %, 60 %, and 80 % by weight of RA.

Adding RA to HSNA increased penetration by 7 %, 4.7 %, 4.7 %, and 2.3 % at substitution levels of 20 %, 40 %, 60 %, and 80 %, respectively. The blending also led to a reduction in softening point, an increase in ductility, and an improvement in flash point. The specific gravity of the blend decreased, attributed to the lower specific gravity of RA (1.020) compared to HSNA (1.060). These results demonstrate that HSNA modified with RA satisfies paving asphalt standards and can be utilised as a binder in flexible pavement construction. Additionally, the results indicate that the physical properties of SNA2 improved with extended oxidation time. Heating SNA2 at elevated temperatures initially led to surface oxidation, and with prolonged heating, deeper oxidation altered the material structure, transforming it into a glossy, black, solid substance.

After 20 hours of heating, the penetration of SNA2 decreased by approximately 68.5 %, and the softening point increased by 47.2 %. This behaviour is consistent with the loss of lighter components and the formation of heavier molecules such as asphaltenes, which contribute to a stiffer binder. These compositional changes explain the variation in aging behaviour and are well-documented in the literature [35, 36]. An inverse relationship was observed between penetration and softening point. A higher softening point reflects a greater concentration of asphaltenes, enhancing the binder's resistance to deformation at high temperatures [37]. Furthermore, the flash point and specific gravity of SNA2 increased by 38.9 % and 3.6 %, respectively. The ductility improved by more than 45.6 % after 20 hours of heat treatment. According to Al-Khalid et al. [38], this improvement in ductility may be attributed to the rise in the sulphur content with extended heating time.

3.2. Chemical composition of asphalt cements

Asphalt cement is a complex material composed mainly of hydrocarbons, with smaller fractions of sulphur, nitrogen, and oxygen functional groups, as well as trace metals such as aluminium, silicon, calcium, and iron [39]. These constituents play a key

Asphalt type	Atomic percentage for element [%] C	O	N	S	Other (Al, Si, Ca, etc.)
RA	90.1	5.0	2.0	2.9	0.0
SNA1	73.8	15.0	3.4	3.3	4.5
SNA2	81.1	10.0	3.3	3.8	1.8
HNA	87.5	6.5	2.0	4.0	0.0
HSNA	91.0	3.5	2.2	3.0	0.3
NA-20	89.2	2.8	4.3	3.4	0.3
20NA	88.1	6.0	2.1	3.0	0.8
40NA	89.0	5.0	2.0	3.0	1.0
60NA	90.0	4.0	2.0	3.0	1.0
80NA	91.5	3.0	2.0	3.0	0.5

Table 5. Elemental composition of asphalt samples.

role in determining the binder consistency, stiffness, and other properties. In this study, the elemental composition of different asphalt types (RA, SNA1, SNA2, HNA, HSNA, NA-20, and NA-RA blends at 20 %, 40 %, 60 %, and 80 %) was determined using EDX with a Vario EL III analyser (Elementar Analysensysteme GmbH, Hanau, Germany). The results are summarized in Table 5, presenting the atomic percentages of the major elements (C, O, N, and S) and trace elements (Al, Si, and Ca).

The results demonstrate clear differences between the natural asphalts and the petroleum asphalt (RA). RA exhibited high carbon content (90 at. %) and low oxygen, consistent with its balanced penetration (47 dmm) and softening point (52 °C). In contrast, SNA1 and SNA2 contained higher percentages of oxygen (10–15 at. %). this significantly accelerates the oxidative aging of these types of NA, which negatively effects the durability and performance of the SNA1 and SNA2 during their service life.

HNA exhibited a markedly different profile, characterised by reduced oxygen and relatively higher sulphur content (4 at. %). The high sulphur content is a characteristic feature of Iraqi natural asphalts, formed during long-term geological processes where sulphur compounds were concentrated through biodegradation of crude oil and the subsequent oxidation [18]. This composition contributes to its more complex and more brittle texture, consistent with its very low penetration (3 dmm) and high softening point (79 °C). HSNA, obtained by blending SNA1 with HNA, showed intermediate values, with higher carbon and lower oxygen content compared to SNA1, reflecting its improved hardness and reduced susceptibility to flow.

The heat-treated NA-20 also shifted towards higher carbon and lower oxygen content relative to untreated SNA2, confirming that heating promotes oxidation, reduces volatile components, and increases binder stiffness. Similarly, the RA-HSNA blends (20–80NA) exhibited progressive increases in carbon content and decreases in oxygen content as the HSNA content increased. This chemical shift is consistent with the trend of reduced penetration and slightly higher softening points observed in these blends.

In summary, oxygen-rich binders (SNA1, SNA2) were found to be softer, and less temperature resistant. In contrast, binders enriched in carbon and sulphur (HNA, HSNA, NA-20, and RA-HSNA blends) exhibited higher hardness and greater thermal stability. These differences in elemental composition are consistent with the variations observed in conventional asphalt properties and suggest a potentially improved performance against rutting in flexible pavements.

3.3. Permanent deformation evaluation

The plastic deformation parameters, the intercept (a) and the slope (b), can be determined from the equation given below by plotting the outcomes of rutting tests in terms of permanent strain (ε_p) against the number of repetitions (N) for each specimen:

$$\varepsilon_p = aN^b. \tag{4}$$

The slope indicates the rate of change in the permanent strain as a function of the variation in loading cycles (N), whereas the intercept reflects the permanent strain at ($N = 1$) in the log-log scale. Figure 8 displays (ε_p) against (N) on log-log axes for all mixtures. Three samples for each type of mixture were used to assess the permanent deformation.

The results revealed that all treated NA mixtures exhibited greater resistance to permanent deformation than the RA mix. Compared to RA, the slope (b) values decreased by 15.6 %, 2.9 %, 21.6 %, 28.8 %, and 32.6 % for NA-20, 20NA, 40NA, 60NA, and 80NA, respectively. A lower slope value reflects increased resistance to cumulative deformation under repeated loading. The intercept values also followed a similar trend. For 20NA, 40NA, 60NA, and 80NA, the intercept values were 13 %, 17.7 %, 19.5 %, and 36 % lower than for the RA, respectively, while NA-20 exhibited an 11.5 % higher intercept value. At 5 000 load cycles, the permanent microstrain values of NA-20, 20NA, 40NA, 60NA, and 80NA mixtures were reduced by 20.6 %, 6.9 %, 51 %, 62.4 %, and 73.5 %, respectively, compared to RA. At 6 000 cycles, the reductions were

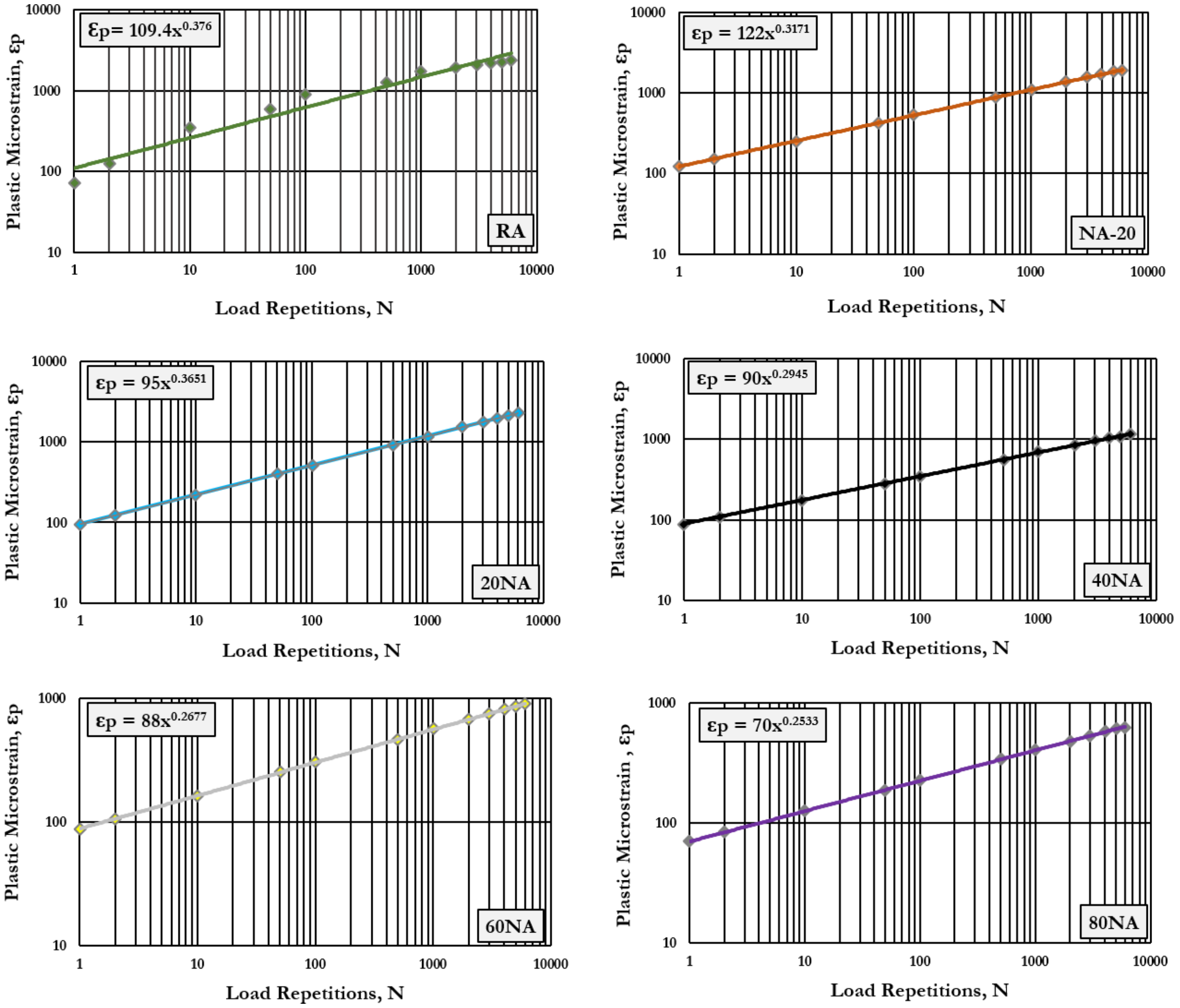

Figure 8. Plastic microstrain versus number of repetition.

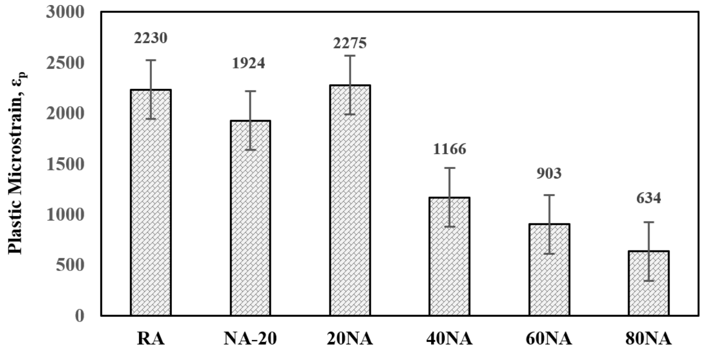

Figure 9. Effect of asphalt mixture type on the permanent microstrain at 40 °C and 6 000 cycles.

17 %, 2.3 %, 49 %, 61 %, and 72 %, respectively. These reductions are illustrated in Figure 9.

The permanent deformation coefficients Alpha (α) and Mu (μ) were derived using the relationships given in Equations (5) and (6) below after the regression coefficients, (a) and (b), had been obtained:

$$\alpha = 1 - b, \tag{5}$$

$$\mu = \frac{ab}{\varepsilon_r}. \tag{6}$$

The (ε_r) represents the resilient microstrain. The permanent deformation parameter, Mu (μ), represents the proportionality constant between the permanent strain and resilient strain (i.e. plastic strain at $N = 1$), and the permanent deformation parameter, Alpha (α) represents the rate at which the incremental permanent deformation decreases as the number of load applications rises. The results demonstrated that NA mixtures exhibited better resistance to permanent

Mixture	α	μ
RA	0.624	0.4862
NA-20	0.6829	0.5298
20NA	0.6349	0.4387
40NA	0.7055	0.3829
60NA	0.7323	0.3606
80NA	0.7467	0.339

Table 6. Plastic parameters for mixtures.

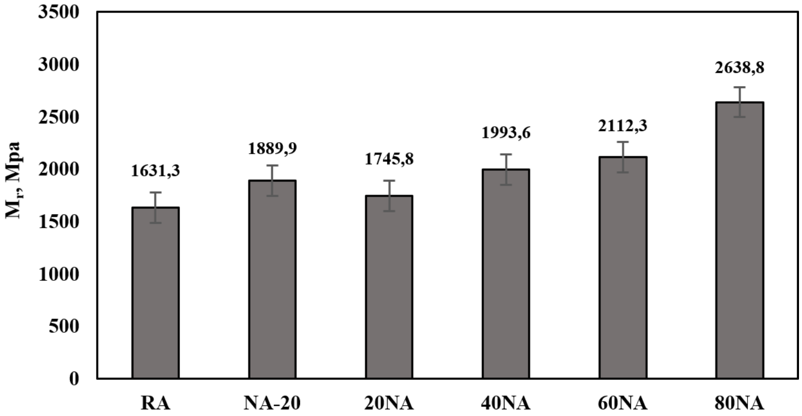

Figure 10. Effect of asphalt mixture type on the resilient modulus at 20 °C and 1 Hz.

deformation than the conventional RA mix. This is evident from higher α values and lower μ values, as summarised in Table 6.

Heat treatment reduces the percentage of light oils and increases the percentage of heavy materials such as asphaltene, which increases the viscosity and hardness of the NA, making the asphalt less susceptible to flow under repeated loads [40, 41]. Meanwhile, the mixtures prepared by mixing HSNA with RA led to a gradual improvement in the performance of the asphalt mixture as the percentage of HSNA increased. To clarify, the 20NA mix led to a slight improvement over the RA mix, since mixing the RA and HSNA creates a balance between hardness and flexibility. However, the effect was not strong due to the low percentage of HSNA. However, 40NA, 60NA, and 80NA mixtures showed a high performance. The high percentage of HSNA allowed the effect of the natural treatment could be clearly seen, as the mixing treatment leads to a physical and chemical reaction between the asphalt components. This ultimately increases hardness, creates a cohesive structure, increases resistance to flow under loads, and raises the resistance to rutting without causing cracks [42].

The M_r is a critical parameter in evaluating the asphalt mixture response to traffic loading and for determining the pavement layer thickness. As illustrated in Figure 10, M_r values for the treated NA mixtures increased by 15.8 %, 7 %, 22 %, 29.4 %, and 61.7 % for NA-20, 20NA, 40NA, 60NA, and 80NA, respectively, relative to the RA mix. The results indicate that treated NA binders are stiffer with a higher tensile strength. Notably, the 80NA mixture exhibited the highest M_r, suggesting a higher load-bearing capacity. Consequently, the elevated resilient modulus of these mixtures can lead to thinner asphalt layers, enhanced the performance under traffic loading, and longer pavement service life.

3.4. Cost analysis and environmental impact of NA

NA deposits are found in several regions of Iraq and have been utilised locally since ancient Mesopotamian civilisations, making them both a historically significant and regionally available binder resource [8]. The evaluation of NA as an alternative binder extends beyond mechanical performance to encompass its economic feasibility and environmental implications. The overall sustainability of NA utilisation depends largely on extraction practices, transport logistics, and processing methods, all of which influence both cost and environmental performance [19, 44]. Given Iraq's abundant NA reserves, available at an approximate raw material cost of $70 per tonne, compared to $270 per tonne for RA, it is essential to assess the cost-effectiveness and sustainability of NA-based binders. This assessment supports their potential large-scale use in pavement applications, particularly in hot-climate regions where performance demands are high.

As summarised in Table 7, the cost analysis demonstrates a clear economic advantage of NA-based binders compared to conventional RA. The production cost of treated NA-20 is approximately $100–105 per tonne, accounting for the energy and oxidation expenses associated with its 20-hour heat treatment

Binder type	Description	Estimated production cost [USD/ton]*	Cost reduction compared to RA [%]
RA	Refinery produced asphalt	270	0
NA-20	Heat-treated at 163 °C for 20 h	105	61
20NA	20 % HSNA + 80 % RA	235	13
40NA	40 % HSNA + 60 % RA	210	22
60NA	60 % HSNA + 40 % RA	185	31
80NA	80 % HSNA + 20 % RA	160	41

* Cost of raw materials and processing based on Iraqi Ministry of Industry and Minerals and Albayati et al. [43].

TABLE 7. Estimated cost for different binders.

at 163 °C. For the RA-HSNA blended binders, the total cost decreases progressively with a higher NA content, from $235 per tonne for 20NA to $160 per tonne for 80NA, corresponding to a 13–41 % reduction compared to pure RA. Overall, the use of NA-based binders can reduce the production costs by approximately 40–60 % compared to conventional RA, making it a highly suitable economical option for pavement construction in Iraq. This cost advantage arises from the abundant local availability of NA, which has been utilised since ancient times and remains widely distributed across several regions [8]. From an environmental perspective, the use of NA helps to reduce the dependence on energy-intensive crude oil refining, thereby potentially lowering upstream greenhouse gas emissions [44, 45]. Its use also promotes resource circularity, particularly when combined with reclaimed asphalt pavement or waste oils, which can further reduce the embodied carbon and improve binder workability [46, 47]. Recent research indicates that hybrid binders consisting of NA and small quantities of additives or waste materials can maintain strong mechanical performance while simultaneously minimising environmental impact [24, 25, 43].

4. CONCLUSION

This research involved conducting a uniaxial compression test on both the conventional and treated NA mixes in order to assess their resistance to permanent deformation. The main conclusions are as follows:

- NA-20 demonstrated good performance in terms of resistance to permanent deformation, with a 15.6 % reduction in slope and a notable increase in the stiffness (M_r) of the mixture compared to RA.
- Mixtures prepared with a high percentage of HSNA (60NA and 80NA) exhibited excellent performance, with significantly higher resilient modulus (M_r) and substantially reduced permanent strain, enhancing their suitability for use in hot climate conditions.
- At cycle 6 000, the permanent strain of NA mixes was reduced by 17 %, 2.3 %, 49 %, 61 %, and 72 % for NA-20, 20NA, 40NA, 60NA, and 80NA, respectively, compared to the RA mix. This demonstrates that NA mixes had a higher resistance to deformation and performed better under repeated loads.
- The M_r improved significantly with increasing HSNA content, increasing by 15.8 %, 7 %, 22 %, 29.4 %, and 61.7 % for NA-20, 20NA, 40NA, 60NA, and 80NA, respectively, compared to the RA mix. This reflects a significantly improved ability of the mixtures to recover after loading, which is a key indicator of the structural integrity and long-term performance of an asphalt layer.
- By utilising the abundant and low-cost NA resources available across various regions of Iraq, high-quality hot mix asphalt incorporating NA can be effectively used in local flexible pavement construction. This approach provides significant economic savings, with production costs up to 40–60 % lower than that of RA, alongside enhanced mechanical performance and durability.

Despite the promising findings regarding the use of NA in improving the physical and chemical properties of asphalt mixtures, this study has certain limitations. The experiments were conducted under controlled laboratory conditions, which may not fully capture the complex behaviour of asphalt pavements in real traffic and environmental conditions in Iraq. Additionally, the study focused on rutting resistance, while the short-term aging and long-term performance under seasonal temperature variations and repeated heavy traffic loads were not fully assessed. From a practical perspective, the incorporation of NA offers a cost-effective and locally available alternative to RA. The improved rutting resistance and enhanced rheological properties suggest potential benefits, such as reducing maintenance frequency and extending pavement service life, which can lead to significant economic and environmental advantages. For future research, it is recommended to conduct full-scale field trials to evaluate the long-term performance of NA-improved mixtures under actual traffic and environmental conditions. Moreover, further studies could investigate the combined effects of NA with other additives, explore optimal mixing ratios, and assess life-cycle environmental impacts using comprehensive sustainability metrics. Such investigations would provide a more robust understanding of NAs' potential for sustainable pavement engineering in Iraq and similar regions.

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