

Baha Vural Kök^a, Mehmet Yılmaz^a, Paki Turgut^b, Necati Kuloğlu^a

^aFirat University Civil Engineering Department, Elazığ/Turkey

^bHarran University Civil Engineering Department, Sanliurfa /Turkey

Evaluation of the mechanical properties of natural asphalt-modified hot mixture

The objective of this study is to evaluate the usage of natural asphalt in hot mix asphalt by means of determining the Marshall stability, stiffness modulus, indirect tensile strength, and dynamic creep tests. Natural asphalt, which consists of 17 % asphalt fraction and 83 % mineral fraction, was obtained from Syrian. The optimum bitumen content was determined to be 1 % lower for natural asphalt-modified mixtures compared to control mixtures. The stiffness modulus values of the natural asphalt-modified mixtures were higher than those of the control mixtures. The moisture susceptibility of natural asphalt-modified mixtures and control mixtures were evaluated during different freeze–thaw cycles. The natural asphalt-modified mixtures were not as susceptible as control mixtures to moisture damage. Adding natural asphalt to mixtures remarkably decreased susceptibility to permanent deformation. The results presented here demonstrate the positive effects of using natural asphalt.

Keywords: Natural asphalt; Stiffness; Moisture damage; Permanent deformation

1. Introduction

Hot-mix asphalt (HMA) mixtures consist of aggregates, asphalt binder, and air voids. Aggregates constitute the skeleton of HMA mixtures and asphalt cement binds aggregates together. The amount of aggregates is (94–96)% and the amount of binder is approximately 4%–6% of the weight of the HMA. Being a thermoplastic and visco-elastic material, asphalt cement is affected by small temperature changes and loading rates. It is well known that rutting is intimately related to the shear strength (and modulus) of HMA mixtures and that fatigue and low-temperature cracking are inherently related to the tensile strength of HMA mixtures [1]. Therefore, to a large extent, the stiffness and strength of HMA mixtures determine the performance of asphalt pavement. Although its low volume fraction compared to the aggregate in HMA and its much lower stiffness and strength when compared with aggregates, the bitumen affects the mixture's properties. On the other hand, although the amount of bitumen is less than that of the aggregate, the cost of bitumen is 7–8 times higher than that of the aggregate in the mixtures and the global price of bitumen increases. The escalating cost of bitumen and energy and lack of available resources have motivated highway engineers to explore alternatives for the construction of new roads. Use

of natural asphalt can improve the performance of mixtures and reduce the price of HMA. Natural asphalts can be found in different forms, such as bitumen deposits, 'lake asphalt', and rock asphalt, and in different degrees of purity (i.e., variable proportions of bitumen and other mineral matter). Naturally occurring bitumen deposits are generically termed asphaltite. The most extensively utilized asphaltite is known as Uintaite, which is a pure natural hydrocarbon (purity in excess of 99 %) containing 70 % asphaltene. It is also known as gilsonite [2]. The most famous source of lake asphalt is Trinidad Lake Asphalt (TLA), which consists of soluble bitumen (53–55)% and mineral matter (36–37)%. Natural rock asphalts have a completely different nature, being formed by the impregnation of oil into limestone, which is transformed into bitumen within the rock over time. It was unfortunate that the utilization of that type of bitumen as road-making material has not been optimized because difficulties concerning its exploration and use have risen. Widyatmoko and Elliot [3] used TLA and Uintaite to modify bitumen and showed that Uintaite or TLA caused an increase in the complex modulus (G^*) and a reduction in the phase angle (δ), indicating an increased elastic response. Aflaki and Tabatabaee [4] indicated that bitumen modification with gilsonite cause an increase in asphalt binder stiffness accompanied by intermediate and low-temperature deterioration. Huang et al. [5] suggested introduction of an intermediate layer between the aggregate and asphalt binder in the HMA mixture as a novel method by which to mitigate the stress and strain concentration. They showed that natural asphalt, gilsonite, has the potential to serve as the intermediate layer in the proposed composite HMA mixture. Gilsonite-modified asphalt concrete was proposed to be used in dense traffic and high temperature areas for better performance of initiation cracking resistance and a higher stiffness modulus [6].

Most studies of natural asphalt use HMA, including use of the bitumen fraction of natural asphalt obtained by extraction. In Indonesia the natural asphalt harvested from Lawele and Kabungka are used together with their mineral and asphalt fractions. Mixtures that include Lawele natural asphalt satisfied the requirements and show better performance than mixtures containing Kabungka natural asphalt in terms of resistance against water and temperature, the resilient modulus and permanent deformation [7]. The study also showed that the oil-contaminated sand can be used for secondary roads, roads beds, and road subbases [8].

In this study, Syrian natural asphalt was used as it is found in nature. The natural asphalt was added to hot bituminous mixtures together with its asphalt and mineral frac-

tions. The objective of this study is to compare the moisture susceptibility of natural asphalt (NA) modified mixtures and control mixtures during different freeze–thaw cycles. In addition, we aim at comparing the behavior of NA-modified and unmodified mixtures at different temperatures in the dynamic creep test.

2. Materials and sample preparation

Limestone aggregate was used in the asphalt concrete mixture. The properties of the aggregate are given in Table 1. A crushed coarse and fine aggregate, with a maximum size of 19 mm, was selected as the dense graded asphalt mixture. The gradation of the aggregate mixtures is given in Table 2.

Asphalt cement, B 160/220 obtained from Turkish Petroleum Refineries, was used as the binder for mixture preparation. The mixing and compaction temperatures were determined for the binder by using the 170 ± 20 and 280 ± 30 cP viscosity values, respectively. The physical and rheological properties of the bitumen are given in Table 3.

Natural asphalt (Fig. 1) was obtained from Syria and consisted of two materials, including the asphalt and mineral aggregate. The results of the extraction test indicated that the mixture is composed of 17 % asphalt fraction and 83 % mineral fraction. The mineral fraction contains 22.56 %

No. 50 (0.30 mm), 64.68 % No. 100 (0.150 mm), and 12.76 % No. 200 (0.075 mm). SiO_2 forms 99 % of the mineral fraction by weight. The results of the NA and base asphalt analyses are given in Table 4. While the asphaltane and resin contents of NA are higher, the saturates and aromatics contents are lower than those of B 160/220.

In this study the specimens were classified into two groups. The first group included the control specimens (C)



Fig. 1. Natural asphalt.

Table 1. Physical properties of the aggregate.

Properties	Standard	Aggregate			
		Coarse	Fine	Filler	Natural asphalt
Abrasion loss (%) (Los Angeles)	ASTM DC 131	28	–	–	–
Frost action (%) (with Na_2SO_4)	ASTM C 88	4.5	–	–	–
Specific gravity (g cm^{-3})	ASTM C127	2.603	–	–	–
Water absorption (%)	ASTM C127	1.34	–	–	–
Specific gravity (g cm^{-3})	ASTM C128	–	2.611	–	–
Specific gravity (g cm^{-3})	ASTM D854	–	–	2.711	2.03

Table 2. Aggregate gradation.

Sieve size (mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	95	87	65	39	22	15.33	13.45	8.06	7

Table 3. Fundamental properties of the binder.

Properties	Standards	Results	Specification limits
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	190	160–220
Softening point ($^{\circ}\text{C}$)	ASTM D36	40.9	35–43
Viscosity (cP, 135°C)	ASTM D4402	237.5	Maximal 3 000
Viscosity (cP, 165°C)	ASTM D4402	87.5	–
$G^*/\sin \delta$ (kPa), 58°C	AASHTO T5	1.08	Minimal 1.0
Mixing temperature range ($^{\circ}\text{C}$)	–	159–165	–
Compaction temperature range ($^{\circ}\text{C}$)	–	146–152	–
Penetration index (PI)	–	0.12	–

Table 4. Elemental analysis of NA (%).

	Saturates	Asphaltane	Resins	Aromatics
Natural asphalt	2.96	39.20	21.13	36.71
B 50/70	7.55	32.70	16.15	43.60

and the second group of specimens (NA) included 8.33 % NA by the weight of the mixture. NA was substituted with the aggregates in the NA-modified mixtures because NA consists of mineral aggregate between No. 50 and No. 200, 8.33 % (100 g). Hence the gradations of the control and NA-modified mixtures were the same. B 160/220 asphalt was also used in NA mixtures because NA alone was not sufficient to provide the proper asphalt mixture. The asphalt mixture was designed in accordance with the standard Marshall mix design procedure with samples of 10.16 cm in diameter and 6.35 cm thickness. The optimum binder contents were determined to be 5.0 % for control mixtures and 4.0 % for NA mixtures. To investigate the effect of NA under severe adverse circumstances the specimens were compacted by different numbers of impacts. For the dynamic creep test, the specimens were compacted to obtain a 7 ± 0.5 % air void. For the ITS test the specimens were compacted to reach an 8 % air void.

3. Test methods

3.1. Indirect tensile stiffness modulus test

Determination of the stiffness modulus of asphalt mixtures that were measured in the indirect tensile mode is the most popular form of stress–strain measurement used to evaluate elastic properties and is considered to be a very important performance characteristic for pavement. It measures the load-spreading ability of the bituminous layers and it controls the tensile strains induced by traffic at the underside of the roadbase [9]. The indirect tensile stiffness modulus (ITSM) test defined by BS DD 213 (BSI 1993) is a non-destructive test. The ITSM S_m in MPa is defined as

$$S_m = F(R + 0.27)/LH \quad (1)$$

where F is the peak value of the applied vertical load (repeated load) (N), H is the mean amplitude of the horizontal deformation obtained from five applications of the load pulse (mm), L is the mean thickness of the test specimen (mm), and R is Poisson's ratio (assumed to be 0.35). The test was performed as a controlled deformation. The universal testing machine (UTM) was used for the test. The magnitude of the applied force was adjusted by the system during the first five conditioning pulses such that the specified target peak transient diametral deformation was achieved. A value is chosen to ensure that sufficient signal amplitudes are obtained from the transducers to produce consistent and accurate results. A value of 7 micrometers was selected for this test. During testing, the rise time, which is defined as the time required for the applied load to increase from zero to a maximum value, was set at 124 ms. The load pulse application was equated to 3.0 s. The test was performed at 10 °C, 20 °C, and 30 °C.

3.2. Indirect tensile strength test

In the indirect tensile strength (ITS) test, cylindrical specimens are subjected to compressive loads that act parallel to the vertical diametral plane by using Marshall loading equipment. This type of loading produces a relatively uniform tensile stress that acts perpendicular to the applied load plane, and the specimen usually fails by splitting along with the loaded plane. Based upon the maximum load carried by a specimen at failure, the ITS in kPa is calculated from the following equation:

$$ITS = 2F/\pi LD \quad (2)$$

where F is the peak value of the applied vertical load (repeated load) (kN), L is the mean thickness of the test specimen (m); D is the specimen diameter (m). The indirect tensile test was used to determine asphalt concrete mixture moisture susceptibility according to ASTM D 4867 [10].

Resistance to moisture and the effect of NA on moisture-induced damage of asphalt concrete mixtures were evaluated. Three unconditioned (dry) and three conditioned (wet) specimens were tested for each group of mixtures. Wet specimens were vacuum-saturated with distilled water such that 50–80 % of the air voids were filled with water and they were wrapped tightly with plastic film. The specimens were placed into a leak-proof plastic bag containing approximately 3 ml of distilled water. Wet specimens were subjected to successive freeze–thaw cycles. One freeze–thaw cycle consists of freezing for 16 h at -18 °C, followed by soaking in a 60 °C water bath for 24 h. Specified numbers of freeze–thaw cycles such as 1, 3, 5, and 7 were applied to mixtures to determine the effects of NA on moisture damage. At the end of each cycle the bag and the wrapping were removed and the samples were placed in a water bath for 1 h at 25 °C prior to failure analysis. The ITS values of the dry specimens were determined directly. Dry specimens were placed in a water bath for 1 h at 25 °C prior to failure analysis. The ITS ratio (TSR) was determined by the following equation:

$$TSR = 100(P_{\text{cond}}/P_{\text{uncond}}) \quad (3)$$

where P_{cond} is the ITS of the wet specimens and P_{uncond} is the ITS of the dry specimens. The TSR value must be higher than 0.70 after the first freeze–thaw cycle according to ASTM D4867. The main mechanisms of moisture damage in asphalt pavements were identified: loss of cohesion (strength) and stiffness of the asphalt film and failure of the adhesive bond between the aggregate and the asphalt, in conjunction with the degradation or fracture of the aggregate [11]. There are many different available additives that can be directly introduced to the asphalt cement (AC) as a binder modifier, or can be added to the mixture with the aggregate [12]. The use of hydrated lime or other liquid anti-stripping agents is the most common method for improvement of the moisture susceptibility of asphalt mixtures. The studies showed that the hydrated lime appeared to perform better than liquid antistripping agents and indicated that the antistripping additives significantly reduced moisture damage [13, 14]. The effects of NA on the moisture sensitivity of HMA have not been comprehensively evaluated.

3.3. Dynamic creep test

The dynamic creep test was developed to estimate the rutting potential of asphalt mixtures. The dynamic creep test is thought to be one of the best methods for assessing the permanent deformation potential of asphalt mixtures. This test was developed by Monismith et al. [15] in 1970 and is based on the concept of the axial compression test. NCHRP reported that among the five laboratory tests investigated, the dynamic creep test correlated well with the measured rut depth and had a high capability to estimate the rutting potential of asphalt layers [16]. The creep test provides sufficient information to determine the instantaneous elastic (recoverable) and plastic (irrecoverable) components and the time-independent and time-dependent aspects of the material response [17]. By the application of load to samples in each cycle, three sets of diagrams consisting of permanent deformation, resilient modulus and creep modulus versus load cycles are drawn by UTM software.

Zhao [18] defined the cumulative permanent strain curve into three zones: primary, secondary, and tertiary. In the primary zone, the permanent deformation or strain accumulates rapidly. The incremental permanent deformation tends to decrease, reaching a constant value in the secondary zone. Finally, the incremental permanent deformation increases and rapidly accumulates in the tertiary zone. The tertiary stage indicates that the specimen begins to significantly deform and the individual aggregates that make up the skeleton of the mixture move past each other [19]. The point or cycle number at which pure plastic shear deformation occurs is referred to as the “flow number”. The flow number has been recommended as a rutting indicator for asphalt mixtures [20, 21]. The flow number is based on the initiation of tertiary flow or the minimum point of the strain-rate curve [22].

In the repeated creep test the accumulated axial strain, resilient axial strain, peak vertical stress, resilient modulus, and creep stiffness were calculated by the following equations [23]:

$$\varepsilon_c = (L3_n - L1)/G \quad (4)$$

$$\varepsilon_r = (L2_n - L3_n)/(G - (L3_n - L1)) \quad (5)$$

$$E_r = \sigma/\varepsilon_r \quad (6)$$

$$E_c = \sigma/\varepsilon_c \quad (7)$$

where ε_c is the accumulated axial strain ($\mu\epsilon$), ε_r is the resilient axial strain ($\mu\epsilon$), σ is the peak vertical stress (kPa), $L3_n$ is the final displacement level of the transducer for pulse ‘n’ just prior to the application of the stress for pulse ‘n + 1’ (mm), $L1$ is the initial zero reference displacement of the transducers (mm), G is the initial specimen length (mm), $L2_n$ is the maximum displacement of the transducers with stress applied for pulse ‘n’, E_r is the resilient modulus (MPa) and E_c is the creep stiffness or modulus (MPa).

The dynamic creep test was conducted at 40 °C with a 1 h loading time and 0.1 MPa applied stress. A stress level of 100 kPa was reported to be unsuitable for investigating the permanent deformation potential of the asphalt mixtures [24]. Tapkın [25] indicated that lower stress values, such as 100 and 207 kPa, are not feasible because the tertiary creep region under such loading could not be observed

within a reasonable period of time. Therefore in order to clearly evaluate the behavior of the mixture in this test a loading level of 450 kPa and three different temperature, such as 40 °C, 50 °C, and 60 °C, were chosen. The specimen strain during the cycling load was measured in the same axis as the applied stress using two linear variable displacement transducers (LVDTs). A square pulse wave with 500 ms for the pulse width and 500 ms for the rest period were applied. Prior to testing, the specimens were placed into the chamber for 24 h to obtain a uniform temperature distribution. The dynamic creep test consists of 600 s of the preload (10 kPa) condition and 7 200 load cycles.

4. Results and discussion

4.1. Indirect tensile stiffness modulus test

Control- and NA-modified specimens were subjected to the indirect tensile stiffness modulus test (ITSM) at four different temperatures: 10 °C, 20 °C, 30 °C, and 40 °C. The average stiffness modulus results of the mixtures are given in Fig. 2. Each average value was obtained from three specimens.

The stiffness modulus of mixtures decreased with increase of temperature; however, the stiffness modulus values of the NA modified mixtures are higher than those of the control mixtures at each temperature. The maximal difference between the stiffness modulus values of control and NA mixtures is 10 °C. The differences decrease with increasing temperature. The stiffness modulus values of the NA mixture are 28 % and 17 % higher than those of the control mixture at 10 °C and 40 °C, respectively. This finding indicates that the NA modified mixtures exhibit good performance at lower temperatures.

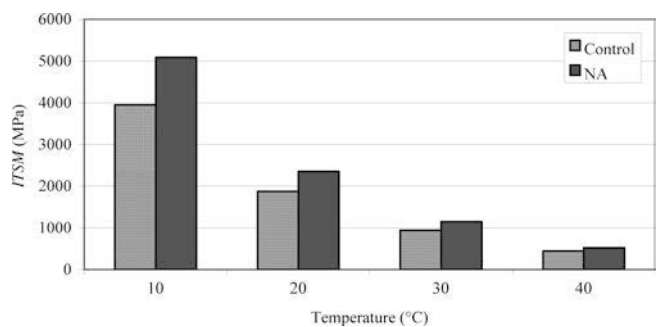


Fig. 2. Indirect tensile stiffness modulus values of the mixtures.

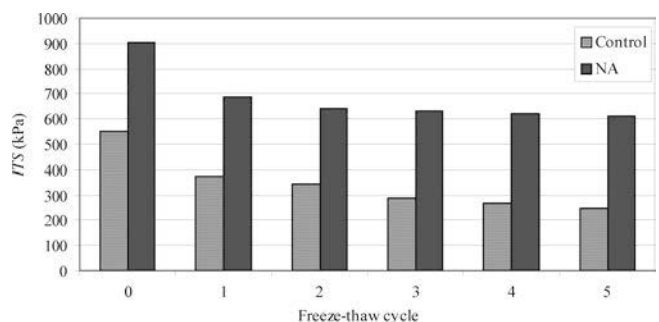


Fig. 3. Indirect tensile strength values of the mixtures.

4.2. Indirect tensile strength test

The *ITS* of the mixture following different numbers of freeze–thaw cycles are given in Fig. 3. Loss of *ITS* of the NA modified mixtures due to freeze–thaw cycles is not as high as the loss for the control mixture.

The decrease in *ITS* could be attributed to loss of adhesion of the mixture and/or cohesion of the binder. The data presented in Fig. 3 indicate that the addition of 8 % NA by weight to mixtures improves the strength characteristic of the mixture and does not allow for easy displacement of asphalt components from the aggregate surface by water, thus providing more practical mixtures than control mixtures. The *ITS* values of mixtures are dramatically reduced by the first freeze–thaw cycle. The values are further reduced by subsequent freeze–thaw cycles, but the *ITS* values decline at a more rapid rate for control mixtures relative to NA mixtures. The strength value of the NA modified mixture is 1.64 times greater than that of the control mixture without undergoing a freeze–thaw cycle. The *ITS* value of the NA-modified mixture increases to 2.43 times that of the control mixture following the fifth freeze–thaw cycle. This finding indicates that the adverse effects of water on NA-modified mixtures are not greater than those on control mixtures. Figure 4 shows the *TSR* for the mixtures after different freeze–thaw cycles.

The *TSR* decreases as the number of freeze–thaw cycles increases. While the *TSR* value of the control mixture decreases sharply, the NA-mixture *TSR* decreases rather slowly with the successive freeze–thaw cycles. The difference between the *TSR* values of the control and NA mixtures increases up to the fifth cycle. The NA mixture *TSR* value is 76% at first cycle. The control mixture has 67% *TSR* value and a 70% *TSR* value was not maintained after the first freeze–thaw cycle. The control mixture *TSR* value decreased by approximately 33% at the end of the fifth freeze–thaw cycle. The *TSR* values of the NA mixture are 1.83 and 2.43 times greater than those of the control mixture at first and fifth cycles, respectively. These results indicate that the NA-modified mixture is more resistant than the control mixture to moisture damage. NA mixtures can resist the stripping effects of water for long periods of time and do not require maintenance after every winter season.

4.3. Dynamic creep test

Figure 5 displays the results of comparisons between the accumulated strain of the control (C) and NA-modified mixtures (NA) at 40 °C, 50 °C, or 60 °C, and at a 500 kPa stress level. Accumulated strain versus the pulse count of repeated creep-test results were obtained from three specimens for the control and NA mixtures. Figure 5 presents the average strain-pulse count values.

Pulse counts of 7 200 and 9 000 at 40 °C were selected for the control and NA mixtures, respectively. Under these conditions the specimens passed the tertiary stage. At 50 °C and 60 °C the test continued until the specimens collapsed. Therefore under all evaluated conditions the specimens reached the tertiary stage, which is hard to obtain at a lower stress level and temperature. The dynamic creep test results at 40 °C are much higher compared to the corresponding values at 50 °C and 60 °C for the control and NA-modified mixtures. The service life times of the

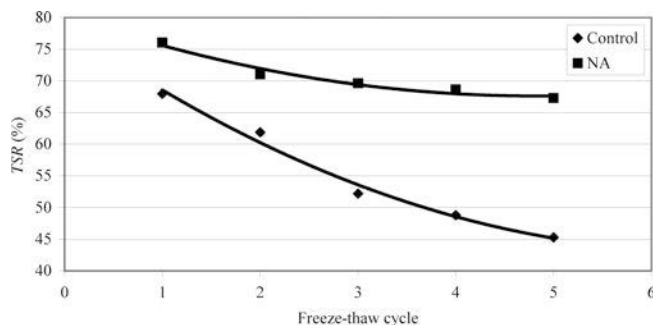


Fig. 4. Indirect tensile strength ratios of the mixtures.

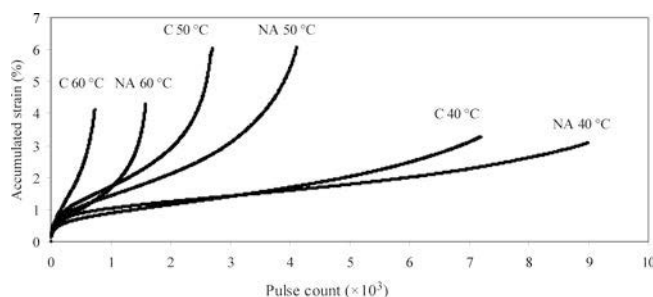


Fig. 5. Accumulated strain values of the mixtures.

NA-modified mixtures are longer than those of the control mixture at all evaluated temperatures. The pulse counts of the NA-modified mixture are 29 %, 52 % and 114 % greater than those of the control mixture at 40 °C, 50 °C, and 60 °C, respectively. The comparisons were made at the same accumulated strain levels. The results indicate a significant enhancement in the behavior of NA-modified mixtures. The improvements attributable to NA are apparent at high temperatures. Therefore, it is expected that NA mixtures will be more resistant to permanent deformation than control mixtures. The addition of NA to mixtures remarkably decreases the susceptibility of the mixtures to permanent deformation.

The effect of NA was evaluated by determining the flow numbers (*FN*s) of control and NA-modified mixes. The flow numbers were determined by plotting the mathematical product of creep stiffness and cycles versus cycle. The curves were regressed using second-order polynomial functions. The *FN* was defined as the maximum point on the curve of this plot. The curves of one of each type of specimen at 40 °C, 50 °C, and 60 °C are given in Figs. 6, 7, and 8, respectively.

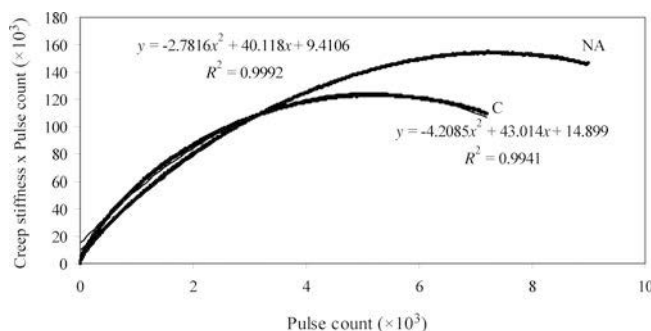


Fig. 6. Creep stiffness times pulse count versus pulse count at 40 °C.

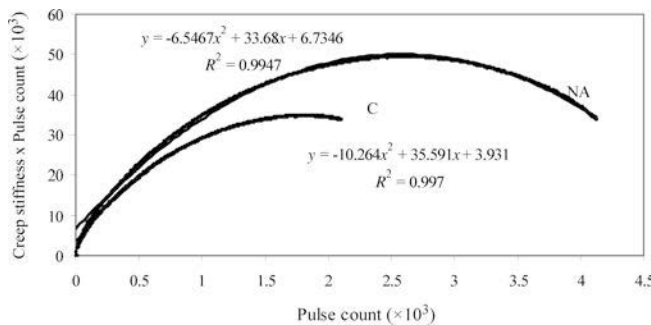


Fig. 7. Creep stiffness times pulse count versus pulse count at 50 °C.

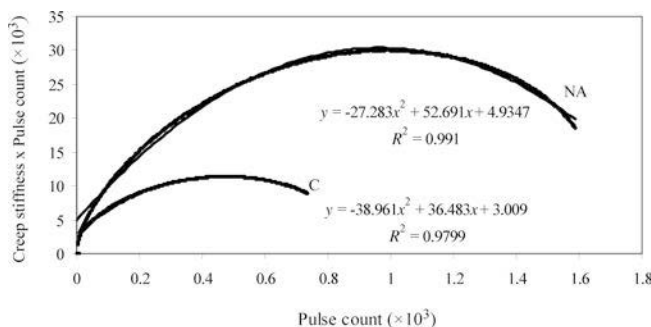


Fig. 8. Creep stiffness times pulse count versus pulse count at 60 °C.

The curves have a maximum point, which permits determination of the *FNs* of the mixtures. Generally, mixtures including NA perform better than control mixtures. The percentage increase in the *FN* is more pronounced with NA-modified mixtures at higher temperatures. For instance, when tested at 40 °C, the *FN* of the control mixture is 5 120 and that of the NA mixture is 7 163, which represents a 28 % increase. The *FNs* for the control and NA-modified mixture were 1 727 and 2 590 at 50 °C, which represents a 50 % increase. At 60 °C the *FN* of the mixture increases from 467 to 965 by the addition of NA, which represents a 106 % increase. NA-modified mixtures show a significant increase in *FN*. NA mixtures are less susceptible to creep even at high temperatures and therefore they can resist high loads without deterioration for longer times than conventional mixtures.

5. Conclusion

Based on the laboratory test results, the following conclusions were drawn:

According to the Marshall mix design the optimum bitumen content was determined to be 1 % lower for NA-modified mixtures compared to control mixtures. The decrease in the optimum bitumen content ensures significant savings due to the high price of bitumen.

The stiffness modulus of mixtures decreased with increasing temperature; however, the stiffness modulus values of the NA-modified mixtures are higher than those of the control mixtures at each evaluated temperature. The maximum difference between the stiffness modulus values of control and NA mixtures was obtained at 10 °C.

The tensile-strength-test results indicated that while the *TSR* of the control mixture sharply decreases with successive freeze–thaw cycles, the NA-modified mixture *TSR* de-

creases more slowly with successive freeze–thaw cycles. The results indicate that the NA-modified mixture is more resistant to moisture damage than the control mixture. The NA mixtures are not as susceptible to water damage as control mixtures. NA mixtures resisted the stripping effects of water with successive freeze–thaw cycles.

Generally, the pulse count of the mixtures decreased with increasing test temperature (from 40 °C to 60 °C). The reduction is more pronounced with control mixtures. The pulse counts of the NA-modified mixture are 29 %, 52 %, and 114 % greater than those of the control mixture at 40 °C, 50 °C, and 60 °C, respectively. The addition of NA to mixtures remarkably decreased the susceptibility of the mixture to permanent deformation. The NA mixture is less susceptible to creep, even at high temperatures.

This paper presents an evaluation of the usefulness of NA in HMA mixtures. The experimental results show that mixtures containing 8.33 % NA exhibit better performance than conventional mixtures lacking NA and therefore can resist high loads without deterioration for longer times than conventional mixtures.

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Correspondence address

Assoc. Prof. Baha Vural Kök
First University
Engineering Faculty, Civil Engineering Department
23119, Elazığ, Turkey
Tel.: +90424 237 00 00/54 18
E-mail: bvural@firat.edu.tr

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