Hindawi
Advances in Materials Science and Engineering
Volume 2018, Article ID 5891963, 7 pages
https://doi.org/10.1155/2018/5891963

Research Article

Investigating Effects of Nano/SBR Polymer on Rutting Performance of Binder and Asphalt Mixture

Mahmoud Ameri,[1] **Mostafa Vamegh**,[1] **Hamed Rooholamini**,[2] **and Farshad Haddadi**[3]

[1]*School of Civil Engineering, Iran University of Science and Technology (IUST), Tehran, Iran*
[2]*Department of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran*
[3]*Department of Civil Engineering, Florida International University (FIU), Miami, FL, USA*

Correspondence should be addressed to Mahmoud Ameri; ameri@iust.ac.ir

Received 21 January 2018; Accepted 13 June 2018; Published 4 September 2018

Academic Editor: Davide Palumbo

Rutting is one of the most common distresses in flexible pavements and can affect vehicle controlling features. Although asphalt binder constitutes a small percentage of the asphalt mixture, its properties play a crucial role in pavement performance and its rutting resistance. One way of improving binder properties and rutting resistance is to use additives. In this research, nanoclay and SBR polymer have been simultaneously used to modify 60–70 penetration binder to study rutting resistance of binder and asphalt mixture. To this end, the storage stability, rotational viscosity, DSR, and RCR tests on binder and marshal stability were performed, and dynamic creep and wheel track tests on asphalt mix were performed to assess rutting performance. The test and statistical analysis results indicated that nanoclay has considerably positive impact on rutting and elastic deformation of neat and SBR-modified asphalt binder and mixture.

1. Introduction

Asphalt pavements are subject to increased tensions due to increased traffic volume and truck traffic (higher tire pressure) which cause cracking, permanent deformation, and surface wear and reduce the asphalt skid resistance [1–3]. Rutting or permanent deformation is a main failure distress that affects asphalt pavement performance especially in areas with hot climate and heavy traffic load. Rutting is the result of cumulative deformations caused by repetitive loads during the pavement life. Development of permanent deformations reduces the service life of asphalt pavements. Furthermore, this distress could decrease the level of safety in road transportation networks and causes road maintenance agencies to incur considerable costs [4–8]. Factors affecting asphalt mixture rutting include materials' physical characteristics, bitumen properties, and pavement volumetric features. However, since asphalt mixture behavior depends on time and temperature, bitumen plays an important part in the creation of rutting especially under high temperature and low-speed heavy load [9, 10]. There are various methods to modify and improve properties of bitumen appropriate for the preparation of asphalt mixture. One method is to use additives and polymers each of which changes some bitumen features [11]. In another approach, microcapsules containing rejuvenator are used to improve the cracking performance of the asphalt pavement by increasing its self-healing properties [12]. Modifying bitumen with additives is usually applied to change phase combination and to improve the mechanical properties of the asphalt mixture [5, 13]. On the contrary, nanoparticles are among the known additives used for the modification of bitumen features [14–16]. Nanoclays are unique materials used as additives to make nanocomposites and to considerably improve the properties of polymeric materials. Structure of nanoclays include small, irregular plates, which are 1 nanometer in thickness and a few hundred nanometers in diameter. One of the most important characteristics of nanoclays which has profound effect on its performance is the very high length/thickness ratio of individual plates (from 300/1 to 1500/1) [17].

Since using additives is an acceptable way of enhancing bitumen properties and nanoclay is capable of improving the asphalt mixture performance, this research is aimed at finding effectiveness of nanoclay and its combination with styrene-butadiene-rubber (SBR) on the rutting of asphalt binder and mixture. Accordingly, a conventional binder test, storage stability, rotational viscosity, dynamic shear rheometer (DSR), and repeated creep and recovery (RCR) tests were performed on neat and modified bitumen and marshal stability, and dynamic creep and wheel track tests were performed on asphalt mixtures.

2. Materials and Preparation

2.1. Materials. In this research, the binder was 60–70 penetration bitumen (PG 58-22) whose properties are listed in Table 1.

Moreover, Cloisite 15A nanoclay and SBR 1502 polymer (both separately and simultaneously) were utilized to modify binder properties, as listed in Table 2.

Also, limestone mineral aggregates with 19 mm nominal maximum aggregate size (NMAS) and limestone powder as filler were used. Table 3 presents their physical properties.

2.2. Sample Preparation. In order to blend modified asphalt binders, SBR was gradually added into the 170°C heated asphalt binder, while high shear mixer was rotating at the rate of 6000 rpm. Nanoparticle was dispersed in unmodified and modified binder using a 60 W ultrasonic mixer for 20 min at a temperature of 150°C.

Using the scanning electron microscope (SEM), the dispersion of nanoparticles in the asphalt binder media was captured. Figure 1 shows that the nanoparticles dispersion that ranged in size from 25 to 5 μm and are homogeneously distributed.

In this research, the nanoparticle-modified binder contained 6% nanoclay by mass of the binder in the optimum case [18, 19] and polymer-modified binder contained 4% SBR polymer by mass of the binder; when applied simultaneously, there were two combinations one of which had 2% NC plus 4% polymer (N2S4) and another had 3% NC plus 3% polymer (N3S3).

2.3. Mix Design. To determine optimal binder content (OBC), use was made of Marshall mix design conforming to MS-02 according to which the OBCs for AC, NC, SBR, N2S4, and N3S3 were 4.9, 5.6, 5.2, 5.5, and 5.5%, respectively. After determination of OBC, cylindrical specimens, which were used in the dynamic creep and wheel track tests, were fabricated by the superpave gyratory compactor (SGC).

3. Experimental Methods

3.1. Dynamic Shear Rheometer (DSR) Test. It is used to assess binder rutting strength under high temperature. The DSR test evaluates effects of time and temperature and measures rheological properties of asphalt binder (phase angle γ and shear modulus $G*$) under medium/high temperature. Rutting strength can be found by measuring γ and $G*$ parameters at a known temperature range and finding $G*/\sin\gamma$ which should be at least 1 kPa for original asphalt binder under test temperature (or maximum pavement performance temperature) so such rutting can be minimum [20, 21].

3.2. Repeated Creep and Recovery (RCR) Test. Repeated creep and recovery (RCR) were proposed in NCHRP 549 Report in 2001 for the assessment and description of binder rutting strength using the DSR device.

Table 1: Physical properties of base binder.

Property (unit)	Specification	Standard
Specific gravity at 25°C	1.03	ASTM D70
Penetration at 25°C (dmm)	64	ASTM D36
Softening point (°C)	54	ASTM D36
Ductility at 25°C (cm)	102	ASTM D113
Flash point (°C)	305	ASTM D92
Ignition point (°C)	317	ASTM D92

Table 2: Modifiers' properties.

Property (unit)	Specification
Nanoclay (Cloisite 15A)	
Organic modifier	2M2HT
Modifier concentration (meg/100 g)	125
Moisture (%)	<2
Weight loss on ignition (%)	43
Anion	Chloride
Density (g/ml)	1.66
X-ray result (d001)	31.5 A
SBR 1502	
Mooney viscosity @ 100°C (MU)	46–58
Volatile matters (wt.%)	<0.75
Total ash (wt.%)	<1.5
Organic acids (wt.%)	4.75–7.5
Soaps (wt.%)	<0.5
Bounded styrene (wt.%)	22.5–24.5
Tensile strength (kg/cm^2)	>250

Table 3: Aggregate properties.

Property (unit)	Specification	Standard
Abrasion loss (%) (Los Angeles)	22.3	AASHTO T96
Flakiness index (%)	16	BS 812
Two or more crushed faces (%)	93	ASTM D5821
Coarse aggregate water absorption (%)	2.2	AASHTO T85
Fine aggregate water absorption (%)	2.4	AASHTO T84
Coarse aggregate specific gravity (g/cm^3)	2.59	ASTM C127
Fine aggregate specific gravity (g/cm^3)	2.32	ASTM C128

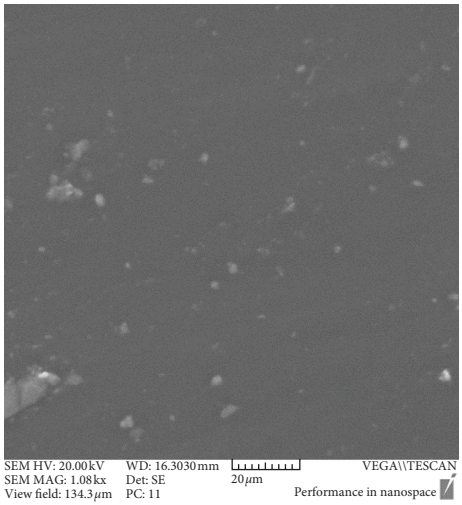

Figure 1: SEM micrographs of nanoparticles.

Being the behavior of asphalt binder linear viscoelastic, which can be observed from constant slope of cumulative strain versus time obtained from RCR, some researchers took the slope of the curve (γ) as a better indicator of high temperature behavior of asphalt binder. [22].

In the NCHRP report, shear stress is proposed in the range of 30–300 Pa for 100 cycles with 1 sec loading and 9 sec rest time [23].

3.3. Dynamic Creep Test. The resistance of asphalt mixtures against plastic deformation can be quantitatively investigated by means of repeated load dynamic or cyclic creep test. Rutting resistance of asphalt mixture can be determined using dynamic creep tests; the results of which are presented as a curve showing cumulative strain versus number of cycles; the curve has 3 zones in the third one of which strain is considerably increased due to large deformations under repetitive loading; the number of this zone's starting cycle is called "flow number" which is a criterion for the investigation and assessment of rutting in asphalt mixtures ([24, 25]; NCHRP 465, 2002 [26]).

3.4. Wheel Track Test. The wheel track test is one of the common methods to measure permanent deformation of asphalt mixture. This test was conducted according to AASHTO Standard T 324 (AASHTO, 2011), to investigate the rutting performance of samples.

4. Results and Discussion

4.1. Binder Conventional Test. As demonstrated in Figure 2, using nanoclay and SBR decreases the amount of penetration in asphalt binder; therefore, the stiffness of asphalt binder should be increased compared to that of base binder. Increase in stiffness led to higher resistance of modified binder against rutting at higher temperatures.

As shown in Figure 3, the modified binders cause an increase in the softening point. As the softening point increases, the stiffness of binder in higher temperatures

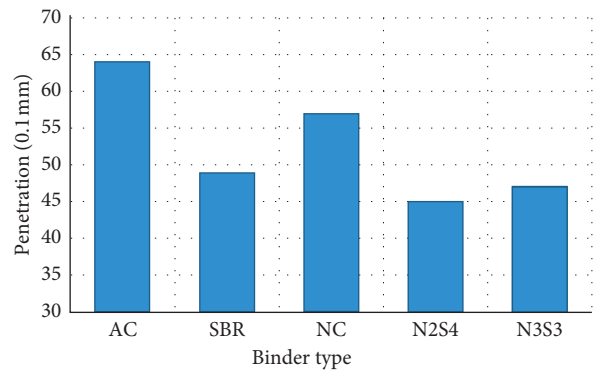

Figure 2: Penetration test.

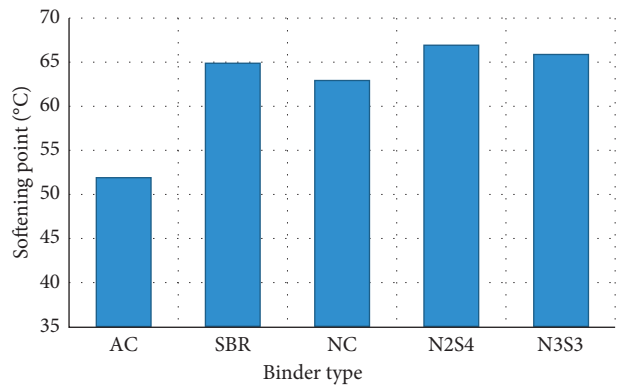

Figure 3: Softening point test.

increases, which confirms the strength of binder against permanent deformation at higher temperatures.

The penetration index (PI) is a simplest factor in evaluating binder performance against temperature variation. Binders with higher PI values consider having lower susceptibly to temperature and the resulted damages. Since binder in asphalt mixes experiences temperature variation during seasonal changes, higher PI values up to +2 would result in favorable characteristics. The PI is calculated according to the following equation:

$$\mathrm{PI} = \frac{1952 - 500 * \log(\mathrm{Pen}_{25}) - 20 * \mathrm{SP}}{50 * \log(\mathrm{Pen}_{25}) - \mathrm{SP} - 120}, \quad (1)$$

where Pen_{25} is the penetration at 25°C and SP is the softening point temperature.

The amount of PI of control specimens is presented in Figure 4. As it is shown, the amount of PI for control samples is negative. However, asphalt binder modified with nanoclay and SBR polymer cause an increase in the amount of PI in modified binder and decrease the temperature susceptibility.

4.2. Storage Stability Test. To study the storage capability and phase separation between binder and additive under high temperature, use has been made of the storage stability test (according to AASHTO PP5) which evaluates the storage stability by measuring softening points of upper and lower parts of a cylindrical container that is divided into three equal parts. The cylindrical specimen is kept at

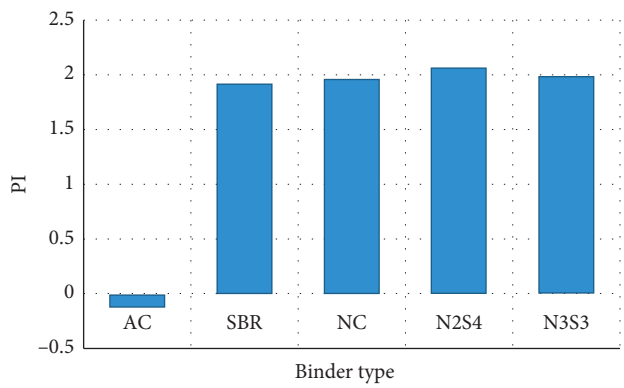

Figure 4: Penetration index.

Table 4: Storage stability.

Binder type	Softening point		Deference
	Upper	Lower	
NC	60.8	59.6	1.2
SBR	65.9	61.4	4.5
N2S4	68.5	66.4	2.1
N3S3	66.1	64.3	1.8

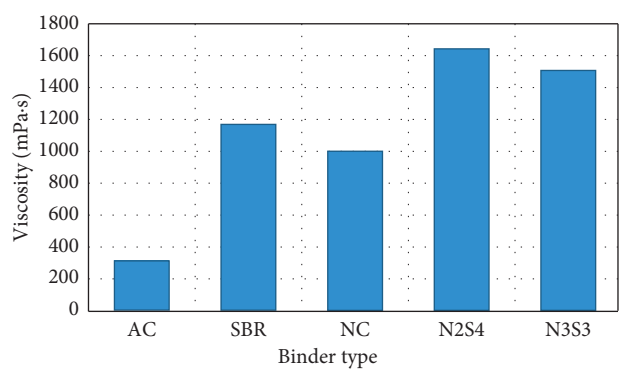

Figure 5: Rotational viscosity.

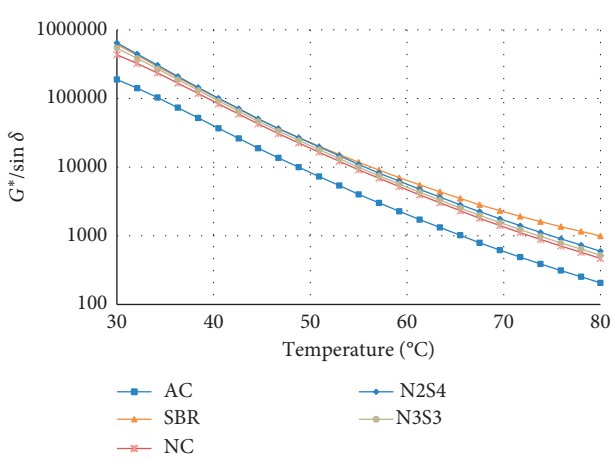

Figure 6: DSR test.

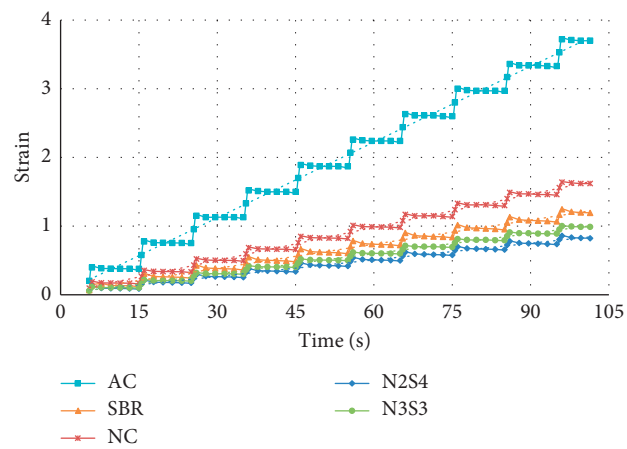

Figure 7: RCR test.

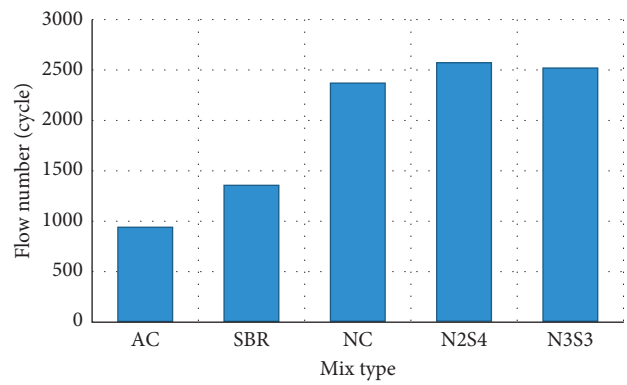

Figure 8: Dynamic creep test.

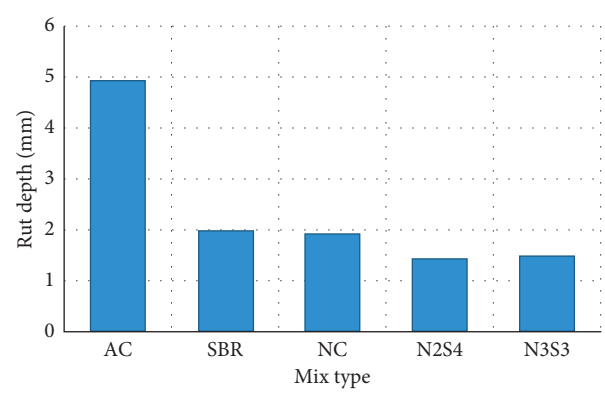

Figure 9: Rutting depth.

a temperature of 163°C for 48 hr. The difference of softening points of upper and lower parts is limited to 2.5°C in order to consider thermally stable [27].

The results in Table 4 show that the nanoclay-modified binder is stable but the modified binder by the SBR polymer is not stable enough because it experiences phase separation between binder and polymer. In specimens modified by nanoclay and polymer simultaneously, the temperature difference of the ductility points is less than 2.5°C meaning

Table 5: ANOVA pairwise Tukey statistical analysis for rutting and flow number.

		Sum of squares	D	Mean square	F	Significance
		ANOVA statistical analysis				
Rutting	Between groups	26.218	4	6.554	656.288	0.008
	Within groups	0.100	10	0.010		
	Total	26.318	14			
Flow number	Between groups	7134837	4	1783709	120.050	0.011
	Within groups	148580	10	14858		
	Total	7283417	14			
		Pairwise Tukey statistical analysis				
		AC	SBR	NC	N2S4	N3S3
Rutting	AC	—	S	S	S	S
	SBR		—	N	S	S
	NC			—	S	S
	N2S4				—	N
	N3S3					—
Flow number	AC		S	S	S	S
	SBR		—	S	S	S
	NC			—	N	N
	N2S4				—	N
	N3S3					—

$\alpha = 0.05$; N, not significant; S, significant.

that there is conformity between binder and SBR polymer which is due to the presence of nanoclay in the combination.

4.3. Rotational Viscosity Test. The rotational viscosity (RV) test is used to assess the modified binder efficiency at high temperature ranges and shows that if asphalt binder has enough ductility for being pumped, displaced, and mixed with aggregates; RV is not to exceed 3 Pa·s at a temperature of 135°C for this purpose; in this study, the test was done in accordance with the AASHTO T316 at the mentioned temperature [28].

Figure 5 shows that RV for all specimens lies in the allowable range. SBR polymer increases binder viscosity more compared to nanoclay, and the highest viscosity belongs to N2S4 (2% nanoclay and 4% SBR).

4.4. Dynamic Shear Rheometer (DSR) Test. This test has been done at a temperature range of 30–80°C with a frequency of 10 rad (1.59 Hz). The results in Figure 6 show that adding SBR and nanoclay to asphalt binder increases its rutting resistance from 127 to 383% at a temperature of 80°C compared to neat binder.

The results of this test show that the performance of the SBR-modified binder is by far better than that modified by only nanoclay or by both nanoclay and SBR combination.

4.5. Repeated Creep and Recovery (RCR) Test. In this research, the test in strain control state was performed with a shear tension of 300 Pa at a temperature of 60°C using a plate 25 mm in diameter and a gap opening of 1 mm; loading time was 1 sec with 9 sec rest (according to NCHRP 549 Report).

According to the results in Figure 7, nanoclay and SBR polymer enhance the rutting resistance of the modified binder compared to neat one. Contrary to the DSR test, RCR showed that the synergic performance of binder modified with SBR-nanoclay combination is better than that modified with only nanoclay or SBR. Based on these results, the best performance was that of the N2S4 specimen. Results also revealed that when binder is modified, especially with a combination of nanoclay and SBR, its elastic behavior is significantly improved.

4.6. Dynamic Creep Test. Dynamic creep was carried out at a tension level of 450 kPa with a loading frequency of 0.5 Hz (500 m·sec loading, 1500 m·sec rest) to evaluate the rutting resistance of asphalt mixture according to the Australian code, AS-2891.12.1, at 50°C; in this study, use was made of the "Goh and You" method [29] to determine the flow number (FN).

According to the results in Figure 8, nanoclay and SBR polymer cause modified specimens to have higher strength against deformation compared to the unmodified mixture; modification, especially with a combination of nanoclay and SBR, causes shear deformations to occur in higher cycles, while the unmodified mixture has larger deformations in the first phase of loading.

4.7. Wheel Track Test. In this test, cylindrical specimens are tested by wheel track apparatuses. Ambient temperature was 50°C, and loading frequency was 1 Hz. All in all, the specimens were loaded by 8000 cycles, and then depths of rutting in each specimen were measured.

As it is shown in Figure 9, the specimen modified with nanoclay and SBR polymer shows lower depth of the rutting in asphalt mixture. The results indicate that using both of these modifiers at the same mixture considerably increases the stiffness in asphalt mixture.

4.8. ANOVA Analysis. Analysis of variance (ANOVA) was employed to conduct pairwise Tukey statistical analysis with $\alpha = 0.05$. With respect to pairwise Tukey statistical analysis tabulated in Table 5, rutting decreases in the mixtures containing both modifiers (N2S4 and N3S3) more than that in the SBR-modified mixture which is mainly due to nanoparticles penetration into the SBR matrix structure in the nanoscale and more microstructural resistance against permanent deformation [30]. Therefore, it can be inferred that nanoclay and its combination with SBR lead to greater rutting resistance compared to the SBR-modified and neat asphalt mixes. It is worth noting the mixtures containing NC and N2S4 have approximately the same rutting performance, and greater portion of nanoclay in SBR and nanoclay compound reduces the flow number.

5. Conclusion

The main objective of the present research was to evaluate the impact of introduction of nanoclay and SBR copolymer and their combination into the asphalt binder on rutting performance. Based on the results of tests and analyses, the following conclusions can be drawn:

(1) Since polymers do not have enough stability in asphalt binder, it can be stated that the presence of nanoclay in binder containing polymer will cause polymer-binder compatibility to enhance and storage stability of the modified binder with SBR/nanoclay to lie in the allowable range.

(2) Using nanoclay and polymer increases the stiffness of binder, improves the strength, and decreases the temperature sensitivity in binder.

(3) Adding nanoclay and SBR polymer and their combination to binder increase viscosity and OBC of neat asphalt binder.

(4) The DSR test results show that SBR and nanoclay modified binders enhance its rheological properties and highly increase rutting resistance compared to the neat binder.

(5) According to the RCR test results, it can be stated that adding nanoclay and SBR polymer to binder not only increases its strength against rutting but also enhances its elastic properties; deformations in the modified binder with SBR/nanoclay are recovered though.

(6) Considering results obtained from the dynamic creep test, nanoclay, SBR, and their combination have positive effect on rutting resistance and elastic deformations.

(7) Wheel track test results shows asphalt mixtures containing modified binder have less rutting depth. These results are in line with the dynamic creep test.

(8) A review of the results of all the tests shows that N2S4 has the best performance and rutting resistance which can be attributed to the presence of nanoclay, with its unique binder improving features, in combination with the SBR polymer.

Data Availability

Underlying data will be provided by email upon any request from readers.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] F. Haddadi, M. Ameri, M. H. Mirabimoghadam, and H. R. A. Hosseini, "Validation of a simplified method in viscoelastic continuum damage (VECD) model developed for flexural mode of loading," *Construction and Building Materials*, vol. 95, pp. 892–897, 2015.

[2] S. Tayfur, H. Ozen, and A. Aksoy, "Investigation of rutting performance of asphalt mixtures containing polymer modifiers," *Construction and Building Materials*, vol. 21, no. 2, pp. 328–337, 2007.

[3] M. Baqersad, M. Mohammadafzali, B. Choubane, C. Holzschuher, A. Hamedi, and H. Ali, "Precision assessment of the Florida texture meter in hot mix asphalt," *Journal of Transportation Engineering, Part B: Pavements*, vol. 144, no. 2, article 04018003, 2018.

[4] O. V. Laukkanen, H. Soenen, T. Pellinen, S. Heyrman, and G. Lemoine, "Creep-recovery behavior of bituminous binders and its relation to asphalt mixture rutting," *Materials and Structures*, vol. 48, no. 12, p. 4039, 2015.

[5] T. Xu, H. Wang, Z. Li, and Y. Zhao, "Evaluation of permanent deformation of asphalt mixtures using different laboratory performance tests," *Construction and Building Materials*, vol. 53, pp. 561–567, 2014.

[6] M. Ameri, M. H. Mohammadi, S. M. Motevalizadeh, and A. Mousavi, "Experimental study to investigate the performance of cold in-place recycling asphalt mixes," in *Proceedings of Institution of Civil Engineers–Transport*, pp. 1–11, Thomas Telford Ltd., London, UK, March 2018.

[7] A. Mehrabi and S. Farhangdoust, "A laser-based noncontact vibration technique for health monitoring of structural cables: background, success, and new developments," *Advances in Acoustics and Vibration*, vol. 2018, Article ID 8640674, 13 pages, 2018.

[8] S. M. Motevalizadeh, P. Ayar, S. H. Motevalizadeh, S. Yeganeh, and M. Ameri, "Investigating the impact of different loading patterns on the permanent deformation behaviour in hot mix asphalt," *Construction and Building Materials*, vol. 167, pp. 707–715, 2018.

[9] R. Delgadillo and H. U. Bahia, "The relationship between nonlinearity of asphalt binders and asphalt mixture permanent deformation," *Road Materials and Pavement Design*, vol. 11, no. 3, pp. 653–680, 2010.

[10] E. Santagata, O. Baglieri, M. Alam, and D. Dalmazzo, "A novel procedure for the evaluation of anti-rutting potential of asphalt binders," *International Journal of Pavement Engineering*, vol. 16, no. 4, pp. 287–296, 2015.

[11] S. A. Tabatabaei, A. Kiasat, and F. K. Alkouhi, "The effect of styrene-butadiene-rubber (SBR) polymer modifier on properties of Bitumen," *World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, vol. 7, no. 10, pp. 785–788, 2015.

[12] H. Behbahani, M. J. Ayazi, and A. Moniri,, "Laboratory investigation of rutting performance of warm mix asphalt

containing high content of reclaimed asphalt pavement," *Petroleum Science and Technology*, vol. 35, no. 15, pp. 1556–1561, 2017.

[13] S. Shirzad, M. M. Hassan, M. A. Aguirre, L. N. Mohammad, S. Cooper, and I. I. Negulescu, "Microencapsulated sunflower oil for rejuvenation and healing of asphalt mixtures," *Journal of Materials in Civil Engineering*, vol. 29, no. 9, article 04017147, 2017.

[14] S. Hosseinnezhad, E. Fini, and A. Taher, "Application of biomodified montmorillonite clay to enhance asphalt oxidation resistance," *American Journal of Engineering and Applied Science*, vol. 11, no. 2, pp. 433–443, 2018.

[15] A. Kavussi and P. Barghabani, "The influence of nano materials on moisture resistance of asphalt mixes," *Study of Civil Engineering and Architecture*, vol. 3, pp. 36–40, 2014.

[16] A. Kavussi and P. Barghabany, "Investigating fatigue behavior of nanoclay and nano hydrated lime modified bitumen using LAS test," *Journal of Materials in Civil Engineering*, vol. 28, no. 3, article 04015136, 2015.

[17] Q. T. Nguyen, *Process for improving the exfoliation and dispersion of nanoclay particles into polymer matrices using supercritical carbon dioxide*, Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 2007.

[18] M. Ameri, S. Nobakht, K. Bemana, M. Vamegh, and H. Rooholamini, "Effects of nanoclay on hot mix asphalt performance," *Petroleum Science and Technology*, vol. 34, no. 8, pp. 747–753, 2016.

[19] M. Ameri, M. Vamegh, R. Imaninasab, and H. Rooholamini, "Effect of nanoclay on performance of neat and SBS-modified bitumen and HMA," *Petroleum Science and Technology*, vol. 34, no. 11-12, pp. 1091–1097, 2016.

[20] AASHTO T315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, American Association of State Highway and Transportation Officials, Washington, DC, USA, 2010.

[21] P. Ahmedzade, "The investigation and comparison effects of SBS and SBS with new reactive terpolymer on the rheological properties of bitumen," *Construction and Building Materials*, vol. 38, pp. 285–291, 2013.

[22] R. Delgadillo, D. Cho, and H. Bahia, "Part 1: bituminous materials: nonlinearity of repeated creep and recovery binder test and relationship with mixture permanent deformation," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1962, pp. 3–11, 2006.

[23] H. U. Bahia, D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, and R. M. Anderson, *NCHRP Report 459: Characterization of Modified Asphalt Binders in Superpave Mix Design. TRB*, National Research Council, Washington, DC, USA, 2001.

[24] M. Ameri, R. Mohammadi, M. Vamegh, and M. Molayem, "Evaluation the effects of nanoclay on permanent deformation behavior of stone mastic asphalt mixtures," *Construction and Building Materials*, vol. 156, pp. 107–113, 2017.

[25] I. M. Asi, "Performance evaluation of SUPERPAVE and Marshall asphalt mix designs to suite Jordan climatic and traffic conditions," *Construction and Building Materials*, vol. 21, no. 8, pp. 1732–1740, 2007.

[26] NCHRP Report 465, *Simple Performance Test for Superpave Mix Design*, Transportation Research Board, National Academies Press, Washington, DC, USA, 2002.

[27] AASHTO PP5, *The Laboratory Evaluation of Modified Asphalt Systems*, American Association of State Highway and Transportation Officials, Washington, DC, USA, 1993.

[28] AASHTO T316, *Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer*, American Association of State Highway and Transportation Officials, Washington, DC, USA, 2013.

[29] S. W. Goh and Z. You, "A simple stepwise method to determine and evaluate the initiation of tertiary flow for asphalt mixtures under dynamic creep test," *Construction and Building Materials*, vol. 23, no. 11, pp. 3398–3405, 2009.

[30] H. Rooholamini, R. Imaninasab, and M. Vamegh, "Experimental analysis of the influence of SBS/nanoclay addition on asphalt fatigue and thermal performance," *International Journal of Pavement Engineering*, pp. 1–10, 2017.