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ORIGINAL ARTICLE

The effect of nanomaterials as anti-stripping additives on the moisture sensitivity of glasphalt

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Abstract

Despite the environmental and economic benefits of using glasphalt, it suffers from a number of disadvantages. The most common damage in glasphalt is the effect of water on bitumen-aggregate adhesion and the occurrence of moisture damage. One way to improve the resistance of glasphalt against the moisture damage is to use anti-stripping additives. Accordingly, the effect of two types of nanomaterials including nano hydrated lime (NHL) and nano calcium carbonate (NCC) as bitumen modifiers on the moisture sensitivity of glass asphalt has been investigated in this study. The moisture sensitivity of asphalt mixtures was assessed by the AASHTO T283 test and surface free energy (SFE) method. Indirect tensile strength (ITS) results show that the use of waste glass cullet increases and decreases the resistance of asphalt mixture in dry and wet conditions, respectively. An increase in the number of freeze–thaw cycles causes a decrease in the ITS of the glasphalt. The obtained results showed that using both nanomaterials in glasphalt significantly improved the resistance to moisture sensitivity. Bitumen modification using NHL and NCC, which was added in 2% bitumen, reduced the SFE of cohesion, which resulted in improving the bitumen coating on the aggregate surface and the adhesive between bitumen and aggregate.

Keywords Glasphalt · Moisture sensitivity · Anti-stripping additive · Nanomaterials · Indirect tensile strength ratio · Surface free energy

Introduction

Road construction has significant potential for the use of waste materials because more material is always needed [1]. Preliminary studies on the properties of waste materials showed that these materials can be incorporated into asphalt mixtures as aggregates or asphalt binder modifier [2–5]. Over time, the tendency to use glass and, consequently, the production of waste glass (WG) has increased significantly, in such a way that glass has become one of the most important waste materials produced [6].

Using glass cullet has several advantages and disadvantages [7]. Other most important advantages are that glass cullet is easily accessible and environmentally friendly, and some of its engineering properties are even better than natural aggregates [8]. However, using WG in asphalt mixtures results in the creation of many problems, such as reducing the adhesive bond between asphalt and aggregate, reducing the slip resistance, breaking glass inside the mixture, increasing the sensitivity to moisture and, consequently, reducing the stripping resistance in the glasphalt [7]. It can be noted that the greatest concern for using glass cullet in asphalt mixtures is its high stripping potential. Due to the silica structure of the glass, this material is highly hydrophilic, and this feature is the main reason for the moisture sensitivity of the glasphalt.

Previous studies

Several studies were carried out on using WG in asphalt mixtures. During a study, the maximum amount of glass that

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can be used in asphalt mixtures without any reduction in its slip resistance was investigated. According to the results, using both additives increased the resistance to stripping, except for a mixture containing 20% glass and chemical additive. It was also concluded that using glass cullet up to 15% was acceptable in an asphaltic mixture [9]. Another study examined the possibility of using recycled glass particles in an asphaltic mix with the preservation of properties and performance of asphaltic mixtures. Also, it was concluded that using 10% recycled glass in the mixture did not have a significant effect on crack resistance and mixture stiffness. But it also adversely affected the resistance to stripping [7]. In a study, moisture sensitivity and degradation of glasphalt were evaluated under freeze–thaw cycles. According to the results, the repetition of freeze–thaw cycles in glasphalt causes more damage than control mixtures. Nevertheless, both mixtures were damaged under ten freeze–thaw cycles [10]. The mechanical properties and moisture sensitivity of glasphalt were evaluated using Zycosoil additive. For this purpose, five types of mixtures were prepared with different percentages of Zycosoil (0, 0.5, 2.5, 4.5) and 10% of glass cullet. According to the results, using Zycosoil improved the mechanical properties and moisture sensitivity of glasphalt [11]. In another study, the effect of waste materials as filler on the performance of the hot asphalt mix was studied. According to the results, the compounds containing WG and brick waste powder had better fatigue life and better performance than other mixtures [12]. Another study investigated the possibility of using WG in the road construction industry. According to the results, the optimum bitumen content depended on the amount of recycled glass. On the other hand, the stripping potential of glasphalt could be improved by adding hydrated lime (HL), which was suggested to use 2% HL as an anti-stripping additive. In addition, using glass increased the slip resistance. Also, according to the results obtained from experimental studies, the piece made of 10% recycled glass had a better performance than the piece without glass and no stripping was observed [13]. Another study investigated the effect of glass cullet on improving the dynamic properties of asphalt mixtures. According to the results, using glass cullet and HL increased the hardness modulus of the produced mixture. In addition, 15% of the glass was identified as an optimum amount and using HL improved the adhesive property in the glasphalt mix [14]. Based on the results of previous studies, it is observed that the use of HL has a better performance than liquid anti-stripping and other additives in reducing moisture sensitivity in glasphalt.

Statement and research objectives

Bitumen has weak acidic properties. This causes its adhesion to the glass that has a lot of silica which gives it acidic properties to be weak. The presence of water at the bitumen–glass contact surface easily breaks this weak bond and separates the bitumen from the glass surface, causing stripping in glasphalt. The hypothesis of this study is that the use of alkaline properties such as NCL and NHL cause the bitumen properties to change from being acidic to alkaline. This improves the adhesion between the bitumen–glass and reduces the likelihood of stripping. The main objectives of the present study are:

- Investigation of the moisture sensitivity of the control and modified glasphalt with NHL and NCC through mechanical methods.
- Investigation of the effect of bitumen modification using the additives of NHL and NCC on the parameters of SFE of bitumen, cohesion free energy of bitumen and adhesive between bitumen and aggregate using the thermodynamics method.
- Comparison of the mechanical and thermodynamics experiment results for moisture sensitivity of glasphalt.

Experimental program

Materials

Aggregates

In this study, three different types of aggregate including limestone, granite and quartzite with different water absorption were used. Table 1 represents the chemical composition of the aggregates used in this study. The nominal maximum size of aggregates of this gradation is 19 mm. Table 2 also represents the physical properties of aggregates.

Bitumen

In this series of experiments, AC 60–70 produced by the Pasargard oil company was used. Commonly used tests such as penetration test, softening point test and ductility test

Table 1 Chemical composition of the three types of aggregates used in this study

Properties	Limestone	Granite	Quartzite
pH	8.8	7.1	6.5
Silicon dioxide, SiO_2 (%)	3.8	68.1	74.2
R_2O_3 ($Al_2O_3+Fe_2O_3$) (%)	18	16.2	13.7
Aluminium oxide, Al_2O_3 (%)	1	14.8	10.6
Ferric oxide, Fe_2O_3 (%)	0.4	1.4	7.5
Magnesium oxide, MgO (%)	1.2	0.8	1.5
Calcium oxide, CaO (%)	51.3	2.4	0.6

Table 2 Physical properties of aggregates used in this study

Test	Standard	Limestone	Granite	Quartzite	Specification limit
Specific weight (coarse grain)	ASTM C127				
Bulk		2.59	2.61	2.48	–
SSD		2.60	2.63	2.49	–
Apparent		2.62	2.65	2.52	–
Specific weight (Fine grain)	ASTM C128				
Bulk		2.57	2.60	2.46	–
SSD		2.58	2.62	2.48	–
Apparent		2.61	2.65	2.49	–
Specific weight (filler)	ASTM D854	2.56	2.55	2.44	–
Los Angeles abrasion (%)	ASTM C131	27	19	26	Max 30
Maximum water absorption	ASTM C127	0.8	1.2	1.7	2.8
Fracture percentage	ASTM D5821	89	91	86	Based on traffic
Flat and elongated particles (%)	ASTM D4791	3	9	6	Max 15
Sodium sulfate soundness (%)	ASTM C88	2	4	7	Max 8

Table 3 Characteristics of the base bitumen used in this study

Properties	Standard	AC 60–70	Allowed amount
Degree of penetration	ASTM D5–73	66	60–70
Softening point, (°C)	ASTM D36–76	51	49–56
Ductility,(cm)	ASTM D113–79	105	Min 100
Flash point, (°C)	ASTM D92–78	262	Min 232
Loss of heating, (%)	ASTM D1754–78	0.75	–
Solubility in trichloroethylene, (%)	ASTM D2042–76	99.5	–
Specific gravity at 25 °C, (g/cm^3)	ASTM D70–76	1.02	–

were used to characterize the bitumen properties. Table 3 represents the results obtained from these experiments.

Glass cullet

The glass cullet used in this study is made of waste glass produced by a glazing workshop. The maximum particle size of the glass is 4.75 mm. The gradation of the glass cullet is in accordance with the gradation presented in Fig. 1. Also, the minerals that make up the glass jar in this study are represented in Table 4. On the other hand, in this research, the crumbling glass replaces 10% of the fine-grained part (between 4.75 and 0.075 mm) of each of the three aggregates (limestone, granite and quartzite). Also, the major glass cullet forming minerals are represented in Table 4. On the other hand, in this study, the glass cullet was replaced by 10% of the fine-grained part (less than 4.75 mm) of each aggregate (limestone, granite and quartzite). The amount of glass was 2.025% of the total sizes of aggregates used.

Nanomaterial additives

In the present study, two types of nanomaterials, namely, NHL and NCC, were used to improve the resistance of

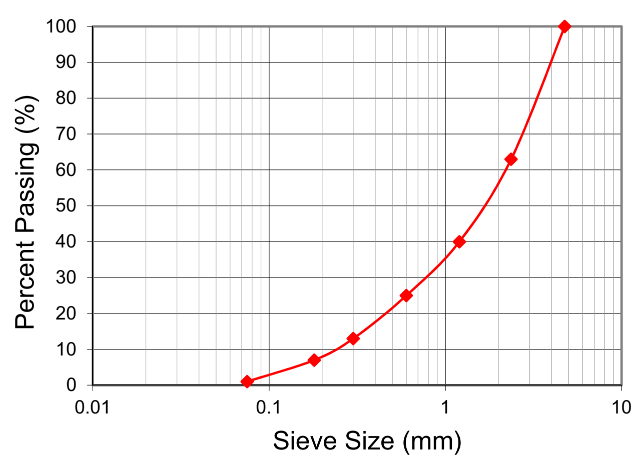

Fig. 1 The work of cohesion and adhesion

glasphalt against moisture. The NHL used in this study is known as American Elenements. It has more than 70% CaO and is considered as a fairly strong base. Also, NCC ($CaCo_3$) is used in this study based on the brand name NM-1060. It should be noted that each of these nanomaterials was used in 2% of bitumen mass to modify it. The physical and chemical properties of two the

Table 4 Specifications of glass cullet forming mineral used in this study

Properties	Glass cullet
Silicon dioxide, SiO2 (%)	70.50
Potassium oxide, K_2O (%)	1.2
Aluminium oxide, Al_2O_3(%)	2.6
Sodium oxide, Na_2O (%)	16.3
Magnesium oxide, MgO (%)	2.9
Calcium oxide, CaO (%)	5.7

Table 5 Physical properties of both nanomaterials used in this research

Properties	NHL	NCC
Structure	Hexagonal	Crystal calcite
Particles shape	Cubic	Cubic
Specific mass, (g/cm^3)	2.24	2.5
Refractive index	1.1–1.5	1.2–1.7
Specific surface area, (m^2/g)	16	2 ± 32
The average size of the particles, (nm)	≈42	≈ 60
Specific gravity, (g/cm^3)	0.5–0.6	0.53–0.54
Degree of acidity	12.4	10–8
Water percentage	≤0.75	≤0.5

Table 6 Chemical properties of both nanomaterials used in this study (%)

Properties	*NHL*	NCC
SiO_2 (%)	0.802	0.713
Al_2O_3 (%)	0.217	0.369
Fe_2O_3 (%)	0.316	0.279
CaO	73.77	78.1
MgO (%)	0.451	0.061
K_2O	0.058	0.061
Na_2O	0.073	0.057
MnO	0.026	0.015

nanomaterials used in this study are presented in Tables 5 and 6, respectively.

Specimen preparation

In the present study, 18 different asphalt mixtures according to Table 7 were used to evaluate the moisture sensitivity potential. To prepare these compounds, as mentioned earlier, three different types of aggregates including limestone, granite and quartzite with AC 60–70, waste glass cullet as a substitute for 10% of fine-grained aggregates and nanomaterial additives including NHL and NCC were used as bitumen modifier.

The laboratory program for this study is illustrated in Fig. 2. In this study, different aggregate compositions were used to investigate asphalt mixtures with different susceptibility to moisture damage, so three aggregates with different mineralogical structures were used.

The mix design of asphalt mixtures is based on the Marshall method, which is based on the basic compositions including aggregate and base bitumen, so that the bitumen content does not affect the analysis of results between different groups of asphalt mixtures.

Subsequently, the base bitumen was converted to modified bitumen using two types of additives, on which a sessile drop test was performed to determine the SFE components.

To investigate the moisture damage potential in different asphalt mixtures, compositions without glass and 10% glass replacement were used. There are six compositions of glasphalt for each aggregate. The first composition includes bitumen and base aggregates. The second and third combinations of bitumen modified with two types of additives and base aggregates are used. The fourth, fifth and sixth compositions are the same, except that they contain 10% of the glass in their aggregate structure. For each compound, ITS test is performed in dry and wet conditions to obtain moisture sensitivity index. Three replications were used for each asphalt mixture sample in mix design and ITS tests to evaluate the accuracy and reproducibility of the data.

Tests

The modified Lottman test (AASHTO T283)

To perform the moisture sensitivity test using the modified Lottman method for each compound, three specimens were prepared in wet conditions and three specimens in dry conditions. As a result, dry and wet specimens were subjected to the indirect tensile resistance test, in which the loading was carried out at a rate of 5.08 inches (2 inches) per minute until the moment the sample faileds. Using Eq. 1, the value of the ITS was obtained for each of the six wet and dry specimens for each asphalt mixture compound.

Table 7 Contact angle between bitumen and probe liquids (degrees)

Types of asphalt binder	Water	Diiodide methane	Ethylene glycol
AC 60–70	92.64	77.84	57.33
AC 60–70 modificate with NHL	92.06	78.32	59.3
AC 60–70 modificate with NCC	92.05	78.82	58.56

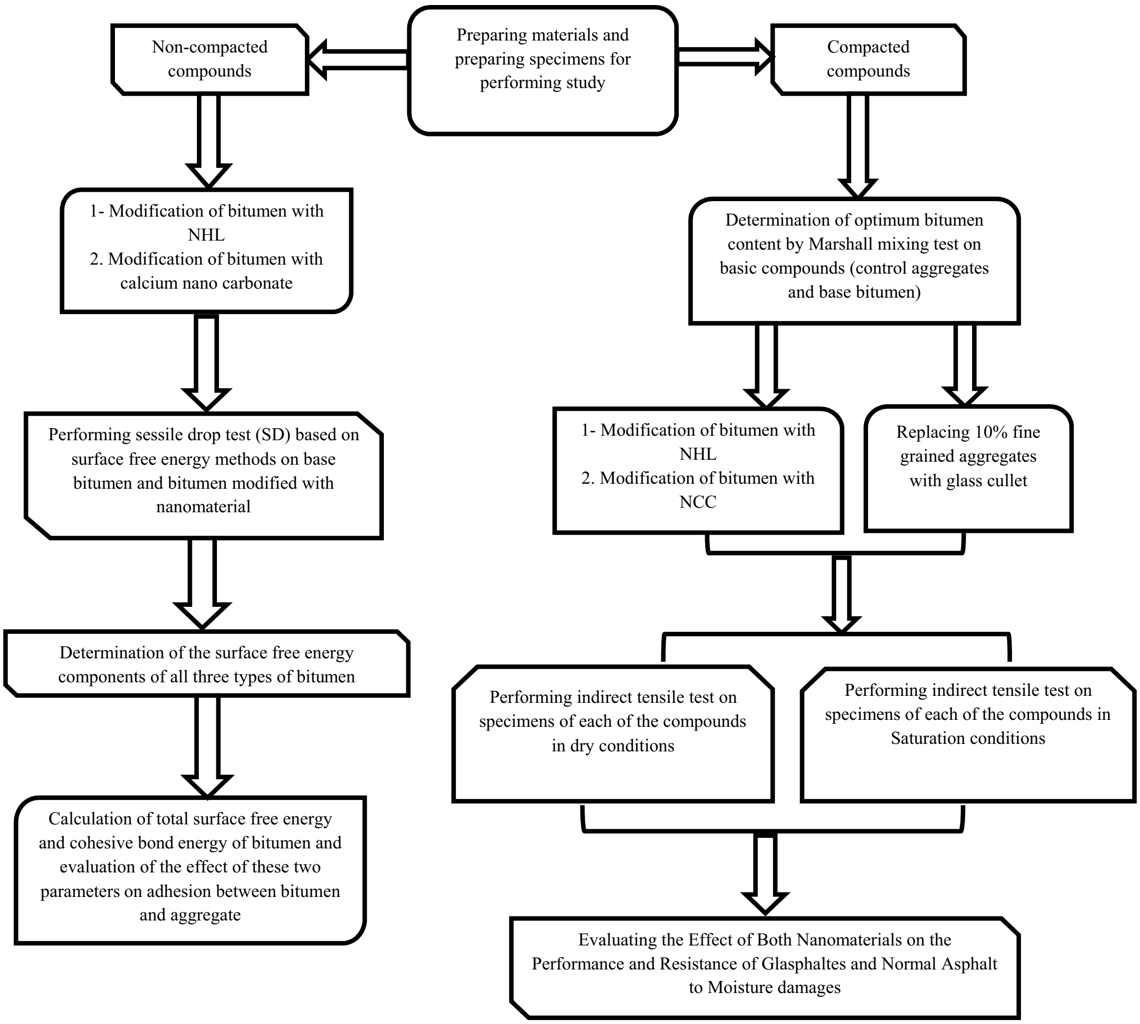

Fig. 2 The laboratory program of this study

$$\mathrm{ITS} = {}^{2000F}/_{t\pi d}, \tag{1}$$

where ITS is the indirect tensile strength (kPa), F is the rupture force (N), t is the asphalt specimen thickness (mm) and d is the diameter of the asphalt specimen (mm).

The average indirect tensile strength for dry (three samples) and wet specimens (three samples) was calculated individually. The moisture sensitivity or stripping potential of asphalt specimens was determined by the average ITS of the wet to dry specimens (in percent) according to Eq. 2.

$$\mathrm{TSR} = \left({}^{\mathrm{ITS}_{\mathrm{wet}}}/_{\mathrm{ITS}_{\mathrm{dry}}}\right) \times 100, \tag{2}$$

where TSR is the indirect tensile strength ratio (%), $\mathrm{ITS}_{\mathrm{wet}}$ is the mean indirect tensile strength of the wet specimens (kPa) and $\mathrm{ITS}_{\mathrm{dry}}$ is the average of the indirect tensile strength of the dry specimens (kPa) [15, 16].

To investigate more precisely the effect of glass on the performance of asphalt mixtures, as well as the effect of anti-stripping additives, 1, 3 and 5 freeze–thaw cycles and melting were applied.

SFE test

Molecules in the volume of a specific material are surrounded by other molecules in different directions. This makes the energy of these molecules higher than that of surface molecules. Therefore, some energy is needed to separate these molecules from the volume and deliver them to the surface conditions. This energy is equal to the SFE of a material. Figure 3 shows that SFE of cohesion in a material, and adhesion in the interface of two materials can be defined as the work required to create a new surface of a homogeneous material under vacuum conditions.

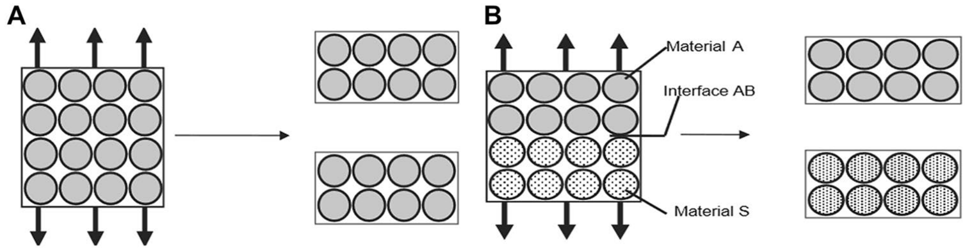

Fig. 3 **a** The work of cohesion and the SFE of a material. **b** The work of adhesion and the SFE of two different materials

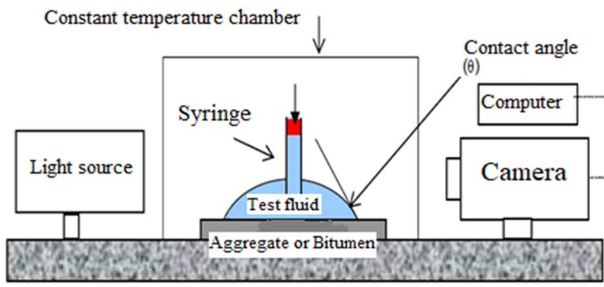

Fig. 4 Schematic diagram of the sessile drip test device

In the present study, the sessile drop method was employed to introduce the components of SFE of the base and modified bitumen. In this method, probe liquids are distributed separately on the flat surface of bitumen. Then, using the camera, some photos are taken from the droplets of the probe liquids formed on the surface of the bitumen. Then, the contact angles of various probe liquids are used using relationships of the work of adhesion to determine the components of SFE of the base and modified bitumen. Figure 4 shows a sessile drop device schematically. As shown in the figure, this device is composed of a small syringe and a camera to create and record photos of a sessile droplet, a 150 °C heater for heating specimens of bitumen to melting temperatures, a glass or aluminum plate to create a layer of hot-melt bitumen on it, and an environmental control system keep the test temperature constant. Also, photo analysis software or manual methods can be used to determine the contact angles of the taken photos.

Results and discussion

The modified Lottman test

The results of ITS Tests of the research specimens in dry conditions are presented in Fig. 5. Using glass cullet increased the ITS of the specimens under dry conditions. Also, using both additives of NHL and NCC increases the

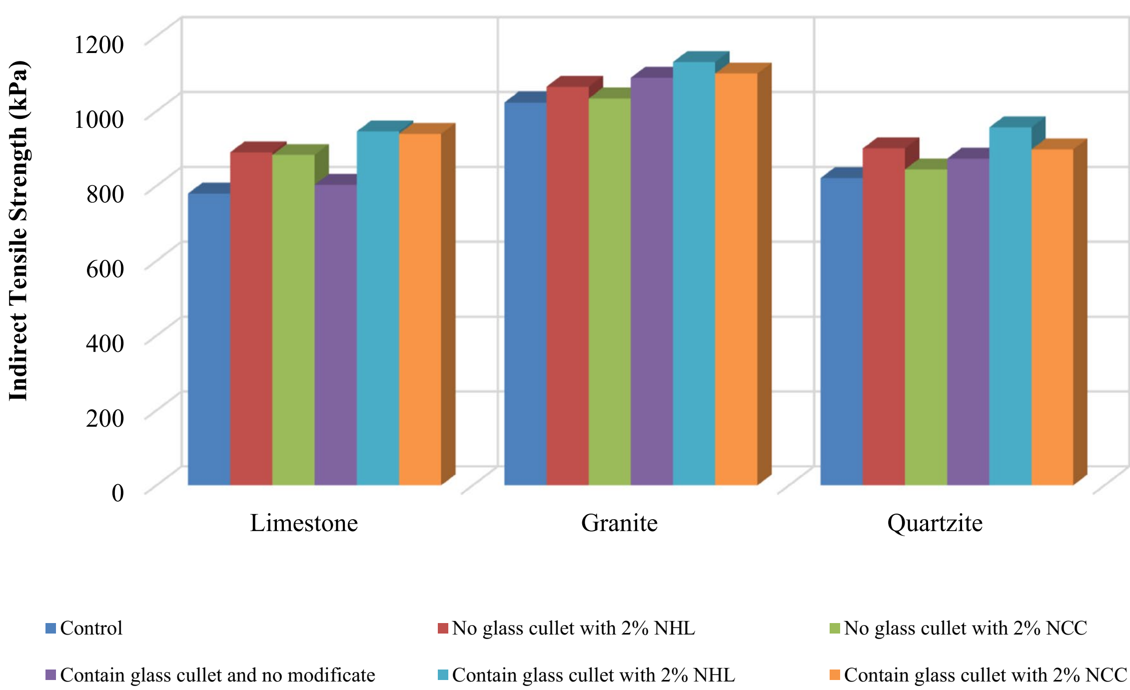

Fig. 5 ITS of asphalt mixes in dry conditions

ITS of all asphalt specimens, whether containing glass or without glass. According to the results, the performance of the two additives was similar. Among them, NHL had a greater effect on the increase of this strength than NCC. In addition, specimens made of granite aggregates had the best performance against loading under dry conditions in both glass and conventional asphalt mixtures.

The results of ITS of asphalt mixtures under wet conditions were obtained for one, three and five periods of freeze–thaw cycles which have been presented in Figs. 6, 7, and 8, respectively. According to these results, using glass

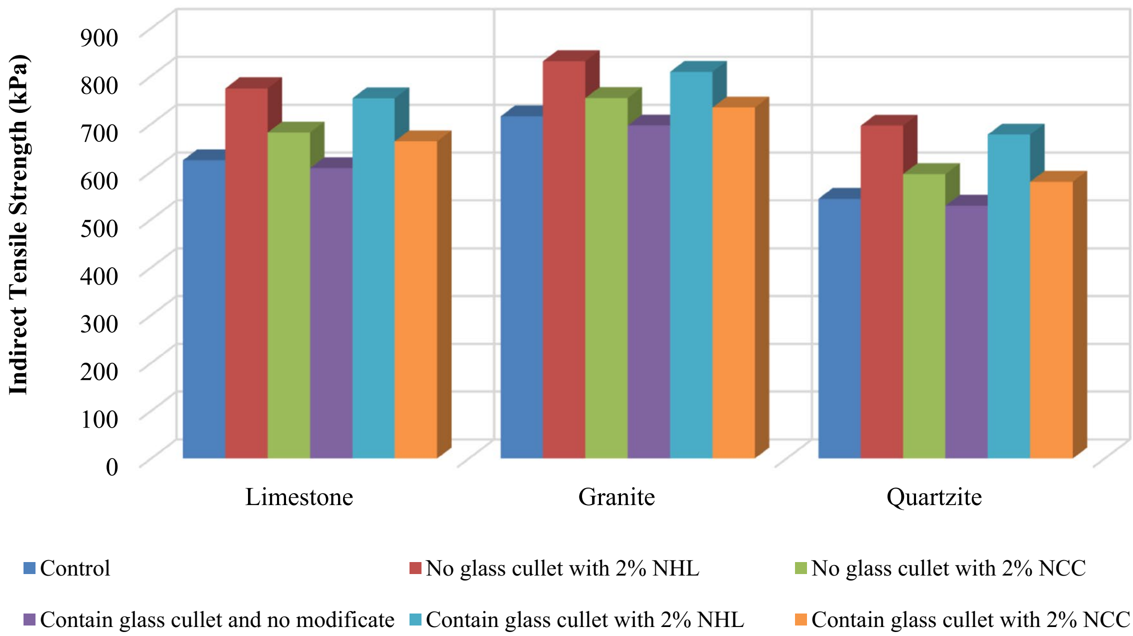

Fig. 6 ITS of asphalt mixes under wet conditions with one freeze–thaw cycle

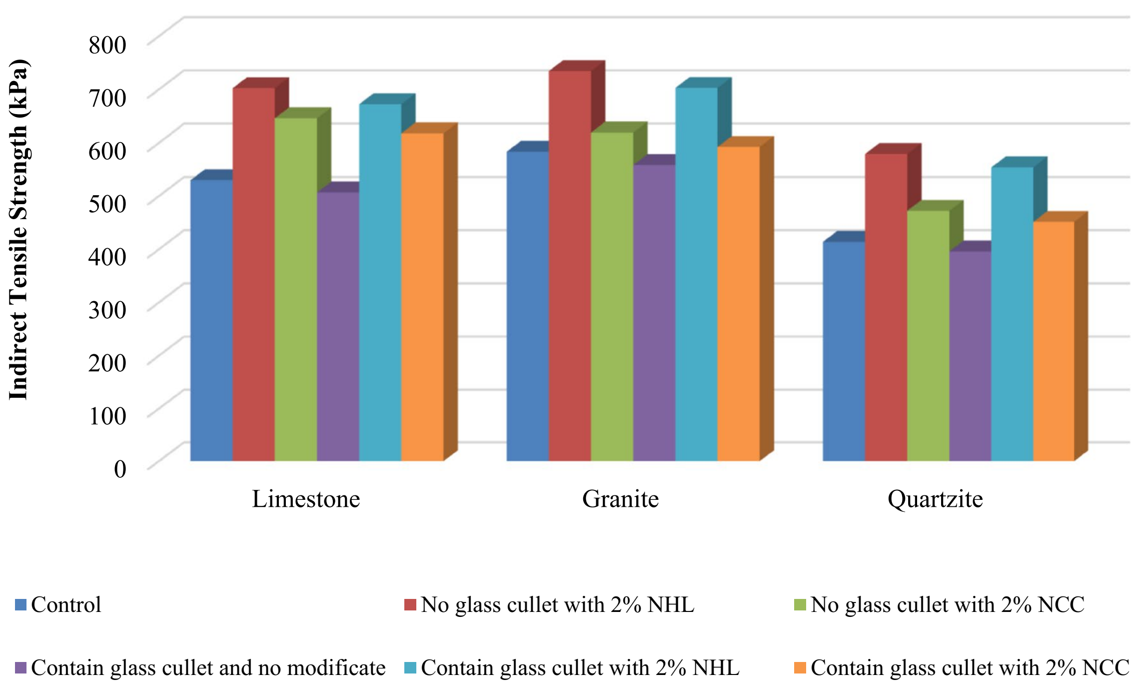

Fig. 7 ITS of asphalt mixes under wet conditions with three freeze–thaw cycles

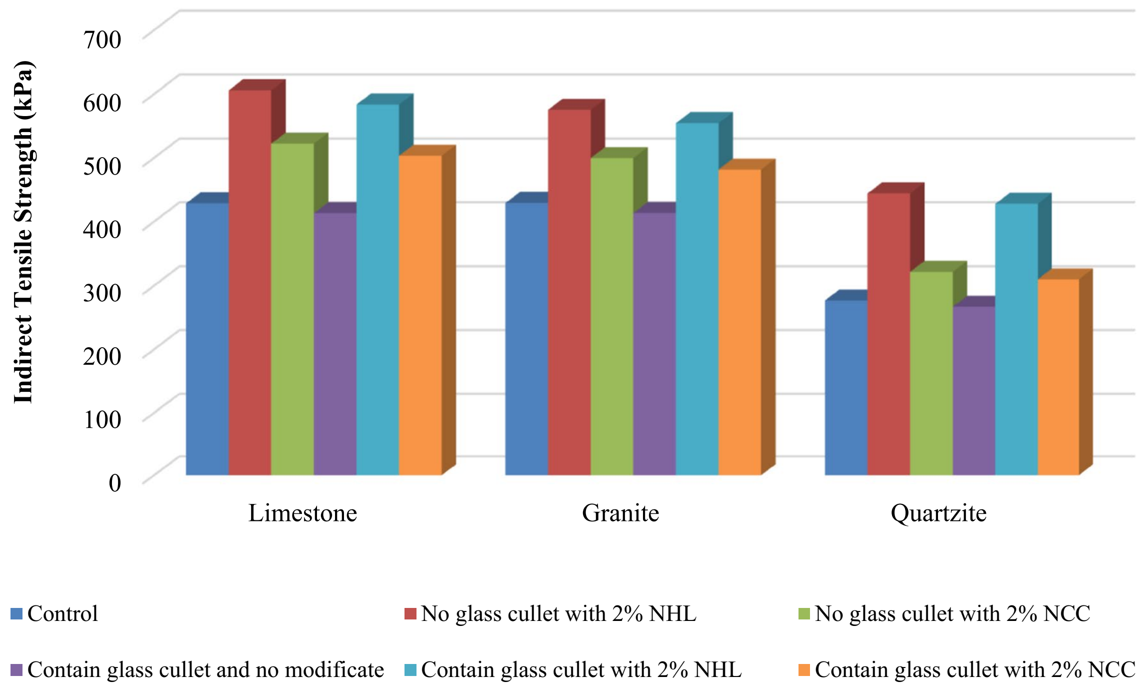

Fig. 8 ITS of asphalt mixtures under wet conditions with five freeze–thaw cycles

cullet reduced ITS in asphalt mixtures made of all three types of aggregates. It indicated the poor performance of glasphalt against moisture sensitivities. Also, using both additives of NHL and NCC led to a significant increase in the resistance of glass and conventional asphalt mixtures made of all three types of aggregate. Among these two nanomaterials, NHL increased the strength more than the other.

Also, the percentage of increase in ITS in wet conditions by these two nanomaterials was higher than that in the dry conditions. On the other hand, according to the results obtained, the rate of reduction of the ITS of specimens made of all three types of aggregate in glasphalt and conventional asphalt mixtures are increased by enhancing the number of freeze–thaw cycles. This reduction could be due to the loss of mixture adhesion or bitumen cohesion due to the presence of more sample specimens to moisture. Furthermore, the results showed that the glasphalt and conventional asphalt mixtures made of limestone aggregate had a higher stability against moisture under all three periods of freeze–thaw cycles than two other aggregates. Also, it was predictable that both granite and quartzite aggregates could experience moisture resistance due to the high water absorption of their forming minerals compared with limestone aggregate.

In Figs. 9, 10, and 11, the values of the TSR index for glasphalt and conventional asphalt mixtures are illustrated. As shown in these figures, the TSR of specimens containing glass and without glass decreased by increase of the number of freeze–thaw cycles.

In addition, using both anti-stripping additives increased the values of this index and, consequently, increased the resistance of specimens prepared with all three types of aggregate in both asphalt mixtures containing glass and without glass. In all compounds, the modified mixtures with NHL have the most stability against moisture. According to the results obtained, it can be concluded that specimens made of limestone and quartzite aggregates had the greatest and the least resistance to moisture sensitivities, respectively, in both glasphalt and conventional asphalt mixtures. Thus, in completing the results obtained from the modified Lottman test, it can be noted that using glass cullet in asphalt mixtures reduced the resistance of these mixtures against moisture sensitivities that using both anti-stripping additives NHL and NCC improved this resistance.

SFE

In the present study, the sessile drop method was used to measure the SFE components of the base and modified bitumen with both nanomaterials. The contact angle between the three probe liquids with the desired bitumen was first measured to determine these components. The results of this measurement are presented in Table 8. Using these angles, the components of SFE of base and modified bitumen were obtained. The results showed that the contact angle between the water and the bitumen was larger than the other angles. This is due to the polar nature of the water, which makes water hardly distribute on the surface of nonpolar materials

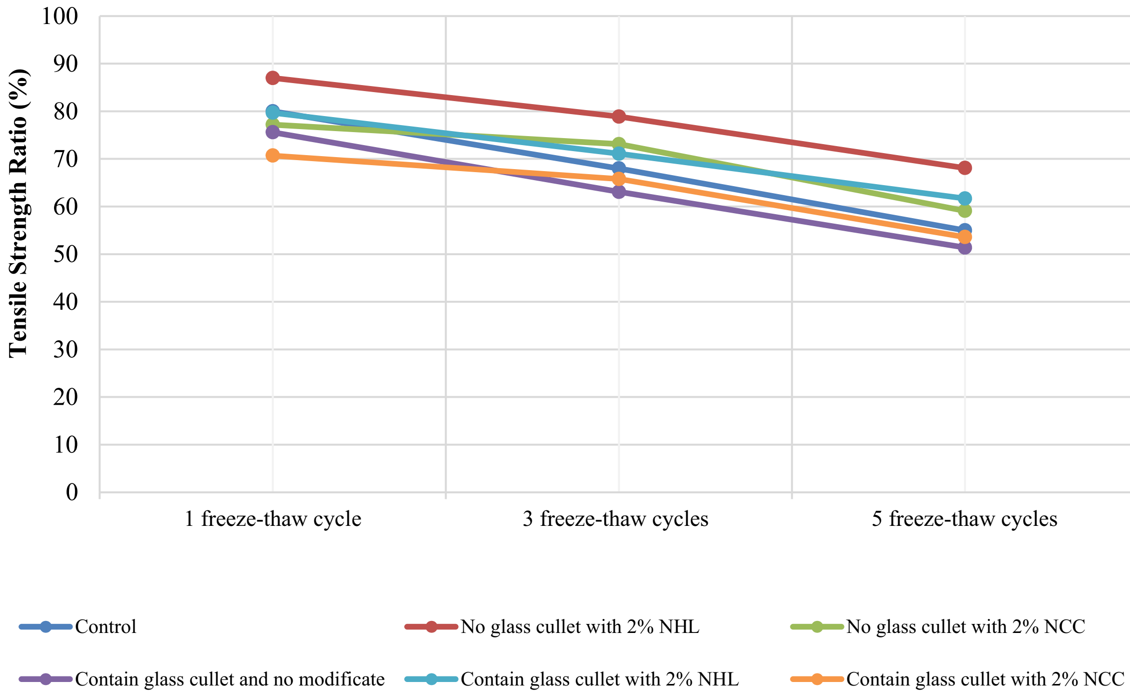

Fig. 9 TSR in asphalt mixtures made with limestone

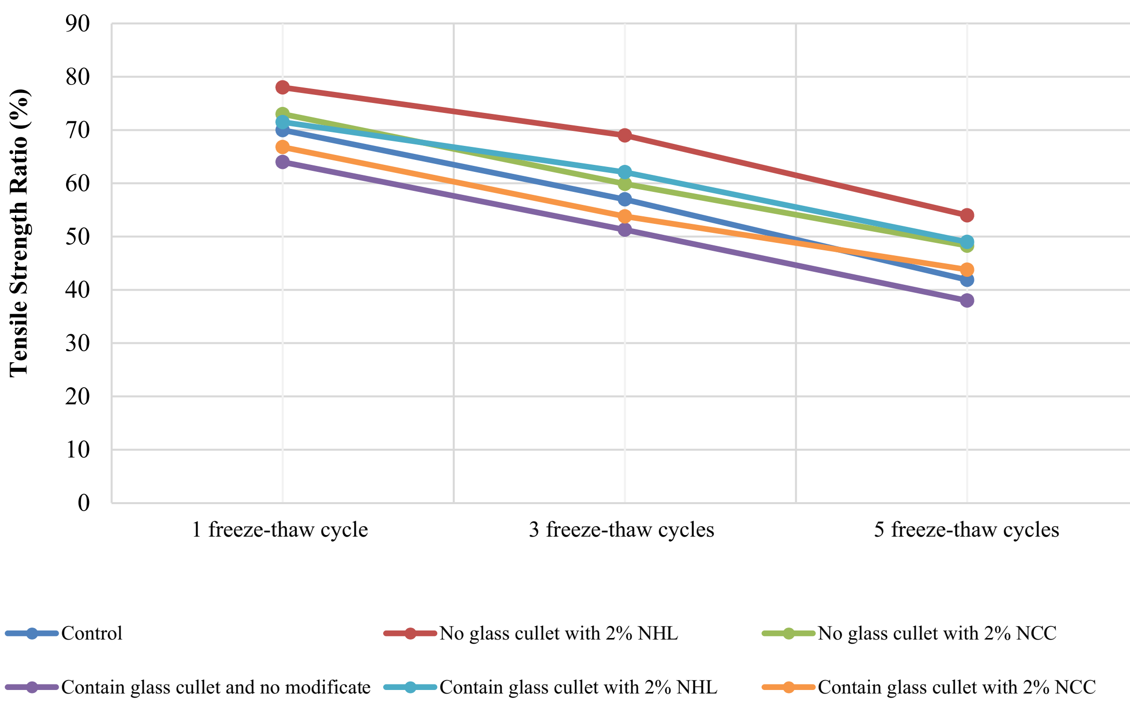

Fig. 10 TSR in asphalt mixtures made with granite

such as bitumen. In contrast, the contact angle with two diiodide methane and ethylene glycol liquids had nonpolar and semi-polar behavior on the surfaces of the bitumen, respectively, which were smaller than the corresponding angle with the water. This is due to the low polarity of bitumen.

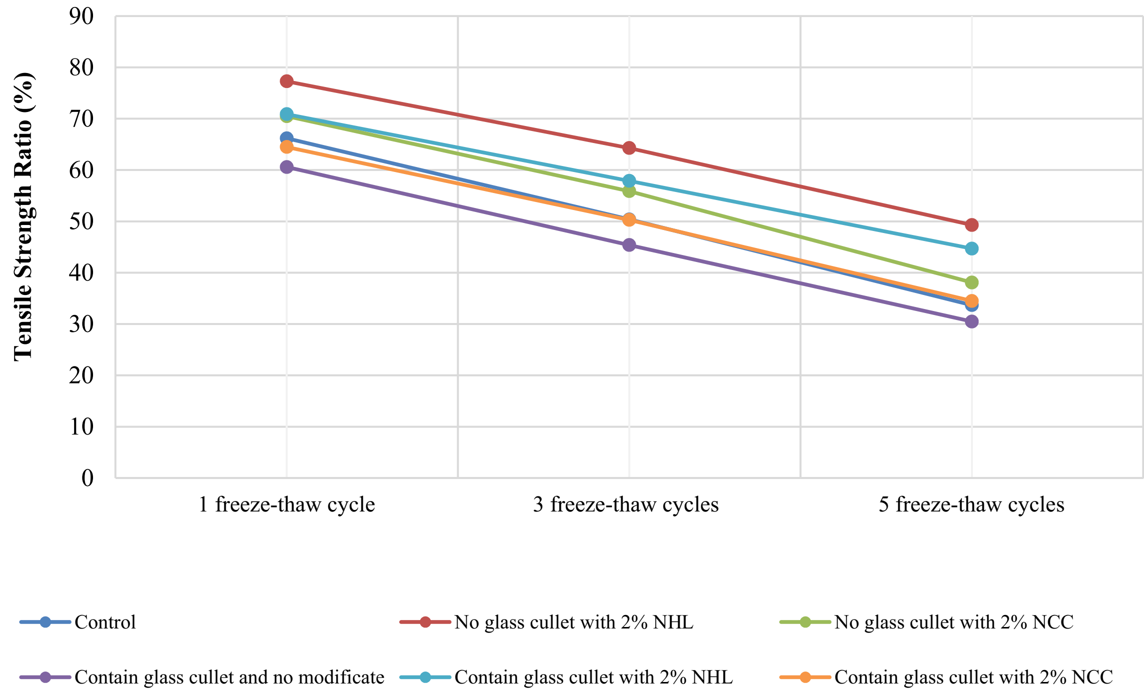

Fig. 11 TSR in asphalt mixtures made with quartzite

The results of a sessile drop test are presented in Fig. 12 to determine the components of SFE of the base and modified bitumen using both nanoscale materials. The results showed that bitumen modification using both nanoscale materials reduced its total SFE. The result of this reduction was the improvement of bitumen wettability on the surface of aggregates and, consequently, increased resistance to adhesion failure. Increasing in wettability made it possible to cover more contact surfaces of aggregate by bitumen, which could help to improve adhesion between bitumen and aggregate. Among these two nanomaterials, NCC had a greater effect on reducing total free energy; however, it should be kept in mind that the total SFE has a dual effect on the moisture resistance of asphalt mixtures because its increase improved the resistance to moisture damages (Cohesive type), which was considered as a positive effect on reducing the cohesive fracture. On the other hand, it reduced the bitumen wettability on the aggregate surface, which was undesirable for the creation of proper adhesion between bitumen and aggregates. Also, the results showed that the bitumen had acid property and the acid component of the bitumen SFE was larger than the base component of the SFE. The bitumen modification using NHL and NCC led to decreasing acid property and increasing the base property of base bitumen. It led to improving adhesion to acidic aggregates such as granite and quartzite, so that more initial energy was required for the stripping phenomenon in asphalt mixtures made of acidic aggregates. Therefore, determining and control of acid and base components in asphalt mixtures play an important role. Also, the polar component of bitumen was very small compared to its nonpolar component. Therefore, it could be noted that bitumen was a material with poor polar properties, and its bond with other materials was

Table 8 Various compounds of asphalt mixes made in this study

Mixture	Aggregate	Asphalt binder	Glass cullet	Additives
1	Limestone	AC 60–70	–	–
2		AC 60–70	–	NHL
3		AC 60–70	–	NCC
4		AC 60–70	10%	–
5		AC 60–70	10%	NHL
6		AC 60–70	10%	NCC
7	Granite	AC 60–70	–	–
8		AC 60–70	–	NHL
9		AC 60–70	–	NCC
10		AC 60–70	10%	–
11		AC 60–70	10%	*NHL*
12		AC 60–70	10%	NCC
13	Quartzite	AC 60–70	–	–
14		AC 60–70	–	NHL
15		AC 60–70	–	NCC
16		AC 60–70	10%	–
17		AC 60–70	10%	NHL
18		AC 60–70	10%	NCC

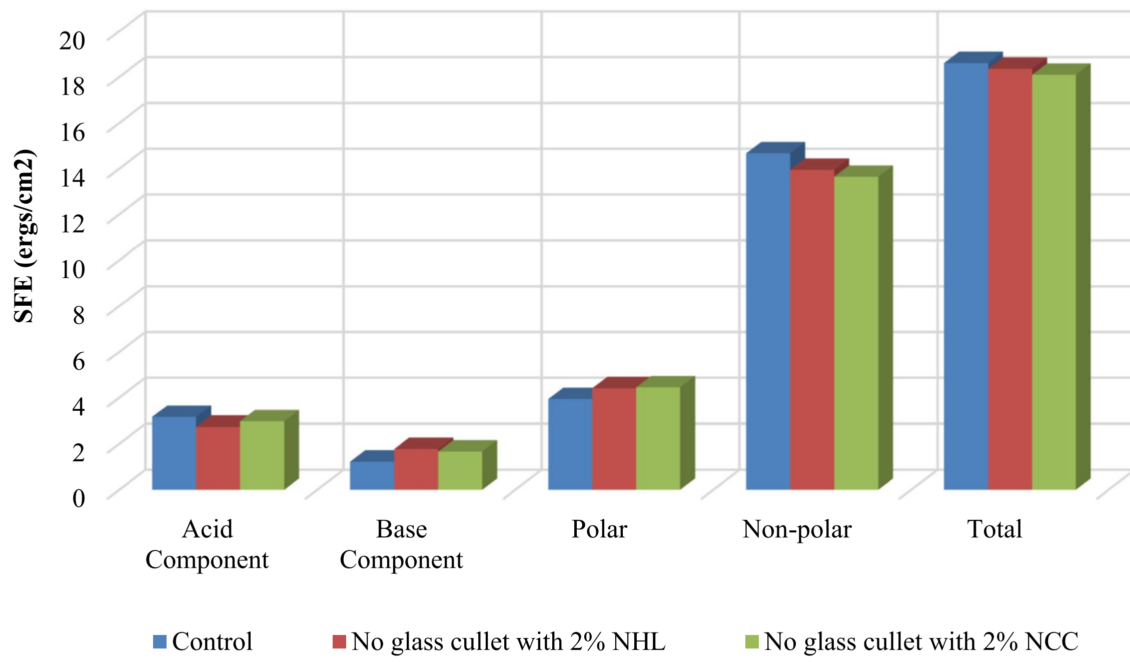

Fig. 12 SFE components of control and modified bitumen

Table 9 Cohesive free energy of bitumen (ergs/cm^2)

Types of asphalt binder	Cohesive free energy
AC 60–70	37.22
AC 60–70 modificate with NHL	36.72
AC 60–70 modificate with NCC	36.2

done mainly through the same nonpolar component of SFE and through covalent bonds.

The cohesive free energy of bitumen was considered as an important parameter in the investigation of the occurrence of moisture damage. There was a direct relationship between this parameter and the total free energy so that it was twice that energy. The values of this parameter for the base and modified bitumen are presented in Table 9. The results showed that using both nanomaterials reduced the cohesive free energy of bitumen. By decreasing this parameter, as the total free energy, the adhesive bond strength between bitumen and aggregate was improved.

Conclusions

Due to the fact that moisture damage is considered as the main source of stripping potential and also causes other failures in asphalt pavements, this phenomenon is expressed as one of the most important parameters in the destruction of glasphalt. Also, anti-stripping additives called NHL and NCC were used to improve the performance and increase the strength of glasphalt against moisture sensitivities. The most important results from the present study are as follows:

- Using glass cullet instead of a part of the stone material led to increasing the ITS in asphalt mixtures made of all three types of aggregates, including limestone, granite and quartzite in dry conditions, while the mixtures made of granite aggregates had the greatest resistance in dry conditions compared with other aggregates.
- Using glass cullet in asphalt mixtures reduced ITS in specimens made of all three types of aggregates, including limestone, granite and quartzite in wet conditions, where the strength was significantly reduced by the increase of the number of freeze–thaw cycles.
- Using both nanomaterials (NHL and NCC) significantly improved the strength of glasphalt and conventional asphalt mixtures made of all three types of aggregates, in both dry and wet conditions, whereas NHL also had a greater effect on the increase of the strength of the mixture in dry conditions as well as against moisture sensitivities compared with NCC. In addition, the effect of both additives on improving the strength of glasphalt and conventional asphalt mixtures against moisture sensitivities was greater than the dry mode.
- TSR of glasphalt and conventional asphalt mixtures decreased with the increase of the number of freeze–thaw

cycles for all three types of aggregates, which under all three types of cycles, glasphalt and conventional asphalt mixtures made of limestone aggregate showed better stability and resistance to moisture sensitivities than two other aggregates. In contrast, the mixtures made of quartzite aggregate showed the lowest TSR values, which indicated the poor performance of this aggregate against moisture sensitivities. In addition, using both nanomaterials, especially NHL, improved the values of this parameter for all specimens significantly.
- According to the results obtained from the thermodynamics experiments, bitumen had more acidic properties; its modification with NHL and NCC reduced this property, resulting in improved adhesion to acidic aggregates such as granites and quartzite, which were sensitive to moisture. Also, using both nanomaterials increased the polar characteristics of bitumen, which could improve adhesion to aggregates with high polar characteristics.
- Bitumen modification with both nanomaterials in general reduced the total SFE of the cohesive energy of the base bitumen, which caused the modified bitumen to be exposed to cohesive failure. In contrast, it was associated with improved bitumen wettability on the surface of the aggregate, which increased the resistance to adhesion failure.

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References

1. Ceran ÖB, Şimşek B, Uygunoğlu T, Şara ON (2019) PVC concrete composites: comparative study with other polymer concrete in terms of mechanical, thermal and electrical properties. J Mate Cycles Waste Manage 21(4):818–828
2. Wang W et al (2018) Laboratory investigation on high-and low-temperature performances of asphalt mastics modified by waste oil shale ash. J Mater Cycles Waste Manage 20(3):1710–1723
3. Muniandy R, Ismail DH, Hassim S (2018) Performance of recycled ceramic waste as aggregates in hot mix asphalt (HMA). J Mater Cycles Waste Manage 20(2):844–849
4. Chai L et al (2019) Mechanical properties of ecological high ductility cementitious composites produced with recycled crumb rubber and recycled asphalt concrete. J Mater Cycles Waste Manage 21(3):488–502
5. Aktaş B, Bozdemir S (2017) Evaluation of waste slags produced by zinc industry in bituminous hot mixtures. J Mater Cycles Waste Manage 19(1):192–200
6. Neşer G, Aytekin V (2015) Modification of bitumen-based roof covering material by glass reinforced polyester recyclate. J Mater Cycles Waste Manage 17(3):583–589
7. Lachance-Tremblay É, Vaillancourt M, Perraton D (2016) Evaluation of the impact of recycled glass on asphalt mixture performances. Road Materials and Pavement Design 17(3):600–618
8. Kandhal P (1993) Waste materials in hot mix asphalt —an overview. In: Waller H (ed) Use of waste materials in hot-mix asphalt. ASTM International, West Conshohocken, PA, pp 3–16. https://doi.org/10.1520/STP19841S
9. Maupin GW (1998) Effect of glass concentration on stripping of glasphalt (No. VTRC-98-R30). Virginia Transportation Research Council. Charlottesville, DC, United States
10. Lachance-Tremblay É et al (2017) Degradation of asphalt mixtures with glass aggregates subjected to freeze-thaw cycles. Cold Reg Sci Technol 141:8–15
11. Behbahani H et al (2015) Evaluation of performance and moisture sensitivity of glasphalt mixtures modified with nanotechnology zycosoil as an anti-stripping additive. Constr Build Mater 78:60–68
12. Arabani M, Tahami SA, Taghipoor M (2017) Laboratory investigation of hot mix asphalt containing waste materials. Road Materials Pavement Design 18(3):713–729
13. Su N, Chen J (2002) Engineering properties of asphalt concrete made with recycled glass. Resour Conserv Recycl 35(4):259–274
14. Arabani M (2011) Effect of glass cullet on the improvement of the dynamic behaviour of asphalt concrete. Constr Build Mater 25(3):1181–1185
15. Lottman RP (1982) Predicting moisture-induced damage to asphaltic concrete field evaluation. NCHRP report 246, NCHRP Institute, Washington, DC, United States
16. Lottman RP (1978) Predicting moisture-induced damage to asphalt concrete. NCHRP report 188, NCHRP Institute, Washington, DC, United States