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Effect of Glass Cullet Size and Hydrated Lime—Nanoclay Additives on the Mechanical Properties of Glassphalt Concrete

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Abstract: In this study, the use of glass waste as aggregate in asphalt mixtures was investigated. Maximum glass aggregate size options of 0.075, 2.00, 4.75 and 9.5 mm. were selected. Conventional bitumen, nanoclay-modified bitumen and hydrated lime-modified bitumen were used. Dense graded asphalt mixtures were designed according to the Marshall method. Mixtures were evaluated for low-temperature cracking, resistance to water damage, fatigue, and permanent deformation behavior with repeated creep, indirect tensile strength, indirect tensile fatigue, modified Lottman and Hamburg wheel tracking tests. Increasing glass aggregate size reduced the water damage resistance of asphalt mixtures because of the smooth surface of the glass particles and nanoclay and hydrated lime modification improved the mechanical properties of the asphalt mixtures. Using 2.00 mm sized maximum glass aggregate showed relatively less water damage and deformation properties due to higher internal friction which is due to the greater angularity of the glass particles. In addition, there was a significant correlation between repeated creep test, modified Lottman methods and Hamburg Wheel tracking test from the viewpoint of deformation and water damage assessments.

Keywords: asphalt concrete; cracking; fatigue; glass aggregate; hydrated lime; moisture damage; nanoclay; rutting; waste material

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1. Introduction

Glass wastes represent a significant proportion of the total amount of waste generated by society. The large amount of glass waste has been an urgent subject at both the national and global levels. Glass recycling can save energy and decrease environmental waste. Nearly 10 million tons of glass waste is generated every year around the world [1]. Some part of the waste glasses is reused by recycling. In the European Union, in 2018, 27 metric million tons of glass were produced but only 21% was recycled [2]. Only 33% of the glass produced in America was recycled in 2019 [3]. On the other hand, hundreds of thousands of tonnes of glass are being stockpiled and landfilled globally every year, which is a serious threat to the environment. Since glass is a non-biodegradable material, it is estimated to take one million years to break down naturally [4]. Because of the difficulty in monitoring emissions for a long time, there are more restrictions in terms of landfilling waste in developed countries [5]. The rate of reuse of recycled glass for making new glass products has been so low because of the difficulties and disadvantages associated with its recycling process, such as lack of recovery facilities in many locations, high processing costs, and poor quality of the recycled glass due to the presence of impurities [6]. Therefore, the reuse of waste glass in the construction area provides an alternative solution to its disposal. Currently, a simple option of waste glass reuse under exploration is in the replacement of natural aggregates in the road construction industry [7]. Waste glasses can be used in the base and subbase layers as well as in the asphalt surface course. This method is easy and economical to implement and contributes to the protection of natural resources.

Asphalt mixtures prepared by using waste glass particles in certain proportions substituted for natural aggregate are called "glassphalt" in the literature. Since the 1960s, various studies have been carried out on glassphalts [8–11]. Due to the high silica content of glass cullet, water damage problems take an important place in the mechanical properties of glassphalt mixtures. Therefore, the quantity and size of waste glasses to be used must be carefully determined.

Due to the high angularity of the glass particles, glassphalts show high stability. Higher stability values can be obtained than conventional asphalt mixtures when the correct maximum size and correct addition ratio are selected for the glass aggregate. In addition, the low absorption of glass aggregates helps to reduce the optimum bitumen content. On the other hand, flat and elongated glass particles can predispose to pavement raveling, stripping, excessive tire wear, and water damage problem due to hydrophilic glass particles. For this reason, it is recommended to use antistripping agents in glassphalts. While glass aggregate was used at a rate of more than 25% compared to the weight of the aggregate mixture in the first glassphalt studies, today it is recommended to reduce the glass aggregate ratio and size [1].

Some researchers [8–13] have suggested that the maximum glass size should be 4.75 mm, while some researchers [14,15] suggest it to be 9.5 mm. Another group of researchers [1,16] emphasized that the maximum glass particle size of 2.36 mm gives good results in view of asphalt pavement performance such as strength index, high temperature stability, and water stability.

On the other hand, because of the risk of damage to vehicle tires and the deterioration of stripping behavior, the content of the glass aggregate must be limited alongside the size [8]. In studies performed to determine the optimum glass content; 15% [10,15] and 10% [1,8,12,13] values are recommended. In one study [17] investigating of the effects of different filler species on the performance of asphalt mixtures, 8% glass content was expressed as optimal. Another study [18], in which glass powder was offered as an alternative to other filler types used in asphalt mixtures, argues that 7% of crushed glass dust content is optimal.

In a study in the literature, aggregates obtained from waste glass were used in asphalt mixtures of six different sizes (1/2, 3/8, No. 4, No. 8, No. 50, and No. 200) instead of natural aggregate at 1%, 2%, and 4% by weight were used. It was observed that the stability of the glassphalt increased by 166% when the glass powder filler passing through the No. 200 sieve was changed from 2% to natural aggregate [19]. In the study where the maximum amount of glass aggregate that can be used without stripping problems was investigated, the maximum glass aggregate size was chosen as 9.5 mm. The applied addition rates were 5%, 12%, and 20%. The water damage resistance of asphalt mixtures is evaluated by the tensile strength ratio (TSR). It has been observed that glass aggregate can be used up to 12% according to TSR ratios when using liquid anti-stripping additive and hydrated lime [15]. In a study where the maximum glass aggregate size was chosen as 4.75 mm, glass aggregates were used at the rates of 0%, 5%, 10%, 15%, and 20%. It has been stated that the stiffness modulus of asphalt mixtures containing 15% glass aggregate and 3–5% hydrated lime is the highest, and the sensitivity of glassphalts to temperature changes is lower than conventional mixtures [10]. In another study investigating the effect of nano zycosoil additive in asphalt mixtures with glass aggregate addition, the maximum glass aggregate size was selected as 4.75 mm and the addition rate was 10%. It was observed that the use of 4.5% nano zycosoil increased the tensile strength and water damage resistance of the asphalt mixture [12]. In another study, it was stated that the use of nano zycosoil at 3.5–5.5% rates increased the deformation resistance of glassphalts and the initial cost was acceptable when compared to the benefits provided [20]. In another study where the maximum glass aggregate size was determined as 4.75 mm, 3–5% hydrated lime was used as a modifier. As a result of fatigue tests, asphalt mixtures containing glass aggregate and hydrated lime showed significantly better fatigue performance than conventional asphalt mixtures [21]. In a study investigating the skid and water damage resistance of glassphalts, glass aggregates with maximum dimensions of 2.36 mm and 4.75 mm and zycotherm as an anti-stripping additive was used. It has been stated that the skid resistance of aggregate mixtures with 4.75 mm sized glass cullet is approximately 20% greater, but there is a decrease in water damage resistance, but acceptable mixtures can be obtained by using 0.1% zycotherm [22]. Waste glass powder, limestone powder, and portland cement were used in asphalt mixtures at the rate of 6% and 8% of the total aggregate weight instead of fillers, and it was observed that glass powder fillers gave higher Marshall stability and lower flow values compared to other additives [23]. In a study where glass aggregates in different ratios were tested in asphalt mixtures instead of natural aggregates, the maximum glass aggregate size of 2.36 mm was selected and it was seen that the most suitable glass aggregate ratio was 10%. It has been stated that mechanical properties such as high-temperature stability, water damage resistance meet the asphalt mix design standards at this addition rate and size [1]. In studies in the literature, it is generally recommended to use smaller-sized glass aggregates. For example, it has been stated that when sizes larger than 2.36 mm are selected, the pavement performance will decrease and stripping and raveling problems may occur in the pavement [24]. Similarly, in some studies, it is stated that when the glass aggregate size is selected small (maximum 4.75 mm), glassphalts behave similarly to mixtures with natural aggregates [25]. In another research, glass aggregates with a maximum size of 2.36 mm and 4.75 mm were used, in which glass aggregates were used instead of natural aggregates, and it was observed that the tensile strength of the asphalt mixture increased with the increase in glass aggregate size [26].

High SiO_2 content in the waste glass triggers the stripping problem. To reduce the moisture susceptibility of asphalt mixtures, hydrated lime, amine-based anti-stripping additives, polymers, and so on can be added to the bitumen or mixtures. In recent years, nanoclays have been attracting attention due to their ability to improve the performance of asphalt mixtures. These innovative materials can also be successfully used in glassphalt and increase resistance to water damage [12]. Due to the unique properties of nanomaterials, their use in asphalt mixtures is remarkable. Nanoclays are effective in increasing the permanent deformation and moisture damage resistance of asphalt mixtures [27,28].

In a survey investigating the effect of nanomaterials on water damage of glassphalts, nano-hydrated lime (NHL) and nano-calcium carbonate (NCC) were used as bitumen modifiers. Glass aggregates with a maximum size of 4.75 mm were added to the asphalt mixtures at the rate of 10% substituted for natural aggregate. Asphalt mixtures were designed with limestone, granite, and quartzite aggregates separately. It has been observed that the use of nanomaterials significantly improves the resistance of glassphalts to moisture sensitivity, and mixtures designed with limestone aggregate provide higher TSR and stability than other aggregates [29].

In a search for which stone powder, glass powder, and glass powder-hydrated lime composite should be used as alternative fillers in asphalt mixtures, the use of glass powder-hydrated lime composite showed higher mechanical properties than other options, rutting resistance, fatigue life, deformation resistance, and water damage resistance increased and moreover, it was seen that there was an economic gain [30].

The evaluation of glass wastes provides economic and environmental gains. One of the methods of minimizing glass wastes in the economy is to use them as aggregates in asphalt pavements. However, the size and proportion of glass aggregates in glassphalts are the subjects of research. In this context, the main purpose of this study was to investigate the effects of the size of the crushed glass used as aggregate in glassphalt mixtures. In addition, it was aimed to investigate the effects of hydrated lime and nanoclay modification on the mechanical properties of glassphalts at low, medium, and high temperatures, to compare the test results obtained by the repeated creep test, the Hamburg wheel tracking test, indirect tensile fatigue test, and the ASHTO T 283 method in terms of permanent deformation, moisture damage, and fatigue deterioration.

2. Materials and Methods

2.1. Materials

In this study, 50/70 penetration grade bitumen and basalt aggregates were used. Dense graded aggregate was used in accordance with the Turkish Highways Technical Specification [31]. The aggregate gradation was given in Table 1.

Table 1. Used aggregate gradation.

Sieve size (mm)	19	12.5	9.5	4.75	2.0	0.42	0.18	0.075
Passing (%)	100	94	81	47	30	15	11	6

Colorless waste glasses consist of construction glasses, which are the production residue of glass processing factories, were used as aggregate substituted for basalt aggregates. The largest sieve size was chosen as 9.5 mm. Sieving was done with standard sieves (4.75, 2.00, 0.425, 0.18 and 0.075 mm). An image of the sieved aggregates is shown in Figure 1. Glass aggregate gradation was selected the same as basalt aggregate gradation. The maximum size and ratios of the added glass aggregates were listed in Table 2. Chemical analysis results of the glass aggregates were also given in Table 3.

Figure 1. A view of the crushed and sieved waste glass aggregates.

Table 2. Glass aggregate ratios in aggregate mixture.

Option	**Maximum Glass Aggregate Size (mm)**						**Glass Aggregate Ratio (%)**
	9.5	**4.75**	**2.0**	**0.43**	**0.18**	**0.075**	
Option 1	✓	✓	✓	✓	✓	✓	15
Option 2		✓	✓	✓	✓	✓	15
Option 3			✓	✓	✓	✓	15
Option 4						✓	3

Hydrated lime was used as additive material at a rate of 2% based on dry aggregate. Nanoclay was also used as another additive in a 3% ratio by weight of bitumen. The nanoclay was produced from bentonite clay. Dimethyl, dehydrogenated tallow, quaternary ammonium was used as the organic modifier. Bitumen modification was made using a high shear mixer at 160 °C temperature for 30 min at a stirring speed of 4500 rpm for both additives.

Table 3. Chemical analysis test results of waste glasses.

Components	Formula	Value (%)
Silicon dioxide	SiO_2	70.4
Aluminum oxide	Al_2O_3	0.11
Titanium dioxide	TiO_2	0.086
Ferrous oxide	Fe_2O_3	0.205
Magnesium oxide	MgO	5.03
Calcium oxide	CaO	7.01
Sodium oxide	Na_2O	12.95
Potassium oxide	K_2O	0.51
Sulfur trioxide	SO_3	0.23

2.2. Mixture Design

Dense graded asphalt concrete was designed according to the Marshall Design method (ASTM D 1559). Optimum bitumen content was taken as the percentage of bitumen corresponding to 4% air voids. Designs were made for pure bitumen, hydrated lime (HL) modified bitumen, and nanoclay (NC)-modified bitumen and optimum bitumen content calculated as 5.30%, 5.60%, and 5.63% respectively.

2.3. Test Methods

In this study, the Hamburg wheel tracking test, repeated creep test, modified Lottman (AASHTO T 283) method, indirect tensile strength test, and indirect tensile fatigue test were performed. Conditioned samples were used in all tests except for the Hamburg wheel tracking test. The conditioning was carried out in accordance with the AASHTO T283 method. In the Hamburg wheel tracking test, samples were tested in water.

2.3.1. AASHTO T 283 Moisture Damage Test

The modified Lottman test was adopted as a standard with AASHTO designation T 283 and was later recommended by SHRP investigators as a tool for detecting moisture damage in SUPERPAVE-designed asphalt mixes [32]. The method evaluates the resistance of mixtures to water damage or the loss of strength of compacted hot mix asphalt (HMA). To determine the loss of strength due to water and freeze-thaw, the averages of the indirect tensile strengths of the samples in conditioned and unconditioned groups are taken and proportioned. The tensile strength ratio (TSR) and the resistance of the mixture to water damage are directly proportional. Asphalt mixtures with TSR values lower than 0.80 are considered to be resistless to water damage [33].

In this work, 101.6 mm diameter Marshall briquettes were produced by using nanoclay modified bitumen, HL modified bitumen and pure bitumen. Maximum glass aggregate size was selected as 0.075 mm, 2.00 mm, 4.75 mm, and 9.5 mm. The water damage assessment was conducted following AASHTO T 283 method.

2.3.2. Indirect Tensile Strength Test

Indirect tensile strength values are used to evaluate the relative quality of bituminous mixtures [34]. The cylindrical asphalt sample is loaded under pressure with constant deformation until it is deformed. Deformation in the test phase is defined as the time when there is no increase in the applied load or when the highest load occurs and the highest load to which the sample can bear is taken as the indirect tensile strength. The indirect tensile strength found in the test can be used in evaluating the cracking potential of the bituminous mixtures [35].

For the indirect tensile strength test, conditioned Marshall briquettes were used in accordance with the conditioning system described in the AASHTO T 283 method. Pure bitumen, nanoclay modified bitumen, and HL modified bitumen options were produced. Options with basalt and glass aggregates were also evaluated in this method. Tests were performed at 0 °C temperature. All samples were kept at 0 °C temperature for 18 h before the test.

2.3.3. Repeated Creep Test

Repeated creep test can be used to predict the rutting potential of asphalt mixtures. The test can be performed under test conditions such as different temperatures, loading stresses, loading periods, test durations, and several loads [36]. In the repeated creep test, the relationship between the cumulative permanent deformation and the number of load cycles is expressed. As the amount of deformation increases, the rutting resistance is reduced. In this study, repeated creep tests were performed on conditioned and unconditioned asphalt briquettes under EN-12697-25 (A) test standard. The conditioning was carried out following AASHTO T 283 method. The tests were carried out at 40 °C temperature, under the tension of 95 kPa, at a frequency of 0.5 Hz and 36,000 loading cycles.

2.3.4. Hamburg Wheel Tracking Test

For fast and reliable performance testing of hot mix asphalt, the Hamburg wheel tracking device (HWTD) was originally designed to measure permanent deformation behavior, but then it was evaluated as sufficient to determine the potential resistance to moisture damage of asphalt mixtures. The device began to be explored to characterize the water sensitivity of asphalt mixtures and to predict field performance. This test was found to be sensitive to aggregate quality. It has become a popular method for evaluating permanent deformation and stripping of asphalt pavements [37].

Test temperature is of great importance to reveal the results of the test in a meaningful. According to the wheel tracking test results applied in water at different temperatures, samples were dispersed because of the decrease of the stiffness of the sample when the test temperature was chosen to more than 60 °C [38]. It was proposed that the temperature of the test should be selected below 50 °C to avoid excessive permanent deformations not associated with water damage. In a study, 40 °C and 50 °C test temperatures were selected and it was seen that the results obtained at 50 °C were inconsistent, the performance of the modified mixtures at 40 °C could be predicted properly and consistent results were revealed [39].

In this study, cylindrical specimens 150 mm in diameter and 60 mm in thickness, compacted with a gyratory compactor, were used for the Hamburg wheel tracking test. The test was carried out according to the AASHTO TP 324 standard, in the process described as double core, in water, and at a temperature of 40 °C.

2.3.5. Indirect Tensile Fatigue Test

Fatigue for asphalt pavements is explained as the phenomenon causing cracking (consisting of crack initiation and propagation phase) due to the tensile strains generated in pavements when subjected to load repetition, temperature variation, and inadequate construction practices collectively [40]. The fatigue behavior of asphalt mixtures can be evaluated by indirect tensile fatigue test (ITFT) [41]. Fatigue test can be conducted at controlled stress (load) or strain modes. During the controlled stress mode amount of applied stress is kept constant, and the amount of strain increases. In controlled strain mode, the strain value (deformation) is kept constant while the stress decreases during the test [42].

ITFTs were performed in Cooper universal test machine with EN 12697-24 (Annex E) standard. The test was carried out at 25 °C. Samples were placed in a temperature-controlled cabinet 12 h before the test. 250 kPa constant stress was applied with a frequency of 10 Hz and a rest period of 1:4.

3. Results

3.1. Moisture Damage Test Results and Evaluations

Water sensitivities of glassphalts prepared with modified (nanoclay: NC and hydrated lime: HL) and conventional (C) bitumen were evaluated by the AASHTO T 283 method. Maximum glass aggregate size was increased from 0.075 mm to 9.5 mm and four glassphalt mixtures were prepared. Figures 2–4 show unconditioned indirect tensile strengths (ITSs), conditioned indirect tensile strengths, and tensile strength ratios (TSRs) of the mixtures, respectively. The values shown in the figures are the average of the values obtained from the three samples.

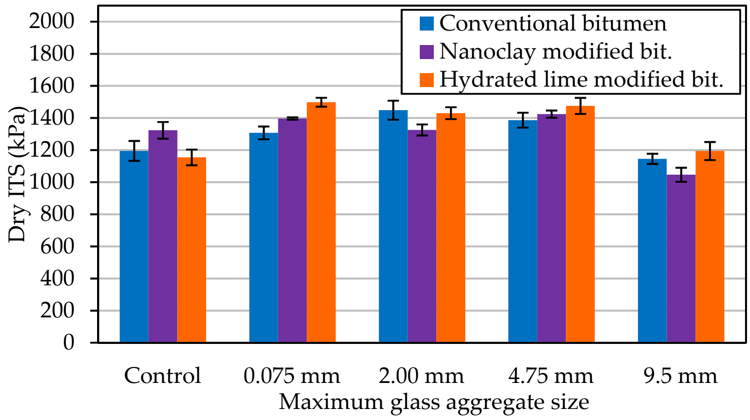

Figure 2. ITS values of unconditioned glassphalt mixtures.

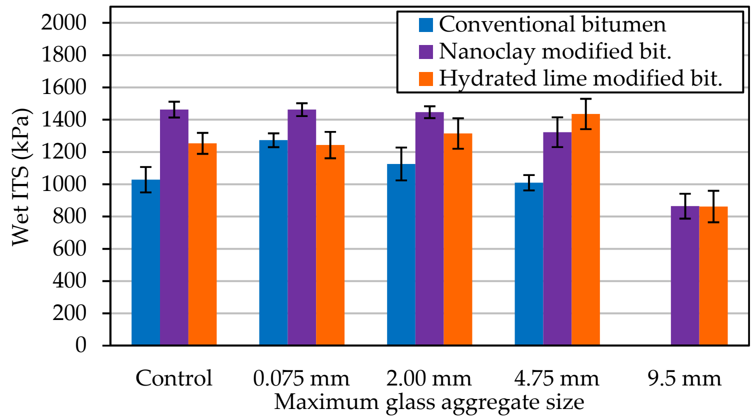

Figure 3. ITS values of conditioned glassphalt mixtures.

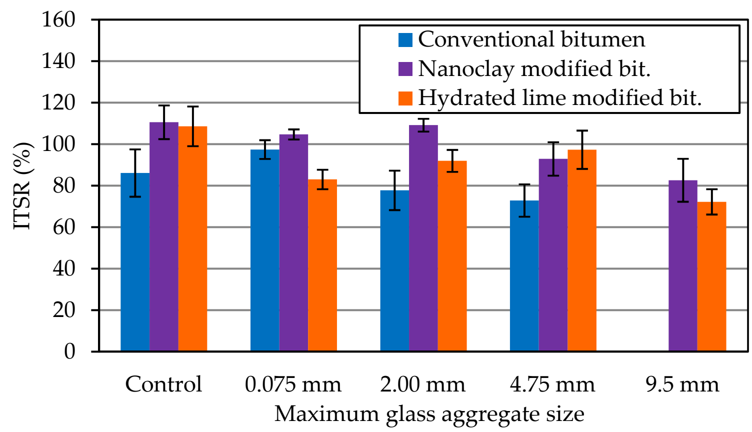

Figure 4. Tensile strength ratio and glass aggregate size relationship.

As can be seen from Figure 2, unconditioned mixtures containing 0.075, 2.0 and 4.75 mm glass aggregates have higher tensile strength than control mixtures. However, when glass aggregate was used at the maximum size of 9.5 mm, the strengths of mixtures with unmodified and nanoclay-modified bitumen decreased and the strength of hydrated lime modified bituminous mixtures increased according to control mixtures. The use of nanoclay and hydrated lime as modifier increased the tensile strengths of mixtures including 0.075 and 4.75 mm glass aggregate. However, this increase was not clearly seen in other glass aggregate sizes for both additives. When the conditioned samples were used (Figure 3), the effect of the modifiers was seen more clearly than the unconditioned samples. The mixtures prepared with modified bitumen showed higher tensile strengths except HL modified mixture including 0.075 mm glass aggregate. On the other hand, in the options used pure bitumen, the addition of glass dust as filler gave the highest strength. While the glass aggregate size increased up to 4.75 mm in HL modified mixtures, tensile strengths increased. Indirect tensile strengths of the NC modified mixtures have not changed significantly for control mixtures and mixtures included 0.075 and 2.00 mm sized glass aggregate. However, dramatic decreases were seen in options using glass aggregates in 4.75 and 9.5 mm sizes. Also, tensile strengths cannot be determined from asphalt mixture samples included 9.5 mm-sized glass aggregates due to dispersion of briquettes in the hot water conditioning phase.

The use of broken glass as aggregate in different sizes affected the water sensitivity of asphalt mixtures (Figure 4). When 9.5 mm glass aggregates were used in the mixtures without modified bitumen, asphalt briquettes were dispersed in the hot water conditioning step. However, interestingly, the use of glass dust in filler size increased the water damage resistance of these mixtures. However, the further increase in the size of the glass aggregate reduced the resistance to moisture damage. Glass aggregates break more angularly than basalt aggregates. When small glass aggregate size (0.075 mm) is used, it creates high cohesion in the mastic. However, when the size increases, the smooth surfaces of the glass aggregates increase. Due to smoothness and low bitumen absorption, adhesion loss occurs between bitumen and glass aggregate. The bond between bitumen and aggregate can break more easily and stripping problem may occur. Moreover, stripping behavior due to the high SiO_2 content of the glass aggregates may trigger.

The TSR value was greater than 0.80 for all options using modified bitumen except for options using 9.5 mm glass aggregate. The highest TSR values for mixtures using 0.075 and 2.00 mm glass aggregates were obtained with nanoclay-modified blends. In the case where 4.75 mm sized glass aggregate was used in the mixture, hydrated lime modification afforded the best results. Given the tensile strength and TSR values at 25 °C, it appears possible to use waste glass as small and medium-sized aggregate in asphalt mixtures when using modified bitumen in terms of water damage. However, attention must be paid to the ratio of glass aggregate used.

The main problem encountered is that the water damage performances are lower in asphalt mixtures with glass additives, which results in stripping of the aggregate. Compared with mineral aggregates, glass aggregates are less absorptive because they have less voids and a smooth structure. Presence of organic acids in asphalt and aggregates, ion exchange can occur. SiO_2, which is the main element of glass, does not establish such an ion exchange link with asphalt. All these features accelerate the distress of the glassphalt mixture. Hydrated lime can be used to prevent this distress mechanism [43].

In a study evaluating the stripping problem of glassphalt mixtures, two different wearing course mixtures were evaluated. Chemical anti-stripping additive and hydrated lime were used in each mix. As the percentage of glass increased in conventional and modified admixtures, TSR values generally decreased. With increasing percentages of glass aggregate, it has been observed that the hydrated lime modification does not yield a significant gain. However, it has been found that mixtures with less susceptibility to stripping are effective in producing higher TSR values [15].

Anti-stripping properties of the hydrated lime produce stronger cohesion between aggregate-glass particles and bitumen. Furthermore, when the glass particles are compared with conventional aggregates, high angularity of the glass cullets plays an important role in the increased dynamic modulus behavior of the asphalt mixture [44].

3.2. Indirect Tensile Strength Test Results and Evaluations

The indirect tensile strength tests were performed at 0 °C to evaluate the low-temperature cracking properties of the glassphalt mixtures. In the tests, Marshall briquettes with a diameter of 101.6 mm, conditioned according to the AASHTO T 283 conditioning procedure, were used. The averages of the indirect tensile strength values obtained from three identical samples for each mixture option were taken and the test results were summarized in Figure 5.

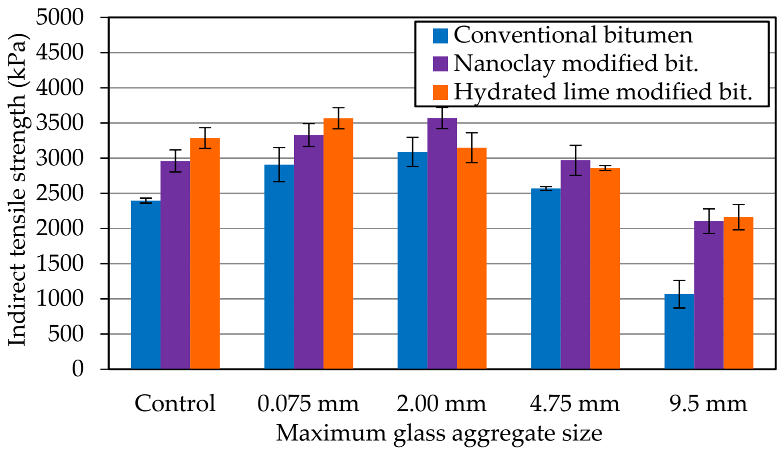

Figure 5. Indirect tensile strengths of glassphalt mixtures at 0 °C.

High tensile strength values indicate that the asphalt mixture has high resistance to cracking. It can be seen from Figure 5 that the mixtures with small size glass aggregates (0.075 and 2.00 mm) exhibit higher cracking resistance than mixtures prepared with completely basalt aggregates. However, as the glass aggregate size increases further, the cracking resistance also decreases. Compared to the control mixture with conventional bitumen, all mixtures except for 9.5 mm sized glass aggregates were found to have lower cracking potential. Modification of the bitumen with nanoclay or hydrated lime has a significant positive effect in terms of cracking resistance.

It has been reported that asphalt concrete samples containing crushed glass and 3–5% hydrated lime exhibit very good fatigue performance compared to conventional hot mix asphalt. The fatigue life of samples containing 5% and 10% crushed glass aggregate was 50% and 100% longer, respectively, than conventional HMAs at the same temperature [21]. This increase in fatigue life can prevent the cracking of the asphalt pavement layer by increasing the internal friction angle of the mixture and improving the interlocking between the different particles due to the high angularity of the glass particles. Due to the anti-stripping properties of hydrated lime, bitumen provides better adhesion between aggregates and reduces the relative displacement of stone aggregates to a minimum. Thus, the fatigue life of the pavement increases and the initial cracking and crack propagation slow down [21].

Moisture damage and cracking resistances of the mixture can be improved by adding nanomaterials in asphalt mixtures or bitumen. A significant increase in the tensile strength values of the asphalt mixtures was found with the 4.5% nanozycosoil modification. The increase in tensile strength indicates that the modified mixture can withstand larger tensile stresses before cracking [12,27].

3.3. Repeated Creep Test Results and Evaluations

Conditioned and unconditioned samples were tested at 40 °C temperature and 36,000 pulses. Figures 6–11 show the test results of unconditioned and AASHTO T 283 conditioned mixtures. The curves in the graphs were drawn by taking the average of the three test results.

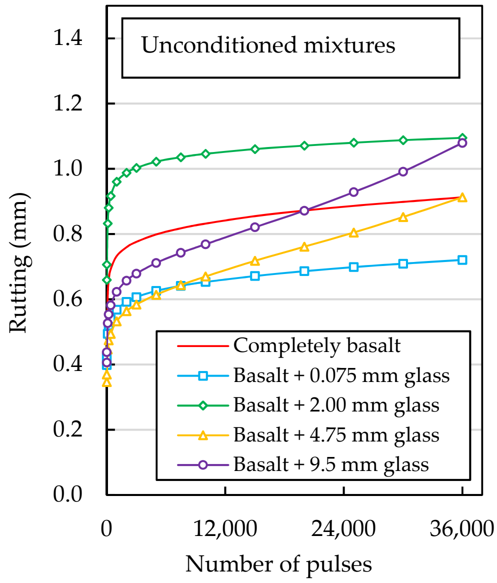

Figure 6. Repeated creep curves for mixtures with conventional bitumen.

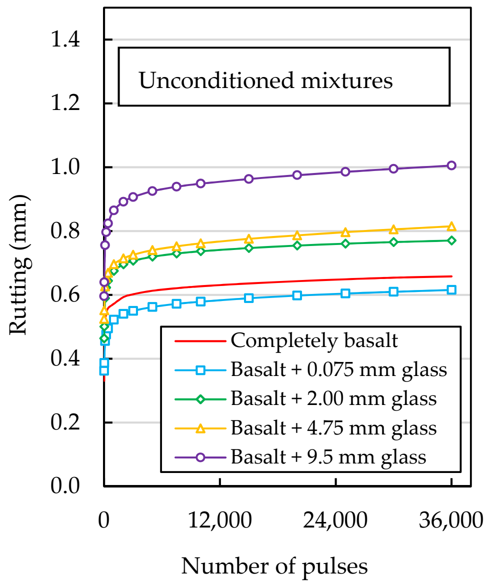

Figure 7. Repeated creep curves for mixtures with NC modified bitumen.

As can be seen from Figures 6–8, in all asphalt mixtures containing glass dust in the filler size, both conventional and modified bitumen, the smallest deformation potential was found. The nanoclay-modified mixtures—with the maximum glass aggregate size selected as 9.5 mm—showed the highest deformation. Conventional and hydrated lime modified bituminous mixtures included 9.5 mm sized glass aggregate tend to exhibit greater deformation at higher loading numbers than other mixtures due to the slope of the deformation curve in the second zone. According to the test results, it is not possible to make the same generalization for all three mixture types (conventional, NC-modified and HL-modified) using glass aggregates of 2.00 and 4.75 mm maximum aggregate sizes.

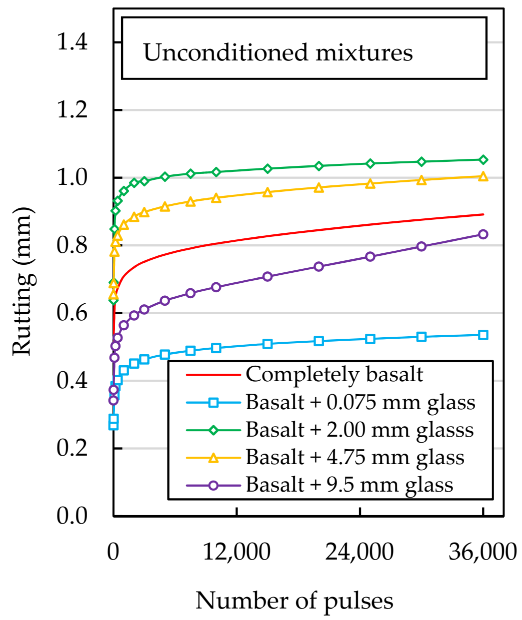

Figure 8. Repeated creep curves for mixtures with HL modified bitumen.

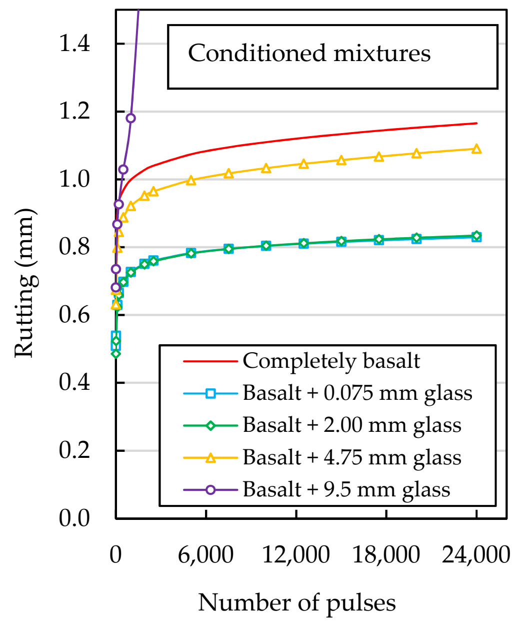

Figure 9. Repeated creep curves for conventional mixtures.

Effect of the glass aggregate size was shown more obvious on the conditioned samples in Figures 9–11.

Mixtures with 9.5 mm maximum sized glass aggregate exhibited much higher deformation values than other mixtures and even tertiary regions were formed in the creep curves. Conventional and nanoclay modified bituminous mixtures using glass aggregates of 0.075 and 2.00 mm revealed the smallest deformation value. For the hydrated lime modification, no significant difference was observed between the complete basalt aggregate and the small size of the glass aggregate. However, glass aggregate options with a maximum size of 4.75 mm showed the highest performance in terms of deformation resistance. It was also found that the modification of the nanoclay and hydrated lime increased the rutting resistance of the conditioned and unconditioned mixtures.

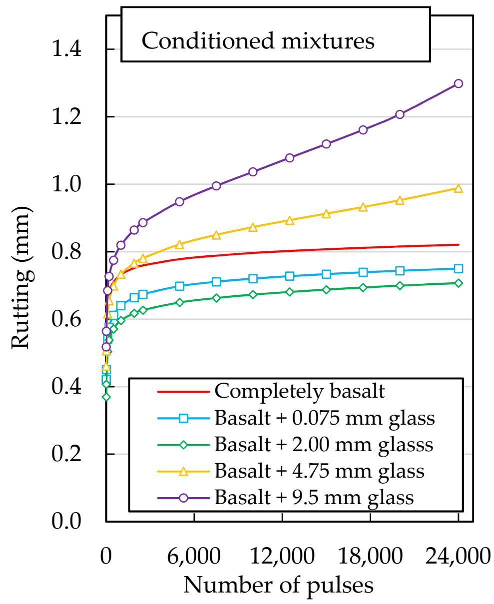

Figure 10. Repeated creep curves for NC modified mixtures.

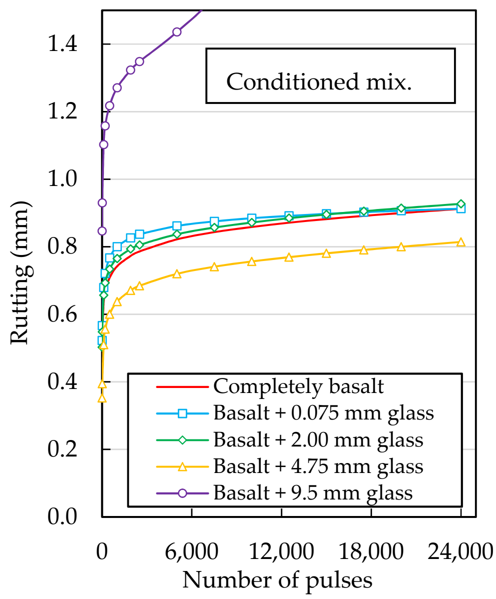

Figure 11. Repeated creep curves for HL modified bitumen.

In a study to investigate the effect of nanotechnological material on rutting resistance of glassphalt mixtures, the nano material was added to the asphalt binder by 3.5 and 5.5% by weight of bitumen. Waste glass cullets were used as 0%, 5%, 10%, 15% and 20% ratios in asphalt mixtures and the maximum glass aggregate size was chosen as 4.75 mm. Deformation resistances of glassphalt mixture modified with nanomaterial have increased significantly [20]. It has been stated that when 15% crushed glass is used, the asphalt mixture may perform better performance than the conventional dense graded mixture in terms of the rutting at 50 °C test temperature [44].

3.4. Hamburg Wheel Tracking Test Results and Evaluations

Hamburg wheel tracking test was carried out in water. The test was realized at the same temperature (40 °C) so that the results obtained could be compared with those obtained from the repeated creep test. Three tests were performed for each option. The obtained deformation curves were given in Figures 12–14.

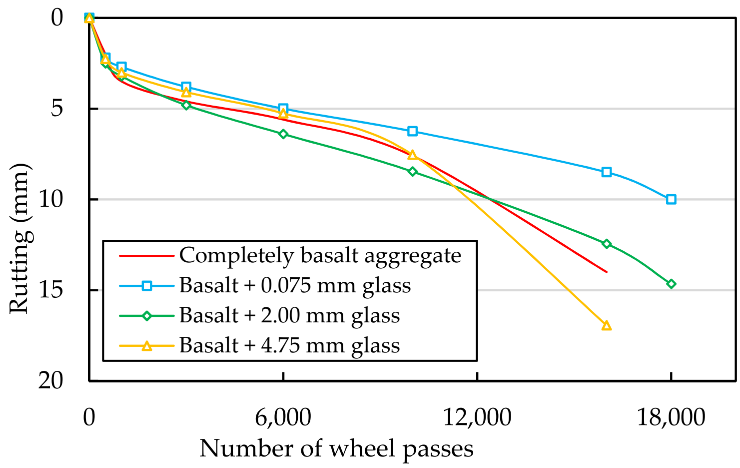

Figure 12. Hamburg test curves of conventional glassphalt mixtures.

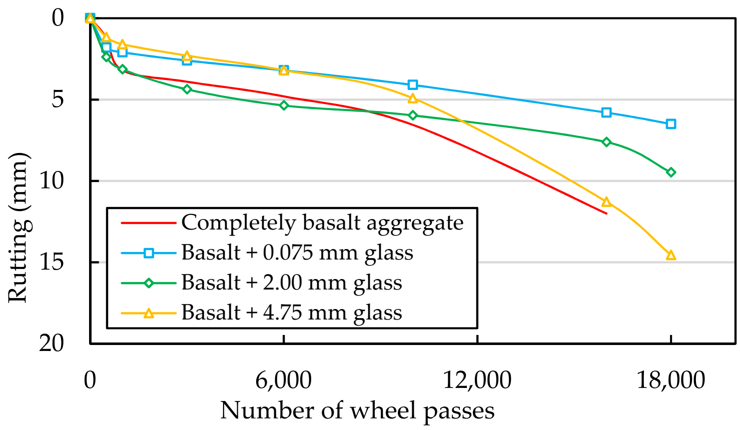

Figure 13. Hamburg test curves of NC modified glassphalt mixtures.

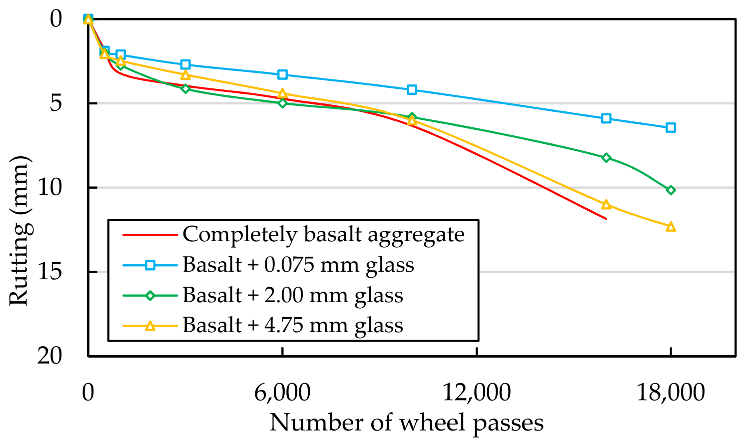

Figure 14. Hamburg test curve of HL modified glassphalt mixtures.

According to test results, it was seen that the addition of glass aggregates instead of basalt aggregate increased the deformation resistance of asphalt mixtures. Mixtures using glass dust instead of basalt filler showed the highest rutting resistance. At the same time, the increase in the size of the glass aggregate accelerated the stripping behavior. Mixtures used glass aggregates of 4.75 mm size reached the stripping inflection point in smaller wheel passages compared to other mixtures. On the other hand, the addition of glass dust as filler also improved the stripping behavior of asphalt mixtures.

In order to determine the maximum amount of broken waste glass in asphalt mixture, two different sizes of broken glass were selected, 0–0.315 and 0.630–2.5 mm, and the evaluations were made in terms of the rutting and cracking resistance. Glass aggregates were used in place of mineral aggregates in contents of 5%, 10%, 15%, 20% and 25% by mass. The use of waste glass aggregate in the asphalt mixture reduced the binder content and increased the workability of the mixture. The use of 10% glass aggregate in the asphalt mixture did not affect the thermal cracking resistance as much as the rigidity of the mixture. The rutting resistance of the glassphalt mixture increased but stripping resistance was negatively affected by the presence of glass. The thermal cracking resistance of the glassphalt mixture was found to be equivalent to that of the reference mixture [45]. An increase in the percentage of glass aggregate in the mixture increases the aggregate angularity and achieves better interlocking. Specimens containing more than 15% glass cullets can resist larger stresses and permanent deformation also can reduce. Better interlocking between aggregates and large-sized glass particles reduces the amount of deformation. In samples with a low percentage of glass fragments, fatigue crackings occur much earlier [11,46].

3.5. Indirect Tensile Fatigue Test Results and Evaluations

Indirect tensile fatigue test was performed for all designed asphalt mixture options under 25 °C temperature and 250 kPa stress after AASHTO T 283 conditioning. Three samples were used for each mix option. The fatigue life of the mixtures was taken as the average of the fatigue life of the three samples and is shown in Figure 15.

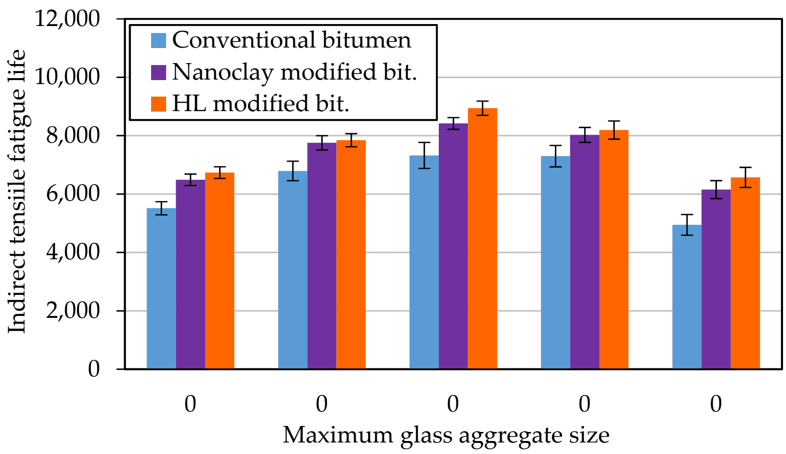

Figure 15. Indirect fatigue life of glassphalt mixtures.

According to the test results, the use of small size glass aggregates instead of basalt aggregate increased the fatigue life of the mixture. However, it is seen that fatigue life decreases in basalt aggregate options when the broken glass size is 9.5 mm. Even if the glass aggregates are more angular than the basalt aggregates, they are likely to have poor bitumen adhesion due to their smooth surface when they are large in size. This affects fatigue life. Options with a glass aggregate size of 2 mm showed the best fatigue behavior, including modified mixtures. By increasing the maximum size of glass aggregate to 4.75 mm, there was little reduction in fatigue life compared to the 2 mm glass size options. Both nanoclay and hydrated lime modification improved the fatigue behavior of the mixtures.

The increase in population, mobility, traffic volume and axle loads, and changes in production and consumption habits cause more stress on asphalt pavements. For this reason, asphalt pavements must be designed to be more resistant to both environmental conditions and traffic loads. For this reason, increasing the quality of asphalt pavement components, gradation changes, or using additives are frequently used methods. The supply of aggregates, which make up more than 90% of the asphalt mixture, is getting more and more difficult due to the decrease in resources and legal restrictions. For this reason, it is a necessity to protect aggregate resources and to use existing materials more efficiently. Researchers have focused on the use of various waste-based materials in asphalt pavements to improve the mechanical properties of asphalt pavements and increase their durability.

In this study, it has been seen that filler material obtained from waste glass or glass aggregate with a maximum size of 2.00 mm can be used together with nanoclay or hydrated lime instead of natural basalt aggregate. When waste glass aggregate was added to the asphalt mixture, it was observed that the cracking resistance, fatigue life, rutting, and water damage resistance of the mixture were all improved. When evaluated in these aspects, glassphalts are eco-friendly asphalt mixtures that are also sustainable in terms of mechanical properties and durability, so as to minimize maintenance treatments and achieve cost-effective asphalt pavements in the long term. The improvement of the mechanical performance of the material, the reduction of waste in landfills, extraction of natural aggregates, and the energy necessity to produce, build, and maintain asphalt pavements are themselves indicators of the environmental sustainability of a solution.

Since asphalt mixtures are produced at high temperatures, high greenhouse gas emissions are emitted. For this reason, it is necessary to pay attention to designing a long-lasting asphalt pavement that will minimize fuel, energy, and natural resource consumption. The use of waste glass aggregates substituted for natural aggregates in asphalt pavement construction is considered to be one of the most appropriate areas for potential recycling of waste glass, as it can reduce the consumption of natural resources and waste disposal costs, as well as protect the environment from harmful effects.

4. Conclusions

The effect of the glass aggregate size on the mechanical properties of the glassphalt mixtures modified with hydrated lime and nanoclay was evaluated. Following conclusions can be concluded from the research.

The use of glass aggregates substituted for mineral aggregates in asphalt mixtures significantly affects the mechanical properties of the asphalt mixture. According to the indirect tensile strength test results, the use of glass aggregate instead of filler or 2.00 mm maximum-sized mineral aggregates increases the tensile strength of asphalt mixtures. When glass aggregates are used larger size, the tensile strength of the unconditioned samples increases, but there is a decrease in the conditioned ones.

The presence of glass aggregate in asphalt mixtures increases the moisture damage sensitivity. However, when modified bitumen is used, TSR ratios usually remain above 0.90 up to 4.75 mm glass aggregate size. According to the AASHTO T 283 method, the nanoclay modification for the produced glassphalts gave more effective results than the hydrated lime modification. The use of glass aggregate as filler according to the Hamburg wheel tracking test results revealed the highest resistance to water damage when both conventional and modified bitumens were used. When the glass aggregate size increased, moisture sensitivity increased. AASHTO T 283 method and the Hamburg wheel tracking test revealed similar results in view of the prediction of water damage.

Among all the unconditioned mixtures, the smallest deformations were seen in glass dust added mixtures instead of filler according to the repeated creep test results. In conditioned mixtures, filler and glass aggregates with a size of 2.00 mm exhibited high performances. Similar results were obtained from the Hamburg wheel tracking test. However, as the use of glass aggregate at the maximum size of 2.00 mm increased the stripping sensitivity, waste glass is considered to be more suitable to be used instead of filler. HWTT results are similar to the AASHTO T 283 method for water damage assessment and the repeated creep test for the evaluation of deformation resistance.

The highest fatigue life was observed in mixtures containing 2.00 mm sized glass. The fatigue life of the mixture was increased with the modification of nanoclay and hydrated lime. Hydrated lime provided better fatigue behavior than nanoclay as a bitumen modifier.

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