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Evaluating the Effect of Liquid Antistrip Additives on Moisture Sensitivity of Glassphalt

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ABSTRACT: With the rapid economic growth and continuously increased consumption, a large number of waste materials are generated. Waste materials reusing will reduce the demand for the natural resources of the raw materials, and it will reduce the spaces used as landfills. Among these wastes is glass, which is widely used in our daily life. The major problem with the use of glass in asphalt mixes has been the incompatibility of glass and asphalt binder at their interface particularly in the presence of moisture. The objective of this research is to promote the strength of glassphalt against moisture damage with liquid anti-strip additives (LAA) based on the properties that affect the adhesion between the aggregate-asphalt binder and the cohesion strength of the asphalt binder. Surface free energy (SFE) and laboratory testing in different freeze-thaw cycles were used to evaluate the effect of LAA on the moisture susceptibility of glassphalt. The fine part of natural aggregate (NA) was replaced by CG at rates of 0, 5, 10, 15, and 20%. The results showed that, for mixtures containing crushed glass (CG), the tensile strength ratio (TSR) is lower than those of the control mix, and they decreased when the CG increased in the mix. The use of LAA caused the TSR of glassphalt to increase up to 80%. Also, the results of the SFE method showed that adding LAA causes the total SFE of the asphalt binder to increase, which results in a decrease in stripping between the glass aggregate and asphalt binder in the presence of water.

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1- Introduction

Recycling is considered to be one of the most important bases of sustainability. Almost all the products we utilize, whether they are metal, concrete, plastic, wood, or even glass, will eventually turn into wastes that must be disposed [1]. Dealing with the growing problem of disposal of these materials is an issue that requires coordination and commitment by all parties involved. One solution to a portion of the waste disposal problem is to recycle and use these materials in the construction of highways [2]. The use of waste materials (recycling) in the construction of pavements has benefits in not only reducing the number of waste materials requiring disposal but can provide construction materials with significant savings over new materials. The use of these materials can provide value to what was once a costly disposal problem [3]. Crushed glass is a readily available, environmentally clean, relatively low-cost material whose engineering performance properties generally equal or exceed those of most natural aggregates [4]. Waste glass is considered one of the most important parts of the collected waste materials, it is nonmetallic and inorganic, it can neither be incinerated nor decomposed, so it may be difficult to reclaim. Waste glass has been used in highway construction as an aggregate substitute in HMA paving. Many countries have recently incorporated glass into their roadway specifications, which had encouraged greater use of the material [3]. When crushed waste glass is incorporated in HMA mix the resulting mixture is sometimes referred to as "glassphalt" [5].

In recent years, the discovery of several economic and environmental benefits could increase the use of recycled glass in highway construction, evaluating the engineering properties of glass and aggregate mixes necessary. The uses of recycled glass have varied widely, depending on the specific application. Crushed recycled glass, or cullet, has been used independently and has also been blended with natural construction aggregate at different replacement rates [6].

Glassphalt is used in the structural layers of the pavement below the surfacing layer to prevent the problems that occur when it is used as surfacing asphalt. These include lack of skid resistance and poor bonding of glass cullet to the bitumen in the asphalt mix, which results in stripping and raveling problems [2].

1- 1- Literature review

To date, there have been few studies concerning the recycling of waste CG aggregate in the asphalt pavement industry. Arabani [7] assessed the behavior of HMA in different temperature conditions depending on the variation of

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the admixture contents and the gradation of the aggregates will be evaluated. Afterward, for the first time, models for the prediction of the stiffness modulus of waste glass-asphalt in terms of three different parameters including temperature, percentage of additives, and the aggregate gradation was presented in this study. The results of this research are indicative of an improvement in the dynamic behavior of glass-asphalt mixture in comparison with conventional HMA. In 2012, the linear viscoelastic behavior of glassphalt mixtures is investigated by Arabani and Kamboozia [8]. In this paper, the experimental model of the visco-elastic behavior of glassphalt mixtures was presented that can describe this behavior of glassphalt under dynamic loading and different temperatures. To achieve this goal, a series of repeated load axial tests are conducted under different temperatures and stress levels. The effects of loading stress and temperature on the creep behavior were investigated. Also, the predictions from the Burgers model were compared with the experimental results. Results showed that both of experimental visco-elastic models and the Burgers model show a good precision in simulating the material creep response in the viscoelastic range at least for the testing stress level and temperature given in their paper.

There are few studies in the field of moisture damage of glassphalt. One study was conducted by Wu et al. [9] in which, the performance of asphalt concrete was studied where some of the fractional fine aggregates is substituted with CG material. In this study, the Marshall test was used to examine the influence of optimal asphalt content, volume properties, and strength of asphalt concrete when different percentages of CG were added. The tests data from the modified Lottman test, freeze-thaw pedestal test, and wheel tracking test immerged in water showed that the resistance against water damage of glass-asphalt concrete is more feeblish than ordinary asphalt concrete. The properties can be improved by using hydrated lime admixture. The high-temperature stability and fatigue performance of glass-asphalt concrete were also tested and the results are satisfactory. The result of this research has demonstrated that the recycling and use of waste glass in asphalt concrete is feasible. In another study that had been conducted by FHWA in 1998, it had been tried to determine the maximum amount of glass that can be used in glassphalt without sacrificing stripping resistance. Two mixes, each containing chemical, and hydrated lime antistripping additives were made at several glass content. The AASHTO T283 test was used to assess the stripping resistance of the mixes. Both additives procedures adequate stripping resistance with exception of the mix containing 20 percent glass and chemical additives. Based upon the result of the AASHTO T283 test as a performance indicator, it was found that using up to 15 percent glass in glassphalt is acceptable [10]. In another study, the finite element method was applied to model the fatigue behavior of glassphalt and conventional mixtures. To assess the efficiency level of the presented model, all mixtures were tested using a 4-point bending test. The estimation models have predicted the fatigue life of similar samples with only a 3% error. Also, laboratory results showed a 5% improvement in the fatigue performance of the glassphalt rather than conventional mixtures [11]. Jo et al. [12] applied waste glass aggregate (WGA) to manufacture for paving asphalt mixture containing reclaimed asphalt pavement (RAP). The WGA below 5 mm which is replaced the part of natural fine aggregate (NFA) was used to manufacture recycled warm mix asphalt mixture (RWMA) that contained RAP, crumb rubber modifier (CRM), waste polyethylene (W-PE), and warm mix additive. Performances of RWMA for the base layer were satisfied the specification of the Ministry of Land, Infrastructure, and Transport, even if WGA was substituted for NFA up to 15%. This was believed to be due to the increased stiffness of the aged binder in RAP and the influence of CRM, W-PE used as modifiers, and warm mix additives. A laboratory investigation was carried out by Eisa et al. [13] into the effect of adding Glass Fiber (GF) on some properties of HMA mixtures. Results of the study led to important conclusions regarding using of GF to improve most of the properties of HMA mixtures. Finally, this study recommended a proposed mix with 0.25% GF by weight of the total mix.

Moisture damage is one of the main distresses in asphalt mixtures that are caused by poor asphalt binder cohesion or asphalt binder-aggregate adhesion. This distress is more critical for glassphalt due to the structure of the glass aggregates .[[14, 15

2- The Statement and Objectives of the Present Study

Although the glass is a nonmetallic inorganic material that cannot be decomposed or burned and many countries have recently incorporated glass into their roadway specifications, till now there is no use of recycled glass in our country.

Many applications could make use of recycled glass such as using glass as aggregate in road base and sub-base, aggregate in asphalt, aggregate in tiles, aggregate in decorative concrete for architectural facades, filtration material, an alternative to fill and bedding material, aggregate in concrete and asphalt. Considerable interest was shown from the 1970s to using waste glass as a part of the aggregate phase in asphalt mixes. Glass being hydrophobic results in a low asphalt absorption capacity, causing adhesion problems, or "stripping". In this study, it has been tried to overcome this major limitation with the addition of LAA to asphalt binder to promote adhesion between asphalt binder and glassphalt aggregate.

The specific objectives of this study are to:

- Find out the effect of adding different percentages of crushed waste glass as fine aggregate on the moisture damage of asphalt mix,
- Study the effects of adding LAA on asphalt binder, and
- Determine the effect of LAA on moisture sensitivity of glassphalt.

3- Materials

3- 1- Aggregate and asphalt binder

The chemical compositions of the granite aggregate used in this study are listed in Table 1. The physical properties of the aggregates are given in Table 2. The gradation of the aggregate (mid limits of ASTM specifications for dense aggregate gradation) is given in Fig. 1. The nominal size of this gradation was 19.0 mm. In this experimental investigation, a pure asphalt binder of 60/70 penetration grade from the Isfahan mineral oil refinery was used. To characterize the properties of the base asphalt binder, conventional test methods, such as the penetration test, softening point test, and ductility were performed. The engineering properties of the asphalt binder are presented in Table 3.

Table 1. Chemical composition of the aggregate.

Properties	Granite
pH	7.1
Silicon dioxide, SiO_2 (%)	68.1
R_2O_3 (Al_2O_3+Fe_2O_3) (%)	16.2
Aluminum oxide, Al_2O_3 (%)	14.8
Ferric oxide, Fe_2O_3 (%)	1.4
Magnesium oxide, MgO (%)	0.8
Calcium oxide, CaO (%)	2.4

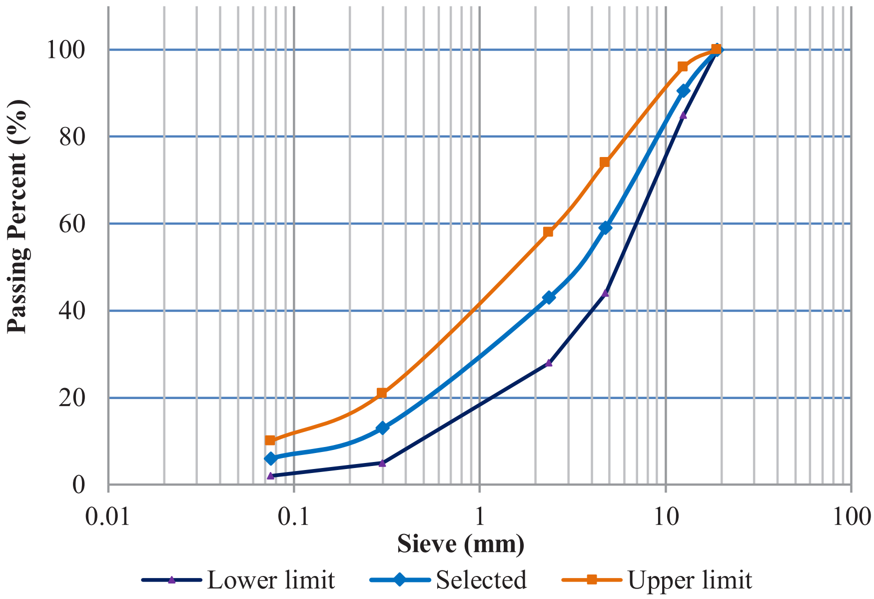

Fig. 1. Gradation of aggregates used in the study.

Table 2. Physical properties of the aggregate.

Test	Standard	Granite	Specification limit
Specific gravity (coarse agg.)	ASTM C 127		
Bulk		2.654	-----
SSD		2.667	-----
Apparent		2.692	-----
Specific gravity (fine agg.)	ASTM C 128		
Bulk		2.659	-----
SSD		2.661	-----
Apparent		2.688	-----
Specific gravity (filler)	ASTM D854	2.656	-----
Los Angeles abrasion (%)	ASTM C 131	19	Max 45
Flat and elongated particles (%)	ASTM D 4791	6.5	Max 10
Sodium sulfate soundness (%)	ASTM C 88	1.5	Max 10-20
Fine aggregate angularity	ASTM C 1252	56.3	Min 40

Table 3. Results of the experiments conducted on 60/70 penetration grade asphalt binder.

Test	Standard	Result
Penetration (100 g, 5 s, 25 ºC), 0.1 mm	ASTM D5-73	64
Penetration (200 g, 60 s, 4 ºC), 0.1 mm	ASTM D5-73	23
Penetration ratio	ASTM D5-73	0.36
Ductility (25 ºC, 5 cm/min), cm	ASTM D113-79	112
Solubility in trichloroethylene, %	ASTM D2042-76	98.9
Softening point, ºC	ASTM D36-76	51
Flashpoint, ºC	ASTM D92-78	262
Loss of heating, %	ASTM D1754-78	0.75
Properties of the TFOT Residue		
Penetration (100 g, 5 s, 25 ºC), 0.1 mm	ASTM D5-73	60
Specific gravity at 25 ºC, g/cm3	ASTM D70-76	1.020
Viscosity at 135 ºC, cSt	ASTM D2170-85	158.5

3- 2- Additives

ZycoTherm is a liquid heat-stable antistripping additive specially designed to lower the life cycle cost of asphalt roads. This additive is an odor-free additive that increases moisture resistance and lowers mixing compaction temperatures up to 80°C. Their heat stability allows them to be stored in a tank for up to one week. Moreover, they can be injected directly into the asphalt storage tank. The dosage of this anti-stripping additive is normally between 0.4 and 1.2% by weight of asphalt binder, depending on the aggregate and the asphalt used. This additive is manufactured by Zydex Company, and its physical properties are given in Table 4.

Table 4. Properties of the ZycoTherm.

Properties	ZycoTherm
Appearance at 20ºC	amber liquid at 20°C
Density at 20ºC, kg/m³	950
Pour point, ºC	7°
Flash point, ºC	>180
Viscosity, cP	870 mPa (at 10ºC)
Viscosity, cP	400 mPa (at 20ºC)
Total amine	4.6-5.2 (meq/g)
Water	<0.8%

Table 5. Chemical composition of the CG.

Properties	Crushed Glass
Silicon dioxide, SiO_2 (%)	70.5
Potassium oxide, K_2O (%)	1.2
Aluminium oxide, Al_2O_3 (%)	2.6
Magnesium oxide, MgO (%)	2.9
Calcium oxide, CaO (%)	5.7

3- 3- Glass

Ordinary glass is rigid and brittle and easy to crush to form satisfactory particles for asphalt mix applications. The broken glass used in asphalt mix is characterized by:

1. Numerous long and flat particles (especially for big broken glass particles). This may cause problems like stripping of the asphalt film from glass particles surfaces, infirm skid resistance, abrasion of tires, too high reflectance, etc.

2. The surface of broken glass particles is exceeding smooth and the silica content is relatively high, making glass particles a hydrophilic acid aggregate. Pavements with glassphalt may then be sensible to water damage (especially when glass particle size is increased).

3. The angularity and friction angle affords insufficient transverse stability (at braking or start-up).

4. Low asphalt absorption ratio and density may cause bleeding problems.

5. Excellent light reflection properties assure safe nighttime driving, but when glass particle size is increased there is a risk of dazzling.

6. Volume stability is good because the inflation coefficient when heated is small (about 8.8×10^{-6}cm/cm/°C-9.2×10^{-6}cm/cm/°C when the temperature is below 700°C). This is beneficial to the resistance of low-temperature cracking.

7. The asphalt absorption ratio is near zero which is unfavorable to the adhesion of the asphalt film to the broken glass particles.

Glass is a non-metallic inorganic made by sintering selected raw materials comprising silicate and other minor oxides. The chemical compositions of the CG are listed in Table 5. The results of this analysis are based on the X-ray Diffraction test.

The CG used in this research is prepared from the waste glass of the glass cutting workshop. The maximum and minimum particle sizes of CG were 4.75 and 0.075 mm, respectively. This gradation is presented in Fig. 2. Initially, some of the base aggregates were removed and the glass was replaced at 0, 10, and 20%. It is noteworthy that this replacement has been in the fine-grained section of materials.

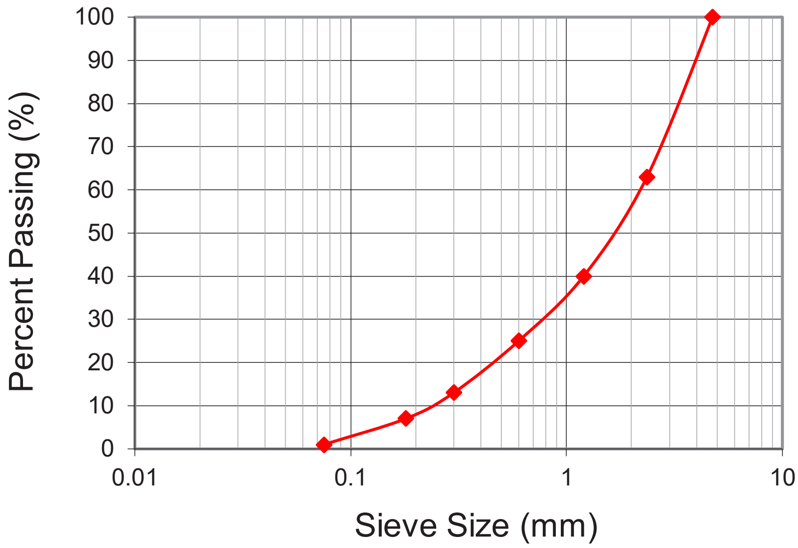

Fig. 2. The gradation of CG used in this research.

Fig. 3. Samples of 1200 gr of aggregate materials with 0, 5, 10, 15, and 20% CG.

Fig3 . shows samples of 1,200 grams of aggregate materials in which the required amount (0 to 20%) has been removed from the fine-grained part and the CG has been replaced.

4- Experimental and set up and procedure

The following tests were performed on each sample in three duplicates. For each aggregate blend and asphalt binder, at least three separate samples were produced to determine the reproducibility of the results. Table 6 shows the composition of the asphalt mixtures, the tests performed, and the number of samples.

4- 1- Mix design

The optimum asphalt binder content for the mix design was determined by taking the average values of the following three bitumen contents:

1. Binder content corresponding to maximum stability,
2. Binder content corresponding to maximum bulk specific gravity,
3. Binder content corresponding to the median of designed limits of percent air voids in the total mix.

The stability value, flow value, and voids filled with bitumen are checked with the Marshall Mix design specification.

4- 2- Tensile Strength Ratio test (TSR)

The stripping resistance (water susceptibility) of asphalt mixtures was evaluated by the decrease in the loss of the indirect tensile strength (ITS) after the freeze-thaw cycle according to the AASHTO T283 test procedure [16].

The tensile strength of an HMA mix is generated by the cohesive strength of the asphalt binder and the bond strength at the binder-aggregate interface. The tensile strength is calculated from the maximum load the sample can undergo before cracking. A mix with higher tensile strength provides better resistance to fatigue and thermal cracking[17]. Therefore, any additives that can generate a higher tensile strength in the HMA mix in the dry and moisture-conditioned stages will improve the long-term performance of an HMA pavement. This test involves loading a cylindrical specimen with vertical compressive loads; this generates a relatively uniform tensile stress along the vertical diametrical plane. Failure usually occurs in the form of splitting along this loaded plane [18].

Six samples from each mix (dry and wet) were prepared and compacted. The compacted specimens should have air void contents between 6.5% and 7.5%. Half of the compacted specimens are conditioned. First, vacuum is applied to partially saturate specimens to a level between 55% and 80%. Vacuum-saturated samples are kept in a 60° C water bath for 24 h. After this period the specimens are considered conditioned. The other three samples remain unconditioned. The failure load for each sample was recorded at 25° C (Fig. 4).

The ITS for each sample was calculated using the following formula:

$$ITS = \frac{2F}{\pi t d} \tag{1}$$

Where ITS is the indirect tensile stress (kPa), F is the failure load (kN), t is the sample thickness (m), and d is the sample diameter (m).

The indirect tensile strength ratio (TSR) was determined by the following equation:

$$TSR = \frac{ITS_{cond}}{ITS_{uncond}} \tag{2}$$

Table 6. Laboratory compounds used in this study.

Row	Aggregate	itumen	CG (%)	ZycoTherm (%)	Test	Purpose	Sample Numbers
1			0				30
2			5				30
3			10	0	Marshall Stability, Bulk unit weight, Maximum unit weight	Mix Design	30
4			15				30
5			20				30
6			0				12
7			5				12
8			10	0	Indirect tensile strength	Moisture sensitivity	12
9			15				12
10	Granite	C 60-80	20				12
11			0				12
12			5				12
13			10	0.5	Indirect tensile strength	Moisture sensitivity	12
14			15				12
15			20				12
16			0				12
17			5				12
18			10	1	Indirect tensile strength	Moisture sensitivity	12
19			15				12
20			20				12

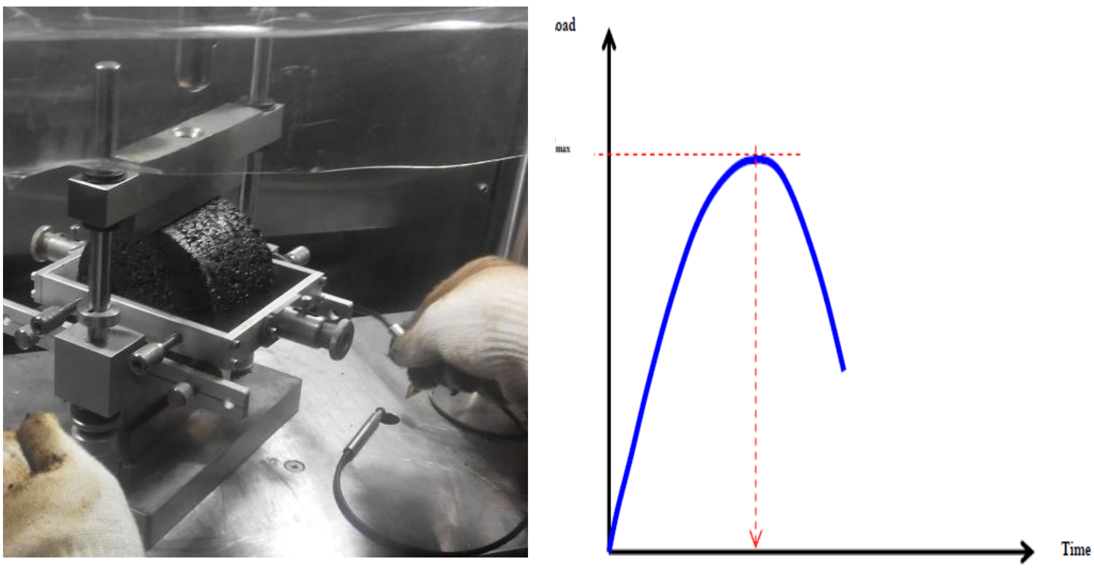

Fig. 4. Components of the Indirect Tensile Strength Test for an HMA mix.

Where ITS_{cond} is the indirect tensile strength of the wet specimens, ITS_{uncond} is the indirect tensile strength of the dry specimens.
To investigate the effectiveness of additives 1, 3, and 5 freeze-thaw cycles were applied to specimens at the AASHTO T283 test.

4- 3- Surface free energy measurement

In this study, the surface energy of the asphalt binder was measured using Wilhelmy Plate (WP) established by Herfer et al. [19], respectively.

Based on the Young–Dupre' equation, Good and Van Oss [20] proposed the following relationship between the Gibbs free energy of adhesion $\Delta G_{L,S}$, adhesion work $W_{L,S}$, contact angle θ of a probe liquid (L), in contact with a solid (S), and surface energy characteristics of both the liquid and solid.

$$-\Delta G^{a}_{L,S} = W^{a}_{L,S} = \Gamma^{Total}_{L}(1+\cos\theta) = 2\left[(\Gamma^{LW}_{s}\times\Gamma^{LW}_{l})^{0.5} + (\Gamma^{+}_{s}\times\Gamma^{-}_{l})^{0.5} + (\Gamma^{-}_{s}\times\Gamma^{+}_{l})^{0.5}\right] \tag{3}$$

Eq. (3) is the fundamental equation used to calculate surface energy components of bitumen by measuring contact angles. In this equation, the solid (S) is replaced by the bitumen under consideration and the liquid (L) is any probe liquid, in this context defined as a liquid with known surface energy characteristics. If the square roots of the three unknown surface energy components of the bitumen are represented as x_1, x_2, and x_3; Eq. (3) can be rewritten as follows:

$$\Gamma^{Total}_{L}(1+\cos\theta) = 2\begin{bmatrix}(\Gamma^{LW}_{L})^{0.5}\times x_1 + \\ (\Gamma^{-}_{L})^{0.5}\times x_2 + \\ (\Gamma^{+}_{L})^{0.5}\times x_3\end{bmatrix} \tag{4}$$

The measured contact angle of a probe liquid with bitumen and surface energy components of the probe liquid is substituted into Eq. (4) to generate a linear equation with unknowns x_1–x_3.

For measuring contact angle between a liquid, in 1863, Wilhelmy first proposed an indirect measurement method, whereby a plate is immersed into a liquid. This is a quasi-static contact angle measurement technique since the plate is in motion (moving at a few microns per second) throughout the process. From simple force equilibrium considerations, the difference between the weight of a plate measured in air and partially submerged in a probe liquid, (ΔF) is expressed in terms of buoyancy of the liquid, liquid surface energy, contact angle, and geometry of the plate. Thus, the contact angle between the liquid and surface of the plate can be calculated from this equilibrium, as shown in Eq. (5).

$$\cos\theta = \frac{\Delta F + V_{im}(\rho_L - \rho_{air}\times g)}{P_t \times \Gamma^{Total}_{L}} \tag{5}$$

where P_t = perimeter of the bitumen coated plate,
Γ_L^{total} = total surface energy of the liquid,
θ = dynamic contact angle between the bitumen and the liquid,
V_{im} = volume immersed in the liquid,
ρ_L = density of the liquid,
ρ_{air} = air density, and
g = local gravitational force.

There are three unknowns for the asphalt semi-solid in Eq. (4): Γ^{LW}_S, Γ^{-}_S, Γ^{+}_S. These unknowns are the three components of asphalt surface free energy: Lifshitz-van der Waals, Lewis base, and Lewis acid, respectively. To solve for these parameters, at least three solvent liquids whose surface energies are known must be used to produce three simultaneous equations. Water, glycerin, and formamide were used here as liquid solvents because of their relatively large SFE, immiscibility with asphalt binder, and differing SFE components.

5- Results and Discussion

5- 1- The mix design

The results of the mix design parameters of different asphalt mixtures are presented in Table 7. The optimum bitumen percentage is obtained based on the average of three percent bitumen corresponding to the following parameters: a) maximum stability, b) maximum unit weight, and c) a percentage of air void equal to 4%. It can be seen from Table 7 that with an increase in CG content, the optimum of asphalt binder has been decreased. The main reason for this event is that the surface of the glass is smooth. All of the asphalt binders that have been added to the mixture are effective.

Other parameters corresponding to the optimum asphalt binder contents were listed in Table 8. As can be seen, the amount of void in mineral aggregate (VMA) increased with the addition of CG. The main reason for this can be considered as the broken glass, which makes it harder for the aggregates to fall inside each other. On the other hand, because glass has less bitumen absorption, the percentage of bitumen in the space decreases, and more bitumen is spent freely between the aggregates.

5- 2- The AASHTO T283 test

The TSR values of the mixtures under different freeze-thaw cycles are given in Figs. 5 to 7. As can be seen, the TSR of samples decreases with an increase in the number of freeze-thaw cycles. The decrease in TSR with an increase in freeze-thaw cycles could be attributed to the loss of adhesion of the mixture and/or cohesion of the binder. It can be concluded from Figs. 5 to 7 that adding LAA to mixtures, improves the adhesion and cohesion of binder and does not allow the displacement of asphalt components from the aggregate surface easily by water thus providing more reasonable mixtures than without treated mixtures. An increase in the number of freeze-thaw cycles causes to decrease in TSR. The samples containing 5 percent CG and 1 percent Zyco-Therm have the highest value of TSR (83%) in the first cycle that reaches 71% at the end of the fifth cycle. The acceptable values of TRR are different in different manuals but in most of them, 75% of TSR is acceptable at the one cycle.

Table 7. Mixing design parameters to determine the optimal bitumen percentage.

Crushed Glass Content (%)	Asphalt binder at maximum stability (%)	sphalt binder at the maximum unit weight (%)	Asphalt binder at air void=4% (%)	ptimum Asphalt Binder (%)
0	5.6	5.6	5.4	5.5
5	5.5	5.6	5.4	5.5
10	5.3	5.6	5.4	5.4
15	5.3	5.4	5.2	5.3
20	5.1	5.3	5	5.1

Table 8. Optimum asphalt binder of different CG.

Asphalt mixture types	Crushed Glass Content (%)	ptimum Asphalt Binder (%)	*VMA* at Optimum Asphalt Binder (%)	*AV* at Optimum Asphalt Binder (%)	*VFA* at Optimum Asphalt Binder (%)
1	0	5.5	13.4	4	70.1
2	5	5.5	13.6	4	70.6
3	10	5.4	13.7	4	70.8
4	15	5.3	13.9	4	71.22
5	20	5.1	14.1	4	71.6

The chemistry of the aggregate surface affects the degree of the water sensitivity of the asphalt aggregate bond. The mineral composition of granite and CG has been presented in Tables 1 and 5. These tables show that CG has more hydrophilic properties because the SiO_2 percent of CG is higher than that of granite. Also, the CG aggregate has no asphalt binder absorption that causes to asphalt binder to separate from the CG surface. For the mentioned reason, with an increase in CG content in glassphalt the moisture susceptibility of glassphalt increased.

As seen from Figs. 5 to 7, TSR decreased from the unconditioned to conditioned specimens for all mixtures, implying the presence of damage in the mixtures. Mixtures with LAA generally exhibited less decrease than mixtures without LAA after conditioning. Different additives have different improvement effectiveness in water resistance. Results of adding ZycoTherm Show that the addition of these additives in 0.5 and 1 percent causes the TSR of specimens exposed to this condition to improve. Adding 0.5% of the said additives results in a significant increase in the samples' TSR. Also, adding 1% of the additives leads to an increase in the TSR value. However, the grading of TSR diagrams in the 0.5-1% part is less than that of the 0-0.5%. To investigate the effectiveness of additives 1, 3, and 5 freeze-thaw cycles were applied to specimens at the AASHTO T283 test. It is seen that the loss of TSR of the mixtures treated with additives due to the freeze-thaw cycle is not as high as the mixture without them. The reduction of TSR values in cycles 1 to 3 is more than cycles 3 to 5.

Fig. 8 shows the effect of using an anti-stripping liquid additive on the moisture damage of a glassphalt. As can be seen in the asphalt mixture without additives, the surface of the exposed aggregates is visible. This indicates that the failure occurred at the bitumen-aggregate contact surface, but in the latter case it is observed that the use of additives has resulted in less stripping and failure has occurred in the bitumen membrane.

5- 3- The surface free energy of asphalt binder

The surface free energy components of the asphalt binder were determined using the Wilhelmy Plate method.

Asphalt is a single-phase homogeneous mixture of many different molecules, which may be differentiated into two broad classes: polar and non-polar. The non-polar molecules serve as a matrix or solvent for the polar molecules, which form weak "networks" of polar-polar associations that give asphalt its elastic properties. The polar materials are uniformly distributed throughout the asphalt, and, upon heating,

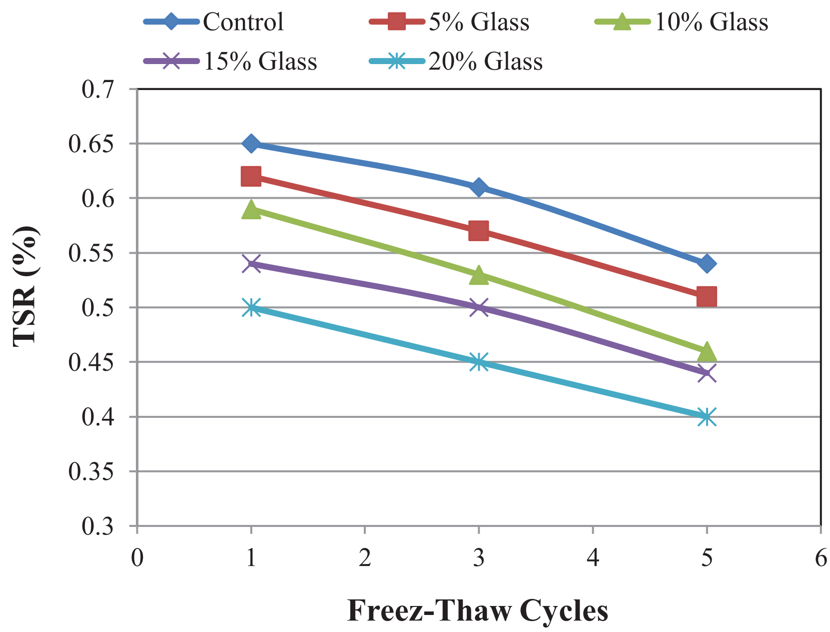

Fig. 5. Effects of freeze-thaw cycle and CG content on TSR (without LAA).

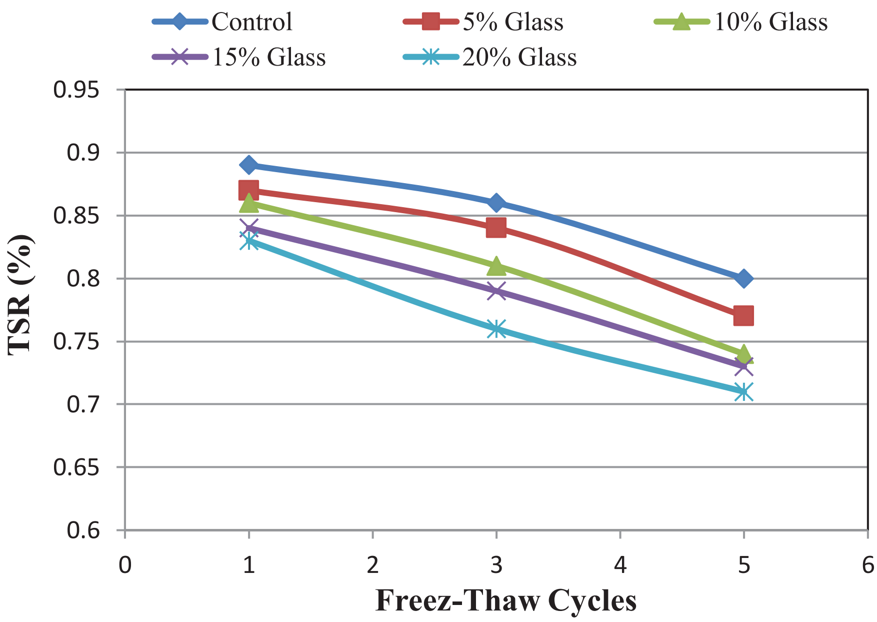

Fig. 6. Effects of freeze-thaw cycle and CG content on TSR (with 0.5 percent LAA).

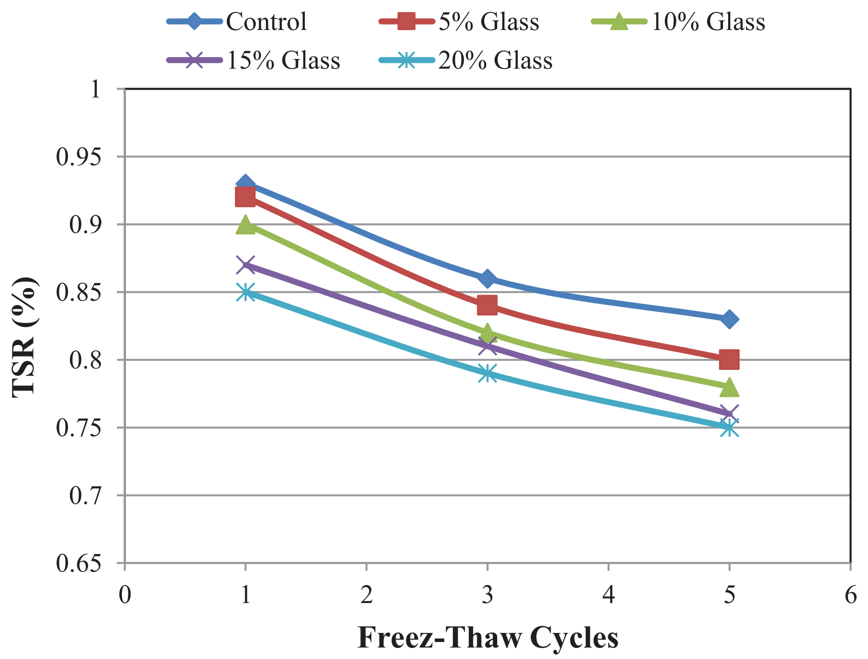

Fig. 7. Effects of freeze-thaw cycle and CG content on TSR (with 1 percent LAA).

A) Glassphalt with antistripping addives B) Glassphalt without antistripping addives

Fig. 8. Effects of LAA on stripping potential of glassphalt.

Table 9. SFE components of asphalt binders.

Asphalt binder types	AC	AC+ 0.5 percent ZycoTherm	AC+ 1 percent ZycoTherm
Contact angle (°) with water	104.33	104.71	103.57
Contact angle (°) with Glycerol	96.49	97.66	96.67
Contact angle (°) with Formamide	97.01	97.64	96.62
Total SFE, Γ(ergs/cm^2)	15.63	16.50	18.06
Lifshitz-van der Waal Component, Γ^{LW}	13.69	14.85	16.49
Acid-Base Component, Γ^{AB} (ergs/cm^2)	1.94	1.65	1.56
Acidic component, Γ^{+} (ergs/cm^2)	1.45	0.96	0.74
Basic component, Γ^{-} (ergs/cm^2)	0.65	0.71	0.83

the weak interactions are broken to yield a Newtonian fluid. Asphalts that have too much polar material will be subject to fatigue cracking in thin pavements, brittleness, and thermal cracking. Good asphalts have a proper balance of polar and non-polar molecules. Asphalts that have too much non-polar material, or asphalts in which the non-polar materials are too low in molecular weight, will be subject to fatigue cracking in thick pavements, moisture sensitivity, and rutting [21]. Asphalt binder is naturally acidic. The acid and base components of AC 60-70 were 1.45 and 0.65 ergs/cm^2, respectively. In the case of an acidic aggregate and an acidic binder, the surface chemistry of Lewis acids and bases does not favor adhesion, and a good bond between an acidic aggregate and an acidic binder is difficult to obtain.

In this study, one LAA was used and added to the binder in 2 different percentages. The first group of asphalt binders used in this study is AC 60-70 binder. The second group of specimens used AC 60-70 binder that was modified with 0.5%, and 1% ZycoTherm.

Table 9 shows the total SFE and its components for the asphalt binder with and without LAA treatment obtained in this study.

Comparisons between the results show that adding liquid LAA increases the total surface free energy of the asphalt binder, and it is clear from the results that increasing the percentage of additive causes the total SFE to increase. As is clear from the data in Table 8, the SFE of the asphalt binder without additives was 15.63 erg/cm^2. The SFE values for the asphalt binder treated with 0.5% and 1% ZycoTherm were 16.76 and 19.31 ergs/cm^2, respectively.

Most aggregates have electrically charged surfaces (polar surfaces). The asphalt binder, which is composed chiefly of high molecular weight hydrocarbons, exhibits little polar activity; therefore, the bond that develops between asphalt and the aggregate is primarily due to relatively weak dispersion forces [22]. As can be seen in Table 8, LAA causes an increase in the non-polar SFE of the asphalt binder.

Table 8 shows that the acid SFE of the asphalt binder decreased significantly, while the base SFE increased. The values of the acid SFE in the asphalt binder treated with 0.5% and 1% ZycoTherm were 0.96 and 0.74 ergs/cm^2, respectively. Also, the values of the base SFE in the asphalt binder treated with 0.5% and 1% ZycoTherm were 0.71 and 0.83, respectively.

Table 8 shows that the acid-base (polar) SFE of the asphalt binder without LAA (1.94 ergs/cm^2) is greater than that of the asphalt binder with LAA in all percentages.

As some part of the natural aggregate was replaced by CG, the moisture damage of the asphalt mixture increased. When LAA is added to the pure asphalt binder, the better adhesion between CG and modified asphalt binder has been achieved. It will be expected that the use of LAA has a positive impact on the moisture strength of glassphalt.

6- Conclusion

Increasingly, on a global scale, nations are making advances in the use of recycled materials in road construction. The use of recycled aggregates instead of natural materials is helping ease the burden on the rapidly dwindling landfill capacity. Additionally, economic interest has been created due to increased landfill and transport costs. In this study, the effect of using CG as recycled material and ZycoTherm as an LAA on moisture damage of asphalt mixture was investigated. The main conclusions of this paper are:

- The surface of broken glass particles is exceeding smooth and the silica content is relatively high, making glass particles have hydrophilic properties than granite aggregate. With the increase in CG in glassphalt, the moisture damage increased as a result of mentioned reasons.
- The TSR results showed that the LAA caused a significant increase in the moisture strength of glassphalt.
- Adding LAA increases the total surface free energy of the asphalt binder.
- Adding LAA caused to decrease in the acid component of SFE and an increase in the basic component of SFE of the asphalt binder that cause to increase in adhesion between

asphalt binder and acidic aggregate such as CG.

- Use of LAA cause to increase in adhesion and cohesion of the mixture. This change prevents from stripping of aggregate from asphalt binder and causes to mixtures have a better strength against moisture damage after several freeze-thaw cycles.

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