Scientia Iranica A (2012) 19 (3), 341–345

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
www.sciencedirect.com

Modeling the fatigue behaviors of glasphalt mixtures

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Received 30 September 2010; revised 12 January 2012; accepted 13 February 2012

KEYWORDS
Hot mix asphalt;
Fatigue phenomenon;
Waste materials;
Crushed glass;
Model.

Abstract Phenomena related to the fatigue behavior of pavements are among the most important concerns confronting pavement designers. Damage caused by pavement fatigue requires large amounts of money to be budgeted for the maintenance and rehabilitation of highway and airport pavements, and this expenditure motivates research into methods to reduce the fatigue damage. One of these proposed solutions is the inclusion of waste materials in the material used for pavement construction to increase its strength against dynamic loading. Many models have been developed for predicting the fatigue behaviour of asphalt concrete pavements, but none exist for asphalt mixtures modified by the addition of waste materials. This paper presents the first model of the fatigue behaviour of glass-asphalt (glasphalt) mixtures, which is able to describe the fatigue behaviour of glasphalt under dynamic loading. The proposed model is then compared with a number of previously suggested models for the behaviour of Hot Mix Asphalt (HMA). Glasphalt concrete mixtures are shown to have a longer fatigue life than HMA.

1. Introduction

Glasphalt is essentially similar to Hot Mix Asphalt (HMA), except that about 5% to 40% of its coarse and fine aggregates are replaced with crushed glass particles. Glasphalt was subjected to evaluation tests in the early 1960s, which confirmed that it can be used for certain types of pavement. Since then, glasphalt has not been commonly used, due to the excessively high cost of producing crushed glass [1]. Glass is a non-metallic inorganic material that cannot be decomposed or burned. Materials made from glass are fragile and contain a lot of silicon; moreover, because they are hydrophilic, they show low convergence in cohesion with bitumen. This cohesion will further decrease in the presence of water, which would result in the stripping of the asphalt layer due to vehicle movement. Anti-stripping agents are usually used to prevent such problems [2]. The recycling of glass will be useful for utilising currently-available resources, while reducing environmental impact. The behaviour of materials used in structures is an important concept that engineers should consider. Therefore, the efficiency and behaviour of waste materials should be studied, in order to ascertain whether they are better than, or at least equal to, currently-used materials [3]. On this point, the study by [4,5] showed that higher internal friction, which is due to the higher angularity of glass particles, plays an important role in increasing the stiffness modulus of samples with glass cullet content. On the other hand, the high smoothness of crushed glass particles does not allow their adequate absorption of bitumen. Therefore, greater glass content than a certain limit decreases the stiffness modulus of the sample [4,5]. An experimental study by Hughes in 1990 indicated that the stripping phenomenon would not be of major concern in glasphalts, if 3%–5% lime were added to the mixture as an anti-stripping agent [6]. Another study in 2008 showed that glasphalt pavements are longer-lived and possess greater resistance to damage [7]. Moreover, the study by Su and Chen [8] confirmed the improved behaviour of experimental specimens containing 10% waste glass, compared to conventional HMA, after a one year working period [8]. An investigation carried out in 2004 found satisfactory performance for glass-asphalt concrete pavements containing 10%–15% crushed glass content, and suggested a maximum size of 4.75 mm for glass particles, considering

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Peer review under responsibility of Sharif University of Technology.

Production and hosting by Elsevier

doi:10.1016/j.scient.2012.02.021

Table 1: Continuous type gradation for HMA, Topka layer.

Sieve size	1″	3/4″	1/2″	3/8″	#4	#8	#50	#200
Percent passing	–	100	95	–	59	43	13	6

Table 3: Grading of the crushed glass aggregates.

Sieve size	#4	#8	#16	#30	#50	#100	#200
Percentage passing	100	63	42	27	14	9	2

technical properties and safety hazards (such as the cutting of skin and puncturing of tires). In this study, 2% of a type of lime was used as the anti-stripping agent [9].

However, it should be noted that the use of a large amount of crushed glass, as well as large glass particles, may cause inadequate friction and interlocking strength in pavements. However, the use of a higher proportion of glass particles may be suitable for the lower layers of pavements. In practice, the same facilities and design methods used for conventional HMA can be used for glasphalt pavements as well [10]. Su and Chen used recycled glass at a ratio of 30% for the binder and bitumen base layer of pavements to evaluate the suitability of glasphalt concrete pavements for certain traffic loadings. The maximum size of the glass particles used in the glasphalt mixture was 20 mm. The results of this study showed an improvement in the performance of glasphalt mixtures under traffic loading [11]. Another study, in 2009, indicated that the adding of crushed glass particles to the mixture under optimal conditions would double the fatigue life of pavements [12].

Several models have been proposed for the behaviour of asphalt mixtures. [14,13] suggested models for the mechanical behaviour of conventional HMAs [13,14]. Park et al. [15] suggested three distinct models for conventional HMA; HMA with high durability bitumen and HMA modified by SBS [15]. Additionally, [16] presented a model for predicting the behaviour of asphalt concrete mixtures with crumb rubber [16]. However, no models have been developed, to date, for the behaviour of glasphalt mixtures.

This study proposes the first model for the behaviour of glasphalt mixtures. Glasphalt mixtures with varying crushed glass content and at three different temperatures are subjected to experiments with varying levels of stress. Finally, the proposed model for glasphalt is compared with previously-developed models for HMA.

2. Experimental procedures

The aggregates used in this study were graded using the continuous type III scale of the AASHTO standard, which is presented in Table 1 [17]. Pure bitumen 60–70 was used in the preparation of the samples. The characteristics of the bitumen were controlled and presented in Table 2. The crushed glass used in this research was supplied from the waste glass of a glassmaking company. The maximum size of the glass aggregates was 4.75 mm. The grading of crushed glass aggregates is given in Table 3 [18], and the chemical properties of the used glass are presented in Table 4. The admixture of the glass-asphalt mixture was hydrated lime with a high calcium content, which works as an anti-stripping agent. In this study, 3%–5%wt of hydrated lime was used as the anti-stripping agent [19], and its properties are presented in Table 5. Hydrated lime, due to its high stiffness and anti-stripping characteristics, can increase the HMA's stiffness modulus and strength against moisture by changing the characteristics of the used bitumen. Some other characteristics of the hydrated lime include its ability to increase the stiffness modulus and strength of the mixture, as well as providing greater strength against moisture and the prevention of crack propagation [20]. To mix the lime and aggregates, this study used the method of spreading dry lime over moisturised stone aggregates. This method requires equal distribution of the hydrated lime on the aggregates; thus, the aggregates were moisturised to a minimum water content of about 2%–3% above the saturation water content of the aggregates with a dry surface (SSD condition). The lime-mixed aggregates were retained for a period of time for preparation and drying. This method permits increased certainty about the equal distribution of lime over the aggregates [21]. In addition, the part of the lime that does not cohere to the aggregates will be distributed throughout the mixture, modifying the properties of the bitumen by increasing its viscosity.

The fatigue life of the samples was determined by the Indirect Tensile Method using a Nottingham Asphalt Testing (NAT) apparatus. The Marshall test was carried out to determine the optimum bitumen content of asphalt concrete mixtures containing different percents of waste glass cullet aggregates. The results obtained by the Marshall test for samples with Topka gradation are provided in Table 6. The Marshall test was done according to ASTM D1559 [12]. Specimens were prepared with crushed glass contents of 0%, 5%, 10%, 15% and 20%wt. The optimum content of hydrated lime was also determined by the Marshall test on glasphalt mixture specimens with optimum bitumen content containing various proportions of glass [22]. The fatigue life of the specimens was identified by using the indirect tensile fatigue test (ITFT) method on samples with 100 mm diameter and 40 mm thickness. This loading was accomplished by applying repeated loads at a frequency of 1 Hz until the failure point of the specimen. The failure was also characterised by measuring the vertical deformation of the samples. Fatigue life tests are usually carried out via two methods: loading with constant stress and loading with constant strain. In the constant stress test, strain increases with the number of pulses of loading, while in the constant strain test, stress decreases with the number of pulses of loading [23]. By maintaining a certain tensile strain for each level of stress, the relation between the tensile strain and the number of cycles related to the failure can be determined. In this study, fatigue life tests were performed at 5, 25 and 40 °C, with constant stresses of 250 and 400 kPa. The program for specimen preparation and testing, and

Table 2: Properties of bitumen used in this study.

Total bitumen content	Weight drop	Inflammation point	Ductility	Softening point	Penetration index	Specific gravity at 25 °C
%	%	°C	Cm	°C	mm/10	–
99	0.75	262	112	51	66	1.02

Table 4: Chemical properties of the used crushed glass aggregates.

Silica oxide%	Sodium oxide%	Calcium oxide%	Magnesium oxide%	Aluminum oxide%	Bur oxide%	Potassium oxide%	Iron oxide%
73	15	5.55	3.6	1.5	0.4	0.4	0.3

Table 5: Properties of the used hydrated lime.

Minimum percentage of $Ca(OH)_2$ of the total weight	Maximum percentage of CaO of the total weight	Maximum percentage of H_2O of the total weight	Maximum percentage of aggregates remaining on #30	Maximum percentage of aggregates remaining on #200
90	7	3	2	12

Table 6: Results obtained by the Marshall test for samples with Topka gradation.

Glass content (%)	Bitumen content (%)	Stability	Flow	Unit weight	Void	VMA	VFA
0	5	970	2.39	2.314	5.22	15.22	65.71
	5.5	1103	2.43	2.351	4.52	14.32	68.43
	6	1147	3.15	2.347	4.33	14.92	1147
	6.5	1069	3.21	2.346	3.75	15.41	75.66
5	5	1059	2.03	2.323	5.09	14.73	1059
	5.5	1159	2.56	2.33	4.77	14.92	68.03
	6	1262	3.06	2.341	4.24	14.97	71.68
	6.5	1209	3.34	2.334	3.93	15.68	74.93
10	5	1230	2.55	2.331	4.82	14.27	66.22
	5.5	1300	2.81	2.346	4.3	14.17	69.66
	6	1278	2.98	2.34	4.09	14.84	72.45
	6.5	1192	3.4	2.304	3.84	16.60	76.87
15	5	1273	2.71	2.314	4.59	14.73	68.84
	5.5	1305	2.95	2.329	4.21	14.63	71.22
	6	1311	2.92	2.332	3.65	14.97	75.62
	6.5	1294	3.11	2.305	3.42	16.40	79.15
20	5	1227	2.32	2.301	4.82	15.04	67.96
	5.5	1247	2.88	2.318	4.46	14.87	70.00
	6	1210	3.18	2.312	4.09	15.54	73.67
	6.5	1180	3.65	2.283	3.74	17.04	78.05

more detail regarding the mixtures, are presented in Table 7. It should be noted that asphaltic specimens have a laboratory ambient temperature when placed in the temperature chamber of a Nottingham asphalt tester. Indirect tensile fatigue tests were immediately carried out on asphaltic samples with the temperature of the chamber being 5, 25 or 40 °C. Thus, at the beginning of the test, the core of the asphaltic specimens have no nominal temperature of 5 and 40 °C, and actual temperatures were gradually reached during the experiments. According to the research goal, although the relative results obtained in the experiments do not indicate the actual number of cycles for nominal temperatures, the provided fatigue models are independent of nominal temperatures and completely represent the actual behavior of glasphalt mixtures. With regard to the large number of experiments, in this manner, the time required to perform the tests was significantly reduced.

3. Results and discussion

Figure 1 through Figure 4 show the number of cycles needed for failure and the final tensile strain of asphalt concrete specimens, given with variations of temperature, crushed glass content and two levels of stress. It can be seen that asphalt concrete specimens containing crushed glass and hydrated lime show considerably better fatigue performance than conventional HMAs. For instance, the fatigue lives of specimens containing 5 and 10 % crushed glass content at 5 °C, are 50 and 100% longer, respectively, than those of conventional HMAs at the same temperature. This increase in fatigue life is caused by the high angularity of the glass particles, which prevents cracking of the asphalt pavement layer by increasing the internal friction angle of the mixture and improving the interlocking between different constituent particles. Similarly, the distribution of crushed glass aggregates in all directions will increase the specimen's strength against shear displacements, and which will, consequently, impede crack propagation. Better adhesion among bitumen, stone and glass aggregates, as a result of the anti-stripping properties of hydrated lime, will also minimise the relative displacement of the stone aggregates and increase the fatigue life of the samples by slowing down cracking and crack propagation. In Figures 2 and 4, we see that the induced tensile strain of HMA specimens in a fatigue test varies in a similar way to fatigue life. Furthermore, Figures 1 and 3 show that the fatigue lives of the glasphalt specimens with crushed glass content increase with lowered temperatures. The reason for this behaviour is the high sensitivity of the stiffness modulus of HMA to temperature. Using the results of experimental studies, along with software-aided analysis, models can be developed for predicting the fatigue behaviour of conventional asphalt and glasphalt under different temperatures and loading conditions. The fatigue life of an asphalt concrete specimen depends on the tensile strain

Table 7: Program for specimen preparation and testing.

Parameter	Levels
Percentage of waste iron powder	(0%, 5%, 10%, 15%, 20%) by weight
Test temperatures	(5, 25, 40) °C
Type of gradations	Topeka
Stress	250 and 400 (kPa)
Height of the HMA specimens	40 mm
Percentage of hydrated lime	3%–5%

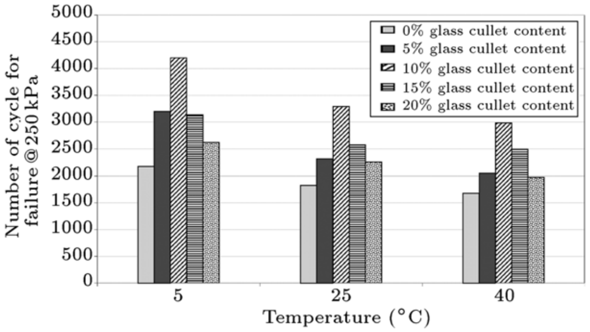

Figure 1: Number of cycles required for failure vs. temperature for different glass contents at a stress level of 250 kPa.

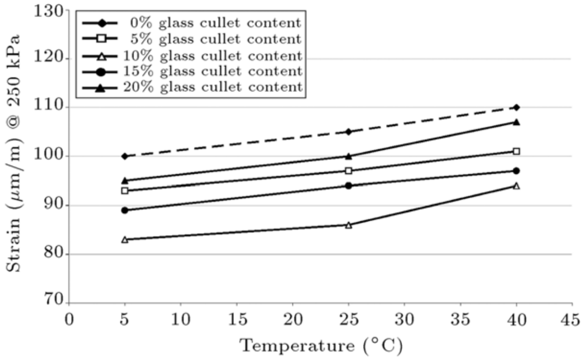

Figure 2: Final tensile strain vs. temperature for different glass contents at a stress level of 250 kPa.

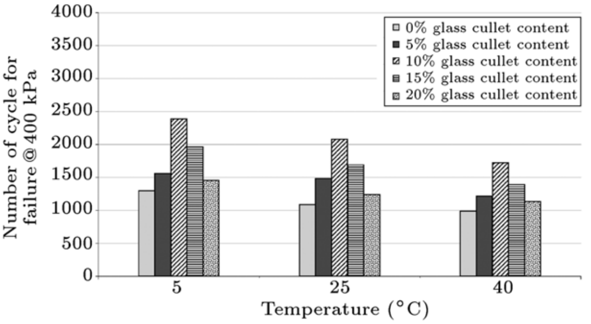

Figure 3: Number of cycles required for failure vs. temperature for different glass contents at a stress level of 400 kPa.

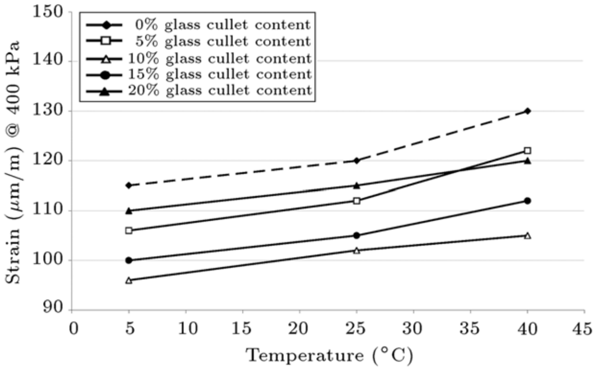

Figure 4: Final tensile strain vs. temperature for different glass contents at a stress level of 400 kPa.

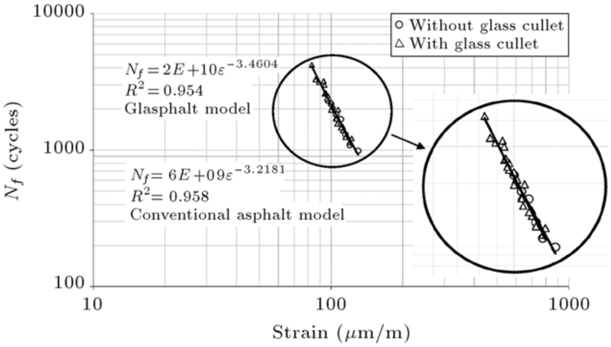

Figure 5: Comparison of the proposed models for the fatigue life of glasphalt and conventional asphalt concrete.

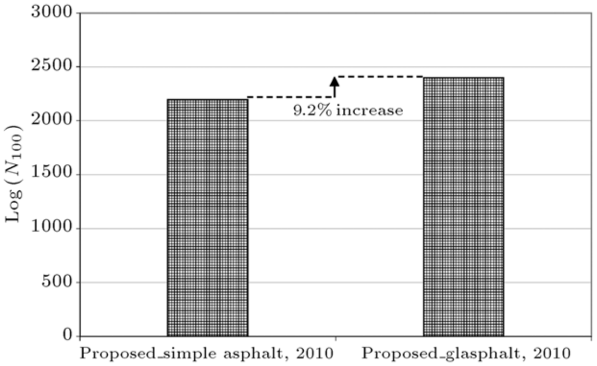

Figure 6: Comparison of the number of cycles required to reach a strain of 100 μm for glasphalt and conventional asphalt.

that is induced under load in the specimen. This law can be expressed as Eq. (1):

$$N = a\varepsilon_t^b \tag{1}$$

In this equation, N is the number of loadings achieved prior to the onset of failure, and the power "b" usually is about −4. The experimental results of these two types of HMA are presented as two separate plots in Figure 5. The model suggested for the fatigue life of the glasphalt specimen is as follows:

$$N = 2E10\varepsilon_t^{-3.4604} \qquad R^2 = 0.954 \tag{2}$$

The model proposed for the fatigue life of conventional asphalt concrete is:

$$R^2 = 0.958 \qquad N = 6E9\varepsilon_t^{-3.2181} \tag{3}$$

For better interpretation of the differences in the fatigue life behaviour of conventional asphalt concrete and glasphalt, a portion of Figure 5 is magnified to show the considerable differences in the fatigue model of two types of asphalt concrete. It can be concluded that the use of crushed glass does not have much influence on a decrease in the tensile strain of asphalt mixtures, but does noticeably improve the fatigue life of the specimens. The number of cycles required to reach a strain of 100 μm is usually used as a comparison metric of fatigue life models of HMAs. This metric is presented in Figure 6 for the suggested fatigue life models for conventional and glass-containing asphalt concretes, showing that glasphalt mixtures can stand up to 9% more cycles.

4. Conclusion

In this study, modelling using analytical tools is applied for the first time in predicting the behaviour of glasphalt mixtures. Glasphalt mixtures with differing crushed glass content and at three different temperatures are subjected to experiments with various levels of stress. Comparison of the proposed model for glasphalt with models proposed for conventional asphalt mixtures shows that specimens containing crushed glass, as well as hydrated lime, have noticeably better fatigue performance. In addition:

- As a result of the higher angularity of the glass particles, glasphalt has a higher internal friction angle and better interlocking between different constituent particles. These characteristics would consequently reduce the final tensile strain in the specimen, due to applied stress, and prevent initial cracking and crack propagation in the specimen.

- The distribution of crushed glass aggregates in all directions will increase strength against shear displacements in the specimen, which will consequently prevent crack propagation.

- Better adhesion among bitumen, stone and glass aggregates, as a result of the anti-stripping properties of hydrated lime, will minimise the relative displacement of the stone aggregates and increase the fatigue life of the samples by slowing down initial cracking and crack propagation.

Acknowledgments

The authors are thankful to the learned referees for their fruitful suggestions for improving the presentation of this research.

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