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Numerical and laboratory investigation of fatigue prediction models of asphalt containing glass wastes

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ABSTRACT

In the present study, the finite element method was applied to model the fatigue behavior of glassphalt and conventional mixtures. In order to assess the efficiency level of the presented model, all mixtures were tested using 4-point bending test. Accordingly, it can be seen that there is high consistency between the laboratory results and outputs of 3D finite element model presented in this study in both conventional asphalt and glassphalt mixes. 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.

1. Introduction

Fatigue life is known as one of the primary long-term characteristics of the asphalt pavements [1,2]. Major destruction in lifetime of pavement is including: rutting, fatigue cracking, and thermal cracking. Lots of costs are required for reparation and reconstruction of these defects, so initial prevention is usually economical [3,4]. Alligator cracks are major forms of pavement destruction due to fatigue failure of the pavement, which happens when the pavement loading cycles passes the fatigue life of the pavement [5], or when the internal damages rise to a specific amount [6]. Several experimental research and modeling in order to increase fatigue life and permanent deformation reduction along asphalt mixture vehicle tires path are conducted that ride to use proper additives, asphalt mixture resistance increase against dynamic loads, pavement thickness increase and using more resistant asphalt mixture in order to increase asphalt concrete mixture against vehicles [7–11]. There are two methods for increasing asphalt mixture resistance against fatigue and rutting that both methods increase operation cost of pavement including (1) using more resistance asphalt mixtures, and (2) increasing the thickness of the pavement [12].

In the past decades, for increasing the flexibility of the pavement and resistance upon harmful factors including fatigue, temperature alteration based cracks and permanent deformation, wastage compounds that have potential to be used as pavement mechanical properties modifier that have been used in hot mix asphalt [13]. Aim to the improvement of the pavement properties; two different approaches are: (1) using modified bitumen, and (2) using the modified asphalt mix.

over the past few years, the soaring trend of reconstruction and reparation cost of road and airport pavement that are due to amount and traffic increasing imposed to pavements that all lead to extensive research in additive material in asphalt mixture construction to increase dynamic loads. The most significant issues in road protections are low resistance pavement against dynamic loads and short service life.

Basically, fatigue phenomenon is based on the elastic and viscoelastic behaviors of asphalt mixtures. Various factors, including time, loading speed, loading time, resting period, temperature, stress level, loading mode, moisture, and aging, have an effect on the deformation behavior and performance of asphalt concrete [14–18]. Classical methods for fatigue evaluation are based on S-N diagram (amount of force in respect of number of cycles to failure), which are already utilized in many engineering designs. This method models the overall behavior of the part and does not present any relationship between the number of cycles and damage imposed on the part or length of the cracks. One of the alternative methods of fatigue life predicting is the use of crack and failure rules based on inelastic strain energy in the stable cycle of the part. Since modeling the behavior of failure and forming cracks under a high number of loading cycles are very time consuming, it is possible to examine the part behavior at low number of cycles and predict crack length and its distribution under a high number of cycles by empirical formula. Fig. 1 shows the process of failure and creation of crack in asphalt pavement.

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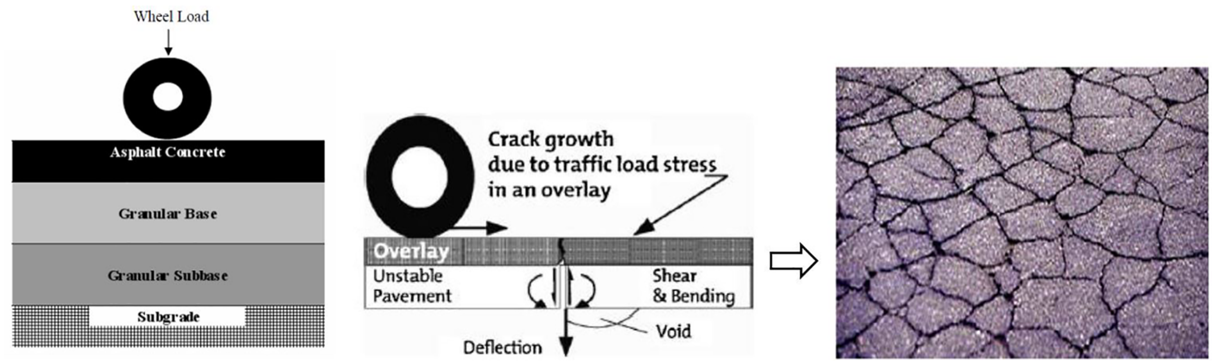

Fig. 1. Crack growth due to applied traffic loads [19,20].

1.1. Fatigue phenomenon in pavement

Since the creation of cracking is usually taking place in a specific period of using asphalt pavement, fatigue cracks are known as the most crucial failures of asphalt pavement. Crack propagation on the pavement surface illustrates the lack of cohesion in the pavement. Also, by increasing traffic loads, the rate of crack propagation increases [21,22]. The alligator cracking is the most common types of cracking occurring owing to fatigue function.

1.2. Fatigue strength estimation methods in asphalt mix

The fatigue life of an asphalt mixture is associated with initial strain or stress and also the number of cycles of failure. Equations (1) and (2) presented the fatigue life of mixture.

$$N_f = a\left(\frac{1}{\varepsilon_0}\right)^b \times \left(\frac{1}{S_0}\right)^c \quad (1)$$

$$N_f = d\left(\frac{1}{\sigma_0}\right)^e \times \left(\frac{1}{S_0}\right)^f \quad (2)$$

where N_f is the number of cycles of failure, ε_0 is initial strain, σ_o is initial stress, S_o is rigidity of mixtures, and a, b, c, d, e, f are experimental coefficients [23].

For predicting the fatigue life of asphalt mixtures, similar models are presented. These models can be represented in Eqs. (3) and (4), respectively.

$$N_f = k_1(\varepsilon_t)^{k_2} \quad (3)$$

$$N_f = k_1(\sigma_t)^{k_2} \quad (4)$$

where N_f is number of cycles of failure (fatigue life), ε_t is the tensile strain, σ_t tensile stress, and K1 and K2 are constants.

There is a direct relation between the tensile strains which extend under the load in the mixture and fatigue life. Nevertheless, with various temperatures and loading rates, a single model can be presented in equation (5):

$$N = A\left(\frac{1}{\varepsilon_t}\right)^n \quad (5)$$

where N_f is number of cycles of failure (fatigue life), and n power is approximately 4 [24]. After crack initiation, it propagates upward and leads to weaken the structure of pavement. The damage of asphalt pavement due to fatigue is complicated procedure which is due to the continuous bending, and following by micro cracks in asphalt pavement. Another approach for predicting the fatigue response of asphalt pavement is energy method, since the fatigue life can be dependent upon the amount of wasted energy. Therefore, energy-based models have been presented by many researchers for estimating the fatigue life of mixture. In this method, wasted energy is used to indicate the reduction of mechanical properties of mixture like stiffness during performing test. The amount of wasted energy of viscoelastic materials in each cycle is represented in Eq. (6):

$$W_i = \pi \times \sigma_i \times \varepsilon_i \times \sin\delta_i \quad (6)$$

where W_i is the wasted energy in each cycle in period times of i, σ_t is pressure range in each cycle in period times of i, ε_i is tensile range in each cycle of i time, and δ is the phase angle between wave signal of tensile pressure and degree. For estimating the fatigue life using energy-based method, Eq. (7) was presented.

$$N_f = K_1 \times \left(\frac{1}{W_i}\right)^{K_2} \quad (7)$$

where N_f is number of cycles of failure (fatigue life), Wi is wasted energy, and K1 and K2 are experimental coefficients [25].

1.3. Literature review

1.3.1. Fatigue modeling

In recent years, different types of modeling have been performed on the using additives in asphalt mixtures in order to numerically evaluate fatigue behavior and model its resulted cracks in modified asphalt mixtures. In a research, Kim et al. [14] investigated the mechanism of fatigue cracks in asphalt pavements using finite element program (VECD-FEP + +) and proposed a model for pavement layers and a nonlinear elastic model for the substrate layer using a visco-elastic continuous damage mechanism. They aimed to examine top-down and bottom-up cracks by taking into account important parameters such as thickness of asphalt layers, layer stiffness, pressure distribution under wheels, and level of load applied to the pavement. Suitable conditions were determined for top-down cracking using the results of this parametric study. Damage connection lines in the thicker pavement where a gap develops in the thickness of the pavement with top-down and bottom-up cracking and are turned into larger cracks by simultaneously integrating. This issue was validated using fatigue performance and bottom-up cracks, which had been proved in previous works. Achievements of this study showed that thickness of various pavements and loading conditions significantly affected the pavement response to the damage of layers .Zhi et al. [15] investigated fatigue models and failure criterion based on the results obtained from indirect tensile fatigue test, and indirect tensile stiffness modulus test on asphalt mixtures using polymer modifiers. For this purpose, to model loading conditions, the pavement layers, base, sub-base layers and subgrade soil were considered multi-layer pavement layers. The fatigue model based on the continuous damage mechanism, description of micro-cracks, growth and development of cracks in the top layer using fatigue models and finite element analysis were used to investigate the crack performance in this layer of flexible pavements. In this study, using finite element method, a 3D model was created to simulate traffic loading and different speeds of vehicles. This model could examine the parameters

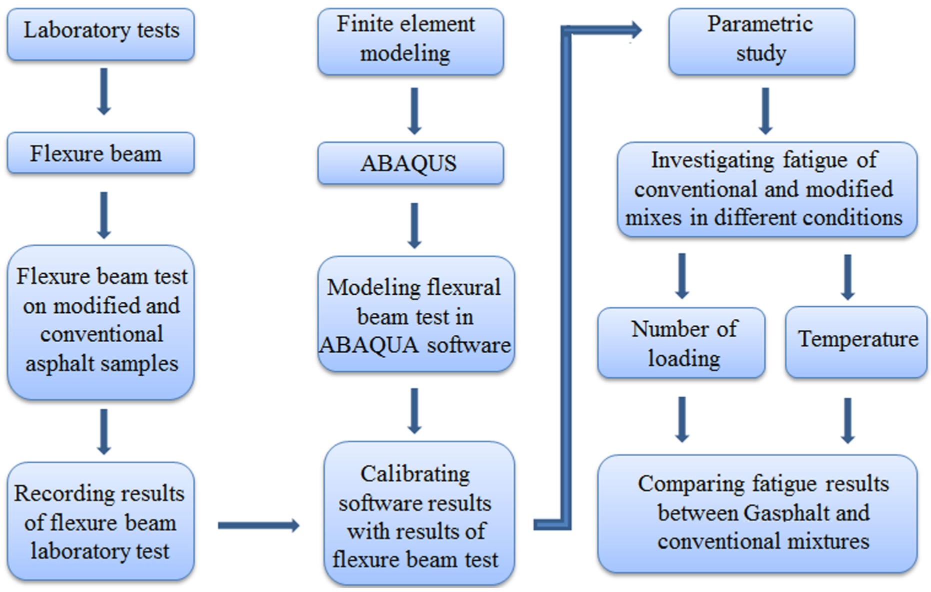

Fig. 2. Strategy of the present study.

needed for fatigue cracking caused by fatigue at high load repetition to respond flexible pavements. The results of this study showed that moving load speed has a considerable impact on the response of elastic and plastic behaviors of pavements. Also, results showed that developing a shoulder with suitable width and appropriate connection to the edge of asphalt layer leads to reduced deformation of pavements. Effects of various load ratios, number of axles, loading axle, number of wheels, features of pavement sections, subgrade soil type, and the studied shoulder width presented considerable effects on the pavement response to fatigue-induced damage.

Mia et al. [16] used finite element analysis method of 4-point bending beam in order to evaluate fatigue phenomenon in flexible pavements. They designed a finite element model to assess fatigue phenomenon according to variables such as loading time, intensity of stress and strain applied to the model, and different thickness of the beam. In the proposed model, a half-sinusoidal loading type with vertical loading and strain control similar to AASHTO was used. They used a linear elastic behavior to perform the analytical process in the finite element method. To evaluate results of their model, they compared results with those presented by the laboratory samples obtained by 4-point bending beam test containing descriptive behaviors of pavement failure. The results of this research indicated the high efficiency of the proposed model in predicting fatigue phenomenon in flexible pavements. In a study, Lancaster et al. [17] used extended finite element method to model the characteristics and expansion of cracks. The aimed to model, develop, and expand cracks in the semi-cylindrical sample and then compare them with the laboratory results of cylindrical asphalt concrete samples containing SBS (styrene butadiene styrene) and control samples. In this research, symmetrical properties were used to reduce the number of nodes and calculation time. The model was validated using the laboratory samples of the asphalt mixtures modified by semi-circular bending test. In this research, they showed that crack modeling by extended finite element method (XFEM) and describing the behavior of materials for describing the sample cracks by simultaneously considering the effect of temperature, time, and repetition of loading cycle could help achieve optimum results in terms of fatigue performance of asphalt mixtures and its resulting cracks. In a comprehensive study, Weise et al. [18] determined the input parameters of asphalt mixtures for the pavement design mechanism and fatigue behavior of samples. They used an extended 3D model by ReFEM finite element program for modeling and studying the stress and strain of samples in 4-point bending beam test. A unique model was implemented to simulate the 4-point bending test. The asphalt sample considered for modeling was linear and elastic with the Poisson's coefficient of $\mu = 0.298$ at 20 °C. They used indirect tensile fatigue and 4-point bending tests to verify and validate the results of their research. Results of this study showed that cracking mechanism in indirect tensile and 4-point bending tests not only was different, but also had clear difference from cracking in real pavements.

1.3.2. Glass cullet in asphalt mixtures

Annually almost 10 million tons of waste glasses are produced in which 3–5% is related to domestic wastes [26]. By using recycled glass in the asphalt mixtures, a large amount of energy can be saved in addition to environmental waste reduction. Thereby, the application of waste glasses in the asphalt mixtures is developing significantly [27–29]. Airey et al. presented an adequate performance of using 10–15% of waste glass in the asphalt mixtures. The amount of 2% lime was used as anti-stripping, and the maximum glass size of 4.75 mm was chosen in order to reduce the possibility of tire puncturing and skin cutting [30]. Androjićand Dimter studied the properties of asphalt mixtures with the replacement of glass cullet as aggregates and filler. The results exhibited a significant effect of glass content on the mixture characteristics such as Marshal stability, air voids, and density. Nevertheless, the performance of the mixture decreased by using a high content of the glass [31]. The effect of glass cullet on the stiffness of asphalt mixtures has been performed by Arabani et al. The results of the study showed that using the glass cullet in the asphalt mixture increases both parameters of stiffness and internal friction of the asphalt mixture due to crushed structure and high angularity of the glass particles [9,32]. The linear viscoelastic performance of asphalt mixtures containing glass particles investigated by Arabani et al. for different levels of stress and temperatures. The achieved results exhibited a lower permanent strain of glasphalt in comparison to the conventional mixture. Also, the thermal sensitivity analysis revealed a higher sensitivity of the glasphalt mixtures rather than the conventional [33]. As a result, it can be expected better fatigue performance for the asphalt mixtures containing glass particles in comparison to the conventional asphalt mixtures based on the strength of the additive materials [34,35].

1.4. Objective and scope of the present research

In this study, laboratory and numerical evaluations were conducted on the performance of asphalt mixtures modified by waste glass cullet

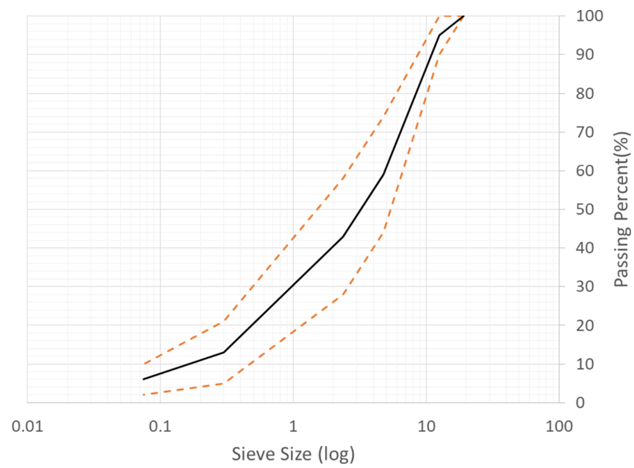

Fig. 3. Gradation curve of the used coarse aggregate.

against fatigue phenomenon in different temperature conditions. In order to develop analytical models, finite element method was used, which included models related to stress–strain relations. Fig. 2 shows the process of this research. The number of five samples were prepared for both mixtures of conventional asphalt beam and the asphalt beam containing glass cullet.

2. Materials and methods

2.1. Samples preparation

The continuous type IV scale of the AASHTO standard was employed in the current study for the gradation of aggregates [36]. The gradation of the aggregates is shown in Fig. 3 and with more detail in Table 1. Also, the physical properties of aggregates is presented in Table 2. The implemented bitumen was the 60/70 penetration grade, which received from the mineral oil refinery of Isfahan, Iran. The properties of asphalt binder are shown in Table 3.

The glass cullet employed in this study was obtained from the glass waste generated by glass manufacturing factories. The largest glass cullet size was limited to 4.75 mm. The gradation curve of glass particles is presented in Fig. 4 and Table 4. Also, aim to prevent stripping distress, the High-calcium hydrated lime was used as additives to glasphalt mixture. According to previous research, asphalt samples containing 10% glass cullet and 5.5% optimum bitumen content were prepared [34].

In the pavement design procedure, some essential parameters are fatigue parameters and E modulus temperature function, which can be achieved through the implementing repeated load tensile test. In the first place, the laboratory program included the fabrication of asphalt slabs. For the preparation of the laboratory samples, first, an asphalt slab with the thickness of 5.0 cm and dimensions of 30 × 40 cm was constructed by a linear friction tester device, turned to beam forms with standard sizes for testing at 5 and 25 °C, and placed in the flexure beam device. In the current study, the test parameters were set as follows: applied load frequency: 10 Hz, sine-wave load shape and stress level: 250 kPa.

Table 1
Gradation of the aggregates used in this study.

Sieve size (mm)	19	12.5	4.75	2.36	0.3	0.075
Lower-upper limits	100	90–100	44–74	28–58	5–21	2–10
Passing (%)	100	94	58	42	14	6

Table 2
Physical properties of aggregates.

Item	Amount
Coarse aggregates(gr/cm^3)	
Bulk Specific gravity	2.631
SSD Specific gravity	2.641
Apparent Specific gravity	2.661
Fine aggregates(gr/cm^3)	
Bulk Specific gravity	2.638
SSD Specific gravity	2.645
Apparent Specific gravity	2.664
Abrasion loss(%)(Los Angeles)	24.1
Flat and elongated particles (%)	17.2

Table 3
Rheological properties of the used binder.

Test	**Standard**	**Amount**
Flash point (°C)	ASTM D 92	261
Softening point (°C)	ASTM D 36	50
Loss of heating (%)	ASTM D1754	0.75
Specific gravity (25°;g/cm^3)	ASTM D70	1.022
Ductility (25°;cm)	ASTM D113	112
Penetration Index (25°;0.1 mm)	ASTM D5	65

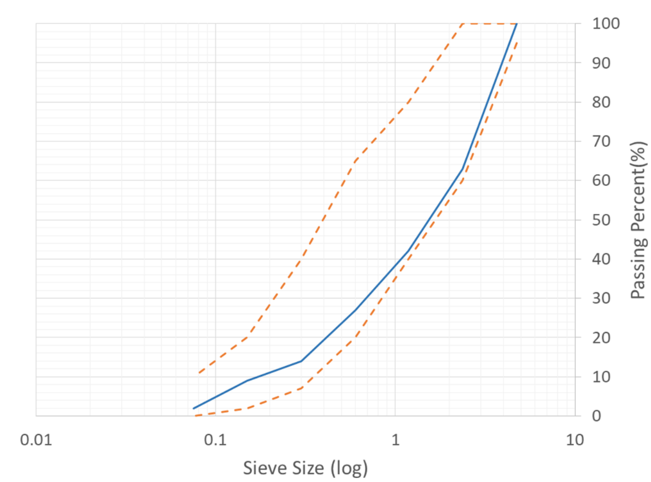

Fig. 4. Gradation curve of the used fine aggregate (glass cullet).

Table 4
The used gradation of the glass cullet aggregates.

Sieve size (mm)	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	64	42	28	15	9	2

2.2. 4-point bending test (4 PB)

4-point bending test (4 PB) is a method for testing fatigue which is utilized to define the resistance of asphalt mixtures to high repetition loads at critical temperature and under loading similar to what is applied to the pavements in roads. The four-point bending test was carried out to evaluate the fatigue life of asphalt mixtures according to ASTM D7460-10, "Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending," and AASHTO T321, "Standard Method of Test for Determining the Fatigue Life of Compacted Hot Mix Asphalt Subjected to Repeated Flexural Bending". In this study fatigue test was performed according to AASHTO T321. According to AASHTO T321 [37], 4 PB test was conducted on a beam with the height, width, and length of 50, 50, and 380 mm, respectively. This test is done by fixing the asphalt beam

Table 5
4 PB Test conditions used in this study.

Item	Employed conditions
Wave type	sinusoidal stress with cycling by zero
Frequency f (Hz)	10
Loading Duration (s)	1/f
Rest period (s)	None
Temperature (°C)	+5, +25

sample under repeated the 4-point loading at a certain strain level. In general, fatigue testing is done using two methods of constant tension and constant strain. In the constant strain mode, strain is left constant, while stress is allowed to change. In the constant strain mode, load remains constant, while strain is allowed to vary [12]. In this study, 4-point bending beam test with the constant stress of 250 kPa was conducted at two different temperatures of 5 and 25 °C. Table 5 shows the testing conditions in this study. The failure of mixtures happened when the material stiffness reduced by 50% of the initial stiffness. Following the fatigue test, the sample's fatigue life at five different strain (μs) levels of sinusoidal loading, then the following equation was used to calculate the fatigue line of specimens:

$$N = K_1\left(\frac{1}{\varepsilon_t}\right)^{K_2} \tag{8}$$

where N represents the number of cycles to failure, ε_t represents the tensile strain used in, K_1 and K_2 are fatigue constants (experimental constants).

In this study, to obtain the K1 and K2 parameters, the number of cycles that lead to the sample's failure with respect to strain (μs) are plotted. After plotting the strain levels with corresponding the number of cycles, the correlation between strain levels with and the number of cycles is obtained, which leads to determining the value of the two mentioned parameters.

In this test, it is essential to specify the deformation and distortion rates of the sample's central part based on strain level (maximum tensile strain measured on beam curvature) using Eqs. (9) and (10).

$$\sigma_t = \frac{p.\ l}{b.\ h^2} \tag{9}$$

$$\varepsilon_t = \frac{108.\ \delta.\ h}{23l^2 + 36.\ h^2.\ (l + \text{Î½})} \tag{10}$$

where σ_t is tensile stress (Pa), $\varepsilon_t$is tensile strain (m/m), P is Range of applied load to the sample, L is beam opening (m), b is beam width (m), h is beam height (m), ν is Poisson's ratio = 0.35 and δ is Beam deformation relative to the neutral axis.

2.3. Finite element analysis

Analysis of fatigue behavior is essential in design procedures. Generally, the finite element method (FEM) is an acceptable numerical analysis method for simulating and predicting the materials' behavior [38,39]. However, considering effective parameters leads to achieving a better result. The parameters that must be taken into account are specimen specification, element size, and applied load [40]. Thereby, in this study, the smaller mesh size was implemented in critical areas for obtaining an accurate answer. The simulation has been done in ABAQUS and fatigue phenomenon in glasphalt and conventional mixtures was performed using a 3D dimensional modeling.

In this study, Poisson's ratio of $\upsilon = 0.35$ was used to model flexure beams of asphalt samples at 5 and 25 °C and assumed applied stress was 250 kPa. So, the methods of loading application and deformation procedure of flexure beam are shown in Fig. 5. Simulation of the real loading process in flexure beam test is complex in finite element modeling. Application of this complex loading leads to very long calculation time and analysis. There is another simple method for modeling this loading, which was used in the present study. This method was introduced and used by Tayebali (1992) [41] and, subsequently, by Pelgröm (2000) [42]. In this simple loading, load is statically employed to the sample with certain frequency of 10 HZ with sinusoidal range and Fourier coefficients that are existed in the ABAQUS library and commensurate with the load and have been created.

Fig. 6 presents a schematic view of the flexure beam and the distance between loading and supporting jaws. The proposed finite element model was a prismatic sample with loading in accordance with AASHTO T321 standard. The top of the sample was in direct contact with the metal jaw of the device.

Dimensions of this model were based on the dimensions of the asphalt samples in flexure beam test so that height, width, and length of the beam were 50, 50, and 380 mm, respectively [37]. Simulation of finite element model and its boundary conditions was completely based on the placement of asphalt sample in the 4-point bending device. For accurate simulation of the boundary conditions, 1 mm empty space was taken into account on the side between the sample and jaw to allow frictionless movement between the steel and sample. The meshing used here was a regular square 3D grid. In sum, 7040 standard 3D elements and 416 elements were selected for each part of steel jaw with similar components [43].

3. Results and discussion

3.1. 4-point bending test results

Results of fatigue life and strain of 4-point bending test are presented in Figs. 7 and 8. In this test, flexure beam test was performed at 5, 25 °C and applied stress of 250 kPa for both cases of conventional and glasphalt mixtures. Based on the achieved results, the values of tensile strain measured in the glass-modified samples were far lower than the same values in the conventional asphaltic samples, which could prove that glass has a high impact on improving the asphalt mixture fatigue life. The results of 4-point bending test were used to calibrate the results of fatigue life prediction models. It was showed that asphalt mixture made with glass cullet causes the thermal sensitivity of mixture to improve [33]. Also, using glasses results in better aggregate interlocking which leads to a higher thermal strength of asphalt [44]. Results showed that by increasing the temperature, the fatigue life of mixtures was decreased. But, the reduction of fatigue life in mixtures containing glass cullet was lower than conventional mixture, since the addition of glass led to an improvement of thermal sensitivity of mixture.

3.2. Modeling of 4-point bending test in ABAQUS software

3.2.1. Stress and strain results

Figs. 9–12 demonstrate the stress rate created in different parts of the conventional and glasphalt mixes models. As expected, the stress values were much higher in the middle of the flexure beam compared with other areas. It is obvious from the stress contour in the 3D model that the modified model could bear more stress due to its increased stiffness after the addition of glass cullet.

Figs. 13–16 show values of strain generated in various parts of the finite element model of glasphalt and conventional mixtures at 5 and 25 °C and stress of 250 kPa. According to the strain contour, it is obvious that tensile strain was maximum in the bottom layer of the beam and, by an increase in the loading repetition, cracks were initiated and developed toward the top of the beam. Also, such tensile strain was generated in pavements due to the passing of wheels of vehicles, particularly heavy vehicles. Considering the pavement thickness and high repetition of loading, cracks were initiated from the highest value of tensile strain and developed upward; finally, pavement failure and

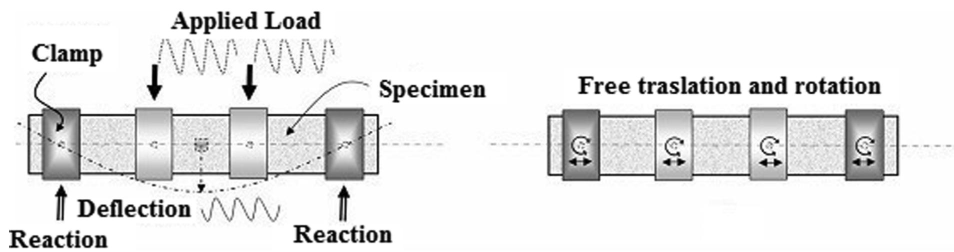

Fig. 5. View of loading, applied load range, and beam displacement.

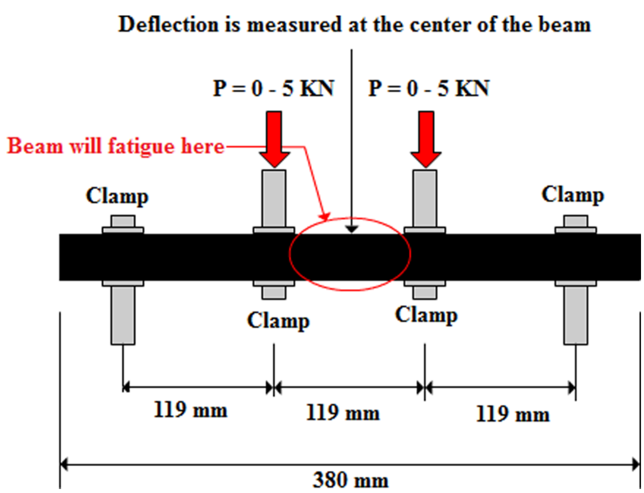

Fig. 6. Schematic view for the placement of jaws in flexure beam [37].

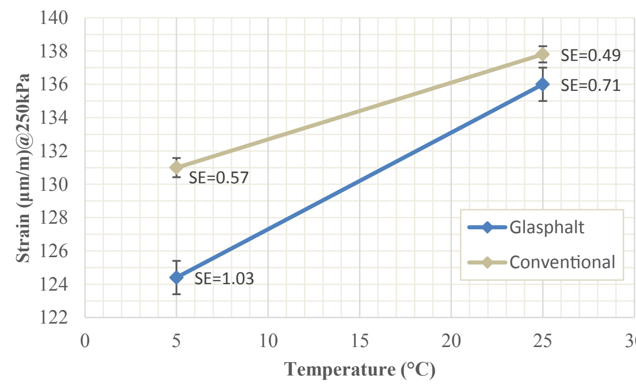

Fig. 8. Strain values of the conventional and glasphalt samples in flexure beam test.

fracture occurred.

The values of predicted strain and fatigue life by finite element model at 5 and 25 °C were significantly different. As presented in previous studies and laboratory results, the increase in temperature increases the elastic strain under high repetition and considerably reduces fatigue life [34,45].

The above values were predicted by ABAQUS software. It can be seen that the difference between conventional and glasphalt mixtures is obvious. Glasphalt mixtures have smaller deformations and are less prone to damage and crack formation owing to the high strength of glass. Comparing the values of stress and strain in the glasphalt and conventional mixtures models illustrated the effectiveness of using glass in increasing the fatigue phenomenon in pavements.

3.2.2. Predicting number of cycle

For predicting the fatigue life of the model proposed by ABAQUS software, the final strain was extracted from the model after loading and placed in Eq. (3). To calculate fatigue life, K1 and K2 values obtained from 4 PB test were used. These values are shown in Table 6.

In Fig. 17, the results of fatigue life predicted based on the process described above are shown in glasphalt and conventional flexure beam samples. Fig. 17 clearly shows that the samples containing glass powder had higher fatigue life and resistance to fatigue phenomenon compared with the conventional samples. Fig. 18 represents strain values predicted by finite element software at two temperatures of 5 °C and 25 °C. Comparison of the results in Fig. 17 shows that the difference in fatigue

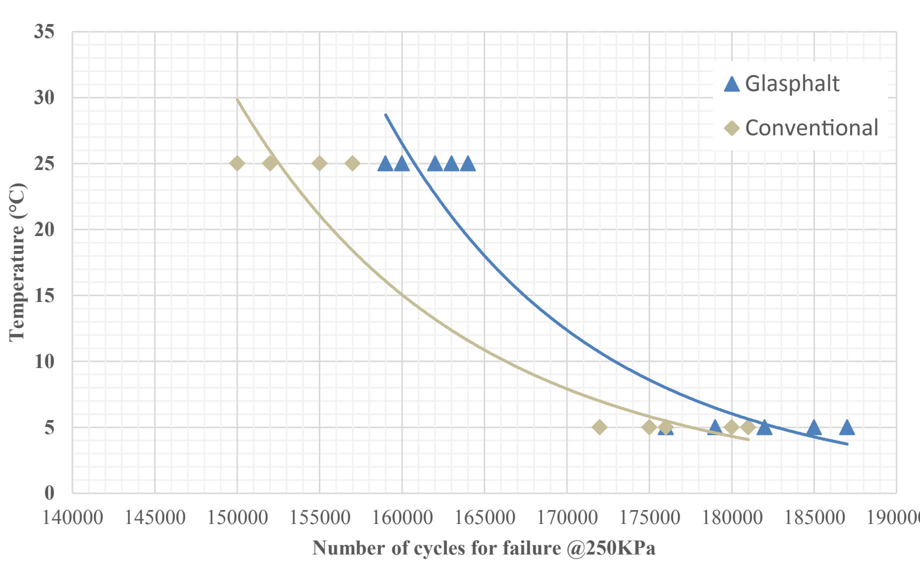

Fig. 7. Fatigue life values of the conventional and glasphalt samples in flexure beam test.

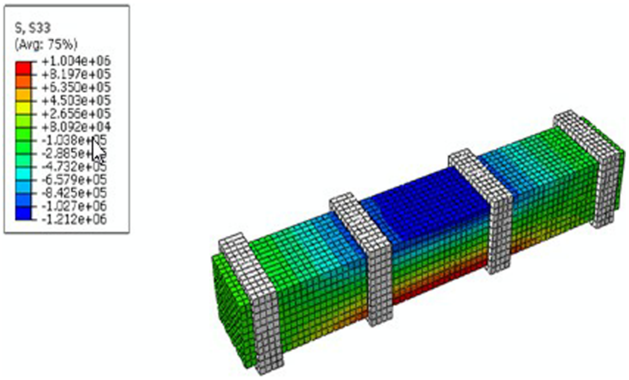

Fig. 9. Stress predicted in 3D glasphalt sample model under pressure of 250 kPa and temperature of 25 °C.

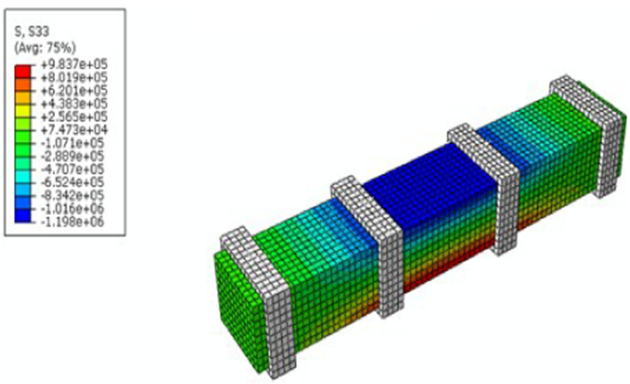

Fig. 10. Stress predicted in 3D conventional sample model under pressure of 250 kPa and temperature of 5 °C.

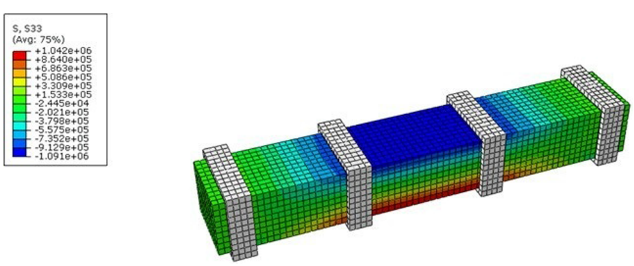

Fig. 11. Stress predicted in 3D glasphalt sample model under pressure of 250 kPa and temperature of 25 °C.

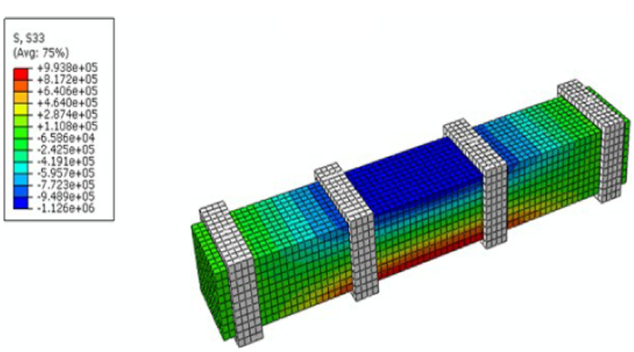

Fig. 12. Stress predicted in 3D conventional sample model under pressure of 250 kPa and temperature of 25 °C.

life predicted by ABAQUS software and laboratory data obtained from 4 PB test was 25% and 57% for glasphalt as well as 7% and 54%, for conventional mixture in the best and worst cases, respectively.

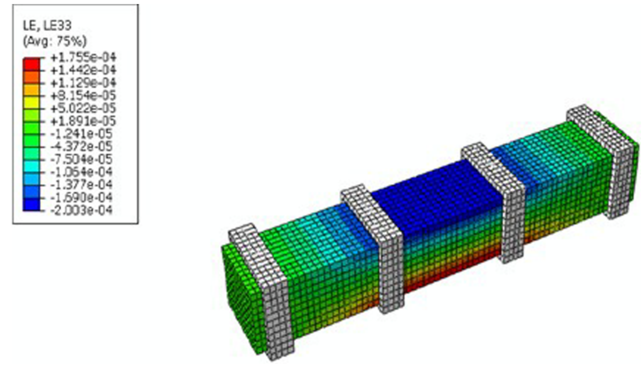

Fig. 13. Strain predicted in the 3D glasphalt sample model under pressure of 250 kPa and temperature of 5 °C.

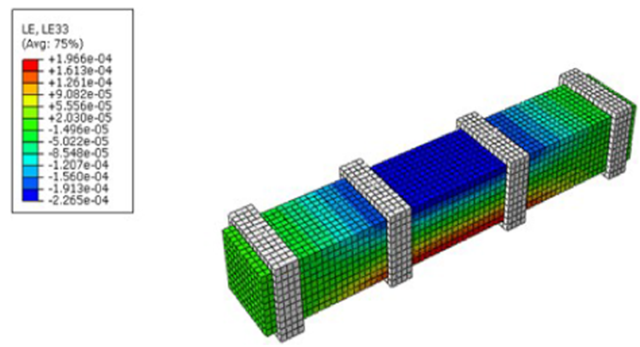

Fig. 14. Strain predicted in the 3D conventional sample model under pressure of 250 kPa and temperature of 5 °C.

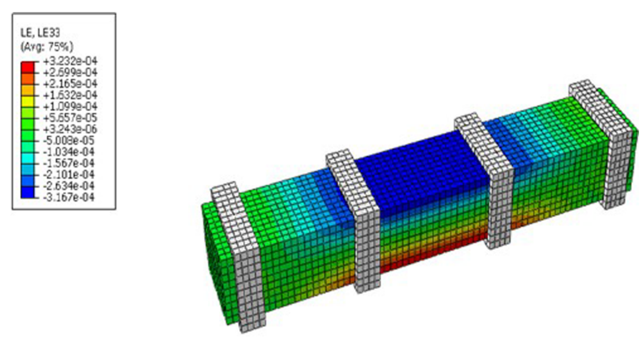

Fig. 15. Strain predicted in the 3D glasphalt sample model under pressure of 250 kPa and temperature of 25 °C.

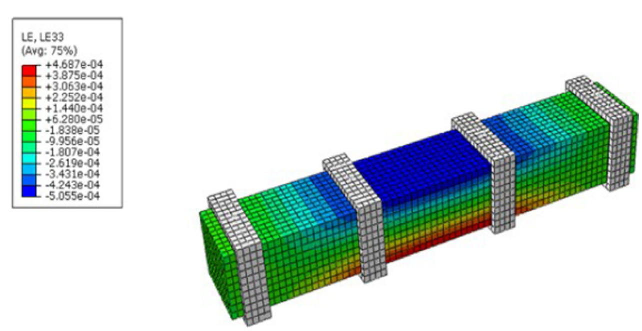

Fig. 16. Strain predicted in the 3D conventional asphalt model under pressure of 250 kPa and temperature of 25 °C.

3.2.3. Calibration of models results

Comparison of the results of fatigue life predicted by the model and fatigue life results measured by 4-point bending test showed that the

Table 6
Values of parameters used in the modeling.

Mixture	Temperature	k_1	k_2
Glasphalt	5	1.42E + 13	− 3.592
Conventional	5	9.747E + 10	− 2.488
Glasphalt	25	5.305E + 11	− 2.675
Conventional	25	8.94E + 17	− 4.873

difference between the two values was 57% in the worst case. It is necessary to compare the predicted fatigue life in ABAQUS with those of the laboratory tests in order to validate the results. In this study, laboratory results of 4-point bending test were used for this purpose.

To improve the modeling accuracy, the K1 and K2 within the Eq. (3) would be revised after several simulations, so that the fatigue life results obtained by modeling would become much more similar to laboratorial results. In this stage, the strain values which were determined in the modeling phase should be kept constant since the simulation (in other words strain and loading stress) is performed through inputting the precise value of Poisson's ratio parameter and Young module in material's characteristics, under precise loading, and definite boundary and support conditions for the samples. The calibration procedure was as follows: The values of K1 and K2 parameters were changed to the necessary extent by trial and error until the results of the predicted and measured fatigue life were appropriately overlapped. Finally, after a series of trial and error and considering fatigue parameters, the results of the predicted and measured fatigue life are shown in Table 7.

Figs. 19 and 20 show the comparison made between the predicted fatigue life and that of laboratory results before and after calibration. In these figures, comparison of the results demonstrated the difference between fatigue life predicted by ABAQUS software and laboratory results obtained from 4-point bending test was 1% and 11% for glasphalt mixtures and also 4% and 13% for the conventional mixtures in the best and worst cases, respectively. According to the similar models presented in this field, this difference could bring appropriate reliability for the models presented in this study. The overall results of fatigue models presented in this study indicated that the addition of glass caused to increase fatigue life and reduce tensile strain in the proposed model and the laboratory samples at different temperatures. In addition glass particle with theirs crushed structures and high angularity made mixtures more resistance to fatigue damage. These findings are in agreement with the conclusion of other researchers [30,31].

Table 8 provides the equations presented in this study for fatigue

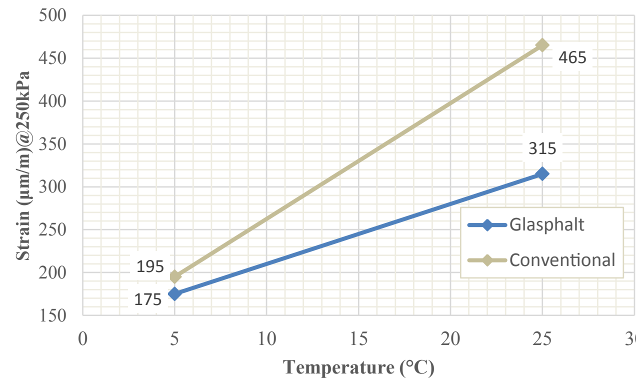

Fig. 18. Strain values predicted for conventional and glasphalt samples.

Table 7
Final values of parameters after validation.

Mixture	Temperature (°C)	K1	K2
Glasphalt	5	1.70E + 16	−4.886
Conventional	5	2.355E + 14	−3.9843
Glasphalt	25	3.15E + 14	−3.6817
Conventional	25	1.43E + 15	−4.8757

bending beam test is modeled by finite element software and then is calibrated and is verified for glasphalt and conventional mixtures at 5 °C and 25 °C.

4. Conclusion

In this study, laboratory and numerical evaluations performed on the fatigue performance of asphalt mixtures modified by waste glass cullet in different temperature conditions. Two types of the mixture were made, including conventional asphalt and the asphalt containing glass cullet. The samples' fatigue performance was examined through the 4-point bending test at different temperatures. The experimental values were compared to the numerical method. Then the best calibration coefficients presented based on the achieved results. Also, other achievements are as follow.

1. Glass particles successfully improved the behavior of asphalt pavement. Glasphalt mixtures presented between 3 and 4% better fatigue

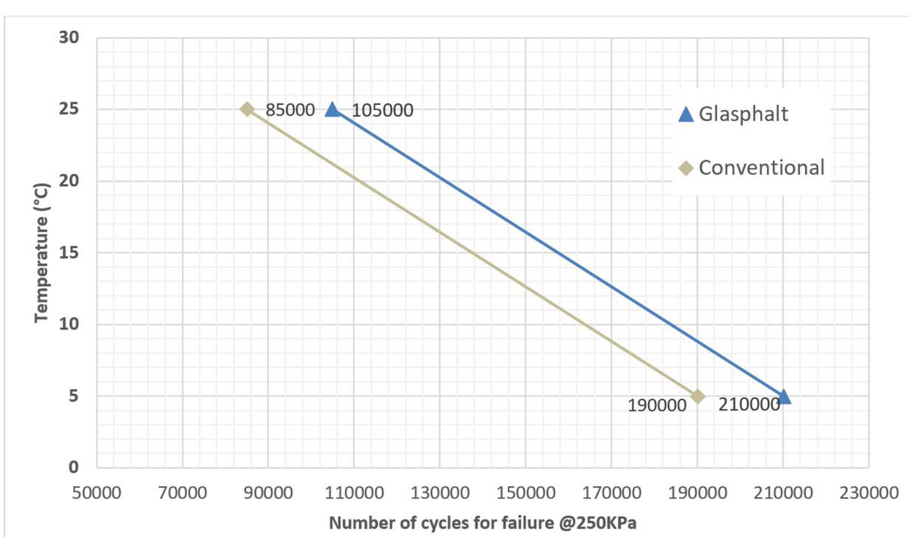

Fig. 17. Fatigue life values predicted in conventional and glasphalt samples.

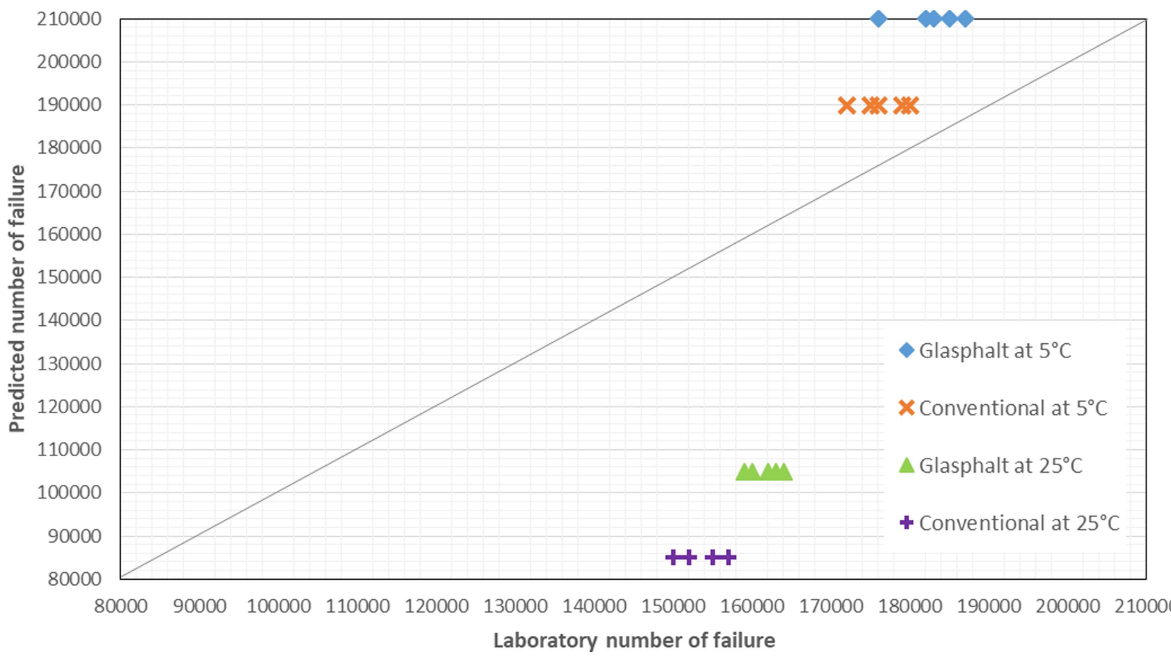

Fig. 19. Comparison of values of laboratory and predicted fatigue life for glasphalt and conventional mixtures before calibration.

performance in comparison to the conventional asphalt mixture at the temperature of 5 °C and stress level of 250 kPa as well as 25 °C. This might be related to the high angularity of glass particles, resulting in better interlocking and hindering initial cracking and crack distribution in the mixture, which leads to the higher capacity of the mixture against applied loads.

2. Asphalt mixtures containing glass cullet exhibited a better fatigue performance in comparison to the conventional mixtures, especially at the high temperature of the test. The reason is the reduction in thermal sensitivity of mixture due to the glass cullet, which leads to rising the number of cycles at high temperatures before failure.
3. During this study, high consistency between the laboratory experimental values and 3D finite element model achieved through calibration coefficients in both conventional and glasphalt mixtures, which approves the proper modeling of the study.
4. Based on the calibration between the experimental results and numerical method, four different estimation model presented for each of the conventional and glasphalt mixtures at the temperatures of 5 °C and 25 °C.

Table 8
Fatigue equations modeled by ABAQUS.

Mixture	Temperature(°C)	Equation
Glasphalt	5	$Nf = 1.70E + 16(\varepsilon_t)^{-4.886}$
Conventional	5	$Nf = 2.355E + 14(\varepsilon_t)^{-3.9843}$
Glasphalt	25	$Nf = 3.15E + 14(\varepsilon_t)^{-4.9617}$
Conventional	25	$Nf = 1.43E + 15(\varepsilon_t)^{-4.8757}$

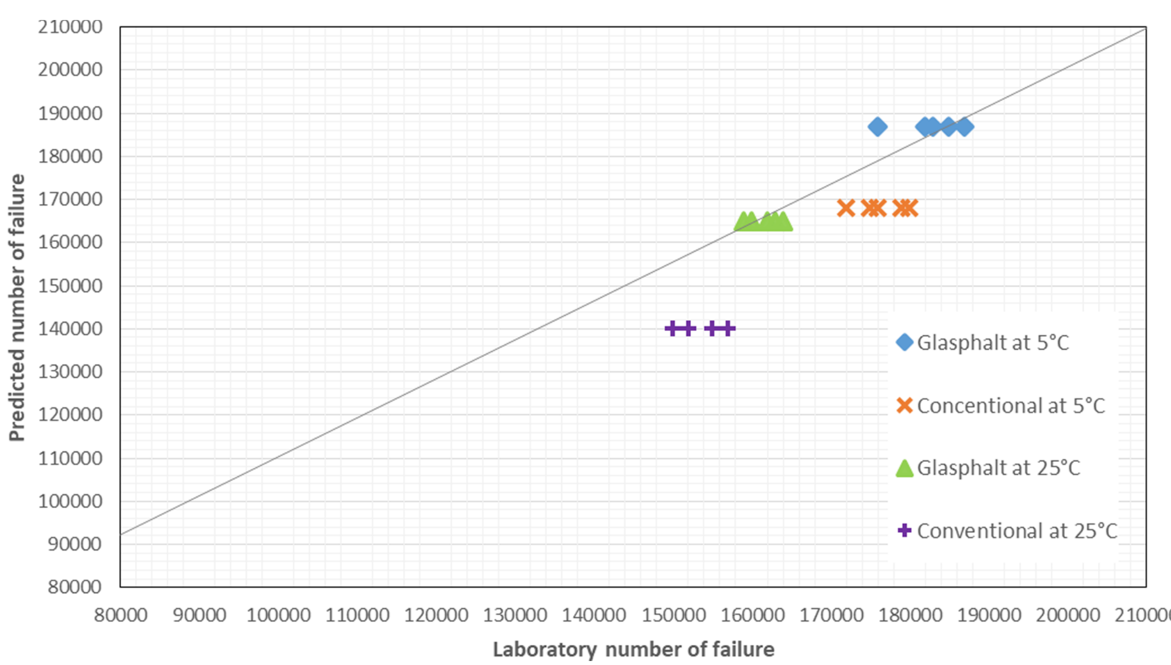

Fig. 20. Comparison of values of laboratory and predicted fatigue life for glasphalt and conventional mixtures after calibration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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