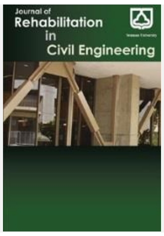

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Presenting a Statistical Model of Fatigue Prediction for the Effect of Loading Frequency on Reflective Cracks Propagation on Asphalt Layers Improved by Geosynthetics

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ABSTRACT

So far, several methods have been proposed for delaying the reflective cracks in pavements. Despite substantial money spent annually on these types of maintenance methods to control reflection cracking in road pavement, none of them has successfully prevented such damage and only delayed crack propagation in improved asphalt overlays. However, some of these methods have been more effective in preventing the initiation of reflective cracks and reducing the severity of their damage in restored pavements. One of the best methods to deal with this issue is using geosynthetic products. The present study investigates the performance of two different types of geocomposites in the reinforcement of asphalt overlays in delaying reflective cracks compared to control samples. To this end, laboratory and statistical studies were performed at different temperatures and loading frequencies. The results showed that using type-I geocomposite will be most effective in increasing fatigue life. On the other hand, among the mentioned factors, the temperature rise will have the most negative effect on the fatigue performance of geocomposite layers in asphalt overlays. Finally, a high-accuracy statistical model of fatigue life based on temperature, frequency, and geocomposite type is presented (i.e., R^2 and Adjusted R^2 of 0.987 and 0.981, respectively).

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1. Introduction

Typically, pavement cracking occurs through the course of the asphalt layer due to exceeding the tensile resistance thresholds on the asphalt materials by traffic or environmental loading[1,2]. Narrowing down the pavement cracking mechanism, the fatigue cracking is the most common load-related failure mode within the asphalt material. As the name implies, such a crack happens under a repetitive loading cycle which, seemingly, decreases the material resistance against the cyclic loads. The fatigue will eventually lead to cracking and then crack propagation to the surface [3,4]. As a result, a path is prepared for the penetration of erosive agents into the pavement, accelerating pavement failure[5-6]. Accordingly, predicting fatigue life is an important issue in designing and evaluating asphalt overlay maintenance. In this respect, continuous efforts have been made to develop models for predicting of modified, reinforced or combined overlays [7-10].

Based on the geosynthetics performance in the industry, only two types of geotextiles and geogrids are used to reinforce asphalt. Geogrids have high hardness, and geotextiles absorb stresses on asphalts. Geocomposites have both of these functions in asphalt. Therefore, these products are mostly used as reinforcement layers in asphalt [11]. This reinforcement leads to delays in the propagation of underlying cracks to the pavement surface and prevents the occurrence of premature reflective cracking [12,13]. One of the most important causes of cracks in existing pavements is the high traffic of vehicles, expansion, and contraction of pavement due to temperature changes. Excessive vehicle traffic and temperature variations are associated with the fatigue phenomenon. Besides, cracks due to fatigue in pavements generally occur for these two reasons. Research has shown that geosynthetics can increase the pavement resistance against reflective cracks up to 4 times.In 1993, some studies were conducted on rigid (concrete) cracked pavements with reinforcement interlayers and asphalt overlays using finite element software. The results confirmed the effect of reinforcement in delaying the crack initiation in the pavement (reflection cracking) [7,8,14]. It was later confirmed that the presence of reinforcements improved the pavement fatigue resistance by up to 4 times [15]. Recently, various studies have been conducted on using geocomposites and their different types as crack regards to repair existing pavements, reduce shear and bending stress in the crack loading range, and lower tensile strains at the crack tip [12,16–20]. The effect of asphalt reinforcement by different geogrids was also investigated. The results showed that using glass fiber grids and nonwoven geotextile increases fatigue life by 7 to 8 times compared to unreinforced coatings, respectively [21,22]. In comparison, other studies showed a 3 to 4 times increase in fatigue life when using propylene or polyester geogrids compared to the case without reinforcement [21,22]. The research results showed the inhibitory effect of reflective anti-crack systems, the type of interlayer or geosynthetics, and the type and amount of asphalt used for the tack coat to create adhesion between the layers in delaying crack initiation. Furthermore, the results showed a higher effect of geosynthetics (especially high modulus geogrids) than geotextiles and stress-absorbing layers in delaying the reflection cracking [2,23–25].

Overall, the efficiency of geogrid-reinforced specimens is between 3 and 6 times that of unreinforced specimens [19,26,27]. Khodai et al. investigated the effect of different temperatures on the fatigue cracks propagation and observed the role of temperature in the number of cracks and their path of movement. According to their results, at 60°C, unlike 20°C, the crack propagation trend for all samples was with the old asphalt overly was from overlay's floor to surface. For reinforced specimens, in the middle of the thickness, the cracks initiate from the layer bottom and move toward the geogrid. Then, they start again from the pavement's surface and expand downward [8].

The effect of temperature and different loading frequencies on mixtures with the stress-absorbing membrane layer interlayer (SAMI) was investigated using a Wheel Torque device. Based on the obtained results, these interlayers could delay the reflective cracks at 20 and 30℃ but were not effective at 10℃. These stress-absorbing layers also outperformed against higher loads than at higher loads [28]. The effect of geocomposite reinforcement on fatigue cracking, reflective cracking, and permanent deformation accumulation of thin asphalt overlays was also investigated. Based on the obtained results, all geocomposites improved permanent deformation resistance than the unreinforced pavement by reducing vertical strain on the bed. In addition, due to the unreinforced pavement, the geocomposites increased the energy required for crack propagation 3-8 times [18]. Overall, these findings suggest that using geocomposites can increase the service life of thin asphalt overlays in terms of cracking and permanent deformation accumulation.

2. Objective and scopes

The present study investigates fatigue cracks initiation and propagation in asphalt slab samples with different geocomposite and control layers at different dynamic cyclic loadings in the crack opening or bending modes. Also, the fatigue life index in asphalt overlays with geocomposite reinforcements is modeled using the statistical regression method. These quadratic regression statistical models are based on mechanistic-experimental relationships in evaluating the fatigue life of asphalt overlays with geosynthetic materials in delaying reflection cracks. Also, in this comprehensive and heuristic study, temperature and load intensity (frequency) in different intervals are used to better simulate experiments with reflective cracks on the performance of such geosynthetic reinforcements in asphalt overlays. These models in prediction Responses are used at different temperature ranges and frequencies within the test range.

3. Material and testing methods

The conventional information of the used asphalt binder for fabricating the specimens, is now presented in Table 1. The aggerates used in the laboratory tests were provided from the asphalt-producing factory of the Qazvin axis near Abyek city. Fig. 1 presents different materials used in the mix design. In this research, prepare hot mix asphalt samples were prepared by using PG 64-18 bitumen. Table 1 presents the specifications of this asphalt.

Based on the data obtained from the Marshall experiments, 4.5 w/w% of the mixture was obtained as the optimal percentage of asphalt.

Table 1. Specifications of used aggerates.

Pure asphalt experiments	Test procedure		Results
	ASTM	AASHTO	
Specific gravity (Gs)	D70	T228	1.02
Penetration grade (PG)	D5	T49	60
Minimum softness (ball-ring) in ℃	D36	T53	49.4
Extention at 25℃ (cm)	D113	T51	100 <
flammability degree (℃)	D92	T48	320
Kinematic viscosity at 120℃ (cST)	D2170	T201	676
Kinematic viscosity at 135℃ (cST)	D2170	T201	311
Kinematic viscosity at 160℃ (cST)	D2170	T201	153

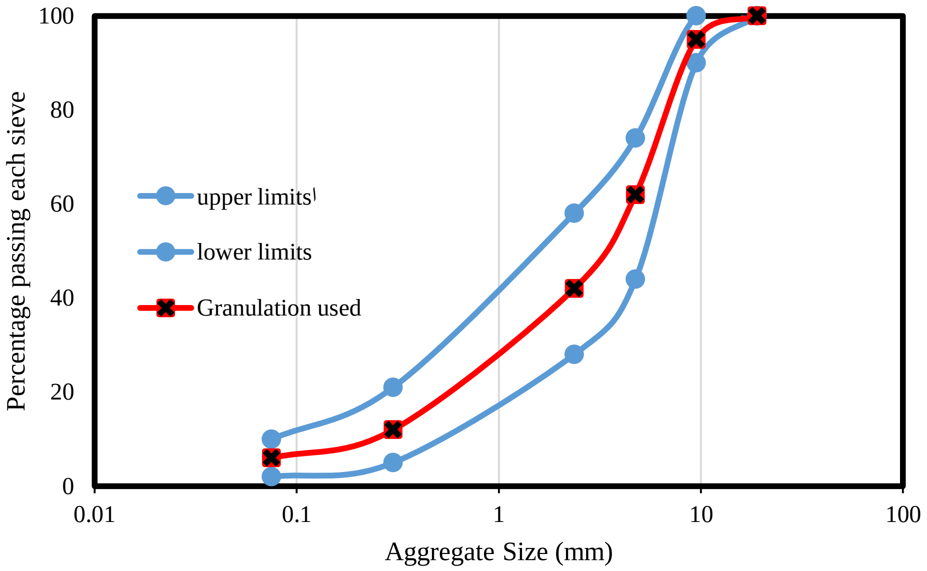


Fig. 1. aggregate distribution used in this research to make asphalt specimens.

3.1. Sample fabrication to compact specimens

The tests were carried out according to the desired conditions, including the number of loading cycles, specimen's height, vertical stress, shear stress, air percentage, specific gravity, and loading period. In this study, asphalt overlay on concrete or old asphalt overlay was simulated using asphalt overlays with a typical thickness of 5 cm using a surface coating (tack coat) placed on the old, simulated pavement with a thickness of 7 cm. The old asphalt concrete pavement was prepared by making the desired asphalt mixture with the required weight (30 kg) in a cubic metal frame of a PReSBox machine with dimensions of 450 mm (L) × 150 mm (W) × 185 mm (H). The specimens were cut according to Fig. 2. Cracks with the required width (6 mm) were created in the bottom layer (Fig). 2. After creating cracks in the middle of the longitudinal part of the sample, the space created in the crack was filled with filler material until making the layer. After making the top layer, the crack should not be filled with materials and asphalt.

Moreover, the width of this filler is proportional to the width of the crack (6 mm), and its material should be selected such that to withstand the mix temperature. In this research, 85-100 Penetration grade asphalt was used as a surface coating layer. After applying the desired geosynthetic surface coating, it was carefully placed on the samples to make a complete connection of asphalt to the geosynthetic fibers and the asphalt layer. This coating is a geocomposite with a strength of 100 kN in two directions and a geocomposite with a strength of 50 kN in two directions. When installing geosynthetics, the fibers should be placed in the direction of the sample length to maximize their maximum tensile performance. After performing the above steps, a coating overlay with a height of 5 cm was made on the bottom slab.

After making the specimens with the mentioned dimensions – i.e., 450 mm (L) × 150 mm (W) × 120 mm (H) – they were placed on a rubber base made of neoprene rubber with an elasticity modulus of 11,000 kPa and stiffness of 6.45 MPa. This rubber or neoprene is used to simulate and model the road base and substrate. Fig. 3 presents a schematic of the samples prepared for loading.

In summary, three types of specimens were fabricated labeled as R, II, I. The summary of each sample is presented in Table 2.

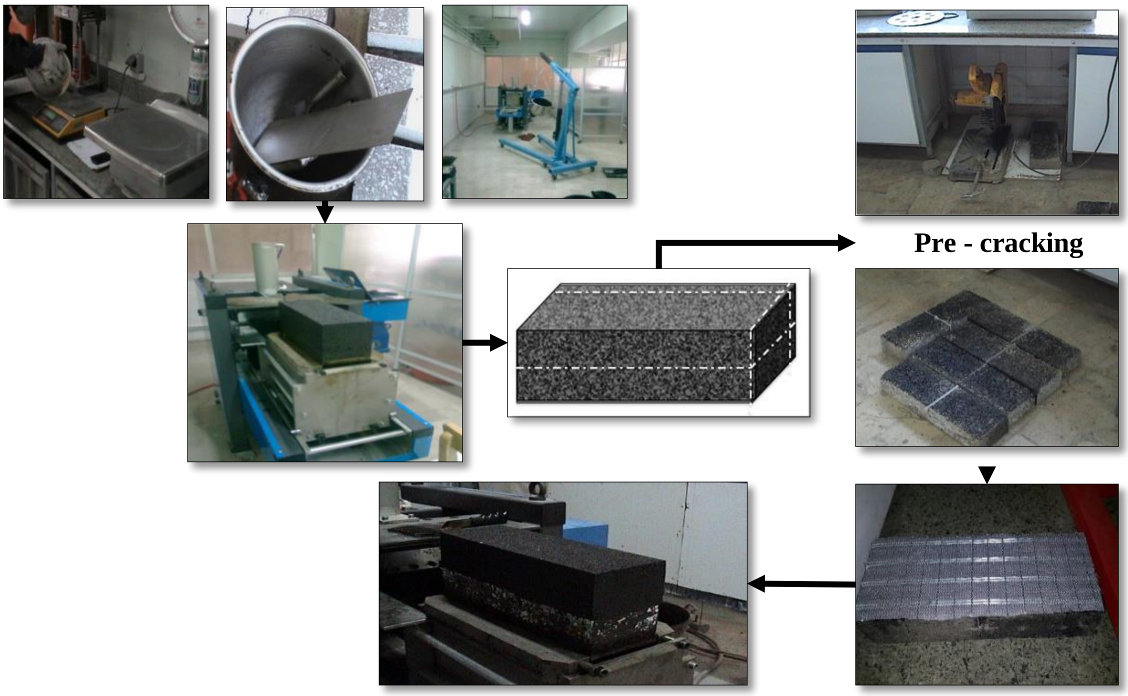
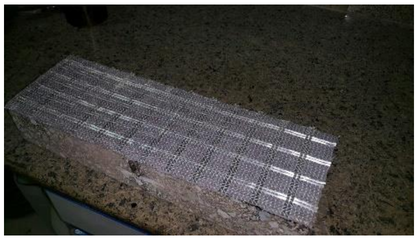


Fig. 2. Specimens' fabrication and preparation for laboratory testing.

Table 2. The summary of each sample.

<table>
<tr><th>Sample ID</th><th>Interlayer type</th><th>Manufacturer</th><th>Interlayer material</th><th>Interlayer's image</th></tr>
<tr><td>G_I</td><td>Geocomposite 100-100Geocomposite 100-100</td><td>Parsian Geogrid 100 (manufactured by Parsian Geogrid Co.)</td><td>Glass grid</td><td></td></tr>
<tr><td>G_{II}</td><td>Geocomposite 50-50</td><td>Parsian Geogrid 50 (manufactured by Parsian Geogrid Co.)</td><td>Glass grid</td><td></td></tr>
<tr><th colspan="5">Technical specifications interlayers</th></tr>
<tr><td>No.</td><td colspan="2">Tack coat binder content used to adhere to AC overlays (Kg/m^2)</td><td>Tensile strength in direction 1 (KN/m)</td><td>Tensile strength in direction 2 (KN/m)</td></tr>
<tr><td>G_I</td><td colspan="2">0.9</td><td>100</td><td>100</td></tr>
<tr><td>G_{II}</td><td colspan="2">0.9</td><td>50</td><td>50</td></tr>
</table>

3.2. Test procedure

A 25-UTM device was used to load the samples. Also, the load was applied using an overhead with using a 100 mm diameter and 25 mm thick exactly on the crack (bending mode simulation). Haversian cyclic load with frequencies of 10, 6, and 2 Hz was defined in Dynamic Creep Test software (V2.03). This type of loading with the mentioned specifications is applied to simulate high-speed traffic.

Fig. 3. The UTM225 test device used for testing.

This load's maximum value is 6.9 kN, which is equivalent to a compressive stress of 690 kPa. In this study, experiments were conducted at 0, 20, and 40°C. For each test, two digital video cameras were installed on either side of the samples to show the crack growth area (crack area) around the crack area. The experiment was continued until the crack reached the sample level. To recap, this test was done at three test temperature under three different loading frequencies including 2, 6 and 10 Hz. The criterion of fatigue life in this research is sample rupture or crack reaching the overlay and placing it in the third failure phase of the deformation-loading time diagram. In this research, for each reported case (in temperature and loading frequency), three tests were performed and the presented data are the average values.

4. Statistical analysis

The response surface methodology (RSM) involves a set of mathematical and statistical techniques for creating an analytical model, where each response (i.e., the dependent variable) is affected by a set of independent variables. Also, it evaluates the interaction of the parameters in each response [29]. The most common design method in RSM is central composite design (CCD) [30]. In the present study, the relationship between the independent variables (i.e., temperature, loading frequency, and type of geocomposite) and the response variable (i.e., the number of fatigue cycles) was determined using the Design Expert 12 software (Stat-Ease, Minneapolis, USA). Next, the obtained data were analyzed as described in the above paragraph.

This method extracts the model equation and predicts its coefficients. The model used in the RSM is generally the equation of the complete quadratic model or its reduced form. The quadratic model is expressed as follows [30–32]:

$$Y = C_{k0} + \sum_{i=1}^{3} C_{ki} x_i + \sum_{i=1}^{3} C_{kii} x_i^2 + \sum_{i<j=2}^{3} C_{kij} x_i x_j \qquad (1)$$

The above equations are obtained by solving the least-squares method and the coefficients of the equation. After obtaining the equation coefficients, the answer is predicted by solving the above equation. Eventually, the models are analyzed using the RSM, which shows the relationship between the responses and the test variables [29].

The statistical significance of each variable in the developed models is determined using the p-value criterion, whose values are from 0 to 1. The p-value was used to determine the statistical significance of each parameter in the developed models. At the current surface, the significance level is defined as 0.05. Therefore, the analysis variance cases with a P-value > 0.05 are not considered and should not be included in the regression model.

The fit of the model was evaluated using R^2, whose high values indicate a better fit between the existing values and the predicted values. However, R^2 alone cannot explain the model's accuracy because this index shows variations around the average response. Thus, another coefficient called the adjusted coefficient of determination (R^2_{adj}) is used. In calculating this coefficient, unlike R^2, the average sum of squares is applied instead of the sum of squares. The parameter should be as close to 1 as possible. Eqs. (2) and (3) present the calculation formula of these two coefficients [29]:

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \quad (2)$$

$$R^2_{adj} = 1 - \frac{SS_{residual} / DF_{residual}}{SS_{total} / (DF_{model} + DF_{residual})} \quad (3)$$

where $SS_{residual}$ represents the sum of the remaining squares, DF shows the degree of freedom, and SS_{total} is the model's sum of the total squares ($SS_{residual} + SS_{model}$).

The main objective of this research was to study the main and interaction effects of factors using the statistical RSM design, according to previous studies [33]. In this study, the effect of independent variables, including temperature (T), loading frequency (F), and interlayer type (G), was evaluated relative to the life of the asphalt overlay at the defined surfaces.

Table 3. Name and Specifications of Asphalt overlays.

Sample & test Specifications				
Loading type	Haversian cyclic load in bending mode			
quantity	Load (kN)		Stress (kPa)	
Maximum load	9.66		690	
Minimum load	0.81		100	
Sample group	**Temperature (°C)**	**0**	**20**	**40**
	Frequency (Hz)	**2**	**6**	**10**
R	0 (°C)	✓	✓	✓
II	0 (°C)	✓	✓	✓
I	0 (°C)	✓	✓	✓
R	20 (°C)	✓	✓	✓
II	20 (°C)	✓	✓	✓
I	20 (°C)	✓	✓	✓
R	40 (°C)	✓	✓	✓
II	40 (°C)	✓	✓	✓
I	40 (°C)	✓	✓	✓
The amount of asphalt used for tack coat (kg/m2)				
R	Reference (Reference samples without geogrid) = -1		0.3	
II	Geocomposite 50-50 (GP Composit Geoparsian) = 0		0.9	
I	Geocomposite 100-100 (GP Composit Geoparsian) = +1		0.9	
Asphalt layers	up		down	
Thickness of HMA	5 cm		7 cm	

The control samples, along with type-I geocomposite and type-II geocomposite in this group, were made at frequencies of 2, 6 and 10 Hz in two layers.

(bottom layer thickness: 7 cm and top layer thickness:5 cm). The top and bottom layers are connected using tack coat 100-85 asphalt made by Pasargad Oil Refinery (0.3, 0.9, and 0.9 kg/cm^2, respectively).

5. Results and discussion

According to Fig. 4, the resistance of control specimens to loading cycles of more than 250,000 increases in asphalt strength due to changes in its properties at low temperatures (0℃).

Analysis of the diagram in Fig. 4, reveals that the fatigue life decreases with increasing the loading frequency in control samples. Therefore, by increasing the frequency from 2 Hz to 6 and 10 Hz, specimens' fatigue life decreases from 19 to 26%, respectively.

Also, the diagram shows that the specimens reinforced with geocomposite II resist more than 400,000 loading cycles up to the failure moment. Indeed, the fatigue life improvement in specimens reinforced with geocomposite II compared to control samples is evident. Analyzing the above diagram also shows that increasing the frequency reduces the fatigue life so that by increasing the frequency from 2 Hz to 6 and 10 Hz, the specimens' fatigue life declines from 24 to 38%, respectively. The diagram also indicates that the fatigue life of specimens reinforced with geocomposite II compared to control samples at loading frequencies of 6, 2, and 10 Hz increased by about 1.4 to 1.7 times. Analyzes show that specimens reinforced with type-I geocomposite can withstand more than 600,000 load cycles at 0℃. The increase in fatigue life in geocomposite I-reinforced specimens compared to geocomposite II-controlled and specimen-reinforced specimens is quite obvious. Also, with increasing the loading frequency, the fatigue life decreases such that by increasing the frequency from 2 Hz to 6 and 10 Hz, the fatigue life of the samples is reduced by about 25-32%, respectively. Comparing the trend of graphs in Fig. 4 indicates that the fatigue life of specimens reinforced with geocomposite type-I compared with control reference samples increased by 2.31 to 2.54 times at loading frequencies of 6, 2, and 10 Hz. This multi-fold increase in fatigue life of specimens reinforced with geocomposite type-I at 0℃ compared to the control specimens confirms the significant effect of this interlayer at low temperatures.

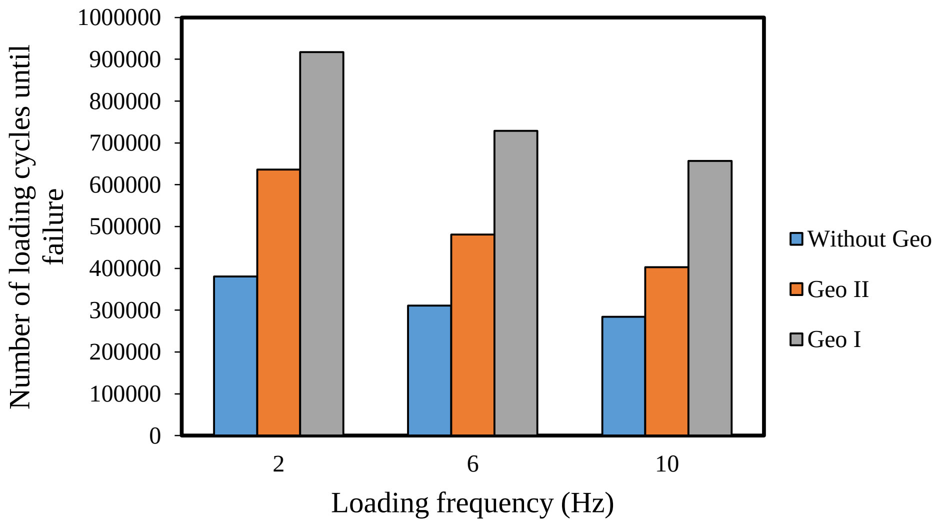


Fig. 4. The number of fatigue life cycles versus loading frequencies for different reinforced specimens at 0℃.

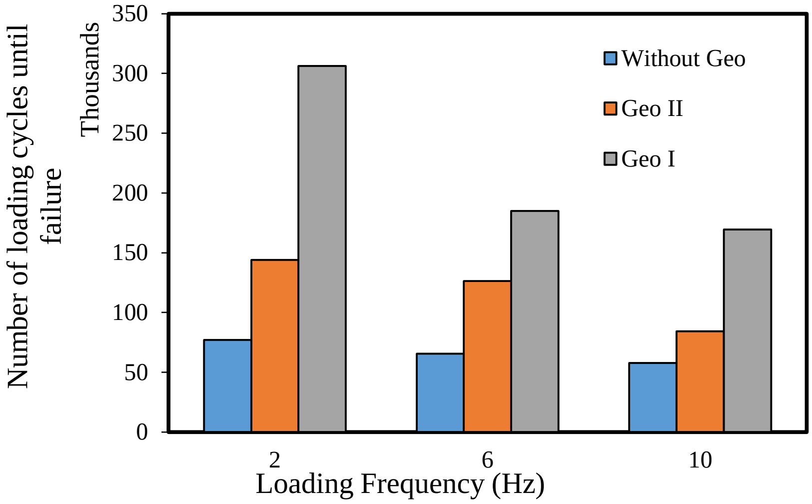


Fig. 5. Number of fatigue life cycles against loading frequencies for different reinforced specimens at 20°C.

According to the literature, the fatigue life of control samples at 20°C at loading frequencies of 2, 6, and 10 Hz is between 50,000 and 80,000 loading cycles in bending mode. Compared to these samples at 0°C, a significant reduction (between 75 and 80%) occurs in fatigue life. This reduction in the fatigue life to reach the crack surface indicates a change in the properties of AC and asphalt as the temperature rises. In other words, with increasing temperature, changes occur in asphalt and asphalt mix, which reduces the adhesion of asphalt and materials and softens the asphalt. Analysis of Fig. 5 shows that with increasing the loading frequency (heavy, medium, and light), the time crack reaches the coating surface decreases such that by jumping the load rate from 2 Hz to 6 and 10 Hz, respectively, a 15 to 25% reduction occurs in the specimen's fatigue life.

According to Fig. 5, specimens reinforced with geocomposite type-I and geocomposite type-II resist 80,000 and 150,000 loading cycles, respectively. These results show the proper performance of geocomposite II and geocomposite I in improving the fatigue life of asphalt slabs compared to unreinforced specimens. Rising the loading frequency from 2 Hz to 6 and 10 Hz increases the severity of base layer failure. As a result, the fatigue life of these specimens increases by 12-41% and 40-45%, respectively.

Comparing the graphs in Fig. 5, it can be seen that the fatigue life of specimens reinforced with geocomposite II and geocomposite I, respectively, compared with control reference samples at frequencies of 6.2 and 10 Hz, respectively. It increased from about 1.5 to 1.95 times and 2.8 to 4 times. This multi-fold increase in the fatigue life of specimens reinforced with geocomposite II and geocomposite I compared to control specimens confirms the very good effect of this interlayer at 20°C. However, this effect increased by 7 to 13% and 23% to 57% at 20°C compared to 0°C, respectively.

According to the performed analyses, the fatigue life of control specimens at 40°C and loading frequencies of 2, 6, and 10 Hz is between 10,000 and 15,000 loading cycles in bending mode. Compared to the same specimens at 0°C and 20°C, a significant reduction occurs in the fatigue life. This reduction is about 95% compared to 0°C and 80-82% compared to 20°C. This sharp reduction in the fatigue life of cracks to reach the surface indicates a change in the asphalt mix and asphalt properties with raising the temperature. In other words, with increasing temperature, changes in the asphalt and asphalt mix properties reduce the adhesion of asphalt and materials and soften the asphalt.

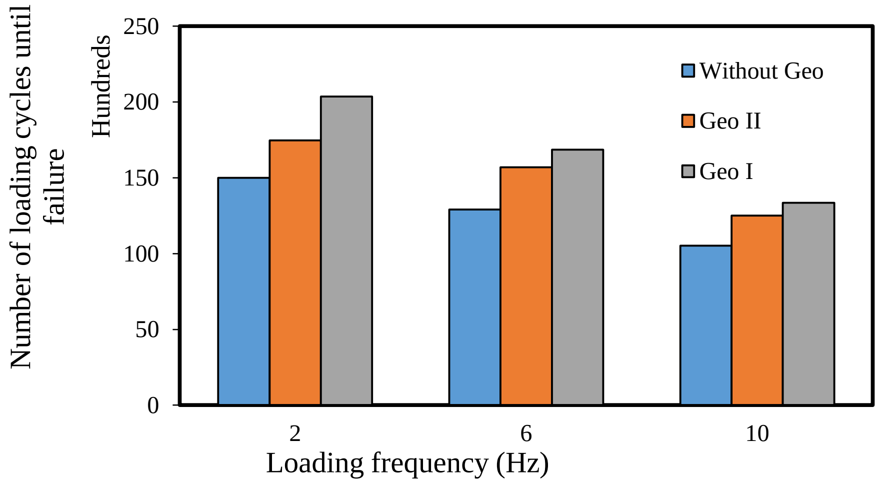


Fig. 6. Number of fatigue life cycles against loading frequencies for different reinforced specimens at 40°C.

According to Fig. 6, with increasing the loading frequency, the time to reach the crack surface is shortened so that by jumping the loading frequency from 2 Hz to 6 and 10 Hz, specimens' fatigue life indicates a 40-51% reduction.

As can be seen, the resistance of specimens reinforced with geocomposite II and geocomposite I against 20,000 and 25,000 loading cycles, respectively, decreases asphalt strength and the adhesion between the layer and coating. These reductions are attributed to changes in asphalt and AC mix properties due to temperature elevation. Certainly, the fatigue life improvement in samples reinforced with type-I and type-II geocomposites compared to control samples is sharp. Analysis of the above diagram shows that the fatigue life decreases with increasing frequency. In this respect, increasing the loading frequency from 2 Hz to 6 and 10 Hz lowers specimens' fatigue life by 11 and 29%, respectively. According to the above diagram, the fatigue life of specimens reinforced with geocomposite II tested at 40°C compared to control reference samples at frequencies of 2, 6, and 10 Hz increased about 1.17 to 1.2 times. Also, the samples tested with geocomposite II at 40°C compared to 0 and 20°C experienced a significant decrease in fatigue life. As a result, a 95% reduction occurred at 0°C compared to 85-87% at 20°C.

Also, the fatigue life improvement in specimens reinforced with geocomposite I compared to control samples at 40°C is considerable. According to Fig. 6, increasing the loading frequency increased the severity of the subsurface failure, thereby reducing the fatigue life. In this respect, increasing the loading frequency from 2 Hz to 6 and 10 Hz reduced specimens' fatigue life by about 17 to 35%, respectively. In addition, the fatigue life of specimens reinforced with type-I geocomposite compared to control reference samples with frequencies of 2, 6, and 10 Hz increased by 1.26 to 1.36 times. The fatigue life of geocomposite I-reinforced specimens at 40°C compared to control specimens confirms the significant effect of this interlayer. Interestingly, the fatigue life of samples reinforced with type-I geocomposite at 40℃ significantly declined compared to 0 and 20℃. These reductions are about 94% compared to 0℃ and 93% compared to 20℃. This significant reduction in fatigue life, both in specimens reinforced with geocomposite II and those reinforced with type-I geocomposite, indicates a change in asphalt mix and asphalt properties to reach the crack surface. Hence, the performance of geocomposite I declined by reducing the adhesion of the coating to them with temperature rise.

5.1. Statistical results

After completing experiments and analyzing the laboratory data, statistical analysis was performed by RSM to provide predictive models for the desired response. In this study, the effect of independent variables, including temperature (T = A), frequency (F = B), and interlayer type (G = C), was evaluated on the life of asphalt overlay.

Model fitting was made using the ANOVA results (including DF: degrees of freedom; SS: the sum of squares; MS: mean square, P-values, and R^2). According to the ANOVA results in Table 5, for all research responses, the accuracy of the studied models can be determined using the coefficient of determination (R^2) and Lack of Fitness (LOF) test.

Also, the P-values obtained for quadratic polynomial regression (P <0.05) for all models indicate that quadratic models are statistically significant. Because the p-value for the Lack of fitness test was not statistically significant for all measured levels (P > 0.1), the proposed model illustrates the data trend.

According to the prediction model's values and its P-values, all variables were statistically significant up to a 95% confidence level. Therefore, the models show the trend of data change well. Eq. (4) expresses the obtained model in a coded manner.

$$Cycles = +1.350E+05 - 2.590E+05\times A - 45724.28\times B - 92738.04\times C[1] - 14435.15\times C[2] + 47840.58\times AB + 1.028E+05\times AC[1] + 13488.83AC[2] + 1.390E+05\times A^2 \tag{4}$$

Table 4. Coding the studied variables in the Design-Expert software.

Temperature = A		
Levels	-1	1
Tempertature	0	40
Frequency = B		
Levels	-1	1
Frequency	2	10
Type of geosynthetic = C		
Levels	C[1]	C [2]
GOE I	-1	-1
GOE II	0	1
without GEO	1	0

According to Table 5, the R^2 and R^2_{adj} values are equal to 0.987 and 0.981, respectively, indicating the high accuracy of the proposed model (Figs. 7a and 7b). According to the model of obtained fatigue life, temperature among the variables has the greatest effect on the values obtained in the model. Also, among the studied variables, temperature decline, frequency reduction, and geosynthetic type have the most important role in the fatigue life model.

Figs. 7c, 7d, and 7e indicate the effect of each of the parameters in estimating the optimal response. According to Fig. 7e, the temperature and loading frequency reductions and using geocomposite type-I have the greatest effect on increasing the fatigue life in asphalt slab samples. However, comparing the graphs reveals that reducing the temperature from 40°C to 0°C will increase the fatigue life more. After temperature, the type of geosynthetics used and then the loading frequency will have the greatest effect on fatigue life changes (about 53,000 loading cycles difference between 40 and 0°C). In other words, 0°C temperature, frequency reduction up to 2 Hz, and using geocomposite type-I will have the greatest impact on fatigue life enhancement.

Table 5. ANOVA analysis for the response variable.

Source	sum of squares	df	mean square	F - value	P-value	significant or insignificant
Model	1.72E+12	8	2.15E+11	170.99	< 0.0001	significant
A-T	1.21E+12	1	1.21E+12	962.23	< 0.0001	significant
B-F	3.76E+10	1	3.76E+10	29.98	< 0.0001	significant
C-G	1.83E+11	2	9.13E+10	72.75	< 0.0001	significant
AB	2.75E+10	1	2.75E+10	21.88	0.0002	significant
AC	1.46E+11	2	7.28E+10	58.01	< 0.0001	significant
A^2	1.16E+11	1	1.16E+11	92.31	< 0.0001	significant
Residual	2.26E+10	18	1.26E+09			
Cor Total	1.74E+12	26				
R^2	0.987					
Adjusted R^2	0.981					

According to Figs. 7c, 7d, and 7e, the simultaneous effect of temperature and loading frequency in specimens reinforced with type-I geocomposite caused the greatest change in specimens' fatigue life. As the temperature falls below 30°C and as soon as the asphalt samples are reinforced, fatigue life indicates an ascending trend. In this regard, the simultaneous reduction of the frequency below 6 Hz combined with these two parameters will intensify this trend.

Another point extracted from these diagrams and models is that the desired response (e.g., the fatigue life of the samples) can be extracted and estimated at different temperatures and with different loading frequencies (within the defined range). For instance, this diagram or model can provide the fatigue life at 10°C or a frequency of 5 Hz for different samples.

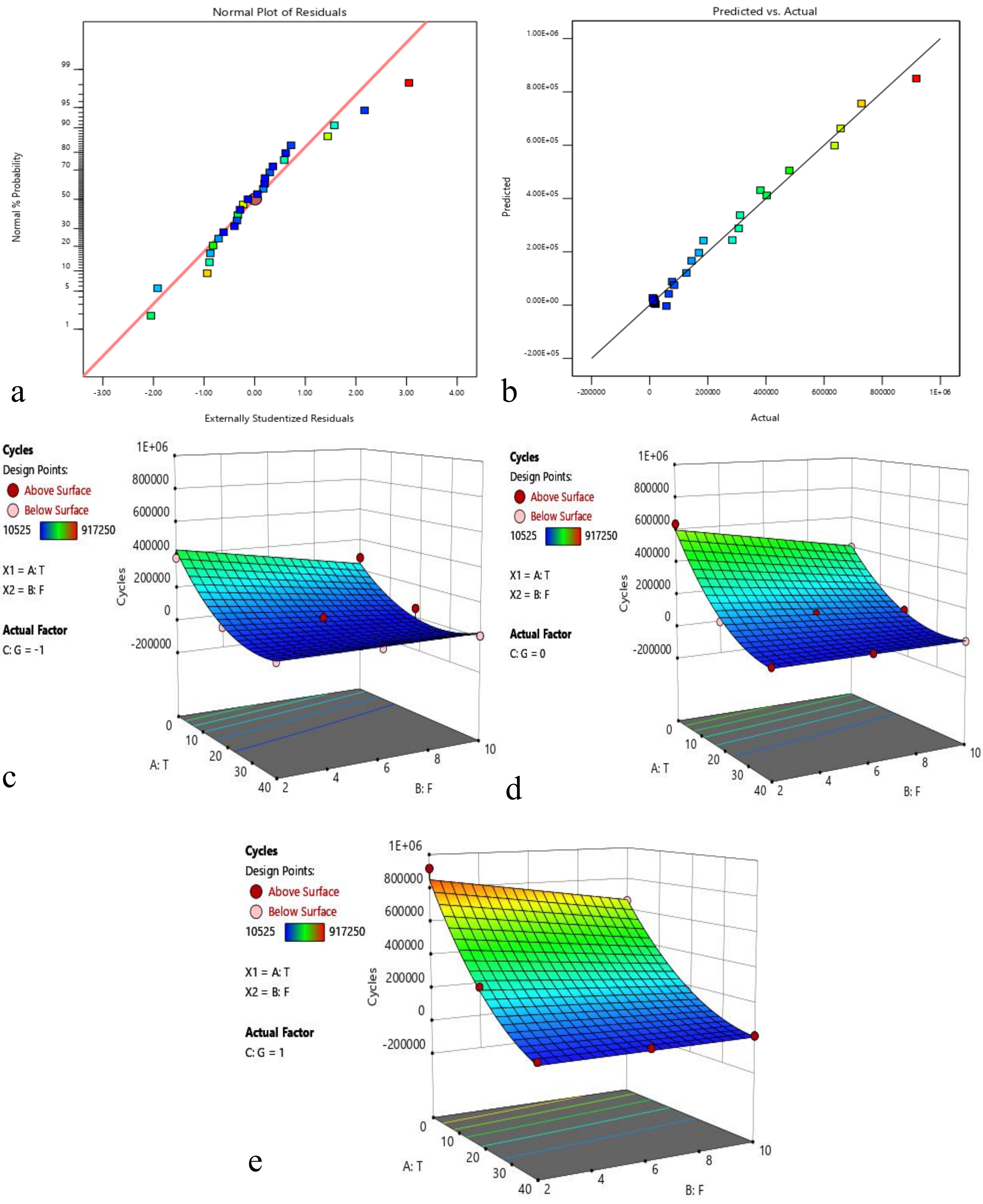


Fig. 7. Result of statistical analysis for the performance of reinforced and control asphalt overlays. **a)** Normal plot of fatigue life response variable. **b)** Plot of actual versus predicted values. **c,d&e)** graph of fatigue life values against temperature and frequency parameters, respectively, in reference asphalt overlays, reinforced with GOE II and GOE I under the influence of the studied parameters.

6. Conclusions

To sum up, laboratory and statistical studies were performed at different temperatures and loading frequencies. Finally, the following results have been extracted:

1. Specimens reinforced with type-I geocomposite outperformed type-II geocomposite and control specimens in increasing fatigue life at all load frequencies and testing temperatures. In this respect, enhancing the tensile strength of geosynthetic specimens directly affected the studied responses and lowered the stress concentration in the cracking zones. These results fully confirm the positive effect of tensile strength interlayers against the control of reflective cracks of AC ovelayers in previous researches.

   The studied geocomposite layers showed better performance at 20℃ than other temperatures .The results showed that, as in the past research, in medium temperatures, the best performance between geosynthetic layers in controlling reflective cracks in asphalt pavements will be obtained.

   Fatigue life increased in reinforced and unreinforced samples at 0℃ because of the changes in asphalt overlay properties (increase in the elasticity modulus of asphalt layers). The resistance of control specimens to more than 250,000 load cycles suggests an increase in this resistance due to changes in its properties at low temperatures (0℃).

   The results demonstrate the effectiveness of most reinforced and unreinforced samples in controlling reflective cracks relative to temperature against other studied parameters. For example, a temperature fall from 40℃ to 0℃ will have the greatest effect on the multi-fold increment of fatigue life.

   After temperature, the type of geosynthetics used and then the loading frequency will have the greatest impact on fatigue life changes (i.e., a 53,000 loading cycles difference between 40 and 0℃).

   Significant reduction is observed in the performance of both reinforced and unreinforced specimens at frequencies above 6 Hz.

   The coding model presented with R^2 and R^2_{adj} equal to 0.987 and 0.981, respectively, provides acceptable accuracy in predicting fatigue life based on parameters of temperature, loading frequency, and type of geocomposite.

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