Adoption of statistical analysis to evaluate the permanent deformation of Polyethylene Terephthalate (PET) modified asphalt mixtures

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Abstract

Permanent deformation (rutting) is one of the most common distress modes in flexible pavement. Rutting performance of asphalt mixture is very susceptible to environmental and loading conditions. In this paper, effects of applied stress and temperature on the permanent deformation of unmodified and Polyethylene Terephthalate (PET) modified asphalt mixtures (0%, 0.5% and 1% of PET by weight of aggregate particles) were evaluated using dynamic creep test at different temperatures (10˚C, 25˚C and 40˚C) and stress levels (200 kPa, 300 kPa and 400 kPa). Response Surface Methodology (RSM) was used to analyze the experimental results. A quadratic model was successfully fitted to the experimental data. According to the results achieved in this study, PET-modified mixtures showed to have higher rutting resistance than the unmodified mixture. Additionally, temperature variation and stress levels played important roles on rutting performance of both unmodified and PET-modified asphalt mixtures.

Keywords: Permanent deformation measurement; Asphalt mixture; Waste PET; Environmental temperature; Applied stress; Response surface methodology.

1. Introduction

In pavement engineering, rutting is defined as accumulation of permanent deformation under repeated traffic loading. In fact, rutting can be occurred in each layer of pavement structure among which asphalt layer has shown a prominent magnitude in rutting [1]. Rutting susceptibility of asphalt layer depends on type of asphalt mixture and amount of voids in the mixture [2].

Previous studies showed that Stone Mastic Asphalt (SMA) had better resistance against rutting damage compared to conventional dense graded mixture [3, 4]. SMA is a type of Hot Mix Asphalt (HMA) which contains more course aggregate particles and provides more course aggregate fraction and asphalt binder. The higher amount of coarse aggregate provides stone-on-stone contact among coarse aggregate particles while higher asphalt content (5.5-7.5% by weight) results in more durability [5]. Furthermore, SMA mixture has higher resistance to plastic deformation and has good properties at lower temperature [6]. Fibers (cellulose or mineral) and mineral filler (cement, hydrated lime and rock dust passing sieve 75µm in a high amount) are commonly used in SMA mixtures to prevent drain-down due to usage of higher asphalt content in the mixture [7]. Also, utilization of asphalt with modified characteristics (e.g. offering higher viscosity) can be another way to prevent drain-down in SMA mixtures [5].

Improving asphalt mixture properties is the aim of engineers and experts to increase service life of asphalt pavement. Using additives such as various types of fibers and polymers is a common way to improve asphalt mixture characteristics [8]. These additives can be added to the asphalt mixture through wet process or dry process. During the wet process additives are pre-blended to the asphalt for binder modification while in dry process additives will be added directly to the mix. Among these additives, waste materials as a secondary materials have the advantages of being cost effective and environmentally friendly. Waste glass, steel slag, tires and plastics are examples of waste materials have been used in asphalt pavements [9].

Waste plastic (polymer) also has prominent utilization in asphalt mixture. There are seven types of recycled polymer namely: LDPE, MDPE, HDPE (low, medium and high density polyethylene), PP (polypropylene), PVC (polyvinyl chloride), PET (polyethylene terephthalate) and ABC (acrylonitrile butadiene styrene) [10]. In case of using waste polymer in asphalt mixture, utilization of waste PET could be beneficial because it is one of the main packaging materials, and a large amount of waste PET is being produced daily. In other words, the usage of natural resources and environmental pollution could be reduced by using waste PET as an alternative in road construction projects.

Statistical analysis is a precise and popular way to explore and to present interactions between parameters affecting one phenomenon. Statistical analysis in pavement engineering has prominent utilization because it helps road engineers and designers to have better justifications about the pavement performance parameters. In this case, factorial Design of Experiments (DOE) which through the use of techniques such as Response Surface Methodology (RSM) -simultaneously consider several factors at different levels, and give a suitable model for the relationship between the various factors and the response came into popularity [11-13].

This method of analysis has been previously used to determine interactions between selected parameters and their correlations with stiffness [14] and fatigue life [15] of modified asphalt mixtures. The main objective of this study is examining the rutting performance of PET modified SMA mixtures at various temperatures and stress levels following by finding interactions between fundamental factors using RSM based on Central Composite Design (CCD).

2. Materials and methods

SMA mixtures were fabricated using 80/100 asphalt penetration grade. Granite-rich aggregate particles were used for this investigation. 9% of filler was utilized.
PET flakes have been used which were obtained from waste PET bottles. For using PET flakes in asphalt mixture, the PET bottles were cut to small parts and by using crushing machine these small parts were crushed. Thereafter, the crushed PET particles were sieved and the particles which were smaller than 2.36 mm in size were used for this investigation.

2.1 Mixture fabrication

In order to fabricate SMA mixture, 1100 g of mixed aggregate and asphalt cement were heated inside an oven at temperature of 160˚C. Thereafter, all the materials were mixed at the temperature of 160˚C. PET particles with different percentages (0%, 0.5% and 1% by weight of aggregate particles) were added directly to the mixture as the method of dry process. The loose mixture was compacted using Marshall Compactor and 50 blows of compaction efforts were applied on each side of the mixture. It is worth mentioning that all the mixtures were fabricated at their optimum asphalt contents.

2.2 Dynamic creep test

Asphalt mixture is a viscoelastic composite material and deforms when it is subjected to an external load; however, the majority of this deformation would be recovered when the load is removed. Nonetheless, a small portion of irrecoverable viscous deformation exists and these small amounts of deformation accumulate by applying large number of loading cycles which eventually result in surface rutting. Hence, for evaluating the rutting performance of PET modified asphalt mixtures uniaxial creep test with dynamic loading was developed. Universal Testing Machine (UTM) that is known as one of the most popular equipment for evaluating the rutting performance of asphalt mixture was utilized [16]. The test was performed at temperatures of 10˚C, 25˚C and 40˚C. In this test, cyclic loads with 1000ms repeating time were applied on the specimens. Besides, stress levels of 200, 300 and 400 kPa were considered. All the specimens were retained at controlled temperature compartment for 3 hours to make sure they reached to uniform temperature. The test was terminated when the accumulative load cycles reach to 1000 cycles and the final accumulative permanent strain value was selected as the final result.

During the test Linear Variable Differential Transducers (LVDTs) were used to gage the vertical displacement of specimen. The LVDTs were positioned in the vertical direction (Fig. 1). The amount of strain can be obtained using Eq. (1):

$$\varepsilon = \frac{h}{H_0} \tag{1}$$

In this equation, ε is the accumulated permanent strain, h is the axial vertical deformation, mm; and H_0 is the initial specimen height, mm.

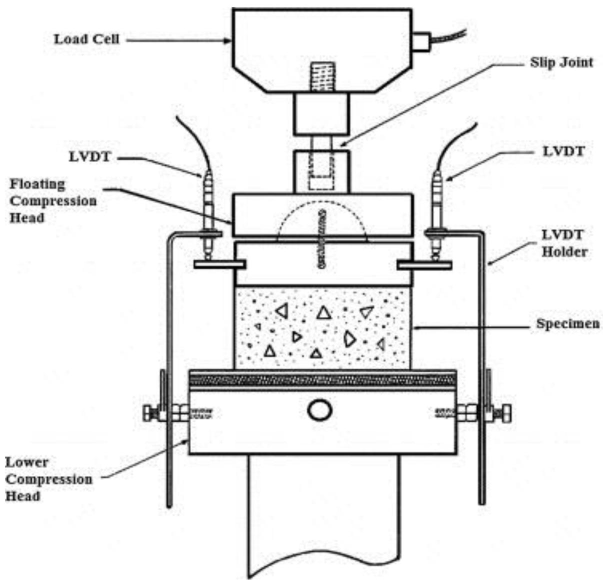


Fig. 1. Dynamic creep test set up [17]

2.3 Method of analysis

One factor at a time (OFAT) methodology is a conventional approach to optimize multifactor experiments. OFAT includes a changeable single factor for a specific experiments design while other factors are kept constant. OFAT is unable to provide appropriate output because the effect of interactions amongst all involved factors in the designs is not examined truly, and it is not capable of reaching the true optimum value [18, 19]. Hence, RSM methodology was introduced for parameter optimization in a way that number of experiments and interaction among the parameters are reduced to minimal value [20-22]. Consequently, the Design Expert 8.0.5 was designated for this study to generate statistical analysis, experimental designs, and to calculate the sorbent adaption conditions.

For this study, a developed quadratic model and a=0.5 were utilized using RSM method for design and data analyzing. In this investigation, the effects of three independent numerical variables including PET modifier (A) from zero to 1%, stress levels (B) from 200 kPa to 400 kPa and temperatures (C) between 10 and 40 ºC, all at three levels, were studied through the central composite design (CCD). Related literature and preliminary studies were used to choose these variables and the irrespective regions of interest [23-28].

Table 2 shows the levels and range of the actual values of independent numerical variables. By using Eq. (2) all defined numerical variables transformed to the coded form.

$$x_i = \frac{(X_i - X_0)}{\Delta X} \tag{2}$$

x_i describes the coded value of the ith independent factor which is dimensionless. Actual value is defined as X_i, X_0 is the center point actual value and ΔX refers to the step change of the ith variable.

Totally 34 experiments in randomized order were performed, together with five replications at center points to provide accurate assessment of errors (Table 1). The permanent deformation was defined as the response to develop design of experiment modeling.

Eq. (3) was introduced to calculate the dependent variables [29, 30]:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} x_i x_j + \varepsilon \tag{3}$$

In the Eq. (3), Y is the calculated response, β_0 is the constant. Independent variables in coded forms are described as x_i, and x_j. The coefficients of β_i and β_{ii} are the linear and quadratic terms. β_{ij} is the interaction term coefficient, ε is the random error, and the studied number of factors is described as n.

Besides, in order to assess appropriateness of the proposed model, analysis of variance (ANOVA) was performed. The coefficients of determination (R^2 and R^2_{adj}) express the wellness of the fit to suggested model. These values can be determined using the following equations [31]:

$$R^2 = 1 - \frac{SS_{\text{residual}}}{SS_{\text{model}} + SS_{\text{residual}}} \tag{4}$$

$$R^2_{\text{adj}} = 1 - \frac{SS_{\text{residual}}/DF_{\text{residual}}}{(SS_{\text{model}} + SS_{\text{residual}})/(DF_{\text{model}} + DF_{\text{residual}})} \tag{5}$$

In this equation, *SS* is the sum of squares and *DF* is degrees of freedom.

Eq. (6), Eq. (7) and an F-test in the program were used to check the model's adequate precision ratio (AP) to determine the statistical importance of the model [32]:

$$\text{Adequate Precision} = \frac{\max(Y) - \min(Y)}{\sqrt{\overline{V}(Y)}} \tag{6}$$

$$\overline{V}(Y) = \frac{1}{n}\sum_{i=1}^{n} \overline{V}(Y) = \frac{p\sigma^2}{n} \tag{7}$$

Where Y is the predicted response, p represents the number of model parameters, residual mean square is described as σ^2, and n is the number of experiments.

After the F-test had been performed, the insignificant terms were found and eliminated from the model. Thereafter, the finalized model was introduced based on the significant variables.

Table 1: Experimental design layout and experimental results of the responses

Run	Factor 1: PET (%)	Factor 2 : stress level (kPa)	Factor 3: Temperature (°C)	Permanent deformation (μs)
1	0	200	10	94
2	1	400	40	1969
3	0.5	300	10	114
4	0	200	40	1253
5	1	300	25	281
6	0.5	300	25	749
7	0.5	200	25	511
8	0.5	400	25	922
9	0	300	25	1139
10	0.5	300	25	743
11	1	400	10	86
12	0	300	25	1146
13	1	200	10	35
14	0	400	10	829
15	0	200	40	1263
16	0.5	300	25	751
17	0.5	300	25	759
18	1	400	40	1970
19	0.5	300	25	744
20	0	400	40	8089
21	1	200	10	334
22	1	300	25	277
23	0.5	300	40	1669
24	0.5	300	40	1669
25	0	400	40	8106
26	0.5	300	10	119
27	1	400	10	83
28	0.5	400	25	931
29	1	200	40	781
30	0	400	10	816
31	0.5	200	25	511
32	1	200	40	781
33	0.5	300	25	752
34	0	200	10	91

Table 2: Analysis of ANOVA for permanent deformation

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	Prob > F	Model performance
Model	100219849.8	9	11135538.87	25.19092	< 0.0001	significant
A	13169022.05	1	13169022.05	29.79108	< 0.0001	significant
B	16465680.45	1	16465680.45	37.24881	< 0.0001	significant
C	31122630.05	1	31122630.05	70.4059	< 0.0001	significant
A^2	455928.201	1	455928.201	1.031405	0.3200	Insignificant
B^2	481279.7481	1	481279.7481	1.088755	0.3071	Insignificant
C^2	1202368.578	1	1202368.578	2.720009	0.1121	Insignificant
AB	10500840.25	1	10500840.25	23.7551	< 0.0001	significant
AC	8877420.25	1	8877420.25	20.08258	0.0002	significant
BC	13682601	1	13682601	30.9529	< 0.0001	significant
Residual	10609098.81	24	442045.7836			
Lack of Fit (LOF)	10563852.97	5	2112770.594	887.2119	< 0.0001	significant
Pure Error	45245.83333	19	2381.359649			
Cor Total	110828948.6	33				
Adequate Precision (AP)			21.043			

3. Results and discussion

Creep test was conducted on the PET modified SMA mixtures at elevated temperatures and stress levels. Table 1 represents the layout for experimental design and the amounts of permanent deformation responses. Having these values, RSM was utilized to find interactions between the outputs and variables which are independent. Eventually, a fitted quadratic polynomial equation was produced after a regression analysis had been applied to all responses described in the design matrix. The highest order polynomials which the additional terms were significant and the models were not aliased have been suggested by the software. This model was utilized to find the optimum condition. The numerical parameters (A, B and C) were used to generate the predictive model according to Eq. (8):

Permanent deformation final equation= *560.75- 811.45A+907.35B+1247.45C- 810.12AB-744.87AC+924.75BC* *(8)*

Checking the adequacy of the model is an important part of the data analysis, as the model functions would give improper responses in case the fit is not adequate [21, 33]. Hence, in this study in order to assess the significance and adequacy of the model ANOVA analysis was performed and the results are reported in Table 2. In addition, this table shows the quadratic models for coded factors, and represents the other statistical parameters for permanent deformation response. In this table, p-values which are less than 0.0001 imply that the model and parameter are significant (model and term p-value <0.05 indicate the model and the term are significant for 95% confidence intervals) for assessing the value of responses [34].

In this study, PET (A), Stress level (B), Temperature (C) and the interaction between the A and B variables (AB), B and C (BC) finally, A and C (AC) with p-values less than 0.05 were significant terms. However, B^2, A^2 and C^2 were insignificant (p-value >0.100). Therefore, in order to improve the model as well as to optimize the result, these insignificant terms can be eliminated from the model [35].

In order to check the fitness of the model, regression coefficients, R^2 and R^2_{adj} were calculated. Values of 0.9043 and 0.8684 were obtained for the R^2 and R^2_{adj}, respectively. This shows that 0.8684 % of the total variation in the permanent deformation response could be explained by the quadratic model. The high R^2 and adjusted R^2 values indicate that there is a good agreement between predicted and actual values [22, 29, 36]. Ratio of signal-to-noise is measured by adequate precision to compare the variety of the estimated amounts at the design points to the average prediction error. Adequate model discrimination was found in this study when the adequate precision ratio of 21.043 was calculated for the permanent deformation which is much higher than the value of 4 [37]. The lack of fit (LOF) F-test was also used to evaluate the adequacy of the model. LOF depicts the variation of the data around the fitted model. It is worth noting that despite the lack-of-fit was significant, the reasonable agreement between the predicted and adjusted R^2 were found for all responses which can be concluded the suggested models can be used to navigate into design space to find an optimum condition [38, 39].

3.1 Statistical analysis

In order to have better understating about model satisfactoriness, diagnostic plots such as the predicted versus actual values are worthwhile. Fig. 2 shows the actual versus predicted values plots of parameters removal for permanent deformation modeling. As it is depicted in this figure there is an adequate agreement between the actual data amounts and the predicted ones. The same thing can be achieved from AP value (AP>4) for the permanent deformation responses (see Table 2). This verifies that predicted model can be used to navigate the design space defined by the CCD.

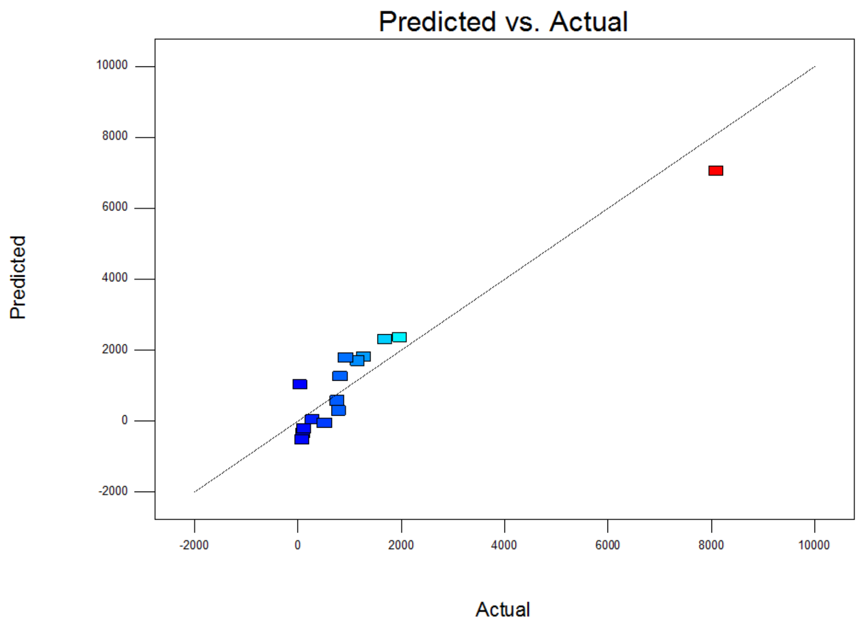
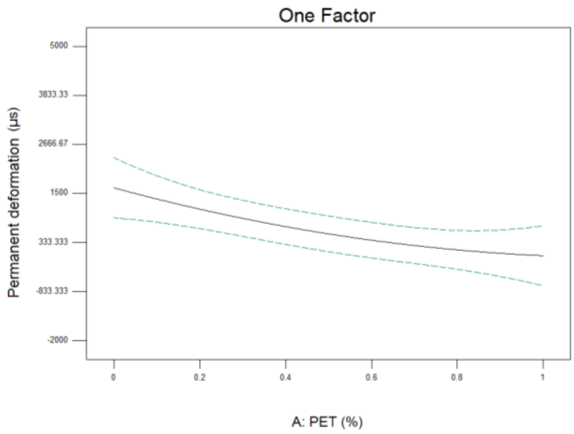


Fig. 2. Design-expert plot; predicted vs. actual values plot for permanent deformation responses

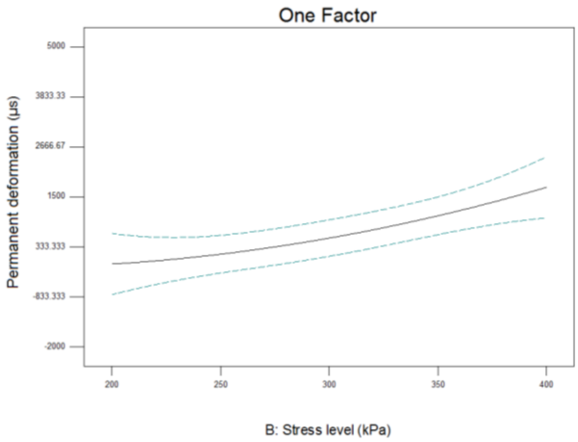
3.2 One factor analysis

One factor analysis is “changing one factor at a time” method. That is to say, in this method a single factor is varied while all other factors are kept constant for a particular set of experiments. And this process exists for optimizing other variables which would be time consuming. In this method, trial and error are commonly existed for the optimization of variables, and, moreover, there is always a lack to reach a true optimum amount which should be obtained by considering the interaction among all the variables [38, 40].

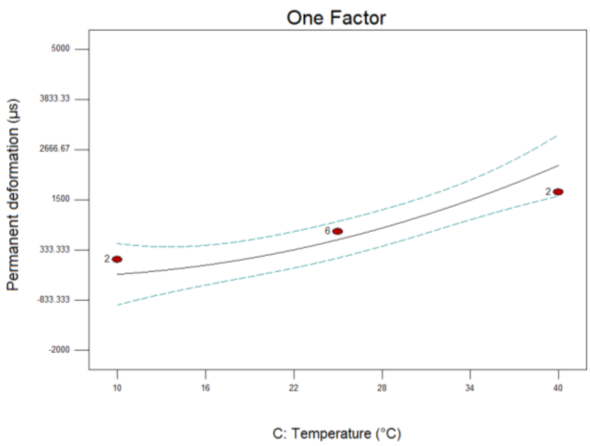
Each factor in this analysis is evaluated separately. Fig. 3(a) reveals the effect of PET on the permanent deformation of SMA mixtures. As it can be seen in this figure the amount of permanent deformation is decreased at higher PET contents. It is also found that by increasing the stress level, the permanent deformation is increased mutually (Fig. 3(b)). Moreover, Fig. 3(c) revealed rising temperature influences the permanent deformation of SMA mixtures in a negative manner.



(a)



(b)



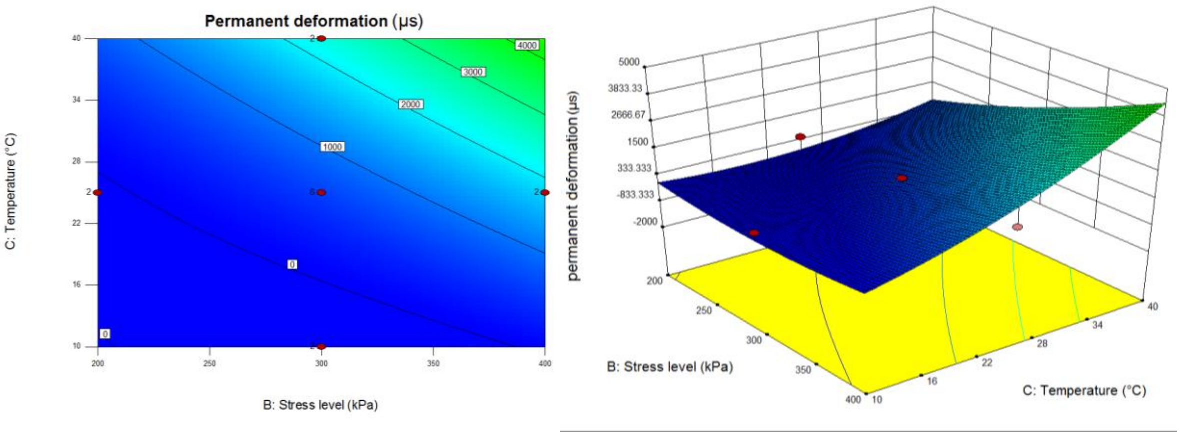
(c)

Fig 3. Effects of PET, stress and temperature variations on the permanent deformation property of PET modified mixtures

3.3 Evaluation of temperature and stress levels on the permanent deformation

Two and three-dimensional response surface plots of the predictive quadratic model for the effect of different stress levels and temperatures on permanent deformation are presented in Fig. 4(a) and (b). The response surfaces were generated based on the Eq. (8).

As can be seen the effect of stress levels, particularly more than 300 kPa, is significant on the permanent deformation at higher temperatures. As it is shown in Fig. 4(a), modified mixtures have better resistance against permanent deformation at lower temperatures (<25˚C) for all stress levels. Additionally, as it is shown in Fig. 4(b), at the lower temperatures (e.g. 10ºC) the stress level variation does not affect the permanent deformation value. This figure also depicts the effect of temperature variation seems to be insignificant on the permanent deformation at lower stress levels.

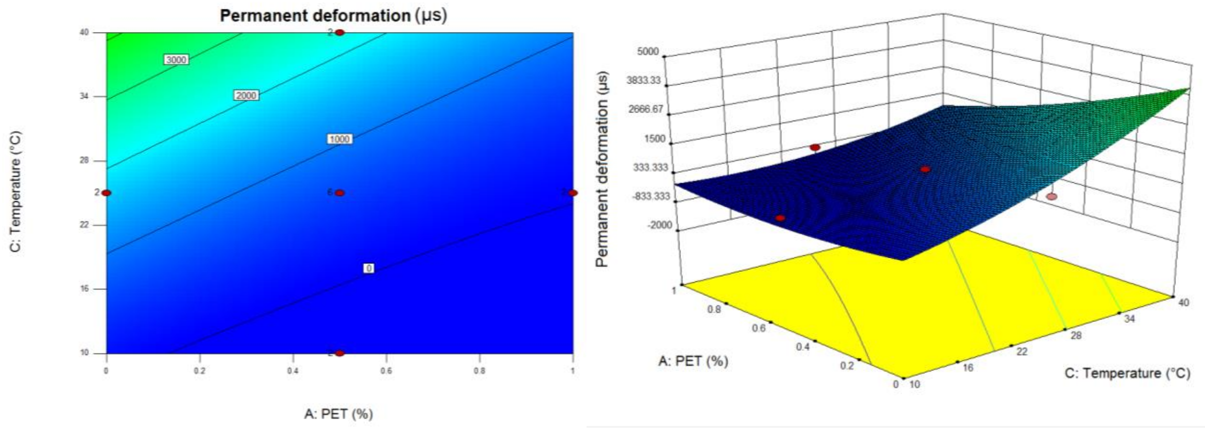


(a) (b)

Fig. 4. Effects of stress level and temperature on the permanent deformation, 0.5% PET (2D and 3D)

3.4 Effects of temperature and PET content on the permanent deformation

Effects of two parameters including PET and temperature are evaluated on the permanent deformation as it is shown in Fig. 5. As it can be seen the influence of adding PET to reduce the permanent deformation seems to be significant. It is depicted in Fig. 5(a) that by adding higher amounts of PET the permanent deformation value is reduced considerably at higher temperatures. Moreover, as it is presented in Fig. 5(b) at lower temperatures the effect of adding PET is not considerable compared to higher temperatures and this might be due to the high solidity of asphalt mixtures at lower temperatures.



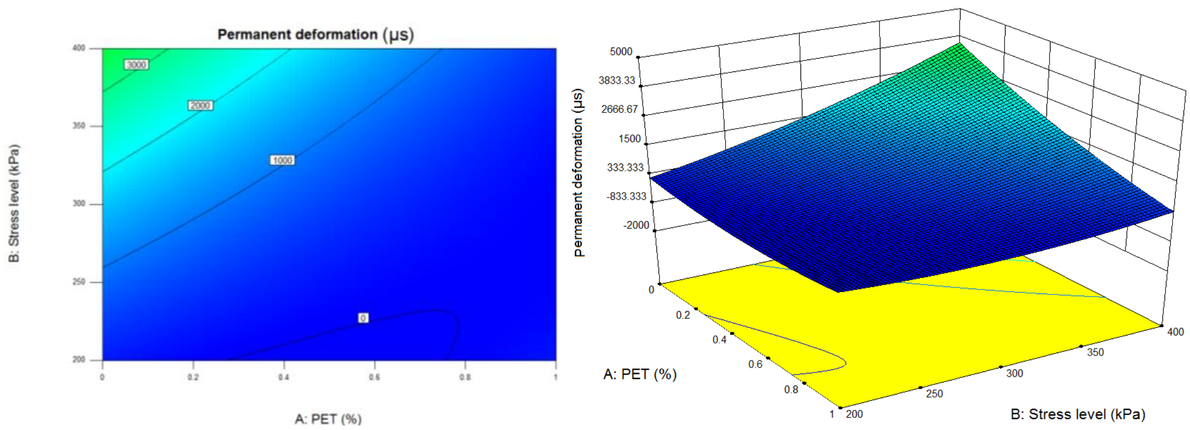
(a) (b)

Fig. 5. Effects of PET percentage and temperature on the permanent deformation, stress level 300 kPa (2D and 3D)

3.5 Effects of PET and stress level on the permanent deformation

Fig. 6 shows the effects of different stress levels and PET percentages on the permanent deformation of asphalt mixture. Higher deformation was found for the mixture with lower PET content especially for those subjected to higher stress levels. It is clearly demonstrated in Fig. 6(a) that by increasing the PET content the permanent deformation is decreased mutually. In addition, for the samples which were fabricated with higher amounts of PET (>0.6%), rising the stress level does not affect the permanent deformation considerably.

Fig. 6(b) shows at lower stress levels asphalt mixtures had lower permanent deformation. Besides, by increasing the stress level the influence of adding PET is more highlighted to reduce the permanent deformation.



(a) (b)

Fig. 6. Effects of PET percentage and stress level on permanent deformation, 25˚C (2D and 3D)

4. Conclusions

This paper aimed to evaluate the effects of applied load and temperature on the permanent deformation of unmodified and PET modified asphalt mixtures. Statistical analysis used in this investigation to measure the interactions between selected variables. A good agreement was found between predicted and actual values which indicated second-order response surface models provide a suitable model to predict the permanent deformation values within the range of defined factors. Based on the results achieved in this study the following conclusions can be derived:

1) At higher temperatures, the effect of stress levels, particularly more than 300 kPa, is significant on the permanent deformation.
2) At all stress levels, modified mixtures had better performance against permanent deformation at lower temperatures (<25ºC).
3) Effect of PET modification at lower temperatures is insignificant compared to higher temperatures and this might be due to the high solidity of asphalt mixtures at lower temperatures.
4) Influence of adding PET is more highlighted for the mixtures subjected to higher stress levels to reduce the permanent deformation.

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