Optimization of Nanocomposite Modified Asphalt Mixtures
Fatigue Life using Response Surface Methodology

N. Bala¹, M. Napiah¹, I. Kamaruddin¹ and N. Danlami¹
¹ Department of Civil & Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

E-mail: nura.bala_g03311@utp.edu.my

Abstract. In this study, modelling and optimization of materials polyethylene, polypropylene and nanosilica for nanocomposite modified asphalt mixtures has been examined to obtain optimum quantities for higher fatigue life. Response Surface Methodology (RSM) was applied for the optimization based on Box Behnken design (BBD). Interaction effects of independent variables polymers and nanosilica on fatigue life were evaluated. The result indicates that the individual effects of polymers and nanosilica content are both important. However, the content of nanosilica used has more significant effect on fatigue life resistance. Also, the mean error obtained from optimization results is less than 5% for all the responses, this indicates that predicted values are in agreement with experimental results. Furthermore, it was concluded that asphalt mixture design with high performance properties, optimization using RSM is a very effective approach.

1. Introduction

Pavement lifetime is one of the most important issues to be addressed for economy and other reasons. Several distresses such as cracking and rutting reduces asphalt pavement lifetime, therefore, there is an urgent need to address this issues in order to sustain asphalt pavement lifespan. Fatigue cracking is a distress which directly decreases the service life of asphalt mixtures. Cracking in asphalt pavement occurs over extended period of time due to effect of two main factors identified as temperature and loading. In most cases, cracking due to repeated load application begins at the bottom of asphalt pavement layers and propagates upward, while cracking due to usually happen from surface layers of asphalt pavement and moved downward to bottom layers [1].

Fatigue cracking due to repeated loading occurs when pavement is stressed to the limit of its service life by repetitive load applications [2]. The repetitive load applications decreases asphalt pavement resistance due to continuous degradation of materials which eventually resulted in formation of micro cracks and complete failure [3, 4]. Therefore, fatigue cracking is considered one of the most challenging distress in asphalt mixtures. The most common method for improving fatigue resistance of asphaltic pavements is through the use of modified bitumen [5, 6]. Previous studies showed that additives such as various types of polymers and fibers provide a structure that extends the life of asphalt pavements. Polymers and fibers increases the adhesion between aggregates and bitumen in the mixture [7].

Recently, nano material have extensively gained a great attention by pavement researchers for the preparation of durable asphaltic mixtures with high performance due to their excellent beneficial properties such as large surface area, excellent dispersion ability, strong absorption, excellent stability.
as well as high chemical purity [8-10]. Optimizing the materials applied in bitumen modification and development of predictive model for prediction of asphalt mixtures performance is a good step, in response to that statistical modeling and optimization techniques such as response surface methodology (RSM) can be utilized.

Application of statistical modeling and optimization techniques is useful as it is excellent in terms of its ability to deal with various constraints and objectives and in describing the interactions among dependent variables that affect a particular response [11, 12]. Response surface methodology (RSM) is a statistical tool mainly employed for the design of experiments, modeling and process optimization through evaluation of both individual effects and interaction effects of different factors (independent variables) under less number of experimental runs [13, 14].

The main objective of this study is to optimize nanocomposite asphalt modification materials and develop model for fatigue life prediction of modified asphalt mixtures using response surface methodology (RSM).

2. Materials and methods

2.1 Materials

An 80/100 penetration grade bitumen was used for the preparation of modified binders blend in this study. Polyolefin polymers namely polyethylene and polypropylene polymer were used with nanosilica for modification to form nanocomposite modified blends. The nanosilica used in this research has an average particle size of 10-25 nanometer and SiO₂ content of 99.8%.

The aggregate used in this study for the preparation of asphalt mixture samples is crushed granite coarse aggregate having a maximum nominal size of 19 mm. Aggregate gradation plot used for the asphalt mixture preparation is shown in Figure 1.

![Aggregate gradation](image)

**Figure 1.** Aggregate gradation

2.2 Methods

2.2.1 Preparation of modified binders: The composite modified binders were prepared by adding various percentages of polymers namely polypropylene and polyethylene together with nanosilica by weight of bitumen as suggested by design expert software. 80/100 pen grade binder was first heated in an oven at a temperature of 150 °C to achieve desirable viscosity for mixing, polymers were first added to the required amount of base binder at a high shearing rate of 4000 rpm prior to nanosilica
addition, the mixing continued until polymers dissolves completely on the base binder. Different percentages of nanosilica were then added gradually and sheared also at a high shearing rate of 4000 rpm for 2 hours. Mixing was done using a propeller blade laboratory bench top multi mix high shear mixer.

2.2.2 Specimens preparation and 4P Beam fatigue test: Rectangular beam fatigue specimens were prepared using rectangular metal mould. The dimension of the beam slabs was approximately 50 mm in height, 65 mm in width and 380 mm long. The beam fatigue tests were conducted in accordance to standard specification ASTM D7460, the test was performed under a strain-controlled mode of loading at a temperature of 20 ºC. A repeated haversine load was applied at a frequency of 5 Hz. The deflection at the center of the beam was measured with a linear variable differential transformer (LVDT). Three replicates were tested for each type of mixtures.

2.2.3 Method of analysis and design of experiments using RSM: Box Behnken Design (BBD) is the most common applied design method used with RSM for statistical evaluation of relationship between independent variables and responses. In this study, the influence of three independent factors polyethylene (PE), polypropylene (PP) and nanosilica content (NS) were studied at three levels. Design Expert software version 9.0.2.0 was used to produce statistical analysis and experimental designs. The response evaluated was fatigue life of the samples. Table 1 presents the levels and ranges of the actual values of independent variables investigated. For the response analyzed, a total of 17 experiments were performed in randomized order with five replication of the central point to enable accurate estimation of experimental errors. Numerical variables for the experiments are transformed into coded form using equation 1.

$$x_i = \frac{(X_i - X_o)}{\Delta X}$$  \hspace{1cm} (1)

where $x_i$ is the ith independent factor coded value, $X_o$ $X_o$ is the actual values of the center point where $\Delta X$ refers to step change for the ith variable.

| Run No. | Parameters | Responses |
|---------|------------|-----------|
| 1       | $x_1$: 3% Polyethylene | Fatigue life (cycles) |
| 2       | $x_2$: 6% Polypropylene   | 107420    |
| 3       | $x_3$: 0% Nanosilica      | 221250    |
| 4       | 3% Polyethylene           | 258640    |
| 5       | 6% Polypropylene          | 73850     |
| 6       | 0% Nanosilica             | 231820    |
| 7       | 3% Polyethylene           | 499020    |
| 8       | 6% Polypropylene          | 164560    |
| 9       | 0% Nanosilica             | 153640    |
| 10      | 3% Polyethylene           | 67030     |
| 11      | 6% Polypropylene          | 78460     |
| 12      | 0% Nanosilica             | 241960    |
| 13      | 3% Polyethylene           | 112730    |
| 14      | 6% Polypropylene          | 102362    |
| 15      | 0% Nanosilica             | 271260    |
The appropriate second order polynomial model recommended by [15, 16] was used for optimal conditions prediction as shown in equation 2.

\[ y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{j=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + e \]  

(2)

where \( y \) is the predicted outcome; \( \beta_0 \) is the experiment central point fixed response value, \( \beta_j \) and \( \beta_{jj} \) are first and second order effects, \( \beta_{ij} \) is cross interaction effect, \( x_i, x_j \) are coded factors while \( e \) is a model random error.

3. Result and discussion

3.1 Statistical analysis

A statistical analysis has been done to have a good understating of the model's performance in terms of fatigue life. After regression analysis has been applied, a fitted quadratic model was developed for prediction of fatigue life response. Quadratic model was selected based on the highest order polynomials in which the additional terms were significant and are not aliased by the RSM software. The developed model equation for fatigue life (FL) with all terms is shown in Equation 3, while the model equation for fatigue life after reduction which removes insignificant terms is shown in Equation 4. The positive and negative signs before the terms in the equations show the synergistic and antagonistic effects of the individual variables on the response.

\[ FL = 3622.5 + 32919.92 x_1 + 55753.5 x_2 + 1.08 \times 10^5 x_3 + 293.28 x_1 x_2 + 6288.33 x_1 x_3 + 5677.5 x_2 x_3 - 4643.83 x_1^2 - 8081.89 x_2^2 - 50787.5 x_3^2 \]  

(3)

\[ FL = -34914.5 + 40088 x_1 + 62310 x_2 + 1.44 \times 10^5 x_3 - 4643.83 x_1^2 - 8081.89 x_2^2 - 50787.5 x_3^2 \]  

(4)

Table 2 presents the statistical analysis (ANOVA) summary for developed fatigue life model before and after model reduction. The coefficient of determination (R²) is used to check the degree of correlation of the models. As seen in Table 2, fatigue life has R² value of 0.94, which indicate that the model has only 6% correlation error. However, after model reduction which removes insignificant terms in the model, the R² value reduces to 0.91. This is because removing the insignificant terms in the model reduces the number of data points used in the calculation of R² value. Furthermore, for both models, their predicted R² are in agreement with their adjusted R² as their differences are less than 0.2 [17]. The high R² values achieved clearly shown that the proposed RSM method is capable to model the fatigue life of the composite mixture in a quite short time with low errors.

The 95% confidence interval (P<0.05) is used to measure the significant of the response model and all the model terms. A low P-value of < 0.05 indicates that the quadratic model selected and its terms are significant. The significance of each variance and the response are evaluated using the 95% confidence interval which corresponds to probability P-value < 0.05. Therefore, for the fatigue life model, only 0.01% chance exists that a model F-value of 18.16 can occur due to noise.
Table 2. ANOVA result for developed model

| Fatigue life response | Factors     | F -Values | P-Values | $R^2$ | Adjusted $R^2$ |
|-----------------------|-------------|-----------|----------|-------|----------------|
| Before reduction with insignificant variables | Model       | 13.4      | 0.0012   |       |                |
|                       | $x_1$       | 15.05     | 0.0061   |       |                |
|                       | $x_2$       | 19.23     | 0.0032   |       |                |
|                       | $x_3$       | 19.83     | 0.003    |       |                |
|                       | $x_1 x_2$   | 0.039     | 0.8491   |       |                |
|                       | $x_1 x_3$   | 1.99      | 0.2011   | 0.9451| 0.8746         |
|                       | $x_2 x_3$   | 1.62      | 0.2433   |       |                |
|                       | $x_1^2$     | 10.29     | 0.0149   |       |                |
|                       | $x_2^2$     | 31.16     | 0.0008   |       |                |
|                       | $x_3^2$     | 15.19     | 0.0059   |       |                |
|                       | Lack of fit | 5.92      | 0.0594   |       |                |
| After reduction without insignificant variables | Model       | 18.29     | <0.0001  |       |                |
|                       | $x_1$       | 14.13     | 0.0037   |       |                |
|                       | $x_2$       | 18.05     | 0.0017   |       |                |
|                       | $x_3$       | 18.61     | 0.0015   |       |                |
|                       | $x_1^2$     | 9.66      | 0.0111   | 0.9165| 0.8664         |
|                       | $x_2^2$     | 29.25     | 0.0003   |       |                |
|                       | $x_3^2$     | 14.26     | 0.0036   |       |                |
|                       | Lack of fit | 4.85      | 0.0741   |       |                |

For an understanding of the developed model satisfactoriness, predicted versus actual values for fatigue life is plotted as shown in Figure 2. As seen all the points for the responses were spread relatively very close to the line of equality, the distribution of the points indicates a satisfactory fitting precision of the models and the experimental results are in agreement with each other.

Figure 2. Predicted Vs. actual plots for fatigue life model
The 3D and 2D plots of fatigue life model at different percentages of nanosilica are shown in Figure 3 and Figure 4 respectively. As seen from Figure 3 all the contour lines were elliptical in shape, meaning there is a perfect interaction between the variables [18]. From Figure 4b and 4c, it can be seen that nanosilica has positive effect on fatigue life behavior of modified mixture by increasing the fatigue resistance. The hot yellowish regions on both plots show the region with the highest fatigue life performance. It can be seen that the region of optimum fatigue life performance lies between 3% to 5% polyethylene content and 3% to 4% polypropylene content.

![Figure 3](image-url)  
*Figure 3. 2D contour plot of fatigue life at (a) 0% NS (b) 1% NS and (c) 2% NS*
3.2 Optimization of design variables

In this study, a numerical optimization method was applied to optimize design variables and evaluates the accuracy of the developed model. The desired goals for the optimization are set; to minimize materials, polymers were set in ranges (0 – 6%) and nanosilica was set at range (0 – 2%) while to improve performance fatigue life was maximized. Three optimal solutions for the mix design were suggested by design expert software but the optimal value was selected based on the highest desirability of 1.0. An additional experiment was conducted based on the optimal predicted mix design proportions. The percentage error (%) between experimental and optimal predicted values was calculated using equation 5.

\[
\text{Error} = \frac{\text{Experimental} - \text{Model}}{\text{Experimental}} \times 100\%
\]  

The optimize solutions and percentage error difference are presented in Table 3, it can be seen that the percent error difference was found to be less than 5%, this indicates that the predicted values for the developed models are in good agreement with the experimental values.
Table 3. Verification of experiment at optimum conditions

| Response   | PE (%) | PP (%) | NS (%) | Predicted | Observed | Error (%) | De |
|------------|--------|--------|--------|-----------|----------|-----------|----|
| Fatigue life | 4.36   | 4.37   | 1.54   | 279742    | 291640   | 4.10      | 0.99 |

4. Conclusion

Based on the results in this study, the following conclusions can be drawn:

- A quadratic model with a high degree of correlation and predicting ability was developed to predict the fatigue life of asphalt mixtures using polyethylene, polypropylene and nanosilica as variables.
- Nanosilica has positive effect on fatigue life of the mixture and the fatigue life of the modified mixture increases with increase in percentage of nanosilica.
- Both the individual effects of polymers and nanosilica are significant in the improvement of the mixture but the percentage of nanosilica used shows higher influence on the fatigue life.

5. References

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