Stress Regression Analysis of Asphalt Concrete Deck Pavement Based on Orthogonal Experimental Design and Interlayer Contact

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Abstract. A three-dimensional finite element box girder bridge and its asphalt concrete deck pavement were established by ANSYS software, and the interlayer bonding condition of asphalt concrete deck pavement was assumed to be contact bonding condition. Orthogonal experimental design is used to arrange the testing plans of material parameters, and an evaluation of the effect of different material parameters in the mechanical response of asphalt concrete surface layer was conducted by multiple linear regression model and using the results from the finite element analysis. Results indicated that stress regression equations can well predict the stress of the asphalt concrete surface layer, and elastic modulus of waterproof layer has a significant influence on stress values of asphalt concrete surface layer.

1. Introduction
The asphalt concrete deck pavement is multi-layered composite system, and it is usually composed of asphalt concrete surface layer, waterproof layer and cement concrete layer. Once the material parameters (such as thickness and elastic modulus) of these layers changed, mechanical response of asphalt concrete deck pavement would also change. On the other hand, the bonding condition between adjacent layers also plays an important part in structural response of asphalt concrete deck pavement, because it has influence on the stress transfer between the layers [1, 2]. The poor bonding condition between adjacent layers reduce shear strength of asphalt concrete deck pavement, thereby result in several pavement distresses such as cracking, shoving and pothole [3-5]. Most former researches assumed two kinds of extreme interlayer bonding condition [2, 6], which are the full-bond condition and the no-bond condition. In fact, it is not reasonable assumptions for the real asphalt concrete deck pavements. The real bonding condition between adjacent layers is thought to be neither the full-bond condition nor the no-bond condition [7], but lies somewhere in between.

A 3-dimensional elastic finite element model of a box girder bridge with asphalt concrete deck pavement was developed by ANSYS software in this research, and the interlayer bonding condition was assumed to be contact bonding condition. The model was used to analysis the influence of multiple material parameters on stress of asphalt concrete deck pavement under the contact bonding condition, and the material parameters of deck pavement will be arranged by orthogonal experimental design. Stress regression equations of asphalt concrete deck pavement will be established by multiple linear regression analysis, in addition, the important material parameters to asphalt concrete deck pavement will be found out.
2. Material Parameters and Computing Method

2.1. Material Parameters and Plans of Orthogonal Test

The main material parameters as influencing factors include elastic modulus of asphalt concrete surface layer, denoted by $E_1$, thickness of asphalt concrete surface layer, denoted by $h_1$, elastic modulus of waterproof layer, denoted by $E_2$, thickness of waterproof layer, denoted by $h_2$, elastic modulus of cement concrete layer, denoted by $E_3$, thickness of cement concrete layer, denoted by $h_3$. The recommended values of these parameters are listed in Table 1. According to orthogonal experimental design [8], the 25 plans which are arranged in this research for the orthogonal tests are all listed in Table 2.

**Table 1 Material Parameters**

| Structural layer                     | Elastic modulus(GPa) | Thickness(cm) | Poisson’s ratio |
|-------------------------------------|----------------------|---------------|----------------|
| Asphalt concrete surface layer      | 1.2, 1.4, 1.6, 1.8, 2.0 | 6, 7, 8, 9, 10 | 0.25           |
| Waterproof layer                    | 0.1, 0.2, 0.3, 0.4, 0.5 | 0.1, 0.2, 0.3, 0.4, 0.5 | 0.30           |
| Cement concrete layer               | 22, 25.5, 28, 30, 31.5 | 8, 9, 10, 11, 12 | 0.15           |
| Box girder bridge                   | 36                   | —             | 0.15           |

**Table 2 Plans for the Orthogonal Tests**

| Test number | $E_1$(GPa) | $h_1$(cm) | $E_2$(GPa) | $h_2$(cm) | $E_3$(GPa) | $h_3$(cm) |
|-------------|------------|-----------|------------|-----------|------------|-----------|
| 1           | 1.2        | 6         | 0.1        | 0.1       | 22.0       | 8         |
| 2           | 1.2        | 7         | 0.2        | 0.2       | 25.5       | 9         |
| 3           | 1.2        | 8         | 0.3        | 0.3       | 28.0       | 10        |
| 4           | 1.2        | 9         | 0.4        | 0.4       | 30.0       | 11        |
| 5           | 1.2        | 10        | 0.5        | 0.5       | 31.5       | 12        |
| 6           | 1.4        | 8         | 0.1        | 0.4       | 25.5       | 12        |
| 7           | 1.4        | 9         | 0.2        | 0.5       | 28.0       | 8         |
| 8           | 1.4        | 10        | 0.3        | 0.1       | 30.0       | 9         |
| 9           | 1.4        | 6         | 0.4        | 0.2       | 31.5       | 10        |
| 10          | 1.4        | 7         | 0.5        | 0.3       | 22.0       | 11        |
| 11          | 1.6        | 10        | 0.1        | 0.2       | 28.0       | 11        |
| 12          | 1.6        | 6         | 0.2        | 0.3       | 30.0       | 12        |
| 13          | 1.6        | 7         | 0.3        | 0.4       | 31.5       | 8         |
| 14          | 1.6        | 8         | 0.4        | 0.5       | 22.0       | 9         |
| 15          | 1.6        | 9         | 0.5        | 0.1       | 25.5       | 10        |
| 16          | 1.8        | 7         | 0.1        | 0.5       | 30.0       | 10        |
| 17          | 1.8        | 8         | 0.2        | 0.1       | 31.5       | 11        |
| 18          | 1.8        | 9         | 0.3        | 0.2       | 22.0       | 12        |
| 19          | 1.8        | 10        | 0.4        | 0.3       | 25.5       | 8         |
| 20          | 1.8        | 6         | 0.5        | 0.4       | 28.0       | 9         |
| 21          | 2.0        | 9         | 0.1        | 0.3       | 31.5       | 9         |
| 22          | 2.0        | 10        | 0.2        | 0.4       | 22.0       | 10        |
| 23          | 2.0        | 6         | 0.3        | 0.5       | 25.5       | 11        |
| 24          | 2.0        | 7         | 0.4        | 0.1       | 28.0       | 12        |
| 25          | 2.0        | 8         | 0.5        | 0.2       | 30.0       | 8         |
2.2. Computing Model

The cross section size of the box girder bridge (with a span of 30m) and its pavement are shown in figure 1, and the direction of z-axis was the same with the driving direction. The loading position in the figure 1 is at the mid-span, and the pavement structure subjected to single-axis double-wheel load of 140KN [9], horizontal force \( F = \lambda G \), \( \lambda \) is the braking coefficient and equals 0.5, and \( G \) is the wheel load.

![Cross section of model](image)

**Figure 1.** Cross section of model (Unit: m)

As previously mentioned, the interlayer bonding condition was assumed to be contact bonding condition, and the concept of contact bonding condition for interlayer modeling can be exhibited in figure 2. The adjacent layers were connected by translational spring elements, contact element and target element at the corresponding nodes.

![Modeling for contact bonding condition](image)

**Figure 2.** Modeling for contact bonding condition

The shear stress transfer between the adjacent layers follows Coulomb friction model [10]:

\[
\tau_{\text{lim}} = \mu P + b
\]

\[
|\tau| \leq \tau_{\text{lim}}
\]

Where \( \tau_{\text{lim}} \) is ultimate shear stress, \( \mu \) is the sliding friction coefficient, it equals 0.5 in this paper, \( P \) is the contact compressive stress in normal direction, \( b \) is the cohesion between the adjacent layer, \( \tau \) is the equivalent shear stress. In equation (1), if \( \mu \) equals 0 or \( P \) equals 0, the cohesion \( b \) still exist, if \( b \) equals 0, two adjacent layers appear cohesive failure. In inequation (2), when \( |\tau| \) between two adjacent layers is less than or equal \( \tau_{\text{lim}} \), the two layers keep sticking, or the two layers start to slide.

2.3. Regression Analysis and Significance Testing

The maximum transverse tensile stress \( \sigma_{x_{\text{max}}} \) and maximum longitudinal tensile stress \( \sigma_{z_{\text{max}}} \) at the bottom of asphalt concrete surface layer, and the maximum longitudinal shear stress \( \tau_{yz_{\text{max}}} \) between asphalt concrete surface layer and the waterproof layer would be calculated as test indexes, which will
be calculated by ANSYS software according to the plans of orthogonal tests. The model of stress regression equation can be written as:

$$\sigma = c_0 + c_1 E_1 + c_2 h_1 + c_3 E_2 + c_4 E_2 + c_5 E_3 + c_6 h_3$$

(3)

Where $c_0, c_1, c_2, c_3, c_4, c_5, c_6$ are the regression coefficients.

The test statistics $F$ in F-test and the multiple correlation coefficient $R$ will be calculated by Analysis of Variance for significance testing of stress regression equation, $F$ and $R$ are defined as follow:

$$F = \left( \frac{S_x}{k} \right) / \left( \frac{S_e}{n-k-1} \right) \square F(k, n-k-1), \quad R = \sqrt{S_x / S_e} = \sqrt{1 - S_e / S_T}$$

Where $n$ is the test times, equals 25, $k$ is the number of the influencing factors, and which equals 6, $S_x$ means regression sum of squares, $S_e$ denotes residual sum of squares, and $S_T = S_x + S_e$. For a significance level $\alpha = 0.05$, the condition that the equation (3) is significant is $F > F_{0.05}(6,18) = 2.66$ or $R > R_{0.05} = \sqrt{mF_{0.05}/(n-m-1 + mF_{0.05})} = 0.6855$.

The test statistics $T$ in t-test will be calculated for determining the order of influencing factors, which is defined as follow:

$$T_i = \frac{\hat{c}_i}{\delta \sqrt{a_{ii}}} = (i = 1, 2, \ldots, 6) \square t(n-k-1)$$

Where $\hat{c}_i$ is the regression coefficient of the $i$ th influencing factor, $\delta = \sqrt{S_e/(n-k-1)}$, $a_{ii}$ is the $(i+1)$th element of matrix $(X^T X)^{-1}$ on the main diagonal, matrix $X$ is defined as follow:

$$X = \begin{bmatrix} 1 & x_{11} & \cdots & x_{1k} \\ 1 & x_{21} & \cdots & x_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{n1} & \cdots & x_{nk} \end{bmatrix}$$

Where $x_{ij}$ is the $i$ th value of the $j$ th influencing factor in table 2. For a significance level $\alpha = 0.05$, the condition that the $i$ th influencing factor is significant is $|T_i| > t_{0.05}(n-k-1) = t_{0.025}(18) = 2.10$, and the bigger the $|T_i|$ is, the more significant the $i$ th influencing factor is.

3. Results Analysis

Assumed that the interlayer bonding condition was contact bonding condition shown in figure 2, the stress values of the asphalt concrete deck pavement can be calculated by ANSYS software according to the plans of orthogonal test in table 2, and then the calculated values of the test indexes are obtained.

By programing and calculating in MATLAB software, the regression equation of the maximum transverse tensile stress $\sigma_{x_{\max}}$ on the basis of equation (3) can be written as:

$$\sigma_{x_{\max}} = 0.1744 + 0.0756 E_1 + 0.5339 h_1 - 0.3338 E_2 + 2.7344 h_2 - 4.261 E_3 - 0.6313 h_3$$

(4)

The calculated values and regression values of the maximum transverse tensile stress $\sigma_{x_{\max}}$ are exhibited in figure 3.

The test statistics $F = 34.9513 > F_{0.05}(6,18) = 2.66$, and the multiple correlation coefficient $R = 0.9597 > R_{0.05} = 0.6855$. Thereby the equation (4) is significant for the influencing factors. The value of the test statistics $T$ are listed in table 3. From table 3, $|T_1| > t_{0.025}(18), |T_3| > t_{0.025}(18), |T_4| > t_{0.025}(18)$, which means the elastic modulus of asphalt concrete surface layer $E_1$, the elastic modulus of waterproof layer $E_2$, and the thickness of cement concrete layer $h_3$ have a significant influence on the stress $\sigma_{x_{\max}}$. 
Figure 3. Values of the maximum transverse tensile stress

Table 3. Values of the test statistic $T$ of the regression coefficients

| Influencing Factors | $E_1$  | $h_1$  | $E_2$  | $h_2$  | $E_3$  | $h_3$  |
|---------------------|--------|--------|--------|--------|--------|--------|
| Test Statistics     | $|T_1|$ | $|T_2|$ | $|T_3|$ | $|T_4|$ | $|T_5|$ | $|T_6|$ |
| Value               | 5.8094 | 2.0522 | 12.8298| 1.0510 | 0.3900 | 2.4265 |

The regression equation of the maximum longitudinal tensile stress $\sigma_{z,\text{max}}$ on the basis of equation (3) can be written as:

$$\sigma_{z,\text{max}} = 0.2568 + 0.1702E_1 + 0.0035h_1 - 1.135E_2 + 5.1995h_2 + 0.0026E_3 + 0.708h_3$$ (5)

The calculated values and regression values of the maximum longitudinal tensile stress $\sigma_{z,\text{max}}$ are exhibited in figure 4.

Figure 4. Values of the maximum longitudinal tensile stress

The test statistics $F = 27.3777 > F_{0.05}(6,18) = 2.66$, and the multiple correlation coefficient $R = 0.9493 > R_{0.05} = 0.6855$. Thereby the equation (5) is significant for the influencing factors. The
value of the test statistics $T$ are listed in table 4. From table 4, $|T_1| > t_{0.025}(18)$, $|T_2| > t_{0.025}(18)$, which means the elastic modulus of asphalt concrete surface layer $E_1$ and the elastic modulus of waterproof layer $E_3$ have a significant influence on the stress $\sigma_{\text{max}}$.

**Table 4. Values of the test statistic $T$ of the regression coefficients**

| Influencing Factors | $E_1$ | $h_1$ | $E_2$ | $h_2$ | $E_3$ | $h_3$ |
|---------------------|-------|-------|-------|-------|-------|-------|
| Test Statistics     | $|T_1|$| $|T_2|$| $|T_3|$| $|T_4|$| $|T_5|$| $|T_6|$|
| Value               | 3.6664| 0.0037| 12.2263| 0.5601| 0.6669| 0.7627|

The regression equation of the maximum longitudinal shear stress $\tau_{yz,\text{max}}$ on the basis of equation (3) can be written as:

$$\tau_{yz,\text{max}} = 0.1744 + 0.0756E_1 + 0.5339h_1 - 0.3338E_2 - 2.7344h_2 - 4.261E_3 - 0.6313h_3 \quad (6)$$

The calculated values and regression values of the maximum longitudinal shear stress $\tau_{yz,\text{max}}$ are exhibited in figure 5.

![Figure 5. Values of the maximum longitudinal shear stress](image)

The test statistics $F = 15.9312 > F_{0.05}(6,18) = 2.66$, and the multiple correlation coefficient $R = 0.9174 > R_{0.05} = 0.6855$. Thereby the equation (6) is significant for the influencing factors. The value of the test statistics $T$ are listed in table 5. From table 5, $|T_3| > t_{0.025}(18)$, $|T_4| > t_{0.025}(18)$, which means the thickness of asphalt concrete surface layer $h_1$ and the elastic modulus of waterproof layer $E_3$ have a significant influence on the stress $\tau_{yz,\text{max}}$.

**Table 5. Values of the test Statistic $T$ of the regression coefficients**

| Influencing Factors | $E_1$ | $h_1$ | $E_2$ | $h_2$ | $E_3$ | $h_3$ |
|---------------------|-------|-------|-------|-------|-------|-------|
| Test Statistics     | $|T_1|$| $|T_2|$| $|T_3|$| $|T_4|$| $|T_5|$| $|T_6|$|
| Value               | 1.3702| 9.1468| 3.1443| 0.0974| 0.0551| 0.3831|
In conclusion, the elastic modulus of asphalt concrete surface layer and the waterproof layer have a significant influence on the tensile stress of asphalt concrete surface layer, and the thickness of asphalt concrete surface layer and the elastic modulus of waterproof layer have a significant influence on the longitudinal shear stress of asphalt concrete surface layer.

4. Conclusions
A summary of findings and conclusions in this study are presented as follows:
(1) The three-dimensional elastic asphalt concrete deck pavement and box girder bridge model was developed, and the model adopted the concept of contact bonding condition between adjacent layers of deck pavement for more realistic and effective evaluating the stress of asphalt concrete deck pavement.
(2) By multiple linear regression analysis, the maximum tensile stress and the maximum longitudinal shear stress all have a significant linear correlation with the multiple material parameters, and the stress regression equations have an approximate trend as well as the magnitude compared with the calculated values, which can predict the stress values of asphalt concrete surface layer.
(3) The elastic modulus of waterproof layer has a significant influence on the stress of asphalt concrete surface layer. The elastic modulus of asphalt concrete surface layer affect the tensile stress of asphalt concrete surface layer, and the thickness of asphalt concrete surface layer affect the shear stress of asphalt concrete surface layer.

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References
[1] K. Khweir, D. Fordyce, Influence of layer bonding on the prediction of pavement life, Proc., Institution of Civil Engineers Transport, 156(2)(2003)73–83.
[2] M.R. Kruntcheva, A.C. Collop, N.H. Thom, Properties of asphalt concrete layer interfaces, J. Mater. Civ. Eng., 18(3)(2006) 467–471.
[3] J.W. Zhou, D.M. Wang, Q.F. Bai, Analysis on damage causes of asphalt concrete pavement on cement concrete bridge deck, Forest Engineering. 24 (2008)52-55.
[4] X. Hu, K. Su, X.D. Hu, et al, Finite element analysis of asphalt concrete pavement for concrete bridge deck, Journal of Highway & Transportation Research & Development, 24(2007)5-14.
[5] Z. Leng, I.L. Al-Qadi, S. Carpenter, H. Ozer, Interface bonding between hot-mix asphalt and various Portland cement concrete surfaces: assessment of accelerated pavement testing and measurement of interface strain, Transp. Res. Rec. 2127 (2009) 20–28.
[6] H. Kim, M. Arriagada, C. Raab, M.N. Partl, Numerical and experimental analysis for the interlayer behavior of double-layered asphalt pavement specimens, J. Mater. Civ. Eng. 23 (1) (2011)12-20.
[7] S. Chun, K. Kim, J. Greene, B. Choubane, Evaluation of interlayer bonding condition on structural response characteristics of asphalt pavement using finite element analysis and full-scale field tests, Construction & Building Materials, 96(2015)307-318.
[8] S. Wu, H. Chen, J. Zhang, et al, Effects of interlayer bonding conditions between semi-rigid base layer and asphalt layer on mechanical responses of asphalt pavement structure, International Journal of Pavement Research & Technology, 10(3) (2017) 274-281.
[9] CCCC Highway Planning and Design Institute, JTGD60-2004 General Code for Design of Highway Bridges and Culverts, Ministry of Communications of the People's Republic of China, Beijing, 2004.
[10] X. M. Wang, ANSYS Structural Analysis Unit and Application, China Communications Press, Beijing, 2009.