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Research and verification of transfer model for roughness conditions of pavement construction

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Abstract

In order to study the transfer law of roughness during asphalt pavement construction, a mathematical model concerning the effect of sublayer, paving layer, random factors and paving materials compactness on final surface layer roughness was established through theoretical deduction and data statistical analysis. The critical conditions of sublayer roughness transfer to final surface layer were determined through the application of the Error Propagation Theory, allowing to further establish, the transfer model for roughness conditions in asphalt pavement construction, internal relationships among paving roughness, initial compactness and final surface layer roughness were also clarified. Moreover, the best initial compactness under different paving smoothness was determined and the transfer model was verified using typical engineering test data.

Keywords: Pavement engineering; Roughness; Transfer characteristic; Critical condition; Mathematical model; Experimental verification

1. Introduction

Good roughness is one of the essential purposes of asphalt pavement. It not only directly affects the driving quality and the riding comfort, but also the service life and the maintenance cost of pavement [1]. Ghosh's research showed that pavement roughness conditions affect energy consumption throughout the use phase [2]. Janoff's research indicated that good roughness of the pavement has fewer cracks and lower maintenance costs within 10 years [3]. In America, the roughness index in 15 states is set at a maximum gap between the pavement surface and a 3 m straight ruler, while in seven states it is set for 5 mm [4]. The standard in China requires the roughness of the upper layer to decrease from 1.8 mm to 1.2 mm [5]. Moreover, some equipment manufacturers have tried to improve paving roughness through improving the structure of pavers and the performance of leveling systems [6]; the constructors have improved pavement roughness through the improvement of construction technology [7]. Based on the previous studies, this paper established a transfer law for roughness and critical conditions in construction through further theoretical analysis and experimental research, and then built a transfer model for roughness conditions of asphalt pavement construction. The model was verified using a full-scale experiment.

2. The major factors of roughness in asphalt pavement construction

There are many factors that affect pavement roughness, which can be divided into two stages, namely the construction stage and the operation stage. The roughness transfer model of the construction is mainly studied in this paper.

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During the process of construction, the major factors that affect roughness in asphalt pavement are related to the sublayer roughness, the paving operation and the rolling operation.

2.1. The influence of sublayer roughness

The influence of sublayer roughness refers to the reflex action, resulting from layer thickness of uneven sublayer pavement to final surface layer roughness. When the roughness of the sublayer was unsatisfactory, a smooth loose layer can be made by pavers through an automatic leveling system. However, the different loose layer thicknesses caused a compression difference during the rolling process. The poor sublayer roughness was reflected through the rolling to the final surface layer.

2.2. The influence of paving operation

The influence of paving operations refers to the reflex action of the change of layer roughness to final surface layer roughness. The change of layer roughness mainly results from an automatic leveling system, a leveling benchmark, paver operational parameters, working parameters, etc.

The paver is composed of traction engine and working device. The traction engine provides power and the working device realizes the functions of feeding automatic control and layer's automatic leveling control. The floating screed is the working device of paver, and its working principle is shown in Fig. 1. Due to the self-weight, tension of towing point and the synthetic action of supporting force, friction and pile resistance in front of the screed steady layer is spread out when the force is in balance.

The working principle of floating screed is to regulate the height of towing point of big arm to change the included angle between screed floor and paving layer to destroy the balance of existing power, which makes the screed rise or fall to adjust to a new location. Based on a reference datum (e.g. a tie wire), the height of towing point can be regulated by electronic leveling system equipped in the paver.

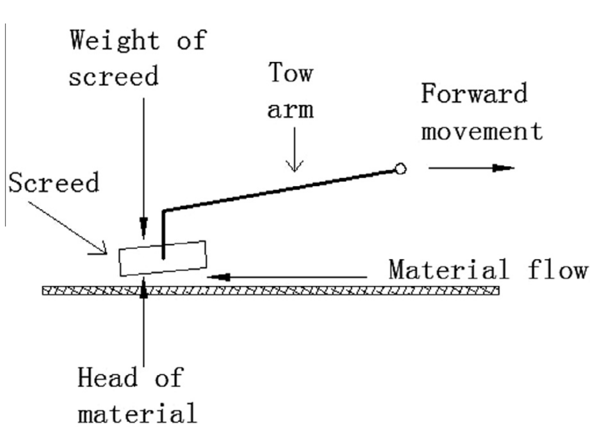

Fig. 1. The working principle of floating screed of a paver.

From the perspective of force balance of screed, factors which break the force balance affect paving roughness during the working process of paver, and they can change the push resistance of material piles in front of screed, paving resistance, towing point, etc.

2.3. The influence of rolling operation

The influences of a rolling process on pavement roughness are: the impact of the tangential thrust generated by a steel wheel on mixture during compaction, the mixture density of the loose layer and the non-homogeneity of mechanical property on roughness. When the roller changes its rolling direction, the brake is implemented, thus producing an inertial force. This force leads to a change in the tangential thrusts the starting, oscillation starting and oscillation stopping of a vibratory roller causes bulge and indentations on the final surface layer. Furthermore, the non-homogeneity of mixture layer material and temperature results in the inconsistent compaction power toward material resistance. These factors affect pavement roughness in direct or indirect ways.

3. The transfer characteristic of roughness in asphalt pavement construction

The influential of roughness in asphalt pavement construction can be divided into certainties and uncertainties. The sublayer roughness and paving operation, which can follow some rules, belong to certainties while the influence of rolling operation on pavement roughness is random and uncertain. However, a large amount of experimental data should be obtained for the statistical analysis.

3.1. The influence of certain factors on the roughness in pavement construction

The influence of an uneven sublayer on the final roughness of the surface layer is analyzed in the following section. By taking out a unit cell from the layers found below the roller steel wheel, the force state can be shown, such as in Fig. 2. As shown, σ_1 is the vertical compacting

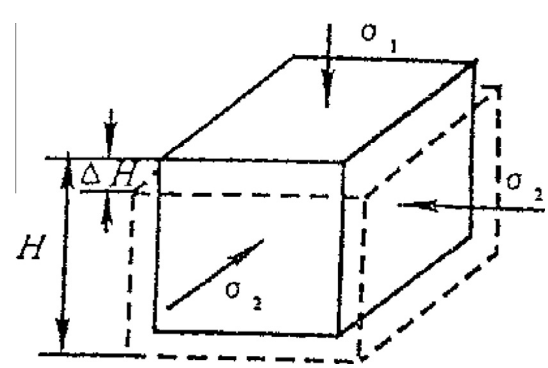

Fig. 2. Unit force diagram.

force from the roller, σ_2 and σ_3 are the horizontal extruding forces between mixtures, thus making them equal.

The expression of the volume ratio of a unit cell before and after compaction is as follows.

Setting a, b, c as the length, width and height of the unit cell before the compaction; and ΔH_a, ΔH_b, ΔH_c as the amount of compression on the length, width and height of the unit cell after compaction, then the following equations can be obtained:

$$V = a \times b \times c \tag{1}$$

$$V_0 = (a - \Delta H_a) \cdot (b - \Delta H_b) \cdot (c - \Delta H_c) \tag{2}$$

By omitting the high-order strains and setting the length and width of unit cell to the same strain ($\Delta H_a/a = \varepsilon_3$; $\Delta H_b/b = \varepsilon_2; \Delta H_c/c = \varepsilon_1, \varepsilon_2/\varepsilon_1 = \mu$), the following equation can be obtained:

$$V_0/V = 1 - \varepsilon_1 + 2\mu\varepsilon_1 \tag{3}$$

where V_0 is the volume of the unit cell after compaction, V is the volume of the unit cell before compaction, ε_1 is the vertical strain of the unit cell, ε_2 is the lateral strain of the unit cell, and μ is equivalent to Poisson's ratio. Using the equation for each variable results in the following equation:

$$\Delta H_0 = \Delta H(1 - \rho/\rho_0)/(1 - 2\mu) \tag{4}$$

where ΔH_0 is the amount of compaction per unit cell, H is the height of unit cell, ρ is the density of the material before compaction, and ρ_0 is the density of the material after compaction.

According to Eq. (4), ΔH_1 is the compaction difference between the amount of compaction in points "1" and "2" on the loose layer is calculated by:

$$\Delta H_1 = \Delta H_{20} - \Delta H_{10} = \frac{(H_{20} - H_{10})(1 - \rho/\rho_0)}{1 - 2\mu} = \frac{\Delta H_{10}(1 - \rho/\rho_0)}{1 - 2\mu} \tag{5}$$

where ΔH_{20} is the amount of compaction of point "2" on the final surface-layer, ΔH_{10} is the amount of compaction of point "1" on the final surface-layer, H_{10} is the thickness of point "1" on a loose layer, H_{20} is the thickness of point "2" on a loose layer, ΔH_1 is the difference in thickness between points "1" and point "2" of the final surface-layer, ΔH_{01} is the difference in thickness between points "1" and "2" on loose layer (namely the roughness of the sublayer).

3.2. The transfer characteristic of paving roughness

In practical construction, uneven roughness appears on the surface of the paving layer due to the performance of the paver, the deformation resistance of the material and the skill level of the operator, etc. Through rolling, the roughness of the loose layer surface can be transferred onto the final surface layer. The difference in the thickness between the two corresponding points on the final surface layer after compaction is expressed as follows:

$$\Delta H_2 = \Delta H_{20}(\rho/\rho_0 - 2\mu)/(1 - 2\mu) \tag{6}$$

where ΔH_2 is the difference in thickness between points "1" and "2" of the final surface layer; ΔH_{02} is the difference in thickness between points "1" and "2" of the loose layer(-namely the roughness of the paving layer).

3.3. The influence of random factors on roughness of pavement construction

When the roughness transfer model between the sublayer and the paving layer is established, it is assumed that the paving roughness of the paving layer material is the same, and the same compaction work is applied on the loose layer by the road roller during the process of rolling. However, the anisotropy of material and other factors can be found during the process of rolling, resulting in some randomness.

3.4. The synthetic roughness transfer characteristic of pavement construction

The synthetic effect of these three factors discussed above on the roughness-transfer characteristic was expressed in Eqs. (7) and (8):

$$\Delta H = \Delta H_1 + \Delta H_2 + \Delta H_3 \tag{7}$$

$$\Delta H = \frac{1 - \rho/\rho_0}{1 - 2\mu}\Delta H_{01} + \frac{\rho/\rho_0 - 2\mu}{1 - 2\mu}\Delta H_{02} + \Delta H_3 \tag{8}$$

where ΔH is the roughness of the surface layer, ΔH_3 is the difference in thickness caused by random factors between point "1" and point "2" of the final surface layer(namely the roughness of random factors).

During the rolling process, the transverse strain is zero. Therefore, Eq. (8) can be simplified to:

$$\Delta H = (1 - q)\Delta H_{01} + q\Delta H_{02} + \Delta H_3 \tag{9}$$

where q is equals to ρ/ρ_0 and is the initial paving compaction degree of paver.

4. Transfer conditions of roughness in pavement construction

The traveled surface roughness is defined as the vertical deviation of pavement surface relative to the ideal plane in the E867 of the American ASTM Standard [8]. The evaluation methods mainly include the international roughness index (IRI), the maximum gap between the pavement surface and a straight ruler, the standard deviation of roughness (σ) and profile index (PI), etc. In addition, the standard deviation of roughness (σ) is adopted to establish the mathematical model in order to analyze and calculate conveniently.

4.1. The deduction for the roughness-transfer conditions of the sublayer

Eq. (9) indicates that the final surface layer roughness in construction is not only determined by the sublayer roughness, the paving layer roughness and random factors, but also the loose laying compactness and the compacted density of the paving layer. When the material densities of two layers are very close, the transfer relationship is not one to one, and the influence of ΔH_{01} is small in Eq. (9). Therefore, the relationship between roughness transfer characteristics and material compactness should be further studied.

Based on the Error Propagation Theory [9], the standard deviation σ of the function $y = F(x_1, x_2, x_i \cdots x_m)$ is obtained below:

Under the conditions that F is continuously differentiable, $x_j(j = 1, 2\ldots, m)$ is a random variable and the first order Taylor expansion of $F(y = F(x_1, x_2, x_i \cdots x_m))$ is taken, Eq. (10) can be expressed as:

$$\Delta F \approx \sum_j \frac{\partial F}{\partial x_j} \Delta x_j \tag{10}$$

where $\partial F/\partial x_j$ is error propagation coefficient, and $a_1 = \partial y/\partial x_1$; $a_2 = \partial y/\partial x_2$; $a_j = \partial y/\partial x_j$; $\ldots$; $a_m = \partial y/\partial x_m$ are the corresponding error propagation coefficients of random variable x_j.

Taking variance for Δx_j, resulting in the following equation:

$$\sigma^2 = \sum_j \left(\frac{\partial F}{\partial x_j}\right)^2 \sigma_j^2 + 2\sum\sum_{i<j} \frac{\partial F}{\partial x_i}\frac{\partial F}{\partial x_j} R_{ij}\sigma_i\sigma_j \tag{11}$$

where σ is the final surface layer roughness determined by the sublayer roughness and the paving layer roughness, R_{ij} is the correlation coefficient between the random variables $x_i(i = 1, 2\ldots, m)$ and x_j. Combining the independent random variables results in $R_{ij} = 0$. When each σ_j is independent, the variance has the relation as expressed by Eq. (12):

$$\sigma^2 = \sum_j \left(\frac{\partial F}{\partial x_j}\right)^2 \sigma_j^2 \tag{12}$$

Based on the Error Propagation Theory, the first two items in Eq. (9) are analyzed separately and the partial derivatives of q, ΔH_{01}, ΔH_{02} are obtained respectively. According to the definition from "Roughness Test Method Measured by Continuous Roughness Instrument" (standard deviation method) [10], pavement roughness is expressed by the standard deviation of the interval determination results. Therefore, the sublayer roughness and the paving layer roughness are represented by $\sigma_{\Delta H_{01}}$ and $\sigma_{\Delta H_{02}}$ in Eq. (13).

$$\sigma^2 = (1-q)^2\sigma_{\Delta H_{01}}^2 + q^2\sigma_{\Delta H_{02}}^2 + (\Delta H_{02} - \Delta H_{01})^2\sigma_q^2 \tag{13}$$

where σ_q is the roughness determined by the non-homogeneity of the density of the material.

According to Eq. (9), the influence of the non-homogeneity of the density of the material is related to ΔH_3 (random factors). Therefore, this influence in Eq. (14) can be ignored, i.e. $\sigma_q = 0$. This results in the following equation:

$$\sigma^2 = (1-q)^2\sigma_{\Delta H_{01}}^2 + q^2\sigma_{\Delta H_{02}}^2 \tag{14}$$

In Eq. (14), the sum of squares of the independent variables enlarges the difference in the standard deviation of roughness between the sublayer and the paving layer. When the difference of the independent variables reaches a certain degree, the larger variance value is dominant and the smaller one can be ignored. According to the Error Theory [11], when Eq. (14) meets the conditions of Eq. (15), the influence of the sublayer becomes so minuscule that it can be ignored.

$$q\sigma_{\Delta H_{02}} \geqslant 3(1-q)\sigma_{\Delta H_{01}}, \text{ i.e. } \frac{\sigma_{\Delta H_{02}}}{\sigma_{\Delta H_{01}}} \geqslant \frac{q}{3(1-q)} \tag{15}$$

Combing Eqs. (14) and (15) results in the following equation:

$$\sigma^2 = \frac{\sqrt{10}}{3}(q\sigma_{\Delta H_{02}})^2, \text{ i.e. } \sigma = 1.05q\sigma_{\Delta H_{02}} \approx q \cdot \sigma_{\Delta H_{02}} \tag{16}$$

Eq. (16) indicates that the effect of sublayer roughness on the final surface layer roughness is extremely small. This effect can be regarded as one of the random factors of pavement construction roughness and is related to ΔH_3. In this case, the roughness transfer characteristic from the sublayer to the surface layer becomes invalid.

The factor K, defined as the critical coefficient of the transfer characteristic of the sublayer roughness, is calculated by the function $K = q/(1-q)$, where q is less than 1. Based on Eq. (15), the relationship curve of the critical coefficient and the initial compaction degree is given in Fig. 3. As indicated, it has a significant impact on the critical coefficient when the initial compaction is greater than 85%.

4.2. The transfer model and verification of roughness conditions

The initial compaction degree of a mixture is different during the construction of asphalt pavement. This can lead to the proportional change of roughness from the sublayer to the surface layer roughness. If the influence of sublayer roughness satisfies the conditions in Eq. (15), it can be categorized into random factors. Combining various influential factors on the transfer characteristic of the final surface layer roughness in different conditions, a transfer

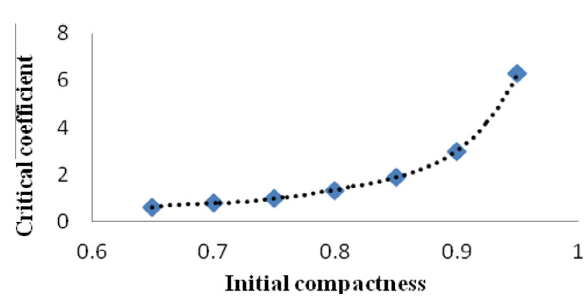

Fig. 3. The relation between initial compaction degree and the critical coefficient.

model for the roughness conditions in asphalt pavement construction is established, which is expressed by Eq. (17):

$$\begin{cases} \sigma^2 = \Psi(q, \sigma_{\Delta H_{01}}, \sigma_{\Delta H_{02}}) \times (1-q)^2 \sigma^2_{\Delta H_{01}} + \sigma^2_{\Delta H_{02}} \sigma^2_{\Delta H_3} \\ \Psi(q, \sigma_{\Delta H_{01}}, \sigma_{\Delta H_{02}}) = \begin{cases} 1, \frac{\sigma_{\Delta H_{02}}}{\sigma_{\Delta H_{01}}} \geqslant K \\ 0, \frac{\sigma_{\Delta H_{02}}}{\sigma_{\Delta H_{01}}} < K \end{cases} \\ K = \frac{q}{3(1-q)} \end{cases} \tag{17}$$

Eq. (17) indicates that when the ratio of sublayer roughness and loose layer roughness is larger than the critical coefficient K of the transfer characteristic, roughness transfer factors include sublayer roughness, loose layer roughness and various kinds of random factors (namely Three Factors Equation). When the ratio of sublayer roughness and loose layer roughness is less than the critical coefficient K of the transfer characteristic, roughness transfer factors include loose layer roughness and various kinds of random factors (namely Two Factors Equation).

According to Eq. (17), when the sublayer roughness is 1.6 mm and random factors roughness is 0.6 mm, the paving roughnesses are 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, 1.2 mm respectively. The curve of influence of initial compaction on the final surface layer roughness is shown in Fig. 4. The results indicate that there is an optimal initial compaction to different paving roughnesses. As the paving roughness increases, the optimal initial compaction also increases.

In order to verify the engineering feasibility of the transfer model for roughness conditions, the full-test data in practical engineering are used. The experiment was carried out in two sections of a highway (K7+000~K8+000 & K12+000~K11+000). The data from the former section dealt with the verification of the Three Factors Equation, and the latter with the Two Factors Equation.

The paving roughness of a paver is 1.1 mm (the erected stringline is employed), and the mixture gradation is AC20. The initial compaction of the layer is adjusted to 81% in order to measure the effects of different sublayer roughness on the final surface layer. The research results are shown in Table.1 and Fig. 5.

The table and curve indicate that when the roughness of sublayer is below the critical value, the change in layer

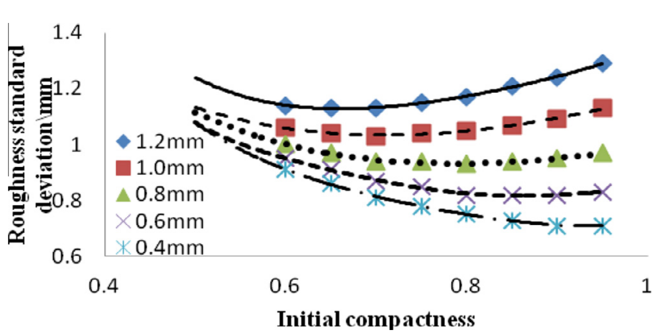

Fig. 4. The relationship between factors and final surface-layer roughness.

Table 1
The statistical characteristic value of roughness in test sections.

Item	Upper-layer	Sublayer	Notes
Number of testing points	1–10	1–10	Variable coefficient is
	11–20	11–20	the ratio of standard
Means/mm	1.18	2.34	deviation and means
	0.95	1.38	
Standard deviation/mm	0.14	0.47	
	0.07	0.27	
Variable coefficient/%	11.9	0.47	
	7.40	0.27	

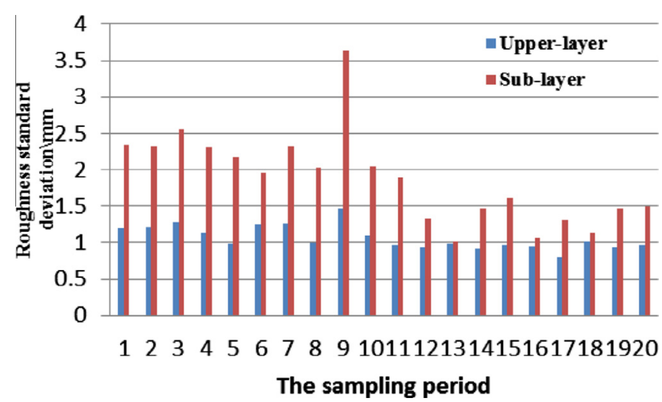

Fig. 5. Final surface-layer roughness in different sublayer conditions: test data for upper layer (blue bar), test data for sublayer (red bar).

roughness is highly influenced by the change of layers underneath, which is marked by No.1-10 in Table 1. If the roughness of the final surface layer and the sublayer have a similar varying pattern, the variable coefficient is higher. When the sublayer roughness is below critical value, the influence of sublayer roughness is not evident. This can be seen in No.11-20 in Table 1. As a result of the lack of influence, the relationship between the final surface layer roughness and the sublayer roughness is also insignificant, the variable coefficient of roughness is smaller. The transfer model for roughness conditions can be verified through this experiment.

5. Conclusion

The following conclusions can be made from this research:

(1) The roughness of a surface is determined by the weighed sum of the squares of the standard deviations of the roughness of the sublayer and paving layer, as well as random factors that influence roughness.
(2) The influence of the sublayer and loose layer roughness is certainty and can be transferred to the final surface layer of asphalt pavement.

(3) The ratio of the roughness of the sublayer to that of the loose layer has a critical value related to the initial compaction of the layers. When the ratio is smaller than this critical value, the influence of the sublayer's roughness on the final surface layer is small and can be defined as one of the random factors. For this situation, the roughness of the sublayer will not be transferred to the final surface layer. Therefore, the roughness of the asphalt pavement is ultimately determined by the quality of the paving roughness and rolling.

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