1st International Conference on Transportation Infrastructure and Materials (ICTIM 2016)
ISBN: 978-1-60595-367-0

Comparison of Designing Indexes for Asphalt Pavement

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ABSTRACT: The differences of stress, strain index and deflection used in asphalt pavement design were pointed out by finite element program based on elastic layered theory. And the necessity of applying strain indicators as controlling indexes during the design was purposed. The study discussed the selection of strain index as well as checking point's positions, and suggested the strain strength can be implemented as strain controlling index. The positions of checking points used to analyze the strain intensity were calculated to be taken in the middle of the surface layer, the top and the bottom of the base course. Finally, the selection of the design indexes in three typical asphalt pavement structures with flexible base, semi-rigid base and rigid base was investigated.

Keywords: Stress index; Strain index; Deflection; Strain Strength; Checking point position

INTRODUCTION

Asphalt pavement structure design indexes are essential for determining the bearing capacity of the pavement and maintaining the service performance. Previous studies conducted by Pettie (1962) and Dormon (1962) reported a conception of controlling the vertical compression strain on the top of the base in order to restrain the permanent deformation in subgrade soil. And this index was then followed by many pavement design methods. SHELL design method, which is a more perfect design method among the contemporary mechanistic-empirical method, conducted strain as the main design index (Deng and Huang, 2007). The vertical compression strain on the embankment surface loading axis can be adopted to control the permanent deformation in order to resist rutting; the horizontal tensile strain in asphalt surface course was introduced to contain the cracking of asphalt course. Permanent pavement also choose strain as the main design index. Monismith (1967) suggested restraining the horizontal tensile strain under the asphalt surface course to 60 $\mu\varepsilon$ and the compression strain on the top of the embankment to 200 $\mu\varepsilon$ can eliminate the structural destruction of asphalt pavement. However, to date the current Specifications for Highway Pavement Design applies the deflection, the flexural stress under the asphalt surface course and semi-rigid base course as the design indexes. But no strain indicators were introduced to restrain the permanent deformation of pavement directly. Yao (2005) argued that Deflection as a holistic, comprehensive, an index cannot accommodate the apparent diversity of the pavement structure, and it is difficult to control the permanent deformation of overall pavement structure or individual layers.

This paper compared the differences among deflection, stress and strain indexes, and assessed the significance of controlling strain index in asphalt pavement design by the given examples. The first section of this paper inspected the variation of the stress and strain indexes when base course modulus is changed and checking point positions are adjusted. Then differences between strain index and deflection are evaluated. Finally, the selection of controlling indexes in pavement design was discussed in regarding to three different typical asphalt pavement structures. The study aims to provide a new controlling indexes system in asphalt pavement design. All the analyzing work is based upon the calculating result of Abaqus, a finite element analysis software designed for pavement mechanics analysis

DIFFERENCES BETWEEN STRESS AND STRAIN INDEX

Stress index was introduced to restrain the fatigue cracking, while the strain index was adopted to prevent the permanent deformation and pavement diseases like rutting caused by the large distortion. In the current design specifications, only the stress index was adopted as a controlling index. However, these two indexes usually performed variously in the pavement design and sometimes even a negative correlation. So it is essential to limit the stress and strain index at the same time, otherwise it may come to the situation that one indicator meet the requirement but the other one does not. This would be further illustrated through calculating and analyzing the instance below.

CAUSED BY THE VARIATION OF BASE MODULUS

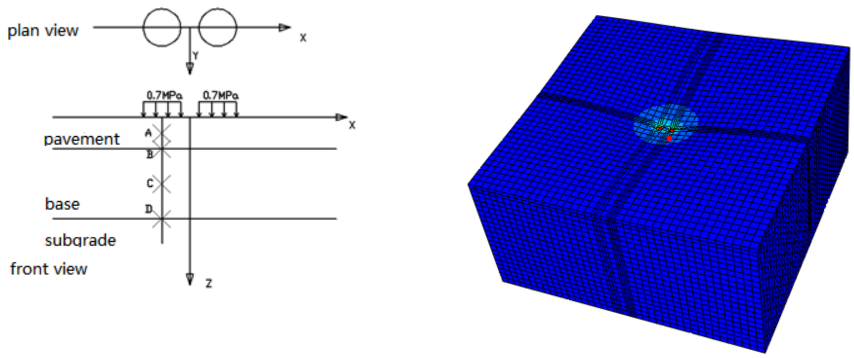


Figure 1. Pavement structure diagram and the model in Abaqus.

Fully continuous pavement structures with parameters shown in Table1 would be analyzed, as shown in Fig.1. The relationship between stresses and strains in the bottom of the base layer would be investigated with only the base modulus altered.

Table 1. Structural layers parameters.

Layer	Thick-ness (cm)	Modulus（MPa）								Poisson's ratio
Surface	18	1400								0.25
Base	40	500	1500	2500	3500	4500	5500	6500	7500	0.25
Subgrade	\	40								0.35

The point D which lied on the bottom of the base layer and directly below the center of one load circle was adopted as the checking point of stress indexes which included tensile stress σ_x、σ_y and horizontal tensile strain ε_x、ε_y. The relationship between stress index, strain index and the modulus of base layer was acquired in Fig.2 and analyzed as shown in Fig.3.

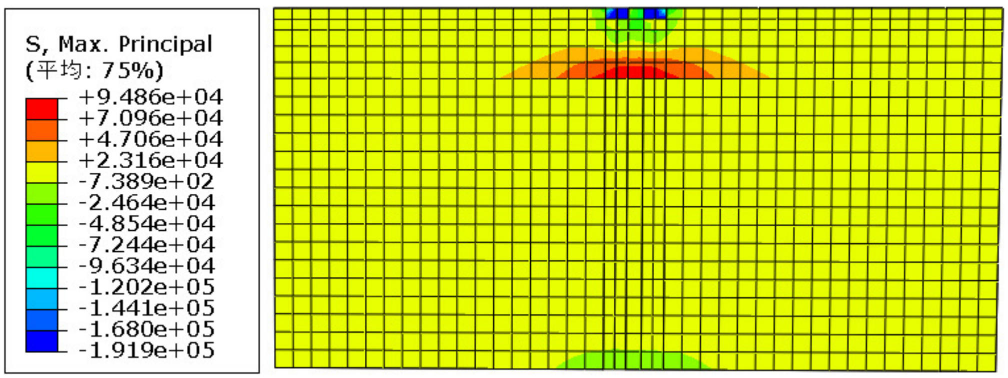


Figure 2. Stress distribution in Abaqus.

With base modulus increases, the tensile stress rises and the tensile strain declines. The variety of two indexes appears in a negative correlation.

In this case, if increase the base modulus to constrain the magnitude of the tensile strain, the tensile stress in the bottom of the base layer would exceed the restriction. Similarly, the tensile strain would exceed the restriction if decrease the base modulus to acquire a smaller tensile stress. This reveals the contradiction of the stress index and the strain index in this situation.

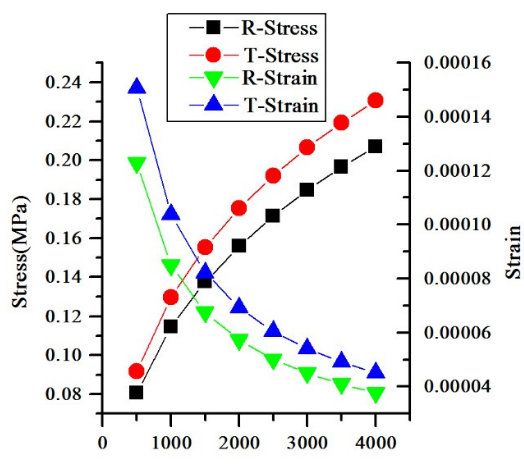


Figure 3. Tensile stress and tensile strain in the bottom of the base.

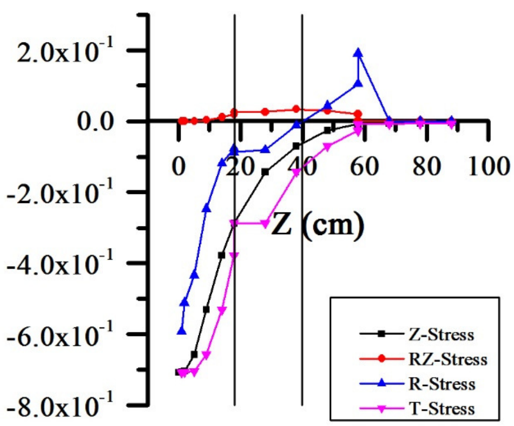
CAUSED BY THE VARIATION OF DEPTH

The distribution of the stress index and the strain index along the depth direction also reflected the difference between them and furthermore, had an adverse influence on the selection of checking point, which is also called the most unfavorable point. For example, when the points in the bottom of each bottom are believed to be the most unfavorable points of stress index, it is detected that the most unfavorable points of strain index are located not in the same position. From the example below, this effect would be explained by observing that the checking point positions of stress index was on the bottom of each layer while the strain index checking points was not.

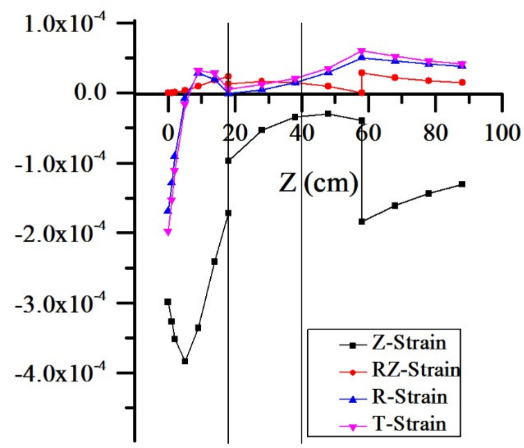
Table 2. Structural layers parameters.

Layer	Thickness (cm)	Modulus （MPa）	Poisson's ratio
Surface	18	1400	0.25
Base	40	2500	0.25
Subgrade	\	40	0.35

The pavement structure with fully continuous layers shown in Table.2 is selected to be investigated about the distribution of the stress index and the strain index along the depth direction in Fig.3. Checking points are picked along a straight line passing through the center of the load circle (line AD in Fig.1).



(a)stress distribution



(b)strain distribution

Figure 4. Distribution of stress and strain with depth.

According to the distribution curve of stress and strain along depth direction, the differences of stress index and strain index are reflected in two aspects:

1. The continuity of stress and strain varying along the depth direction was different. Inspecting the changing of stress indexes, it was discovered that σ_z and τ_{xz} tend to be continuous, while σ_x and σ_y were discontinuous in layer-to-layer locations. When it comes to stress indexes, ε_x and ε_y were continuous, while ε_z and γ_{xz} were discontinuous.

2. The most unfavorable points of stress index and strain index were different. Based on the stress curve in Fig.4 (a), the most unfavorable point of tensile stress is

located in the bottom of the base layer while the longitudinal compressive strain and transverse tensile strain reached peak value near the middle of the surface layer shown in Fig.4 (b). Thus the positions should be chosen near the middle of surface layer other than the bottom of surface course if the strain indexes were controlled.

EXPLANATIONS FOR THE DIFFERNENCES

Although there were differences between stress index and strain index in pavement structure, the two indexes should satisfy the generalized Hooke's law regardless of the plastic deformation and nonlinear property of materials.

$$\begin{cases} \varepsilon_x = \frac{1}{E}\left(\sigma_x - \mu\sigma_y - \mu\sigma_z\right) & \gamma_{xy} = \frac{1}{G}\tau_{xy} \\ \varepsilon_y = \frac{1}{E}\left(\sigma_y - \mu\sigma_z - \mu\sigma_x\right) & \gamma_{yz} = \frac{1}{G}\tau_{yz} \\ \varepsilon_z = \frac{1}{E}\left(\sigma_z - \mu\sigma_x - \mu\sigma_y\right) & \gamma_{zx} = \frac{1}{G}\tau_{zx} \end{cases} \tag{1}$$

Based on the first three equations, normal strain is determined by normal stress in three directions, instead of being caused by normal stress of just one direction. Then there is an explanation of the differences between strain index and stress index.

On the basis of the equation (1), it can be easily deduced that, the stress in the base layer increases simultaneously when the modulus of the base layer increases. In this circumstances, axial strain decreases adversely because the magnifying of the denominator value have a greater influence on the fraction value. In the similar way, hoop stress is increased and hoop strain is decreased.

Another strain distribution caused by the generalized Hooke's law draws is more worth concentrating. As is shown in Fig.4 (a), points near the bottom of the surface layer are compressed in three directions (σ_x、σ_y、σ_z <0, and τ_{xz} is small enough to be neglected). However, tensile stress shows up in this position, shown in Fig.4 (b). This reveals a possibility that materials in surface layer can be damaged by tension even when the whole layer is compressed in three directions.

STRAIN STRENGTH AS AN INDEX

In previous studies, compressive strain of base layer top and tensile strain of asphalt layer bottom were selected as strain indexes in pavement design (Yao, 2003) (Sun et al, 2006). There were two main considerations of selecting the strain indexes:

1. All the strain components should be considered synthetically to investigate the permanent deformations. Because the permanent deformation could developed easily to rutting, no matter the compressive strain, tensile strain or the shearing strain exceeds the limitation.

2. Checking position of strain index should be picked in the most unfavorable position. According to the discussion in part 1.2, the checking position can be selected in the middle of the surface layer other than the bottom of the layer.

Therefore, the practice of selecting compressive strain of base layer top and tensile strain of asphalt layer bottom as strain index was not reasonable enough. In contrast, strain strength $\bar{\varepsilon}$ was recommended here as the strain strength because it could reflect the composite deformation of materials.

$$\bar{\varepsilon} = \sqrt{\frac{2}{9}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2]} \quad (2)$$

DIFFERENCES BETWEEN STRAIN INDEX AND PAVEMENT DEFLECTION

In the current carried out Specifications for Design of Highway Asphalt Pavement in China, there is no direct limitation or further explanation of strain index except asphalt layer bottom tensile stress and design deflection value. Since there has been an elaboration of the differences of strain index and stress index, strain index could not be controlled resulting from the constraint of stress index. Then there was an uncertainty that whether strain index was controlled by the deflection value. The differences of road surface deflection index and stress index are discussed by computational analysis as following.

Pavement structure with continuous layers was elaborated as Table 1. The change situation of the strain index and road surface deflection was inspected in the circumstances that the layer thickness was fixed and base layer modulus was adjusted.

The checking point (point B and C in Fig.1) were selected in the middle of the surface and base layer. Changing the modulus of base layer modulus, the stress strength and pavement deflection of checking points were shown in Fig.5.

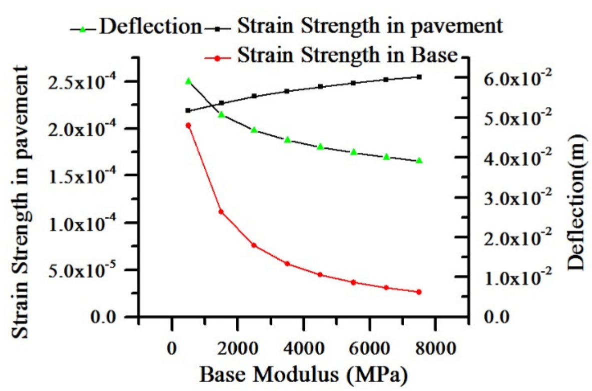


Figure 5. Strain strength and deflection when the base modulus is variable.

As is shown in the above figure, pavement deflection decreased when the base layer modulus increased, which is caused apparently by the increasing overall stiffness of the pavement. However, in the same circumstances, the stress strength decreased in the surface layer and increased in the base layer which means a high probability that the stress index in surface layer may exceed the limitation when the modulus of the base layer was adjusted to reduce the pavement deflection, showing differences between stress index and deflection index. The fact that the permanent deformation of each layer may not be controlled when pavement deflection just reflected the overall pavement structure stiffness was revealed.

In summary, all the design indexes arose in current specifications for design of highway asphalt pavement of China were not able to have a positive influence on the restriction of total strain in pavement structure.

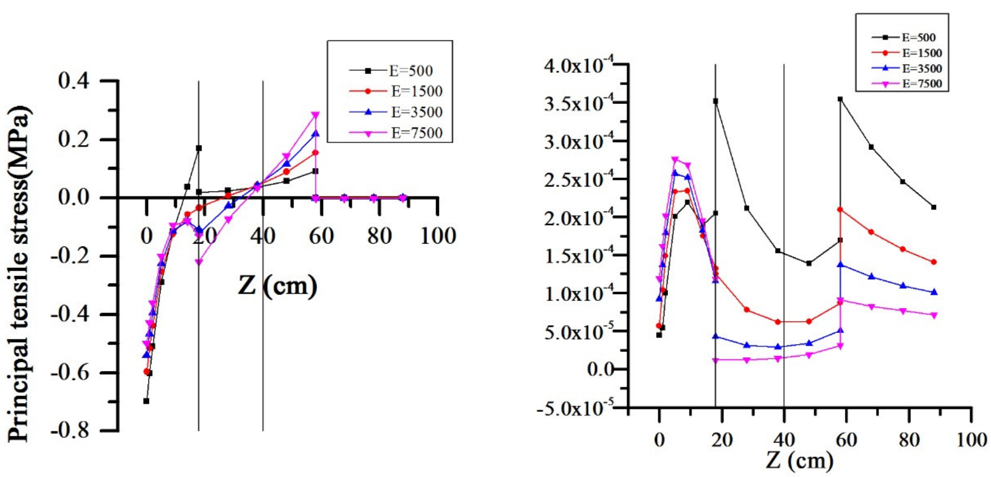
TYPE OF CONTROL INDEX AND PAVEMENT STRUCTURE

In this part, the problem of choosing control indexes when designing asphalt pavement with flexible base layer, semi-rigid base layer or rigid base layer was investigated. During the discussion, stress index and strain index using parameters in pavement structures shown in Table 3 were analyzed with the stiffness of the base layer was variable while other parameters were fixed

Table 3. Structural layers parameters.

Layers	Width	Modulus（MPa）				Poisson's ratio
Surface	18cm	1400				0.25
Base	40cm	500	1500	3500	7500	0.25
Subgrade	\	40				0.35

Given the prerequisite that tensile strength is far less than the compressive strength in materials used for pavement, it can only be destroyed by tension. So tensile stress is taken into consideration among all the stress indexes. According to the first strength theory (maximum tensile stress theory), principal tensile stress σ_1 is selected to completed the analysis. The reason why stress strength $\bar{\varepsilon}$ is chosen to be the control index has been discussed in former part of the paper. The change situation of stress index and strain index when the modus of base layer is variable is shown in Fig.6.



(a)Stress index with variable base modulus (b) Strain index with variable base modulus

Figure 6. Distribution of stress index and stress index.

Observing the figure above, several facts was discovered:

①When strain strength was selected to be the strain index, the most unfavorable point of the surface layer was around the middle of it, and the point of the base layer was on the top or the bottom of the layer.

②The principal tensile stress decreased in the surface course and increased in the base course with the increasing stiffness of the base layer.

③The stress strength increased in surface course and decreased in base and subgrade with the increasing stiffness of the base layer.

Overall, the strain indexes in surface layer and the stress indexes in base layer are recommended in this paper to be the control indicators in rigid base asphalt pavement design while the stress indexes in surface layer and the strain indexes in base and subgrade are recommended to be the control indicators in flexible base asphalt pavement design.

CONCLUSIONS

1. There are differences among deflection, stress and strain indexes. And the stress and deflection adopted as design indexes in the current Specifications for Design of Highway Asphalt Pavement could not restrain the deformation development of pavement effectively. The strain index should be introduced into the design system to restrict the permanent deformation and rutting diseases in pavement design.

2. The selection process of specific strain index should consider all the strain components, and strain strength can be applied to reflect the synthesized situation of the pavement material, and thus it is recommended to be included as the strain index in pavement design.

3. The checking points of strain index are different from the ones of stress index which are located on the bottom of each course. The checking point of strain index in surface course should be situated near the middle of the surface course. And the checking point of base course should be situated either at the top or bottom of the base course.

4. The type of design indexes selected varies with different asphalt pavement structures. Pavement with rigid base should control the strain index in the surface course and the stress index in the base course, while the pavement with flexible base should control the stress index in the surface course and the strain index in the base and subgrade.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the project by the National Natural Science Foundation of China (E080703).

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