Failure Criterion of an Asphalt Mixture under Three-dimensional Stress State

T. Huang¹, J.L. Zheng¹, S.T. Lv¹, J.H. Zhang¹*, P.H. Wen², C.G. Bailey²

¹National Engineering Laboratory of Highway Maintenance Technology, Changsha University of Science & Technology, Changsha, 410114, China.
²School of Engineering and Materials Science, Queen Mary University of London, London E1 4NS, UK.

*Correspondence: zjhseu@csust.edu.cn.

Abstract: A self-developed triaxial test method was adopted to characterize mechanical behavior of the asphalt mixture under three-dimensional stress states in this study. The conventional uniaxial tests and triaxial tests were conducted in the laboratory to verify the triaxial test results obtained using the technique developed. It is shown that the three dimensional stress states affect significantly the ultimate failure strength of AC-13 asphalt mixture and the failure modes are mainly represented both for the tensile failure and shear failure. The nonlinear strength criterion, as well as a linear engineering model of asphalt mixture under three-dimensional stress states in $\sigma_{oct} - \tau_{oct}$ space, was established based on the triaxial compressive/tensile tests, the plane tensile and compressive/axial tensile tests. In addition, a new method to carry out the strength design of asphalt pavement under the three-dimensional stress state was given to consider the failure effect of each stress component to the asphalt pavements.

Key words: Asphalt mixture; triaxial test; three-dimensional stress state; failure criterion; simplified strength model

1. Introduction

At present, 136 thousands kilometers expressway has been built in China, in which more than 90% uses the asphalt pavement structure. In addition, 40-50 thousands kilometers expressway with the asphalt pavement will be constructed by 2030. The design method of the asphalt pavement in China belongs to the mechanical-empirical method and the elastic layered half-space is modeled to calculate the mechanical responses of pavements. The theories of strength with the maximum tensile stress and maximum tensile strain are used as the failure criterions for asphalt pavements.

In general, the pavement works under complex stress states subjected to the traffic loading and thermal effects [1,2,3]. The ordinary strength test such as the uniaxial tensile test [4,5], uniaxial compression test [6,7], bending test [8,9,10] and indirect tensile test [11,12] under simple
stress states cannot be applied to simulate the real multi-axial stress conditions in the pavement structures. Apparently the tensile strength of asphalt materials under one-dimensional or two-dimensional stress state can not represent the failure characteristics of asphalt pavements. Due to the conventional triaxial test is available only for the triaxial compressive tests with a low confining pressure [13,14,15,16,17], it is difficult to study the failure criterion of asphalt mixtures using this test.

Due to the limits of the test equipment, few researchers carried out the study on the failure criterion of asphalt mixtures under complex stress states. Wang et al.[18] proposed a nonlinear failure envelope $I_1 - \sqrt{J_2}$ space based on the failure strength results of the dense asphalt concrete. Desai et al.[19] proposed a response surface for asphalt materials and utilized it as the response function of the yield surface. It can be applied both in the stress invariant and strain variant space. Nevertheless, three-dimensional unequal stress state was not established and the failure criterion was not verified by triaxial results in a three-dimensional stress state, especially at a triaxial tensile stress state. Guan et al. [20] carried out three-directional compression strength tests for three kinds of asphalt mixtures at -10°C with a self-developed simplified triaxial machine, the tested data of strength on the $\pi$-plane are close to a twin shear theory contour curve without the triaxial tensile strength consideration. In general, the tensile performance rather than the shear performance should be considered for asphalt mixtures in a low temperature[21]. Therefore, it is necessary to make efforts to establish the strength criterion of asphalt mixtures under three-dimensional stress states, in which the effects of triaxial tensile strength should be considered. So, the main objective of this paper is to establish the failure criteria under three-dimensional stress states. Moreover, a new design method to carry out the strength design of asphalt pavements was presented under three-dimensional stress states.

2. Test methods and specimen preparation

2.1. Materials and specimens

In order to evaluate the mechanical behavior of asphalt mixtures under three-dimensional stress states, the representative AC-13C asphalt mixture which were widely used in China were tested. As shown in Fig.1, the aggregate particles of AC-13C asphalt mixture are continuously graded to form an interlock structure. The performances of mixtures tested extensively can be referred from the results of Huang [22], in which the SBS modified bitumen was used as the binder and the basalt was used as aggregates.
To ensure the consistency of specimen in the triaxial test, the gyratory compactor was used to prepare cylindrical specimens with 102mm in height and 100mm in diameter. The bitumen-aggregates weight ratio of 5.2% was selected with the airvoid content for these specimens of 4.5% ± 0.5%. Moreover, the tested specimens were obtained by sawing the two ends of original specimens in the water with a diamond blade up to the height of 100mm.

2.2. Test equipment and method

The triaxial test system developed by Zheng and Huang is shown in Fig. 2[22, 23]. For this testing system, a hollow cylinder specimen with an inner radius $r_a$ and outer radius $r_b$ was placed in the triaxial test equipment while the inner and outer surfaces of specimens were loaded by two flexible airbags respectively. Using this airbags, the adjustable radial compressive stress and circumferential tensile stress can be produced consequently. A sketch of hollow cylinder specimen with dimensions and element with principle stresses are shown in Fig. 3.
Fig. 2 Loading structure schematic diagram of triaxial testing equipment.

Note: 1-loading rod, 2-ball hinge pin, 3-hemispherical head compressive(tensile)tip, 4-compressive(tensile) plate, 5-outer airbag cover, 6-outer airbag, 7-inner airbag, 8-specimen, 9-trachea, 10-outer airbag tray.

Fig. 3 A sketch of hollow cylinder specimen and the principle stresses with elements.

The output from 0MPa to 6MPa with the control precision of 0.01MPa can be obtained by those two airbags connected to the pressure control system, as shown in Fig.4. When the main switch is open, the air is compressed into the high pressure vessel by the booster pump with a compression proportion of 6:1. In such control system, two passages are designed in order to isolate.
the pressures from inner and outer airbags. However, it is observed that the booster pump works in an intermittent condition and the export pressure of booster pumps are unstable. Whereas, the pulsation of pressure insignificantly attenuated after the air enter the high pressure vessel and go through the high pressure valve while the pressure value is reduced. Thereafter the stable and reliable gas pressures can be obtained. The pressure reduced is measured with a high precision pressure gauge, pressure sensor, pressure relief valve and output valve. The function of measurement with the pressure sensor is to obtain the pressure using the electrical signals output with a computer. The outputs of pressure are also used to adjust the pressures in those two airbags. And the gas pressure is obtained with the high precision pressure gauges.

![Schematic diagram of pressure control system](image)

Fig. 4 Schematic diagram of pressure control system

Note: line 1-gas passage of inner airbag, line 2-gas passage of outer airbag, 1-main switch, 2-booster pump, 3-high pressure vessel, 4-high pressure valve, 5-pressure reducing valve, 6-precision pressure gauge, 7-pressure sensor, 8-pressure relief value, 9-output valve

The upper and lower surfaces of specimen are loaded through a rigid loading shaft of MTS material testing machine with axial tensile or compressive forces. When the axial force is less than 100kN, it is provided by the MTS landmark test system with the maximum load of 100KN. Then the triaxial tests of specimens are conducted on no less than three effective duplicates. However, when the axial force is close/more than 100kN, it is provided by the MTS civil structure test system with the maximum load of 750KN. Different from the frame structure of MTS landmark test system, the MTS civil structure test system is a suspended structure. Therefore, the axial loading should be guaranteed during the test process. Otherwise, the airbags with their components might be damaged. So, the triaxial tests of specimens are conducted on no less than two effective duplicates when MTS civil structure test system is adopted. It is obvious that the working condition in a three-dimensional unequal stress state can be generated to simulate the
complex stress state in asphalt concrete materials in the pavement structures. The axial stress, $\sigma_z$, radial stress, $\sigma_r$, and circumferential stress, $\sigma_\theta$, are determined as follows:

$$\sigma_z = \frac{P}{\pi (r_b^2 - r_a^2)}$$  \hspace{1cm} (1)$$

$$\sigma_r = \frac{r_b^2}{r_b^2 / r_a^2 - 1} P - \frac{1 - r_a^2 / r_b^2}{1 - r_a^2 / r_b^2} P_b$$  \hspace{1cm} (2)$$

$$\sigma_\theta = \frac{r_b^2 / r^2 + 1}{r_a^2 / r^2 - 1} P - \frac{1 + r_a^2 / r_b^2}{1 - r_a^2 / r_b^2} P_b$$  \hspace{1cm} (3)$$

where $P$ in Eq. (1) is the axial failure load; $r$ is the distance between observing point in the specimen to the symmetric center of the hollow cylindrical specimen; $P_a$ and $P_b$ are the inner and outer pressures; $r_a$ and $r_b$ are the inner and outer radius of the hollow cylinder specimen, respectively. According to the elastic mechanics, $\sigma_r$, $\sigma_\theta$, and $\sigma_z$ are the principal stresses, which can be sorted by numerical values (tensile stress is positive and compressive stress is negative) with principal stresses $\sigma_1$, $\sigma_2$, and $\sigma_3$, respectively.

2.3. Description of the failure criterion under three dimensional stress state

As shown in Fig. 5, in the principal stress space, the isoclinic line (line $n$) has the same direction angle with the principal stress axes $\sigma_1$, $\sigma_2$, $\sigma_3$, and perpendicular to the isoclinic plane. The projection of principal axes on the isoclinic plane are generally represented by axes $\sigma'_1$, $\sigma'_2$, $\sigma'_3$, and the intersection angles among two of them are 120°. The projection of any point $P$ in the isoclinic line is the octahedral normal stress $\sigma_{oct}$. Its projection in the isoclinic plane is the octahedral shear stress $\tau_{oct}$. The direction is represented by lode angle $\theta$ [24,25]. All of these parameters are defined as follows:

$$\sigma_{oct} = (\sigma_1 + \sigma_2 + \sigma_3) / 3 = \sigma_m$$  \hspace{1cm} (4)$$

$$\tau_{oct} = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} / 3$$  \hspace{1cm} (5)$$

$$\theta = \arccos \left[ (2\sigma_1 - \sigma_2 - \sigma_3) / (3\sqrt{2}\tau_{oct}) \right]$$  \hspace{1cm} (6)$$
All points for material failure can constitute a continuous surface which is called the failure envelope surface, as shown in Fig.6. The intersection curve of failure envelope surface and isoclinic plane is called the failure envelope curve. Failure envelope curves are closed. Their sizes change with the change of the average stress $\sigma_m$ ($\sigma_m = \sigma_{oct}$) and their shapes are similar.

For an isotropic material, the axles $\sigma'_1, \sigma'_2, \sigma'_3$ on the isoclinic plane are the symmetric axles of the failure envelope curve. If the strength envelope curve from 0~60° can be obtained, the whole strength envelope can be achieved. To obtain the failure envelope curve, the strength test should be done at the same $\sigma_m$, and the lode angle should be changed from 0°~60° gradually.

As shown in Fig. 7(a), the compressive meridian is a curve on the failure envelope surface which is formed by all the points with a 60° lode angle, and can be obtained by the strength test under different average stresses $\sigma_m$, as well as lode angle $\theta = 60^\circ$. Likewise, the tensile meridian can be gained when the lode angle is $0^\circ$, as shown in Fig.7(b).
2.4. Testing conditions and procedures

2.4.1 Testing conditions

For a triaxial test, 15°C was chosen as the testing temperature and the axial loading rate was 2 mm/min. The testing conditions are the same as the uniaxial compressive test in the current specification of *Standard Test Methods of Bitumen and Bituminous mixtures for Highway Engineering* (JTG E20-2011) in China. Moreover, the dimensions of the hollow cylinder specimens were selected by coring solid cylinder specimens with a dimension of 100 mm × 50 mm × 100 mm (inner radius × outer radius × length). The length and diameter of specimens are also the same as the standard uniaxial compressive test in China. So, it is easy to verify the accuracy of test results. The specimens with the two ends polished were placed into a temperature control chamber for more than 6 hours. The lubricant oil was smeared on the specimen surfaces and loading plates to reduce the friction for the triaxial compressive test. The epoxy resin was smeared on the specimen surfaces and loading plates firmly bonded for the triaxial tensile test.

2.4.2 Test procedures

In the octahedral stress space, the failure envelope curve, tensile meridian and compressive meridian can be used to describe the strength criterion under three-dimensional stress states as mentioned above [24]. The test procedures are as follows [22, 23]:

1. Determine the failure envelope curve. The plane tensile and compressive/axial tensile tests were fulfilled with a constant average stress and the lode angles from 0° ~ 60° changed gradually. For this test, the transverse stress, that is $\sigma_2$ and $\sigma_3$, increased up to the pre-determined values proportionally first by applying pressure by the inner airbag, and thereafter the axial tensile
stress, $\sigma_1$, was inputted by MTS material testing machine until the failure of specimen. The stress path of failure envelope curve is shown in Fig. 8.

![Stress path of failure envelope curve](image)

Fig. 8 Stress path of failure envelope curve.

(2) Determine the tensile meridian. The tensile meridian can be obtained by the triaxial tensile test, that is a strength test with different average stresses, $\sigma_m$, while the lode angle $\theta$ was equal to $0^\circ$. In this test, the transverse stresses $\sigma_2$ and $\sigma_3$ ($\sigma_2 = \sigma_3$) increase to the pre-determined values first by applying synchronously equal pressures with inner and outer airbags, and thereafter the axial tensile stress, $\sigma_1$, was applied by using MTS until the specimen breaks. The stress path of tensile meridian is shown in Fig. 9.

![Stress path of tensile meridian](image)

Fig. 9 Stress path of tensile meridian.

(3) Determine the compressive meridian. The compressive meridian can be obtained by the triaxial compressive test, i.e. the strength test under different average stresses, $\sigma_m$, when the lode angle $\theta$ was equal to $60^\circ$. For this test, the transverse stresses $\sigma_1$ and $\sigma_2$ ($\sigma_1 = \sigma_2$) were applied to the pre-determined values first by applying synchronously equal pressures with inner and outer airbags, and then the axial compressive stress $\sigma_3$ was exerted by MTS until the specimen breaks. The stress path of compressive meridian is shown in Fig. 10.
3. Failure criterions

3.1. Nonlinear failure criterion under complex stress state

The results of triaxial compressive/tensile tests, the plane tensile and compressive/axial tensile tests are presented in Appendix for reference [22,23]. Based on the test results, the failure criteria of asphalt mixtures under three-dimensional stress states are given as follows:

Tensile meridian:

\[
\tau_{oc}^t / \sigma_c = 0.085 - 0.57 \sigma_{oc} / \sigma_c - 0.588(\sigma_{oc} / \sigma_c)^2 R^2 = 0.96 \tag{7}
\]

Compressive meridian:

\[
\tau_{oc}^c / \sigma_c = 0.13 - 0.967 \sigma_{oc} / \sigma_c - 0.17(\sigma_{oc} / \sigma_c)^2 R^2 = 0.98 \tag{8}
\]

Failure envelope curve:

\[
\tau_{oc} (\theta) = \tau_{oc}^t - (\tau_{oc}^t - \tau_{oc}^c) \sin^6(3\theta / 2) R^2 = 0.94 \tag{9}
\]

where \(\sigma_c\) is the uniaxial compressive strength; \(\sigma_{oc}\) is the octahedral normal stress, \(\tau_{oc}\) is the octahedral shear stress; \(\theta\) is the lode angle; \(\tau_{oc}^t\) is the octahedral shear stress in the tensile meridian; \(\tau_{oc}^c\) is the octahedral shear stress in the compressive meridian.

These failure criterions can be verified with the uniaxial tensile strength test, uniaxial compressive strength test as well as the conventional triaxial test [22]. Moreover, the criterions are suitable for calculating the resistances under various stress states.

For the triaxial tensile test, the plane tensile and compressive/axial tensile test specimens failures are shown in Fig. 11. For triaxial compressive test, the specimens are broken mainly due to the shear failure shown in Fig. 12 [22,23].
Since there are many free parameters in this failure criterion, the equation of criterion becomes complicated. In addition, the confining pressures in the pavement structure are relatively small and usually less than 1MPa. In order to simulate the real multi-axial stress conditions in the pavement structures, the tensile meridian could be approximated with a quadratic polynomial, and the tensile and compressive meridians must intersect at the same point when $\tau_{oct} = 0$ [24]. It is assumed that the strength envelope in the region of $0^\circ$–$60^\circ$ is interpolated with the sine function. Therefore, the tensile meridian, compressive meridian and failure envelope curves can be represented, in Fig.13,14 [22,23], as

Tensile meridian:
\[
\frac{\tau^t_{oct}}{\sigma_c} = a - b\sigma_{oct} / \sigma_c - c(\sigma_{oct} / \sigma_c)^2 \quad R^2 = 0.95
\]  

(10)

Compressive meridian:
\[
\frac{\tau^c_{oct}}{\sigma_c} = m\left[a - b\sigma_{oct} / \sigma_c - c(\sigma_{oct} / \sigma_c)^2\right] \quad R^2 = 0.97
\]  

(11)

Failure envelope curve:
\[
\tau_{oct}(\theta) = \tau^t_{oct} - (\tau^t_{oct} - \tau^c_{oct}) \sin^a(3\theta / 2) \quad R^2 = 0.95
\]  

(12)

where $a, b, c, m$ and $n$ are model parameters as shown in Table 1.

Table 1 Model parameters of the nonlinear failure criterion

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$m$</th>
<th>$n$</th>
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<td>0.56</td>
<td>0.01</td>
<td>1.49</td>
<td>7</td>
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</table>
3.2. Simplified linear failure criterion under complex stress state

In engineering analysis, it is difficult to establish nonlinear strength criterions of asphalt mixtures for a pavement structure design. Because different mixtures have different failure envelope surfaces and engineering design department does not possess all testing conditions to establish the failure envelope surface, the nonlinear failure envelope surface should be simplified for the sake of analysis convenience in engineering design.

Usually, the normal stress $\sigma_{oc}$ is less than one-third of the uniaxial compressive strength $\sigma_c$ in pavement structures. Therefore, the test results can be fitted linearly in general stress range. The failure criterion established by linear fitting is found to be safer than the nonlinear fitting. Therefore, the criterion of strength could be simplified as a linear envelope which is called as engineering model of strength criterion. Assuming that the engineering model is linear as below

Tensile meridian:
\[
\frac{\tau'}{\sigma_c} = A - B \frac{\sigma_{oct}}{\sigma_c} \quad R^2 = 0.95 \quad (13)
\]

Compressive meridian:

\[
\frac{\tau'}{\sigma_c} = M \left[ A - B \frac{\sigma_{oct}}{\sigma_c} \right] \quad R^2 = 0.96 \quad (14)
\]

Failure envelope curve:

\[
\tau_{oct}(\theta) = \tau'_{oct} - (\tau'_{oct} - \tau'_{oct}) \frac{3\theta}{\pi} \quad R^2 = 0.83 \quad (15)
\]

where \( A, B, \) and \( M \) are model parameters as shown in Table 2.

<table>
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<th>( A )</th>
<th>( B )</th>
<th>( M )</th>
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<td>Fitting results</td>
<td>0.074</td>
<td>0.59</td>
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Fig. 15 Linear compressive meridian and tensile meridian.

Fig. 16 Linear Failure envelope curve in \( \pi \) plane (\( \sigma_m=0.286 \) MPa)
The comparison between the nonlinear strength model of quadratic polynomial and the linear engineering model of asphalt mixtures in \( \sigma_{oct} - \tau_{oct} \) space is shown in Fig. 17.

![Comparison of failure criterions in the \( \sigma_{oct} - \tau_{oct} \) space.](image)

Seeing from Fig. 16 and Fig. 17, it is clear that the nonlinear failure envelope of asphalt mixtures transformed from the cone which is similar to a shield into a pyramid in the \( \sigma_{oct} - \tau_{oct} \) space due to the linear regression. Therefore, it is more convenient for asphalt pavement design.

By using the same technique, a simplified strength model under three-dimensional stress states can be established by triaxial compressive and triaxial tensile tests. It is not difficult to establish the failure envelope surface for the design of pavement structures with the consideration of the effect of each stress component to the failure analysis in asphalt pavements. Furthermore, the strength analysis process of the asphalt pavements under three-dimensional stress states can be carried out with following steps:

1. The determination of fatigue strength reduction coefficient \( K \) of each structure layer based on fatigue tests. The simplification of the strength criterions of each structural layer under three-dimensional stress states based on triaxial compressive/tensile tests;

2. The stress state analysis at any points of pavement under vehicle/thermal loads by layered elastic half space modeling;

3. The determination of octahedral normal stress \( \sigma_{oct} \), shear stress \( \tau_{oct} \), and load angle \( \theta \) at any point of pavement;

4. The evaluation of stress components to the AC-13 layer of pavement structure by

\[
\tau_{oct}(\theta) \leq \left[ \frac{t_{oct}^f - (t_{oct}^f - t_{oct}^c)3\theta / \pi}{K} \right] / K \quad (16)
\]

Where \( K \) can be taken as 1;

5. Carry out the strength design of other structural layers of asphalt pavement according to the
above steps. So, the strength design of asphalt pavement can be completed.

4. Conclusions and discussion

The nonlinear failure criterions were proposed based on the test results of AC-13C asphalt mixture under three dimensional stress states. It was observed that the failure strength and failure mode of AC-13C asphalt mixtures were affected significantly by the stress states. The nonlinear failure criterions of asphalt mixtures under three-dimensional stress states were validated with triaxial compressive/tensile tests and plane tensile/compressive/axial tensile tests. The difference between the tensile and compressive strength was shown clearly. The criterions proposed in this study are suitable to determine the resistance under various stress state.

The simplified linear failure criterions for engineering design were also proposed based on the triaxial compressive/tensile tests. These criterions are in a simple form and easy to use in asphalt pavement structural design. Moreover, this technique can be extended semi-rigid base. Based on these investigations, a new method to carry out the strength design of asphalt pavement under the three-dimensional stress state is presented with the consideration of the effect of each stress components to the failure analysis in asphalt pavements.

Although this study has many advantages, the triaxial test should be fulfilled for different asphalt concrete materials in order to establish more reliable three-dimensional failure criterions. The further study on the strength design method under three-dimensional stress state should be carried out before it is applied to engineering practice.

Acknowledgments

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Appendix

A: Results of triaxial compressive tests

| $\sigma_1$/MPa | $\sigma_2$/MPa | $\sigma_3$/MPa | Average value | $\sigma_{oct}/\sigma_c$ | $\tau_{oct}/\sigma_c$ | $\theta/$
|----------------|----------------|----------------|-----------------|----------------------|---------------------|-------|

15
### B: Results of triaxial tensile tests

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C: Results of plane tensile and compressive/axial tensile tests
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References:


[22] Tuo Huang. Study on triaxial test method and strength theory of asphalt mixture, School of traffic and transportation engineering, Changsha University of Science & Technology, Changsha, China. 2013.
