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

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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 statesaffect significantlythe ultimatefailure strengthof AC-13 asphaltmixture and the failure modesare mainly representedboth forthe tensile failureand shear failure.The nonlinear strength criterion,as well as a linear engineering modelof 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 underthe three-dimensional stress state was given to considerthe 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 pavementwill 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 calculatethe mechanical responses of pavements.The theories of strength withthe maximum tensile stressandmaximum tensile strainare used as the failurecriterions 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 materialsunder 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 envelopin $I_1-\sqrt{J_2}$ space based on the failurestrength results ofthe 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 variantspace.Nevertheless, three-dimensionalunequal stress state was not established andthe failure criterion was not verified bytruetriaxial results ina 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℃ with a self-developed simplified triaxial machine, the tested data of strength on the π-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 toestablish the strength criterion of asphalt mixturesunderthree-dimensional stress states, in which the effects of triaxial tensilestrength should be considered.So, the main objective of this paper is to establishthefailure criterions under three-dimensional stress states. Moreover,anew design method to carry out the strength designof asphalt pavementswas presented under three-dimensional stress states.

2. Test methods and specimen preparation

2.1. Materialsand specimens

In order to evaluate the mechanicalbehavior of asphalt mixturesunder three dimensional stress states, the representative AC-13Casphalt mixturewhich were widely used in China were tested. As shown in Fig.1, theaggregate particles of AC-13Casphaltmixture 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 SBSmodified bitumenwas used as the binder and the basaltwas usedas aggregates.

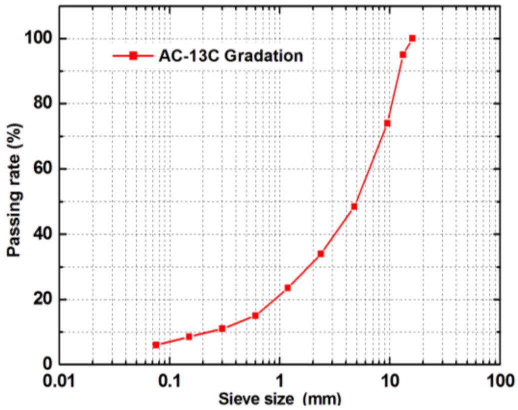


Fig1. Gradation curve of AC-13C asphalt mixture.

To ensurethe consistency of specimen in the triaxial test, the gyratory compactor was used to prepare cylindricalspecimens with102mmin heightand 100mmin diameter.The bitumen-aggregates weight ratio of 5.2% was selected withthe airvoid content forthesespecimens of 4.5% ± 0.5%. Moreover, the tested specimens were obtainedby sawing the two ends of original specimens in the water with a diamond bladeupto the height of 100mm.

2.2. Test equipment and method

The triaxialtest system developed byZhengand 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 wasplaced in the triaxialtest equipment while the inner and outer surfaces of specimenswere loaded by two flexible airbagsrespectively. Using this airbags, the adjustable radial compressive stress and circumferential tensile stress can be producedconsequently. A sketch of hollow cylinder specimen with dimensions and element with principle stresses are shown in Fig.3.

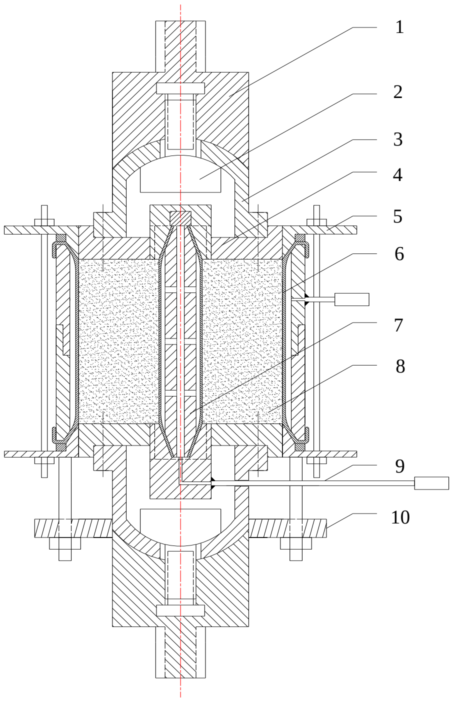


Fig. 2Loading structure schematic diagram of triaxial testing equipment.

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

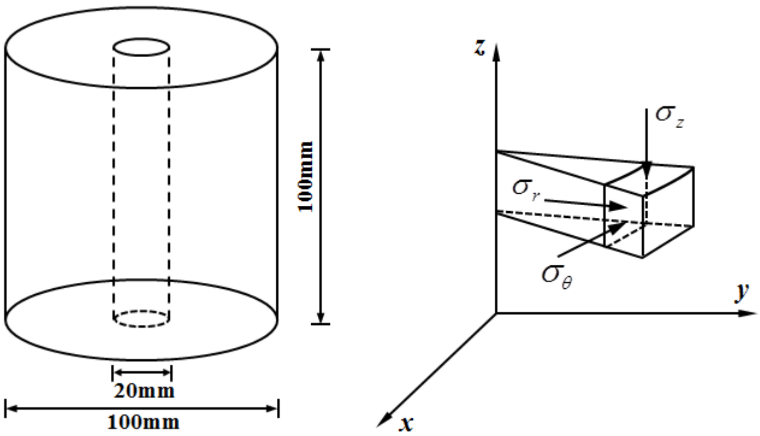


Fig. 3A sketch of hollow cylinder specimen and the principle stresses with elements.

The output from 0MPa to 6MPa with the control precision of 0.01MPa can be obtained by those twoairbags connected to the pressure control system, as shown in Fig.4. Whenthe main switch is open, the air iscompressed intothe high pressure vessel by the booster pumpwith a compressionproportion of 6:1. In such control system, two passagesare 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 issignificantly attenuated after the air enter the high pressure vessel andgo through the high pressure valve while the pressure value is reduced.Thereafter the stable and reliable gas pressures can be obtained. The pressure reducedis measured witha highprecision pressure gauge, pressure sensor, pressure reliefvalve and output valve.The function of measurement with the pressure sensor is to obtain the pressure usingthe electrical signals output with a computer. The outputs of pressure arealso used toadjust the pressuresinthose two airbags.And the gas pressure is obtained with the high precision pressure gauges.

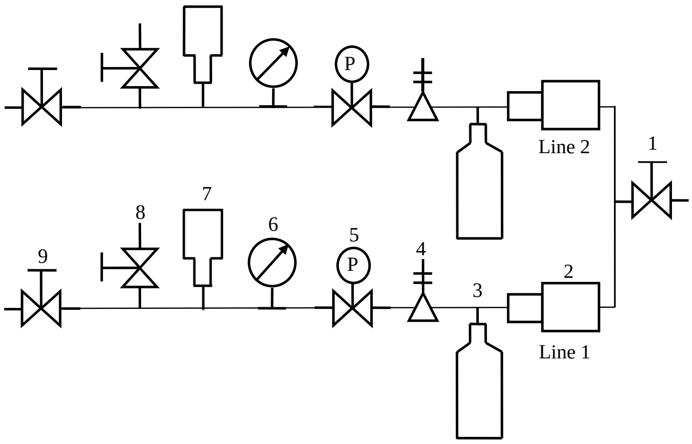


Fig.4 Schematic diagram of pressure control system

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, σ_z, radial stress, σ_r, and circumferential stress, σ_θ, are determined as follows:

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

$$\sigma_r = -\frac{r_b^2/r^2 - 1}{r_b^2/r_a^2 - 1}P_a - \frac{1 - r_a^2/r^2}{1 - r_a^2/r_b^2}P_b \quad (2)$$

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

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 radiusof the hollow cylinder specimen, respectively. According to the elastic mechanics, σ_r, σ_θ and σ_z are the principal stresses, which can be sorted by numerical values (tensile stress is positive and compressive stress is negative) with principal stresses σ_1, σ_2 and σ_3, respectively.

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

As shown in Fig.5, in theprincipal stress space, the isoclinic line (line *n*) has the same direction angle with the principal stress axles $\sigma_1, \sigma_2, \sigma_3$, andperpendicular to the isoclinic plane.The projection of principal axles on the isoclinic plane are generally represented by axles σ_1', σ_2', σ_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 σ_{oct}. Its projection in the isoclinic plane is the octahedral shear stressτ_{oct}. The direction is represented by lode angle θ [24,25].All of these parametersare defined as follows:

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

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

$$\theta = \arccos\left[(2\sigma_1 - \sigma_2 - \sigma_3)/(3\sqrt{2}\tau_{oct})\right] \quad (6)$$

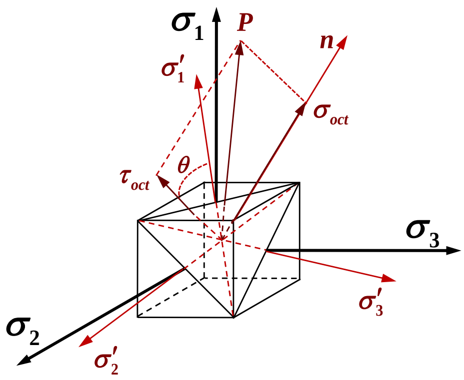


Fig.5Octahedral normal stress, octahedral shear stress and lode angle

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 σ_m(σ_m= σ_{oct}) and their shapes are similar.

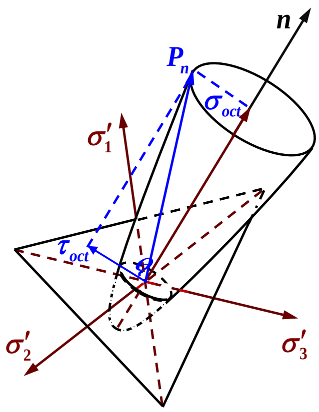
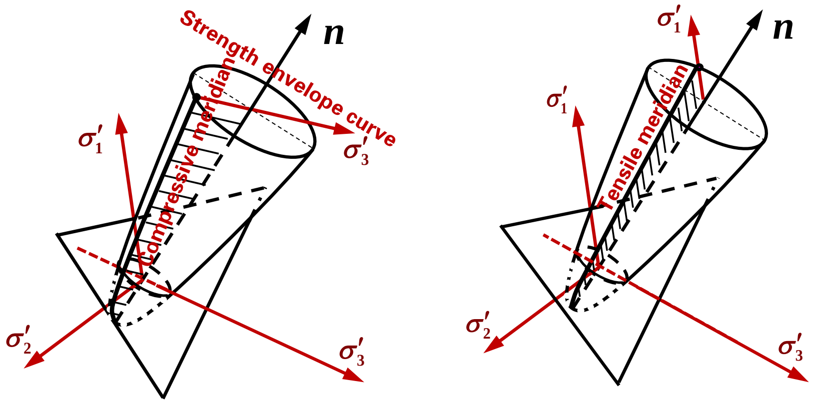


Fig.6Failure envelope surface

For an isotropic material, the axles $\sigma_1^{'}, \sigma_2^{'}, \sigma_3^{'}$ on the isoclinic plane arethe 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 σ_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 σ_m, as well as lode angleθ=60°. Likewise,the tensile meridian can be gained when the lode angle is 0°, as shown in Fig.7(b).



(a)Compressivemeridian and failure envelope curve; (b)Tensile meridian

Fig.7Compressive,tensile meridian and failure envelope curves

2.4. Testingconditions and procedures

2.4.1 Testing conditions

For a triaxialtest,15℃was chosenas the testing temperature and the axial loading rate was 2mm/min. Thetesting conditions arethe same asthe uniaxial compressive test inthe 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 specimenswere selected by coring solid cylinder specimens with a dimension of 10mm×50mm×100mm (inner radius × out 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 morethan 6 hours. Thelubricant oil was smearedon 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 platestofirmly bonded for the triaxial tensile test.

2.4.2 Test procedures

In the octahedral stress space, the failure envelope curve, tensile meridian and compressive meridiancan be used todescribethe strength criterion under three dimensional stress states as mentioned above[24].The test proceduresare as follows[22,23]:

(1)Determine the failure envelope curve.The plane tensile and compressive/axial tensile testswere fulfilled witha constant average stress and the lodeangles from 0°~60° changed gradually.For this test, the transverse stress, that is σ_2 and σ_3, increasedup to the pre-determined valuesproportionallyfirst by applying pressure by the inner airbag,and thereafter the axial tensile stress, σ_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.

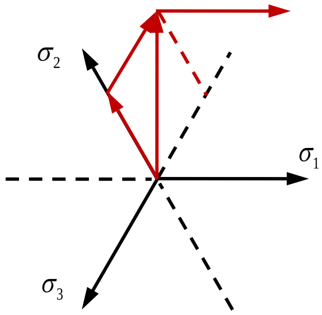


Fig.8Stress path of failure envelope curve.

(2) Determine the tensile meridian. The tensile meridian can be obtained by the triaxialtensile test, that is a strength test with different average stresses,σ_m, whilethe lode angleθ was equal to 0°.In this test, the transverse stresses σ_2 and σ_3 ($\sigma_2 = \sigma_3$) increase to the pre-determinedvalues first by applying synchronouslyequal pressures with inner and outer airbags, and thereafter the axial tensile stress, σ_1 ,was appliedby using MTS until the specimen breaks.The stress path of tensile meridian is shown in Fig. 9.

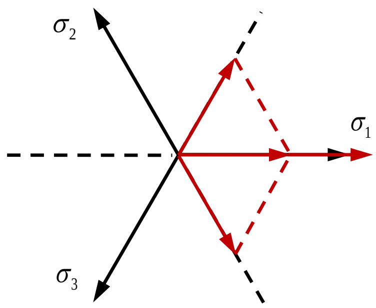


Fig.9 Stress path of tensile meridian.

(3) Determine the compressive meridian. The compressive meridian can be obtained by the triaxialcompressive test, i.e. thestrength test under different average stresses,σ_m, when the lode angle θ was equal to 60°.For this test,the transverse stresses σ_1 and σ_2 ($\sigma_1 = \sigma_2$)were applied to the pre-determined values first by applyingsynchronously equal pressures with inner and outer airbags,and then theaxialcompressive stress σ_3 was exerted by MTS until the specimen breaks.The stress path of compressive meridian is shown in Fig.10.

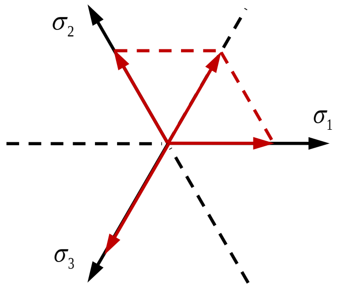


Fig.10 Stress path of compressive meridian.

3. Failurecriterions

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 failurecriterionsof asphalt mixturesunder three-dimensional stress statesare given asfollows:

Tensile meridian:

$$\tau_{oct}^{t}/\sigma_c = 0.085 - 0.57\sigma_{oct}/\sigma_c - 0.588(\sigma_{oct}/\sigma_c)^2 \quad R^2 = 0.96 \quad (7)$$

Compressive meridian:

$$\tau_{oct}^{c}/\sigma_c = 0.13 - 0.967\sigma_{oct}/\sigma_c - 0.17(\sigma_{oct}/\sigma_c)^2 \quad R^2 = 0.98 \quad (8)$$

Failure envelope curve:

$$\tau_{oct}(\theta) = \tau_{oct}^{t} - (\tau_{oct}^{t} - \tau_{oct}^{c})\sin^6(3\theta/2) \quad R^2 = 0.94 \quad (9)$$

where σ_c is the uniaxial compressive strength; σ_{oct} is the octahedral normal stress, τ_{oct} isthe octahedral shear stress; θ is the lode angle; τ_{oct}^{t} is the octahedral shear stress in the tensile meridian; τ_{oct}^{c} is the octahedral shear stress in the compressive meridian.

These failure criterions can beverified withthe 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 inFig.11.For triaxial compressive test, the specimens are broken mainly due tothe shear failure shown inFig. 12 [22,23].

Fig.11Tensile failure.Fig.12Shear failure.

Sincethere 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 τ_{oct} =0 [24]. It is assumed that the strength envelope in the region of 0°~ 60° 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:

$$\tau_{oct}^{t} / \sigma_c = a - b\sigma_{oct} / \sigma_c - c(\sigma_{oct} / \sigma_c)^2 \qquad R^2 = 0.95 \tag{10}$$

Compressive meridian:

$$\tau_{oct}^{c} / \sigma_c = m\left[a - b\sigma_{oct} / \sigma_c - c(\sigma_{oct} / \sigma_c)^2 \right] \qquad R^2 = 0.97 \tag{11}$$

Failure envelope curve:

$$\tau_{oct}(\theta) = \tau_{oct}^{t} - (\tau_{oct}^{t} - \tau_{oct}^{c}) \sin^n(3\theta / 2) \qquad R^2 = 0.95 \tag{12}$$

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

Table 1Modelparameters of the nonlinear failure criterion

Modelparameters	*a*	*b*	*c*	*m*	*n*
Fitting results	0.085	0.56	0.01	1.49	7

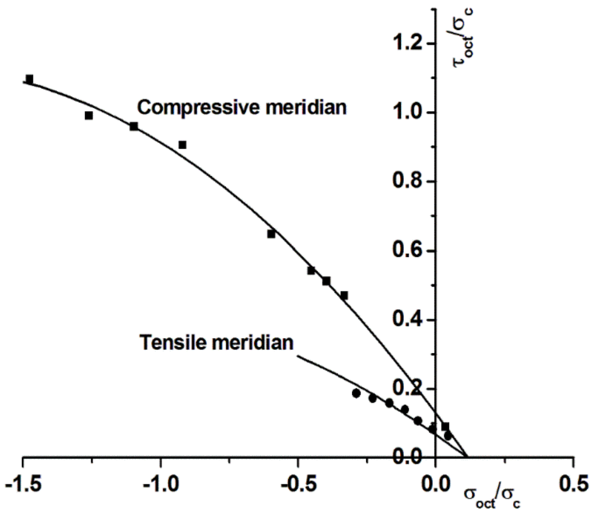


Fig.13Nonlinear compressive meridian and tensile meridian.

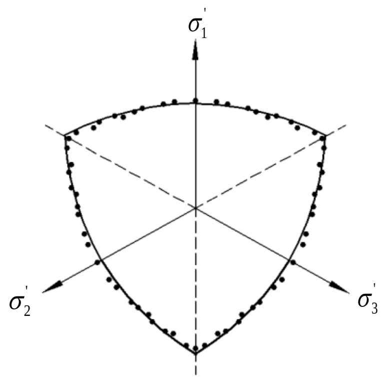


Fig.14 Nonlinear failure envelope curve in $\pi-$plane (σ_m=0.286MPa).

3.2.Simplifiedlinear failure criterionunder complex stress state

In engineering analysis, it is difficult to establishnonlinear 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 σ_{oct} is less than one-thirdof the uniaxial compressivestrength σ_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 saferthan 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 theengineering model is linearas below

Tensile meridian:

$$\tau_{oct}^{t} / \sigma_c = A - B\sigma_{oct} / \sigma_c \qquad R^2 = 0.95 \qquad (13)$$

Compressive meridian:

$$\tau_{oct}^{c} / \sigma_c = M\left[A - B\sigma_{oct} / \sigma_c\right] \qquad R^2 = 0.96 \qquad (14)$$

Failure envelope curve:

$$\tau_{oct}(\theta) = \tau_{oct}^{t} - (\tau_{oct}^{t} - \tau_{oct}^{c})3\theta / \pi \qquad R^2 = 0.83 \qquad (15)$$

where *A*,*B* and *M* are model parametersas shown in Table 2.

Table 2.Model parametersof the linear engineering model

Modelparameters	*A*	*B*	*M*
Fitting results	0.074	0.59	1.65

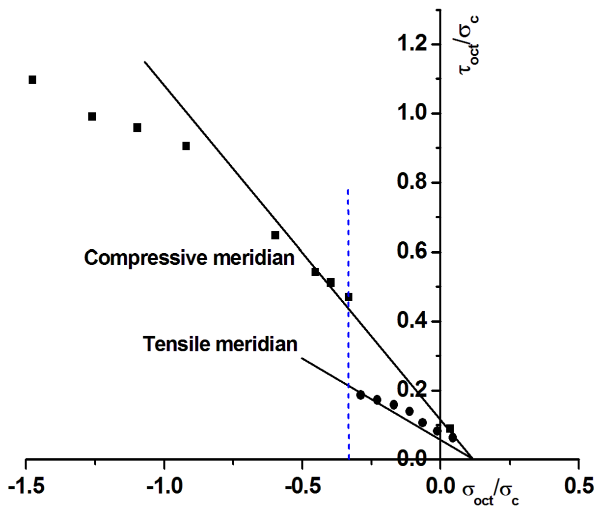


Fig.15Linear compressive meridian and tensile meridian.

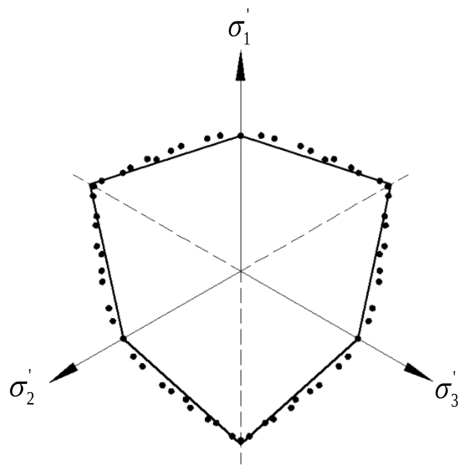
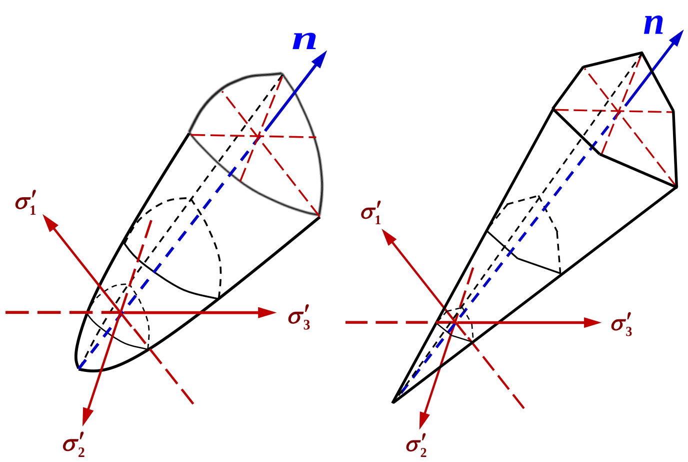


Fig.16 Linear Failure envelope curvein π — plane (σ_m=0.286MPa)

The comparison between the nonlinear strength model of quadratic polynomial and the linear engineering model of asphalt mixturesin $\sigma_{oct}-\tau_{oct}$ spaceis shown in Fig. 17.



(a)Nonlinear failure criterion (b)Linear failure criterion

Fig.17Comparison of failure criterions in the $\sigma_{oct}-\tau_{oct}$ space.

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 stressstates can be established by triaxial compressive and triaxialtensile tests.It is not difficultto establish the failure envelope surface for the design of pavement structures withthe consideration of the effect of each stress components to the failure analysis inasphalt pavements.Furthermore, the strength analysis process of the asphalt pavementsunder three-dimensional stress states can be carried out withfollowing steps:

(1)The determination offatigue 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 statesbased 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 σ_{oct}, shear stress τ_{oct} and load angle θ at any point of pavement;

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

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

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

σ_1 /MPa	σ_2 /MPa	σ_3 /MPa	Average value	$\frac{\sigma_{oct}}{\sigma_c}$	$\frac{\tau_{oct}}{\sigma_c}$	θ /°

0	0	-6.986		-0.326	0.462	60
0	0	-7.263	-7.135	-0.339	0.480	60
0	0	-7.156		-0.334	0.473	60
-0.250	-0.250	-7.910	-7.989	-0.393	0.506	60
-0.250	-0.250	-8.250		-0.409	0.529	60
-0.250	-0.250	-7.806		-0.388	0.499	60
-0.500	-0.500	-8.766		-0.456	0.546	60
-0.500	-0.500	-8.810	-8.679	-0.458	0.549	60
-0.500	-0.500	-8.460		-0.442	0.526	60
-1.000	-1.000	-10.265		-0.573	0.612	60
-1.000	-1.000	-11.089	-10.776	-0.611	0.667	60
-1.000	-1.000	-10.973		-0.606	0.659	60
-2.000	-2.000	-16.239	-15.652	-0.946	0.941	60
-2.000	-2.000	-15.064		-0.891	0.863	60
-3.000	-3.000	-17.124	-17.451	-1.080	0.933	60
-3.000	-3.000	-17.777		-1.111	0.976	60
-4.000	-4.000	-18.636	-19.018	-1.244	0.967	60
-4.000	-4.000	-19.400		-1.280	1.017	60
-5.000	-5.000	-21.134	-21.574	-1.455	1.066	60
-5.000	-5.000	-22.014		-1.496	1.124	60

B: Results of triaxialtensile tests

σ_1 /MPa	σ_2 /MPa	σ_3 /MPa	Average value	$\frac{\sigma_{oct}}{\sigma_c}$	$\frac{\tau_{oct}}{\sigma_c}$	θ /°
0.925	0.000	0.000		0.043	0.061	0
0.981	0.000	0.000	0.952	0.046	0.065	0
0.950	0.000	0.000		0.044	0.063	0
0.739	-0.5	-0.5		-0.012	0.082	0
0.808	-0.5	-0.5	0.754	-0.009	0.086	0
0.716	-0.5	-0.5		-0.013	0.080	0
0.602	-1.000	-1.000		-0.065	0.106	0
0.608	-1.000	-1.000	0.615	-0.065	0.106	0
0.635	-1.000	-1.000		-0.064	0.108	0

0.568	-1.500	-1.500		-0.114	0.137	0
0.575	-1.500	-1.500	0.589	-0.113	0.137	0
0.624	-1.500	-1.500		-0.111	0.140	0
0.315	-2.000	-2.000		-0.172	0.153	0
0.387	-2.000	-2.000	0.391	-0.169	0.158	0
0.471	-2.000	-2.000		-0.165	0.163	0
0.062	-2.500	-2.500		-0.231	0.169	0
0.128	-2.500	-2.500	0.112	-0.228	0.174	0
0.147	-2.500	-2.500		-0.227	0.175	0
-0.091	-3.000	-3.000		-0.285	0.192	0
-0.196	-3.000	-3.000	-0.172	-0.289	0.185	0
-0.230	-3.000	-3.000		-0.291	0.183	0
-0.787	-4.000	-4.000		-0.411	0.212	0
-0.716	-4.000	-4.000	-0.726	-0.407	0.217	0
-0.675	-4.000	-4.000		-0.405	0.220	0
-1.351	-5.000	-5.000		-0.530	0.241	0
-1.435	-5.000	-5.000	-1.362	-0.534	0.236	0
-1.300	-5.000	-5.000		-0.528	0.244	0

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

σ_1 /MPa	σ_2 /MPa	σ_3 /MPa	Average value	$\frac{\sigma_{oct}}{\sigma_c}$	$\frac{\tau_{oct}}{\sigma_c}$	θ /°
0.947	0.108	-0.100		0.045	0.063	10.8
0.908	0.108	-0.100	0.945	0.043	0.061	11.3
0.980	0.108	-0.100		0.046	0.066	10.5
0.912	0.163	-0.150		0.043	0.062	16.7
0.925	0.163	-0.150	0.931	0.044	0.063	16.4
0.955	0.163	-0.150		0.045	0.065	15.9
0.885	0.271	-0.250		0.042	0.065	27.3
0.943	0.271	-0.250	0.902	0.045	0.068	25.8
0.879	0.271	-0.250		0.042	0.065	27.5
0.916	0.314	-0.290		0.044	0.069	30.1
0.887	0.314	-0.290	0.884	0.043	0.067	30.9
0.849	0.314	-0.290		0.041	0.065	32.0

0.780	0.379	-0.350		0.038	0.066	39.5
0.851	0.379	-0.350	0.850	0.041	0.069	37.0
0.918	0.379	-0.350		0.044	0.073	34.9
0.868	0.433	-0.400		0.042	0.074	40.3
0.893	0.433	-0.400	0.846	0.043	0.075	39.5
0.776	0.433	-0.400		0.038	0.069	43.5
0.834	0.509	-0.470		0.041	0.078	46.1
0.820	0.509	-0.470	0.819	0.040	0.077	46.6
0.802	0.509	-0.470		0.039	0.076	47.3
0.777	0.542	-0.500		0.038	0.078	50.0
0.659	0.542	-0.500	0.771	0.033	0.073	54.7
0.876	0.542	-0.500		0.043	0.082	46.5
0.695	0.650	-0.600		0.035	0.084	58.2
0.672	0.650	-0.600	0.746	0.034	0.083	59.1
0.871	0.650	-0.600		0.043	0.091	52.0
0.721	0.704	-0.65		0.036	0.090	59.4
0.687	0.704	-0.65	0.704	0.035	0.089	60.6
0.703	0.704	-0.65		0.035	0.089	60.0

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