

## Research about mechanics theory and damage mechanism of asphalt pavement design

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**Abstract:** Asphalt pavement is the main pavement pattern in China. There have been a serious of achievements over the past decades in mechanics theory and damage mechanism of asphalt pavement. Based on the above two aspects in asphalt pavement design, this paper provides a detailed overview of the application of mechanic theory, evolution of constitutive relation, numerical analysis and experimental study.

### Introduction

Asphalt pavement plays a significant role in road pavement in China, accounting for above 75% of the total highway. Unfortunately, as the development of road transportation, Great changes have happened in road transportation structure. For example, the characteristics of “heavy trucks, high flow and channel traffic” have appeared in road transportation in resent years, which have leded to pavement early damage with varying degree. As a result, many aspects, such as road service life, service level, operational efficiency, traffic safety, environment protection and road management, have been impacted by this phenomenon.

The study about the design philosophy, design method and damage mechanism in asphalt pavement design have attracted scholars’ and engineers’ attention in the past decade. A serious of studies in this field have been lanchd and many achievements have been obtained. This paper aims to outline the researches of mechanics theory and damage mechanism of asphalt pavement from the aspects of mechanic theory, material constitutive relation, numerical analysis and experimental research.

### Study of mechanic theory and damage mechanism in asphalt pavement design

The asphalt pavement design theory is closely related to mechanic theory. The asphalt pavement design has gone through the process from apparent phenomenon to stress mechanism analysis. In other words, the process is from the traditional empirical method to simple strength theory, and then to the current modern mechanics.

#### Traditional empirical method

In early days, based on the survey data of different road type, empirical formula and method were summarized through the analysis of data collected. Then, the life of asphalt pavement could be predicted based on pavement structure damage with the empirical formula obtained. After the analysis of asphalt pavement structure with currently knowledge, the pavement design methods were appropriately proposed.

#### The application of strength theory

Material strength theory has been widely used in early and modern asphalt pavement design duo to asphalt pavement crack, rutting and other damage phenomena. For example, in current rigid pavement design, the max stress at the bottom of board is used to check the strength with flexural strength of trabecular as a comparison standard. In flexible pavement design in China, the same strength theory is used for checking the bottom of asphalt concrete layer in the spring melt. The max

strain at the bottom of flexible pavement as checking standard is used by Royal Dutch Shell method. The max strain energy method is appropriate to check the brittle cracking at the bottom of pavement, as well as the compress soil under the pavement. Tensile pressure with vary performance is considered in Moore strength. So it can be applied for the road surface damage analysis duo to shear slip and grass or based strength checking. [1]

Strength theory and material strength indicator is determined by a variety of tests and field data. It is highly related to the engineering practical experience and calculated methods and parameters based on the experience.

## **The application of modern mechanics theory**

### **Theory of plasticity and fatigue strength**

With the development and application of plasticity mechanics and strength theory, the research about asphalt pavement damage becomes into a rational analysis stage [2,3].

Ensuring sufficient bearing capacity of structure is the mainly application for plasticity in road design. In other words, by using the shear strength indicators and plastic failure theory, the yield damage of structure is analyzed in order to avoid the appearance of such damage. Based on the previous field tests conducted by AASHO, the importance of improving the structure cohesion is certified by using plasticity. Two aspects of cohesion (C) and internal friction ( $\phi$ ) should be considered to ensure the bearing capacity of structure in pavement design based on the above theory. While in practice, merely improving one aspect often happen in engineering, which may lead to inappropriate measures and adverse consequences.

With the development of fatigue damage theory, it is recognized the reason why road damage occurs is that the fatigue stress caused by repeated load overloads the tensile stress of pavement material. According to ten years of extensive tests, great reforms in pavement design with fatigue theory have happened in United States, Britain, the Soviet Union, West Germany and other countries. Moreover, in current asphalt pavement design, this design method based on fatigue theory is used by many countries [4,5,6]. However, for different country, different specific design method is adopted duo to varying situation.

### **Fracture mechanics**

In fatigue strength theory, the reason why material destruct is the cumulative damage happened in material duo to repeated loads. However, the analysis is based on continuous, complete architecture without defects, instead of the structure considering inherent defects or defects duo to usage of structure which may lead to adverse effect on pavement structure. Consequently, there is a deviation between the result of asphalt pavement design using fatigue theory and the reality. Despite the introduction of different correction factors or safety factors, the design results still have a large degree of uncertainty. However, fracture mechanics can compensate for this deficiency in some extent. From the perspective of fracture theory, the structure has inherent defects and under the effect of loads these defects will lead to local strength concentration and inherent injury. Then cracks appear and the growth, expansion and joint of these cracks ultimately cause the structural damage. With the improvement, development and the application of fracture theory, the evolution of pavement design will or is happening.

In the analysis of asphalt pavement structure by using fracture theory, it is generally acknowledged the crack always has width and the curvature of crack tip is not zero. Moreover, stress concentration is considered at seams and traditional strength theory is used to do calculation. By using thermal elasticity method, Monismith[7,8] studied the stress distribution of crack subgrade base (or old roads) and asphalt overlay under traffic loads and temperature loads as well as the dissipate analysis of stress concentration near the top of the crack tip in rubber asphalt interlayer. The result has shown that the soft interlayer can effectively reduce the stress concentration at crack tip and slow the expansion of reflective cracks. Many researchers such as Coetzee, Francken and Marchard [9,10,11,12] et al also

have done the similar analysis. The study of Francken[10] have shown that the stiffness of interlayer material is positive related to the effect of crack prevention. Moreover, the low bonding strength of interlayer may lead to the extension of cracks along the interface in base layer or old roads while the high bonding strength of interlayer will not cause degumming phenomenon and crack will expand vertically. By using Finite Element Analysis, Leslie et.al[13,14,15] explain why tension stress concentration is the main factor of crack expansion in the tip of crack and then analyze the development mechanism of longitudinal crack in the surface. Besides, the expansive direction and stress strength factor are predicted through the change of design parameters of pavement structure and the relative position between loads and cracks. Zhenhua Jiang[14,15] studies the relation between the J integral at the points around surface crack tip and the crack positions, loads' patterns and pavement structural parameters based on actual small cracks of pavement surface. Rui Luo[16,17] obtained the calculated method of stress strength factor of surface crack by using weight function theory and corresponding computer program is also obtained. The conclusion is that the tire pressure and horizontal force have great influence on stress strength factor.

Moreover, to investigate the extension law of crack in semi-rigid base under transit and temperature loads and the measures of preventing cracks, systematic researches are conducted using linear elastic fracture mechanics theory and methods by Zhang Qisun[18], Liu Yihe[19], Zheng Jianglong[20], Wu Ganchang[21], Zhou Zhigang[22] and so on.

### **Fatigue Fracture Mechanics**

Because asphalt pavement structure is affected by transit and temperature loads, the damage of pavement is always characterized by fatigue damage. The study of asphalt pavement fatigue damage can be divided into two phases, namely the traditional fatigue crack without deflects phase and the phase considering fatigue fracture of crack. For the former, lots of tests, analysis and experience have been done by researchers and the results archived are still used in current pavement structural design. In regard to the latter, the studies are mainly about the regularity of fatigue cracking.

Currently, the empirical formula Paris is commonly used when the fatigue fracture mechanism and method are used to analyze pavement fatigue crack [23,24]. The pattern of cracks in asphalt pavement structure is complex under the transit and temperature loads [25]. Consequently, there is a deviation between the formula Paris obtained by crack fatigue experiments and the reality. This mainly is reflected on the number of items in the formula describing expansion rate of fatigue cracking and parameters in the model.

It has been found that it is properly to use Schapery theory to study the fatigue crack expansion process of asphalt concrete and its structure duo to the asphalt properties of temperature sensitivity and thermal viscoelasticity [26]. The Schapery theory is based on formular Paris and use the viscoelastic properties of asphalt to predict two parameters (A, n) in formular Paris. Lately, modified formular used to calculate fatigue fracture parameters in Schapery theory is got by many crack tests of different asphalt concrete [27,28,29].

Asphalt pavement crack can be analyzed by fatigue mechanism [38, 30,31,32]. Then, some valuable conclusion will obtained, which can provide guidance for practice and propose design formula of asphalt overlay [28, 33,34,35]. The study of asphalt pavement fatigue crack is still a hot topic currently duo the complexity of asphalt concrete property.

### **Mechanics of visco-elastic fracture damage**

Asphalt has the properties of temperature sensitivity and viscoelastic at certain temperature. Meanwhile, because asphalt is organic material with great molecular chains and the chains have the function of connecting again after breaking, the damage crack od asphalt have timeliness property. The properties above of asphalt provide a platform for studying the damage mechanism of asphalt pavement using mechanics of visco-elastic fracture damage.

To evaluate the development and healing of asphalt pavement damage under repeated loads, Lytton et al [36] have built a continuum damage model based on elastic-viscoelastic criterion and potential function. The damage development of asphalt concrete under single load with varying stress rate as well as the damage development and healing due to complex loading history were predicted successfully by this model. Scapascio et al [37] analyzed the mechanics of generation and expansion of fatigue damage of asphalt pavement surface under different type of loads by the combining methods of tests and theoretical analysis and conducted Finite Element Analysis. Kim [38] analyzed the causes of pavement early damage by using viscoelastic continuum damage model and evaluated the effect of mix and test conditions on fatigue performance. Actual performance data of test sections was used to verify the section fatigue performance predicted by viscoelastic continuum damage model and models with varying simplified levels were evaluated. Then, simplified method of fatigue cracking test was evaluated.

Nilsson [39] evaluated material model currently used to predict the life of asphalt pavement as well as different continuum damage mechanic model. Then, he compared the evaluated results to previous models.

Shalaby et al [40] assessed pavement damage conditions by using continuum damage mechanic theory. They did the laboratory test of asphalt pavement specimens got from site and compared damage indicators of asphalt concrete at low temperature, such as stiffness modulus, dissipated energy and tensile stress.

Tuskegee [41] proposed a new method of analyzing fatigue expansion property of asphalt concrete and developed the relationship between fatigue crack expansion of pavement and micro-structure and construction process, which was helpful to improve life of pavement and preventing pavement cracks.

Zheng Jianlong, Tang Xuesong, Zhou Zhigang also have done a lot of work in the study of the theory of viscoelastic damage [42,43,44,45,46].

## **Study of material constitutive relation**

Asphalt concrete is temperature sensitive composite material with complex structure and components. To solve the problems in road design, a variety of constitutive relation model were proposed by scholars based on lots of tests and continuum mechanics. Currently, constitutive relation models are no less than dozens, but they can be divided into the following categories.

### **Constitutive relation based on elastic theory**

Currently, Duncan-Chang nonlinear elastic model is used to describe stress-strain relation of asphalt concrete in domestic [47,48]. Jiayi Feng [49], Weibiao Wang [50] and Zhiqiang Li [51] respectively propose some improvements for the Duncan-Chang model. It suggests that hyperbolic relation is only appropriate to stress-strain relation of concrete in middle stress area instead of high and low stress area. Strength envelop of asphalt concrete changes nonlinearly with the increase of lateral pressure. The nonlinear law of strength envelop suggests that the strength theory of asphalt concrete do not meet Mohr-Coulomb theory.

### **Constitutive relation based on elastic-plastic theory**

To evaluate the safety of highway subgrade base, US. Federal Highway Administration (FHWA) has started a plan to research the constitutive relation of subgrade base soil. One of the results is MAT-147 constitutive relation model. It regards soil as homogeneous isotropic medium and elastic-plastic model is used to describe elastic and plastic deformation. This model eliminates two major drawbacks of before improvement of the model by changing the Mohr-Coulomb yield condition used in this model. Because the mechanical property of soil is highly related to soil porosity and moisture content, the effect of pore ratio and pore water pressure is introduced into constitutive relation model. Besides, as the stress-strain curve becomes steep with increasing loading rate, the effect of strain rate is also considered in this model [52].

### **Constitutive relation based on viscoelastic theory**

Due to the thermal viscous characteristic of bitumen, asphalt exhibits viscoelastic behavior at certain temperature. One-dimensional nonlinear viscoelastic constitutive equations [55], such as Burgers model [42, 56], Maxwell model [53, 54] and generalized Maxwell model and improved Burgers model [57] are used to describe the rheological properties of asphalt concrete under different temperature.

### **Constitutive relation based on viscoplastic theory**

As the development of constitutive relation of asphalt concrete, visco-plasticity of asphalt concrete increasingly become the focus of researchers' attention. Drucker-Prager yield function is extensively used to describe the behaviors of confining pressure, aggregate fraction, interlock and expansion in asphalt and other geological materials [60,61]. Laith Tashman et al [62] amended Prager yield function by using micro viscoplastic continuous constitutive model and adding the effect of anisotropic aggregate and the expansion process of cracks and holes. Based on Desai model [59], Erkens [58] proposed ACRE model with three dimensional yield surface, which can describe the state and softening/hardening state of asphalt concrete. Vassilis [63] proposed a super-elastic - viscoplastic constitutive model, which could describe the characters of volume tensor and partial tensor of asphalt concrete under shear loads. In the viscoplastic model, anisotropy of aggregate was considered and stress invariant was amended. Yield function was proposed to describe the effect of soft behavior, anisotropy and damage by introducing the damage variances to describe damage influence in effective stress theory. Krishnan [64] proposed hybrid constitutive relation by regarding asphalt concrete as ideal fluid after ignoring the influence of temperature and chemical reaction. He also assumed that the constitutive relation of each component of mixture only depended on momentum of component ignoring the plastic deformation of asphalt concrete. It is effective for this model to solve problems, such as pavement weeping, permeability and porosity reduction of asphalt pavement.

## **Numerical simulation and experimental study**

### **Numerical simulation**

Some mechanical problems about asphalt pavement design have been received in-depth study with the rapid development of computer technology, which provides a scientific basis for pavement design and checking.

In terms of constitutive relation of numerical simulation, the mechanic analysis of pavement structure has developed from the period of elastic analysis to the current period of elastic-plastic analysis, visco-elastic analysis and visco-elastic-plastic analysis. Then, the elastic response [65], plastic response [67] and response timeliness [68] of pavement structure are analyzed.

In terms of contents of numerical simulation, the analysis of pavement structure has developed from the period of stress analysis to the period of fatigue analysis [67,68], crack analysis [14,15, 20], fatigue damage performance of pavement [74,75] and life prediction analysis [76,77].

In terms of loading condition of numerical simulation, the analysis has been changed from static, quasi-static analysis to dynamic analysis [66].

Moreover, the boundary element method and discrete element method have also been used extensively in the structure analysis of pavement. Based on the characteristic of boundary element method, Xiaoming Huang [69] has proposed a calculation method to solve stress of layered system. Through combining the layered material fundamental solution with boundary element methods Qiang Yue, Fusheng [70] Liu et al created the boundary integral equation in flexible layered pavement. They proposed stress and displacement boundary element method in layered asphalt pavement.

On the basis of considering the performance on fatigue damage restoration, Jun Chen et al [71] established pavement structure model through discrete element method. They also analyzed the force

characteristics of the bottom layer of asphalt pavement structure under sinusoidal force repeated loads.

Also, discrete element method has been applied in the performance simulation of the internal structure of asphalt mixture. O'Sullivan C, Buttlar et al [72,73] has simulated the mechanical properties of the mixture internal structure using discrete element.

### **Experimental Study**

Due to the lack of asphalt concrete fatigue fracture parameters, the result is not accurate when using fatigue fracture mechanics to predict fatigue cracking life. Therefore, researchers have launched a series of studies on the performance of asphalt concrete fatigue fracture and damage. The research in this area can be divided into two categories:

(1) Obtain the fatigue damage parameter of relevant materials should be obtained firstly [38,39,40,41,42]. For example, using a common evolutionary models and classical damage theory of fatigue damage, Zhigang Zhou [46] has obtained the asphalt mixture fatigue damage parameters of direct tension, cantilever bending, three points bending of beam specimen and APA round wheel load. Hongxin Guan [78] identified the asphalt viscoelastic parameters and stress levels of indoor direct tension fatigue test using indoor stress fatigue test method. Besides, through conducting asphalt mixture fatigue damage test under different conditions, he has obtained viscoelastic parameters of fatigue damage model.

(2) Discuss the existing experimental methods. Currently, test methods about asphalt concrete fracture properties and fatigue fracture performance contains direct tensile test (DT), indirect tensile test (IT), four-point flexural tensile test (4PB), three-point bending tensile test (3PB) and try semicircle the flexural test (SCB). Rosier et al [25], who conducted three-point bending test, pointed out that the split end cracking state is type I and type II coexist state. Because the difference in the proportion of the share of the relevant shear, the fatigue fracture parameters in Paris Formula are not consistent with that in type I. Krans et al [79] used DT and 4PB to conduct fatigue fracture test on a so-called micro-dense material concrete. Result showed that the crack growth rate is almost independent of frequency and load, and the effective stress intensity factor has relation with cyclic stress ratio.

### **Conclusion**

This paper reviews the progress of asphalt concrete pavement design theory and research on damage mechanism. Due to temperature sensibility and structure complexity of asphalt concrete, the application of modern mechanics has a wide range of prospects. For example, as the description of constitutive relations under different temperatures involves elastic - plastic - viscoelastic conversion, so it needs an urgent in-depth research. Besides, because the asphalt concrete itself is a defect-rich composite material, therefore self-healing mechanism of the damage is also the focus of current research. Researchers also need to take effort to study the relationship between macroscopic mechanical properties and microscopic damage of asphalt concrete, to study the injury mechanism between cement and aggregate body. It is believed that, through in-depth study of asphalt concrete physical, mechanical and chemical properties, Mechanic-experience method of asphalt concrete pavement design will become more scientific and the development of physical, mechanical and chemical disciplines also will have a new platform.

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