Review Article

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Review on structural damage rehabilitation and performance assessment of asphalt pavements

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Abstract: Asphalt pavements have been extensively used in highway system. However, a great number of asphalt pavements suffer from early distresses after servicing for about 2–3 years, which leads to frequent rehabilitation and increased maintenance cost. To understand the damage propagation principle and the correlated rehabilitation measure, the progress of pavement distress rehabilitation, structural performance, and damage assessment of asphalt pavements has been explored in the perspectives of materials and structures. The current advance on the parameters for describing the cracking and rutting of asphalt pavements has been introduced. The development tendency for the damage self-healing and rehabilitation, and structural assessment has also been discussed. The study can provide a scientific guidance for understanding the generally used structural damage rehabilitation measure and performance assessment methods of asphalt pavements.

Keywords: asphalt pavement, distress, structural degradation, rehabilitation measure, performance assessment

1 Introduction

Until 2019, the total mileage of highways in China has reached 150,000 km, ranking first in the world. Among

them, the proportion of asphalt pavement is about 90%. The actual service life of asphalt pavements built by the current design standards is generally short, far below the design life of 15 years [1,2]. Current studies show that 60% of asphalt highways after serving for 10–12 years and 17% of that after serving for 6–8 years require extensive repairs. The frequent maintenance of asphalt pavement significantly reduces the traffic capacity of the highway and the transportation efficiency of the road network, and also brings about a significant increase in maintenance and repair costs during the operation period. Therefore, to improve the level of preventive maintenance, it is necessary to develop the monitoring technology for exploring the service performance, structural degradation, and damage failure mechanism of asphalt pavement based on the effective response data in field [3–5]. It can be adopted to determine the repair design scheme and rehabilitation effect evaluation of asphalt pavement structural damage. The formulation of maintenance strategies for asphalt pavement structures is of great scientific importance and engineering meaning for the whole life cycle management of pavement structures and the durable study of asphalt pavement structures.

Because of the rapid growth of highway mileage and traffic volume, the demand for high-grade highway maintenance becomes increasingly diversified. The development trend of highways is that the construction and maintenance have equal weight. Therefore, to scientifically maintain and effectively extend the service life of pavements, pavement functional rehabilitation technology will develop from the perspectives of material performance enhancement, structural composition optimization, and repair-effect information [6,7]. To better understand the current domestic and international research and engineering application of structural damage repair of asphalt pavements, this paper will take asphalt pavements as an example and review the main research progress in the academic and engineering fields at home and abroad. The major contents summarize the rehabilitation measure of material and structural performance, and the method to assess the pavement service performance

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and damage. It intends to provide scientific basis and technical guarantee for the whole life cycle maintenance management of pavement structures.

The main objective of the study is to explore the occurrence mechanism of various distresses (i.e., cracks, rutting, and depression) in asphalt pavements and the critical mechanical parameters to control the damage. The rehabilitation measures of the damaged asphalt pavements are summarized from the perspectives of materials and structures. The major assessment methods on structural performance of asphalt pavements are discussed. Suggestions on the development tendency on health monitoring and inverse design of asphalt pavements are also provided.

2 Distresses of asphalt pavements

Asphalt pavement is the most common type in highway transportation system. Besides the advanced functions, asphalt pavements have downsides, which is the sheer variety of distresses existing over the lifetime. The major distresses that deteriorate the performance of asphalt pavements include the cracks (fatigue crack, top-down crack, reflective crack, and block crack), rutting, pot-holes, upheaval, corrugation, and shoving.

2.1 Cracks

Asphalt pavement can suffer from fatigue crack, reflective crack, low-temperature-induced shrinkage cracks, transversal cracks, and so on as shown in Figure 1. Fatigue cracking can be mainly because of the repeated heavy traffic loads improperly distributed on the asphalt

course, as shown in Figure 2. Water penetration or poor subsurface can also lead to the occurrence of fatigue cracks, which appear in spiderweb. Reflective cracks develop from the underlying cracks [2]. Block cracks appear as randomly distributed linear cracks. Transverse cracking is often because of seasonal temperature change-induced shrinkage or reflective cracks. Slippage cracks are generally caused by the weak bonding action or a lack of adhesion between layers. They are in half-crescent shape and clearly show the top surface separating from the under-surface [8]. As the distress is caused by a problem under the road surface, the area surrounding the crack need to be removed and re-laid. This repair requires a partial or full depth patch.

2.2 Rutting

Rutting is caused by vehicles traveling down the pavements over a long period, resulting in clear areas of wear that tires most commonly travel. Heavily rutted pavement may point to poor compaction of multilayers during the construction, settlement of the subgrade, or a poorly designed asphalt concrete (AC) [5].

It generally contains the structural rutting and fluid rutting, as shown in Figure 3. When the traffic load-induced action is beyond the strength of each layer, permanent deformation occurs in asphalt course and sublayers in the multilayered pavement, denoted as structural rutting [2]. Strength is the critical factor. When the shear stress induced by the repeated traffic loads under high temperature exceeds the shear strength of AC, fluid deformation accumulates around the vehicle wheels and induces the transversal cross section in W-shape, as shown in Figure 3(b), denoted as fluid rutting. A physical

Figure 1: Various kinds of cracks developed in asphalt pavements. (a) Fatigue cracks; (b) reflective crack; (c) low temperature induced shrinkage cracks.

Figure 2: Surface shape of cracks in asphalt pavements. (a) Fatigue cracks; (b) block cracks; (c) linear cracks.

photo of rutting is displayed in Figure 3(c). As rutting can be characterized by the deformation, the rutting distress can be decreased or solved by increasing both the compressive and shear strengths of ACs.

2.3 Potholes

Pothole is usually an alligator crack or collection of alligator cracks that have been left untreated until pieces of AC become completely dislodged and leave the road surface, revealing the concrete underlayer, as shown in Figure 4. When the area beneath the asphalt surface

course is compromised, a depression occurs in the pavement, known as a pothole. The major reasons for the occurrence of potholes can be attributed to weak pavement surface, base, or subgrade, thin surface, and poor drainage [6,7]. Potholes can affect the moving stability and cause damage on the traffic vehicles. Asphalt patch is the most common routine maintenance for repairing a pothole. Recurring potholes induced by the repeated traffic loads often start along the bonding surface between the repairing material and the original asphalt pavement. Therefore, it is important to enhance the bonding strength between the old asphalt course and the newly patched ACs, so as to prevent the pothole distresses.

Figure 3: Characteristics of rutting in asphalt pavements. (a) Structural rutting in bottom base and subgrade; (b) fluid rutting; (c) photo of rutting in asphalt pavement.

Figure 4: Appearances of potholes.

2.4 Upheaval

Upheaval is induced by the shear or tension action along the motion direction, typically with cracks forming through the center of the raised area. The combined action of vertical and horizontal forces from the traffic loads makes the inner shear stress or tensile stress beyond the ultimate shear or tensile strength of the AC, resulting in the upheaval, as shown in Figure 5. This type of pavement distress can also be caused by swelling of the subgrade. A full deep patch is required to fix upheaval distress and for the replacement of the subgrade.

2.5 Corrugation and shoving

Corrugation and shoving appear as ripples and waves in the pavement surface. The unusual shapes are created by vehicles stopping and starting. This sort of traffic action

cannot cause this sort of pavement harm on its own, and it is typically with one unstable under-layer, allowing the top surface to develop wrinkles over that surface. The excessive moisture under the road surface is also one cause [9]. If the corrugation or shoving is localized, the reason for the condition can be discovered and treated without removing too much area of the road surface. The damaged areas, including the damaged sublayer, need to be removed and replaced for the repair.

2.6 Depression

Depression is because of the relatively large vertical deformation of pavements under the vehicle loads, and the pavement surface depresses in center with surface upheavals around the two sides of the wheels, as shown in Figure 6(a). According to the causes, it generally includes the uniform depression, nonuniform depression,

Figure 5: Characteristics of upheaval. (a) Occurrence of upheaval; (b) upheaval.

Figure 6: Characteristics of corrugation and shoving in asphalt pavements. (a) Occurrence principle; (b) corrugation and shoving.

and local depression [10,11]. Uniform depression is because of settlement of subbase and surface course under the compression action of environment and vehicle, which is generally with no harm on pavement failure. Nonuniform depression is caused by the nonuniform compression, imperfect compactness of asphalt course, water penetration, and vehicle-induced deformation. Local depression is attributed to the poor construction on backfilled subbase and moisture subgrade, which makes the pavement depressed under traffic loads, as shown in Figure 7. Therefore, the compaction degree can be a significant index to prevent the depression distress [2].

Besides the mentioned distresses, the water permeation and aging of asphalt material can also weaken the structural durability of AC slabs. The couple action of cracks and water permeation can usually cause quick and large-area destruction of asphalt pavements, which should be carefully considered.

3 Rehabilitation measures for damaged asphalt pavements

Asphalt pavements are prone to various distresses far from the design life cycle. To repair the damaged pavements,

Figure 7: Physical shape of depression in asphalt pavements.

many measures have been considered. Generally, it can be divided into two types. One method is by enhancing the material properties of asphalt mixture by adding some capsules, fibers, or other additives. Another method is by changing the structure layout or composition of multi-layered asphalt pavement to improve the overall structural performance.

3.1 Enhanced material performance of ACs

AC is a kind of composite materials with self-healing properties. Self-healing process of AC is the inverse process of crack formation and propagation. The microcracks in ACs can be merged under high temperature and artificial action, so as to recover the strength of asphalt pavements. The artificial action generally refers to the use of additives in asphalt mixtures. The spherical capsules, cylindrical capsules, hollow fibers with healing agent, reinforced steel wool or polymer, nanoparticles, microbes, and modified asphalt binders have been adopted for the self-healing of damaged ACs.

(1) Self-healing technique based on microcapsule

Microcapsule embedded with solid, fluid, or air has been first proposed for the repairing of polymer matrix composites. It mainly consists of core and wall. The core is composed of one or multiple substances in solid, fluid, or air shape [8]. The wall is a thin film composed of different molecules. When the microcracks inside asphalt pavements extend to microcapsules (silica-based microcapsules) mixed in ACs [9], the healing substances in the core move to the surfaces of microcracks under the siphoning action and polymerize with catalyst in asphalt mixtures, finally making the microcracks bonded, as shown in Figure 8. This method can decrease the stress and strain at crack tips and prevent the development of macro-cracks. The good stability, heat resistance, and interfacial condition of microcapsule in asphalt mixtures verify the superiority. However,

Figure 8: Self-healing of crack in AC by microcapsule.

the size of microcapsule, the long-term healing time, and the control of healing quality are still required to be further explored.

Calcium alginate capsule filled with sunflower oil has been synthesized as a repair agent [10]. Deformed spherical capsules release the oil from the cavities to repair the crack and restore the original shape after compression [11], as shown in Figure 9. The oil release ratios of the capsules in AC after compression can be determined by Fourier transform infrared test. Besides, rejuvenator microcapsules and modified epoxy resin microcapsules have been prepared by *in situ* polymerization for crack repair, and the feasibility was checked by fracture and healing tests [12,13]. The structural design of capsules has also been studied, with poly ethylene glycol granulation as core solution [14], as displayed in Figure 10. Cylindrical capsules [15] have also been performed for autonomous healing of cracked concretes in Figure 11. It should be noted that the service life can be increased with reduced repairs and environmental impacts. However, the reliability should be improved.

(2) Self-healing technique based on hollow fiber filled with solution

Hollow fibers filled with solutions (i.e., calcium alginate and polymer) are compartmented to distribute the rejuvenator throughout the asphalt mixture for overcoming some of the problems associated with alternate asphalt pavement healing methods. It can be a promising approach for the development of self-healing asphalt pavement systems [16]. Hollow optical

Figure 9: Self-healing of crack in AC with calcium alginate capsule.

Figure 10: Novel capsule for self-healing of crack in concrete.

fibers filled with polymer solutions have been embedded in concretes for crack repair [17], as shown in Figure 12. The incompatibility between healing agent and cement matrix in the design of self-healing cementitious composites has also been considered [18]. When crack occurs in Figure 13, the leaked solution with accelerator fills in the crack to recover the working performance of AC. The distances between the fibers and the size of the fibers should also be carefully studied and validated by experimental exploration.

(3) Self-healing technique based on additives

Proper design on the degradation and the composition of asphalt mixture can also be a way to equip the AC with self-healing function. Generally, nanoparticles, reinforced steel or polymer fibers, fly ash, and microbes can be additives. For example, the aging properties of asphalt can be improved by additives for absorbing (or reflecting) ultraviolet (UV) light and lessening the permeation rate of oxygen molecules to display lower Young's modulus and higher adhesion [19,20]. Considerable attempts have been conducted to explore the effectiveness of this method. Composite modifier, multidimensional nanomaterials composed of organic expanded vermiculite and surface modified nanoparticles (nano-ZnO, nano-SiO₂, or nano-TiO₂) have been used to improve anti-aging behavior of asphalt [19–21]. Graphene oxide and carbon nanotubes have been added to improve the aging resistance of asphalt binders and mixtures [22]. A high-elasticity asphalt mixture containing inorganic Nano-titanium dioxide (Nano-TiO₂) has been proposed to resist the strong solar UV radiation and large temperature/moisture fluctuation in high altitude regions [23]. Steel wool reinforced porous AC have been used to improve the fatigue resistance by induction heating [24]. Glass fiber reinforced concrete with polymer has been used to evaluate self-healing properties by applying crystalline admixture as healing substance [25]. Black rapid repair fiber concrete has been developed for rehabilitation around manholes in AC pavement [26]. Fly ash and

Figure 11: Self-healing measure for cracked concrete [15]. (a) Top view; (b) side view.

Figure 12: Self-repair model for crack repair in concrete.

Figure 13: Encapsulation-based self-healing cementitious composite.

superabsorbent polymer as a filler in AC have been added to accelerate microwave heating rate and promote self-healing properties [27–29]. Microbes added in cement base suffered from the second hydration reaction have also been tried for self-healing of cracks in concrete [30,31].

(4) Material performance improvement by modified asphalt mixture

Besides the above-mentioned method, the adjustment on gradation of aggregates has also been a way to enhance the self-healing properties and material performance of AC. It means that the binder, fiber reinforced polymer, steel fiber, and carbon fiber grid can be designed as one aggregate to modify the asphalt mixture [4,6]. For example, thermal modified asphalt mixture has been developed to improve the

long-term pavement performance (i.e., rutting and fatigue cracking resistance) [32]. Asphalt mixture with modified binders has been used to improve the fatigue and rutting resistance [33].

3.2 Improved structural performance of asphalt pavements

As some distresses of asphalt pavement are because of the poor design of the pavement structure, improving the structural type can also be a way to enhance the self-healing properties of asphalt pavements. Plain concrete, engineering cementitious composite (ECC), and ECC-dowel combination have been used to prevent the reflective cracking in the AC overlay [34], as shown in Figure 14. Stone materials with the correct repair method have been used for repairs and rehabilitations of pavement performance, as shown in Figure 15, which can substantially minimize traffic delays and financial resources [35]. Chip seal treatments have also been effective in preserving the pavement surface from further cracking and deterioration, and improving the surface macrotexture during the 2-year evaluation period [36]. The impact of stabilized and untreated base layers on the performance (i.e., fatigue and rutting) of flexible pavements has been judged by field sections [37]. Improved structural design methods with

Figure 14: Measure to prevent the reflective crack [34].

Figure 15: Repair measure to enhance the load transfer performance [35]. (a) Structural design; (b) physical photo.

different materials and thicknesses and sensitivity of mechanical parameters of equivalent envelope area have been proposed as new indexes to evaluate the coordination of material design of asphalt pavement structure layers [38].

Given the analysis above, it can be noted that considerable attempt has been devoted to the enhancement on material properties of ACs by adding various additives and changing the composition of asphalt mixtures. It means that the rehabilitation of damaged asphalt pavement can be much well realized by modifying the micro material performance. Besides, the improved design on structural layers can also enhance the bearing capacity of paved asphalt pavements. It is therefore suggested that both the modified structural materials and layers can be adopted to conduct the rehabilitation of damaged asphalt pavements. Various rehabilitation measures have been proposed and each proposed method has unique merit to enhance the target performance of asphalt pavements. Selection of the suitable method usually involves the comprehensive consideration of high efficiency and environmental protection.

4 Assessment methods of multilayered asphalt pavements

4.1 Structural performance

The structural performance of asphalt pavements can be predicted by mechanistic–empirical pavement design guide software in terms of different indexes, such as terminal international roughness index, permanent deformation, total cracking (reflective and alligator), AC thermal fracture, AC bottom-up fatigue cracking and top-down fatigue cracking, and so on [39]. In addition, mechanistic approach using layer elastic analysis and the AASHTO empirical approach can also be used to judge the structural performance of asphalt pavements [40]. Different from the finite element simulation and

theoretical analysis, field and laboratory testing can also be adopted to assess the toughness and fatigue performance [41]. The generally used indexes for describing structural performance of asphalt pavements includes bending stress ratio [42], moisture susceptibility [43], international roughness index, rutting depth index, skid resistance index, pavement structural strength index, pavement condition index [44], structural capacity index, resilient modulus of subgrade [45], and other functional parameters. The correlated regression equations of these indexes can be obtained from the references. It should be noted that for the development of asphalt pavements, the feature parameters can be improved and reliable indexes can be put forward to well configure the structure response under different conditions (i.e., extremely high or low environmental temperatures, high-frequency heavy traffic load, and high moisture).

Besides, for the fast development of structural health monitoring technique, the response of asphalt pavements in operation recorded by piezoelectric sensors [46], strain gauges, accelerators, and optical fiber-based sensors [47–51] has also become prevail. It is desired that suitable indexes based on the long-term monitoring data of pavements in field can be developed, so as to much accurately assess the pavement behavior.

4.2 Damage description

Asphalt pavement is under tension in horizontal direction and under compression in vertical direction. When the overall bearing capacity of the multilayered pavement is below the mechanical or temperature load-induced response, structural damage may occur. Crack and rutting are the most common distresses in asphalt pavements.

Fatigue cracking deterioration is one of the major distresses in asphalt pavements. N–S method, simplified mechanical method, damage mechanics, and energy method can be used to describe the fatigue damage [52].

Internal structure after fatigue damage and the influence of microstructure characteristics on fatigue performance can be explored by energy-controlled testing [53]. Stiffness of asphalt mixtures subjected to a repeated, cyclic load has been considered an indicator to represent the fatigue crack damage evolution and evaluate the fatigue performance. Fatigue damage model and failure criteria on AC materials with different kinds of polymer modifiers (polypropylene, crumb rubber, cellulose fiber, asbestos fiber, and gilsonite) have been established based on the indirect tensile fatigue tests and indirect tensile stiffness modulus tests [54]. The instantaneous stiffness modulus can be determined:

$$S = (1 - D)S_0 \quad 0 \leq D \leq 1, \quad (1)$$

where S and S_0 are the instantaneous and initial stiffness modulus of the asphalt mixtures, and D is the damage coefficient.

Reflective cracking is one of the most serious distresses associated with existing hot-mix asphalt or Portland cement concrete (PCC) pavements overlaid with a thin bituminous layer. Thermal reflective cracking mechanisms have been studied by simulation [55]. The modeling results demonstrated that the slab curling and opening of PCC joints/cracks can increase the thermal reflective cracking, while the rubblization of PCC slabs before the construction of an overlay can significantly decrease it. The thermal reflective cracks propagated from the bottom to the surface. Falling weight deflectometer data and energy ratio approach have been adopted for cracking evaluation [56].

Rutting is the progressive accumulation of the permanent deformation in different layers of the pavement under combined effect of traffic loads and high temperatures. Considerable attempt has been performed to explore the rutting prediction. Empirical and theoretical methods are provided to evaluate the rutting resistance performance [57]. Rutting has been predicted as the summation of permanent deformation [58]. However, improved prediction models have been proposed in recent years based on the latest techniques [59]. For example, based on fiber Bragg grating sensing technology, linear viscoelastic rutting prediction model has been put forward [60], and the accumulated deformation in depth point z is:

$$S_z = C_T \frac{1}{m(T_j) + 1} \int_0^l \int_0^h A(T_j) q^{n(T_j)} t^{m(T_j)+1} dz dt, \quad (2)$$

where C_T is the dynamic correction factor of road temperature T and regressed from testing data, with formula

of $C_T = 4.923 \times 10^{11} e^{-0.4858T} + 142.5 e^{-0.09116T}$; $m(T_j)$, $A(T_j)$, and $n(T_j)$ are the creep parameters of the j th sublayer at temperature T ; h is the depth; l is the total time correlated with the deformation S_z , t is the accumulated loading time, with formula

$$t = \frac{NS}{Bv}, \quad (3)$$

where N is the times of loading, S is the contact area, B is the contact width, and v is the vehicle speed.

Souliman et al. [61] have suggested the rutting by the following relationship:

$$\varepsilon_p(N_R) = A(N_R)^B + C[e^{D(N_R)} - 1], \quad (4)$$

where $\varepsilon_p(N_R)$ is the permanent strain, N_R is the number of loading cycles with rutting failure. A , B , C , and D are regression constants.

Rutting resistance of asphalt pavements in field can also be conducted by testing field cores [62]. Material factors on permanent deformation have been studied. Compound strain rate has been proposed to reflect permanent deformation of asphalt pavement under realistic axial load

$$\varepsilon_c = \sum_{i=1}^{13} a \cdot \sigma_i^b \cdot p_i, \quad (5)$$

where σ_i is the stress level, MPa; p_i is the percentage of represented repeated times at each interval, %; a and b are the regression constants.

Mechanical properties of asphalt mixtures have also been tested to evaluate the degradation of pavement structure [63]. Degradation index has been defined as the ratio of elastic modulus of original asphalt mixture to that of aged mixture which shows the aging degree of asphalt mixtures

$$I_d = \frac{S_{e0}}{S_e}, \quad (6)$$

where S_{e0} is the elastic modulus of the original asphalt mixture and S_e is the elastic modulus of the aged asphalt mixture. I_d decreases with the increase in aging time.

It can be noted that tremendous effort has been contributed to predict the crack and rutting distress of asphalt pavements. However, the widely approved structural performance and damage indexes are still required for further investigation. It is still significant to bridge mechanistic analysis and mechanistic-empirical analysis related results (i.e., stresses, strains, and damage) and pavement distresses (such as cracking amount).

5 Conclusion

For the significant position of asphalt pavements in the transportation system, a review on the pavement distresses, rehabilitation measure, structural performance, and damage description has been conducted. The advance on the rehabilitation measure and the structural (damage) performance assessment methods of asphalt pavements has been comprehensively declared, and the possible tendency is given for the scientific instruction on achieving high-performance asphalt pavements. The following conclusions can be drawn from the study:

- (1) Crack and rutting are the most common distresses in asphalt pavement, and the quick rehabilitation is particularly important for maintaining the structural performance and traffic capacity of asphalt pavements.
- (2) The rehabilitation measures for asphalt pavements from the materials and structures have been intensively investigated. The method by adding capsules, fibers, nanoparticles, and microbes in asphalt mixtures to make the AC with damage self-healing properties has received high attention. It may become an approved approach in future, with the rapid development of new materials and smart fabrication techniques.
- (3) The structural performance and damage assessment methods are still in progress, and widely approved indexes are desired to describe the characteristics of asphalt pavements. The structure design, material selection, construction quality, and subsequent pavement maintenance and preservation activities should be comprehensively considered. It can be a development tendency to bridge these aspects together by the smart structural health monitoring system of asphalt pavement in field.

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