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Milling process simulation of old asphalt mixture by discrete element

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HIGHLIGHTS

- Milling process of old asphalt mixture is simulated by discrete element.
- Parallel bond model is used in the discrete element simulation.
- Cutting depth and speed affect the cutting tool force obviously.
- Cutting angle changes from 40°–50° have no significant effect on the cutting tool force.

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ABSTRACT

Great amount of milling materials are produced every year because of the rapid increase of pavement maintenance. However, the utilization of the milling materials is still low because many broken aggregates and large-piece of asphalt mixture are produced in the milling process. Improving the quality of milling materials to increase its recyclability is an important research direction. In this study, a discrete element model of asphalt mixture was established, AC-16 asphalt mixture specimens were created, which used Styrene-butadiene-styrene (SBS) modified asphalt after aging, and the parameters of the PFC model were determined by uniaxial compression test and simulation of the test by PFC. The force of the cutter tool was analyzed, the optimal conditions for reducing the damage of asphalt mixture aggregate and avoiding the cutting down of asphalt mixture into larger pieces in the milling process were investigated through the simulation of milling process under different milling conditions. Results show that for AC-16 asphalt mixture, using a cutting speed of 0.5 m/s and cutting angle of 45° can reduce the amount of broken aggregates, and the cutting angle of 40° when the cutting depth is 25 mm at a cutting speed of 1 m/s should not be adopted to avoid the milling down of large pieces of old asphalt mixture.

1. Introduction

At present, the amount of old asphalt pavement milling materials in China is extremely large at approximately 10 million tons per year. However, given the shortcomings of the current milling operations, pavement aggregates tend break or several block masses are milled; this condition adversely affects the recycling of milling materials, which results in the low utilization of old asphalt mixtures, exacerbation of the wear of milling tools, and increase in milling operating costs. One of the main reasons of these shortcomings is that current milling machines adopt the same milling operations with different old asphalt pavements. Different old asphalt mixtures have different mechanical properties; hence, calculating the stress in the milling process of asphalt mixtures with different aging characteristics is necessary.

Currently, the finite element method is widely used to simulate the milling operation of asphalt pavement, considering the pavement structure as a whole. The mechanical properties of pavement are described by an entire pavement constitutive model, such as Johnson–Cook's and Maxwell's constitutive models; however, the anisotropic characteristics and interfacial properties of asphalt mixtures are ignored [1]. Moreover, the asphalt mixture cut by a milling machine has been aged for many years, and the constitutive model adopted in existing research has not considered the influence of the aging of the asphalt mortar on the model.

J. Blum and R. Auderegg [2] used different excitation methods and combined the models to find the optimal operation point of the model by considering its effectiveness based on the dynamical model of a two-mass oscillator and a simple model of the pavement material. The size of the machine or the current fuel consumption of the machine was reduced while maintaining the same output. Hai-Rong, Jiao, and Xiao [3] investigated the motion trajectory on a milling cutter and built the model of cutting

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thickness and the cumulative cutting thickness of the rotor as rotor angle varying. The results show that the cumulative cutting thickness of the rotor has a periodic change with high frequency, and the period is determined by its rotating speed and the number of cutters installed on it. García-Ordás [4] proposed a new approach for categorizing the wear of cutting tools used in edge profile milling processes based on machine learning and computer vision techniques.

Liu S. [5] used the Johnson–Cook model to characterize the mechanical properties of pavement and used the finite element software ABAQUS to simulate the stress and strain of different cutting speeds and depths, and optimize the cutting speed, depth, and design of tool and material selection in the milling machine. Duan [6] focused on the effect of placing the tools of the milling drum on the milling process, created a finite element model of the milling drum using UG software, and conducted numerical simulations in ANSYS to determine the area where the tool was prone to wear. Xiong [7] described the characteristics of asphalt pavement using the Johnson–Cook model and investigated the values of tool stress, milling resistance, and resistance moment under various milling and tool parameters using finite element method. Liu Ya [8] simulated the milling process of pavement using ABAQUS and explored the stress, strain, and energy dissipation of the tool under different cutting speeds.

In recent years, discrete element method is used to analyze the microscopic mechanical behavior of asphalt mixture. You Zhanping [9] set up three-Dimensional discrete element models for asphalt mixtures, the corresponding microscopic parameters are proposed. Abbas and Liu Yu [10,11] use Burger's model to simulate the viscoelastic behavior of asphalt mortar, and Liu also predicts the dynamic modulus of asphalt mixtures. Chen Jun [12] set up discrete element models of asphalt mixtures and analyzes the cracking process. Liu Yu [13] proposed that viscoelastic discrete element model is better to simulate the viscoelastic behavior of asphalt mixture.

In this study, the discrete element model of asphalt mixture is established to simulate the milling process and analyzes its mechanical response. Three milling parameters, namely, cutting speed, cutting angle, and cutting depth, are analyzed. To simulate the asphalt mixture milling process and analyze the force, the asphalt mixture specimens are made by using SBS-modified asphalt after aging and the uniaxial compression test is conducted. The parameters of the PFC model are determined by the simulation of uniaxial compression test using PFC. The discrete element model is set up and used to calculate the force between the cutting tool and asphalt mixture under several milling conditions for one kind of asphalt mixture, considering the minimum force of the cutting tool as the objective function to reduce the number of the production of broken and large-piece aggregate, respectively. The reasonable parameters of the asphalt mixture in the milling operation are proposed for certain conditions, which have considerable significance to improve the efficiency of milling operation, reduce the cost of milling operation, and promote the milling machine design.

2. Establishment of 3D discrete element model for asphalt mixture

The shape and size of particles are different and their contact relationship is complex because asphalt mixture aggregates are irregular blocks. Therefore, based on a previous study [14], the aggregate is expressed using particles with different diameters, and the viscoelasticity of the asphalt mortar is characterized by a parallel bond model defined among the particles [1].

The PFC model for the asphalt mixture can be used as follows:

(1) PFC command and FISH language are used to program in the PFC software. Particles of different sizes are randomly generated in the specified range according to the median of the gradations of AC-16 asphalt mixture aggregate, which is a kind of asphalt concrete with a nominal maximum aggregate size of 16 mm. The percentage of the mass of each aggregate is shown in Table 1.
(2) Speed is applied to the wall to achieve the loading of particles using wall movement. The wall is a manifold surface composed of triangular facets in 3D, which can translate and rotate, and the wall movement does not obey the equations of motion. The applied stress through the loading of the particles must be considerably lower than the strength of the material to reach a static equilibrium state.
(3) A large difference exists in the radius of the particles in the model; thus, some "floating" particles are unavoidable when the particles are randomly generated. The constraint will be less than three because such "floating" particles are not in full contact. These particles will have a certain influence on the compressive strength of the model; hence, they must be eliminated by rotating, moving, or increasing bond radius.
(4) As the parallel bond model is good to characterize the viscoelastic characteristics of asphalt mixture [1], the microscopic parameters of the parallel bond model are used to simulate the mechanical properties of the asphalt mixture mortar to obtain the final asphalt mixture model.

The contact of the parallel bond model can be defined as follows. (All in international units.)

Contact model linear bond range contact type ball–ball
Contact method bond gap 5.0 e-5contact method deformability emod 1.2 e9 krat 0.5
Contact method pb_deformability emod 1.2 e9 krat 0.5
Contact property pb_ten 7.3e6 pb_coh 4.0e6 pb_fa 40.0 (e-5 refers to 10^{-5}, e6 refers to 10^{6}, and e9 refers to 10^{9}, which are the same below).

3. Verification of asphalt mixture discrete element model

3.1. Uniaxial compression test of asphalt mixture

The rotating film oven aging test (RTFOT) is used to simulate the characteristics of aging asphalt. Li [15] suggested that the aging time of asphalt is in some way connected with the actual service life of asphalt pavement. The milling pavements are mostly old asphalt mixture that have served 8–12 years, and most of the surface course asphalt mixture use SBS-modified asphalt in China. Thus, SBS-modified asphalt mortar with aging time of 600 min (corresponding to the asphalt pavement that has been servicing for approximately 10 years) [15] is used to form the aging asphalt mixture specimen for the establishment and verification of the PFC model.

Table 1
Gradation of AC-16 asphalt mixture.

	The mass percentage (%) through the following sieves (mm)										
Aggregate size	19	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Mass percentage (%)	100	95.0	82.5	65.0	40.0	27.5	19.5	16.0	11.5	8.0	5.0