APPLICATION OF MESO-MODEL OF CONCRETE LOW-VELOCITY IMPACT IN PAVEMENT

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Abstract: Concrete pavement is one of the typical highway structures at home and abroad. Most of the existing research on the performance of concrete pavement is based on the macroscopic angle of view. The complex meso-structure inside is ignored. Due to the incomplete research on concrete pavement structure, it is difficult to reveal the physical mechanism of concrete pavement deformation and damage. In order to understand the failure mechanism of concrete pavement more clearly, this paper started from the microscopic perspective. Firstly, based on the experimental phenomena, a multi-grade aggregate model was randomly placed in the concrete slab, and the interface between the aggregate and mortar was generated at the same time to establish a three-dimensional three-phase mesoscopic bone and the finite element calculation model of the material. Secondly, the damage effect of concrete specimens in homogeneous modeling, meso-modeling and experimental phenomena were compared to verify the accuracy of the selected concrete material parameters and the feasibility of meso-modeling method. Finally, the concrete failure form under three different aggregate contents and the influence of internal aggregate content of the concrete pavement on the mechanical properties of the concrete pavement were analyzed. The calculation results showed that compared with the macroscopic simulation, the mesoscopic model was more consistent with the experimental phenomena of the failure effect of the concrete specimens. And the numerical simulation results with the aggregate content of 46.6% were the most consistent with the experimental results. Comparing the failure modes of concrete specimens with different aggregate contents, it was found that the concrete specimens with an aggregate content of 60.6% have a lighter degree of damage. When the aggregate content was 30.6%, the impact tooth penetrated half of thickness of the concrete specimen, and the aggregate content is 60.6% of the impact teeth penetrated one third of the concrete specimen. Therefore, the higher the aggregate content is, the stronger the ability of the concrete specimens has to resist damage.

1. Introduction

Concrete is very common in the construction industry. Due to its advantages of good stability, high strength, strong durability and low maintenance cost, road construction mostly adopts concrete pavement in our country. However, long-term rolling has caused different degrees of damage to the concrete pavement one after another, resulting in a greatly reduced service life. Due to the hardening of the concrete pavement, it is very difficult to repair the damaged pavement. How to quickly and effectively repair the damaged concrete pavement, increase the service life of the pavement, and explore the mechanical properties of the concrete pavement is a hot research topic. In the old concrete pavement reconstruction project, Gu et al. [1] used the Drop Hammer Hest Machine to study the destructive effect of concrete slab under low-velocity impact. Tang et al. [2] used three-dimensional finite element method
to study the structure of the old pavement, the force and deformation characteristics of the soil foundation during the impact compaction process. Sun et al. [3] used a four-flute impact roller to crush the concrete pavement and study the old pavement structure, the stress and deformation characteristics of soil foundation. Zhou et al. [4] treated the old concrete pavement with resonance crushing technology, and simulated and calculated the pavement structure before and after the crushing. Zhao et al. [5] established an ABAQUS three-dimensional finite element model to analyze the mechanical behavior of the old concrete pavement under the action of MHB. Li et al. [6] used micro-cracking homogenization crushing technology to micro-crack concrete pavement.

The above theoretical research on the failure mode of concrete pavement is basically from a macro perspective, regarding concrete as a continuous homogeneous medium for research, ignoring the complex microstructure inside the concrete material. It is difficult to reveal the physical mechanism of material deformation and destruction. At the micro level, concrete is a multi-phase conforming material composed of coarse aggregates, cement compound, porosity and aggregates and cement mortar bonding bands. The mechanical properties of each group of components are very different.

To this end, this article is based on the experiment of low-velocity impact concrete slabs. From the meso-level perspective, firstly, a multigrade aggregate model was randomly placed in the concrete slab. And the interface of aggregate and mortar was generated at the same time. A three-dimensional three-phase meso-aggregate finite element calculation model was then established. Secondly, the calculation result of meso-modeling was compared with homogeneous modeling and experimental phenomena, and the reliability of the selected concrete material parameters and the feasibility of meso-modeling method was validated. Finally, the influence of aggregate content in concrete on the formation of cracks and the influence of aggregate content on the ability of concrete to resist damage were studied.

2. Establishment of calculation model

2.1 Introduction to calculation model
The best device diagram is shown in Figure 1(a). [6] The calculation finite model shown in Figure 1(b) composed of four parts: drop hammer, bearing plate (impact tooth), aggregate, and concrete slab. Each part uses the three-dimensional solid unit 3Dsolid164, and uses Lagrange contact algorithm. The impact hammer model has an outer diameter of 150mm and an inner diameter of 35mm and a height of 100mm. The bearing plate model has an outer diameter of 300mm and a height of 30mm. The size of the concrete slab is 500mm in length, 500mm in width and 80mm in height.

![Drop Hammer Impact Test Device](image1)

![Calculation Finite Model](image2)

(a)Drop Hammer Impact Test Device  (b)Calculation Finite Model

Figure 1 Calculation Model

2.2 Establishment of mesoscopic concrete model
In order to understand the internal mechanical properties of materials more clearly at the mesoscopic level, many meso concrete calculation models were established. Guo et al. [7] regarded concrete as a dual-phase composite material composed of coarse aggregate and mortar matrix, and established a three dimensional pie-shaped concrete meso-aggregate model. Tang et al. [8] used the elastic damage constitut
relationship to describe the mechanical behavior of concrete materials at the meso level, and established a random aggregate numerical model and the corresponding meso-element parameter selection method. Pan [9], established a pebble aggregate model based on Bezier curves, and studied the difference in tortuosity between pebble and gravel aggregate concrete meso-models through parameter analysis. Monte Carlo function was used to write a program in this experiment. The coarse aggregate model was randomly put into the concrete slab. Meanwhile, the aggregate and mortar interface was generated. When the aggregate was placed, the principle that the aggregates can not intersect or overlap each other should be followed. And the volume control principle was adopted to fill the meso-aggregate. The aggregate distribution is shown in Figure 2.

![Aggregate distribution](image)

(a) 30.6% Aggregate  (b) 46.6% Aggregate  (c) 60.6% Aggregate

Figure 2 Aggregate distribution

2.3 Material model definition
The Drop Testing was used to verify the calculation model. Common steel materials were used for the drop harmer and impact teeth in the experiment. The axial compressive strength of the concrete slab was 31MPa, and the splitting tensile strength was 5.1MPa. The concrete slab and coarse aggregate were depicted by HJC (Holmquist-Johnson-Cook) constitute model. The HJC constitute model is proposed for concrete materials, which considers the strain rate effect, the damage evolution effect, the confining pressure effect, and the impact of crushing and compaction effects.[10]

3. Finite Element Model Verification
In order to verify the validity of the meso-modeling and the accuracy of the constitute parameters, the macroscopic model of low-velocity impact of concrete and the meso-model were established and compared with experimental phenomena.

As is shown in Figures 3, 4, and 5, when the meso-scale concrete specimen failed under the one-tooth calculation model, a through-type crack was formed in the center of the concrete specimen. On the homogeneous concrete specimen, multiple cracks was formed in the center of the impact. Two of the main cracks extended diagonally to the edge of the board. Under the three-tooth calculation model, a number of herringbone diagonal cracks were formed in the center of the meso concrete specimen, which gradually extended to the edge of the slab. The center of the homogeneous concrete specimen formed a triangle-like failure core, and the cracks extended from the triangle to the edge of the slab. Under the four-tooth calculation model, a quadrilateral fractured block was formed in the center of the concrete specimen, and the cracks developed at the four corners gradually extended to the edge of the slab.

The calculation results of three calculation models were compared with experimental data, showing that it is convenient and effective to adopt meso-modeling to simulate the low-velocity impact process of concrete and analyze the failure mode of the meso-concrete.
4. The effect of aggregate content on the failure mode of concrete slab

In order to analyze the effect of aggregate content on the failure mode of concrete slab under low-velocity impact, as is shown in Table 1, comparison of different working conditions was analyzed. The numerical simulation results were obtained for different tooth shapes, different aggregate contents, and different velocities.

| Table 1 Working Condition Instruction |
|---------------------------------------|
| Name | One-tooth calculation model |
| Working condition | Working condition 1 | Working condition 2 | Working condition 3 |
| Aggregate content | 30.6% | 46.6% | 60.6% |
| Impact velocity | 6m/s | 12m/s | 18m/s |

| Name | Three-tooth calculation model |
| Working condition | Working condition 4 | Working condition 5 | Working condition 6 |
| Aggregate content | 30.6% | 46.6% | 60.6% |
| Impact velocity | 6m/s | 12m/s | 18m/s |

| Name | Four-tooth calculation model |
| Working condition | Working condition 7 | Working condition 8 | Working condition 9 |
| Aggregate content | 30.6% | 46.6% | 60.6% |
| Impact velocity | 6m/s | 12m/s | 18m/s |

4.1 Calculation results of one-tooth model

With different aggregate contents, the failure modes of one-tooth calculation model were roughly the same. When the impact teeth contacted the load-bearing slab, the aggregates were firstly damaged. After the internal structure of the concrete slab was damaged, the overall concrete slab began to fail. Comparing the calculation results under the three aggregate contents in Figures 6, 7 and 8, it can be concluded that the concrete specimens with an aggregate content of 30.6% gradually formed divergent cracks in the center of the concrete specimens as the velocity increased. And the failure mode was to form an oblique main crack in the center. The main crack developed from the short sides of the impact tooth and gradually extended to the edge of the plate. The cracks developed at the stress concentration of the impact tooth gradually extended outward while the aggregate content was 46.6%. The failure mode was a through-type straight crack in the center. When the aggregate content was 60.6%, a diverging crack at the stress concentration of the impact tooth was formed. The failure modes were four cracks diagonally to the concrete. From the Figure 3, it can be obtained that the numerical simulation result of the aggregate content of 46.6% was more consistent with the failure effect in the experiment.
4.2 Calculation results of the three-tooth model

With different aggregate content, the failure modes of three-tooth calculation model were different at the ultimate failure, but the overall failure effect was roughly the same. When the internal structure of the concrete specimens was destroyed, the surface elements of the concrete specimens began to fail. As is shown in Figures 9, 10 and 11, when the aggregate content was 30.6%, a pit shaped like an impact tooth was formed in the center of the specimen, and multiple cracks that developed outward were formed at the stress concentration of the impact tooth. The failure mode was a herringbone crack in the center of the specimen. When the aggregate content increased to 46.6%, multiple short cracks were generated in the specimen. When the concrete specimen failed, many cracks developed obliquely to the edge of the plate. When the aggregate was 60.6%, a main herringbone crack that did not develop to the edge of the plate was formed on the specimen. By comparing the failure mode of the concrete specimen in Figure 4, the aggregate content of 46.6% is more consistent with the experimental results. From the analysis of crack formation and fracture shape of concrete specimens under different aggregate contents, we can know that a flat fracture was produced by the perforative crack in the fracture zone. And the main crack developed by the two impact teeth and the crack at the bottom of the concrete specimen formed a stepped fracture zone. A number of criss-crossing tiny cracks were generated at the crack core to form the core area of the concrete specimen failure.
4.3 Calculation results of the four-tooth model

The tendency of the main cracks when the concrete slab was completely destroyed under the action of four-impact teeth was roughly the same. As is shown in Figures 12, 13 and 14, when the aggregate content was 30.6%, a number of outwardly diverging cracks appeared in the center of the concrete specimen. When the specimen was damaged, four oblique cracks along the direction of the impact tooth gradually developed to the edge of the plate. When the aggregate content increased to 46.6%, many small cracks were produced in the attachment of the impact tooth by the concrete specimens. When the concrete specimen was damaged, a quadrilateral fracture block was generated in the center of the specimen, and an oblique crack developed to the edge of the slab at the four corners of the quadrilateral. When the aggregate content increased to 60.6%, the damage effect was roughly the same as that of the aggregate content of 46.6%, but the diagonal cracks did not develop to the edge of the slab. By comparing the failure mode of concrete specimens in Figure 5, the aggregate content of 46.6% was more consistent with the experimental results.

5. Conclusions

In this study, the failure mode of the low-velocity impact process of concrete pavement was simulated by the method of mesoscopic modeling, and the effect of aggregate content on the failure mode of concrete slab was analyzed. Conclusions are as follows:

1) Through comparison with homogeneous modeling and experimental phenomena, the accuracy of the meso-modeling method was verified. It is found that the final failure form of the concrete specimens with an aggregate content of 46.6% was the most consistent with the experimental results.

2) Through the calculation results of the different aggregate contents, it was shown that the aggregate content has a certain influence on the load-bearing capacity of concrete specimens. When the aggregate content was large, the damage degree was lower under the same load. For example, the 60.6% aggregate content requires a greater impact load under four impact teeth to form the same trend of cracks as the others.

3) When the concrete was fractured under impact load, in addition to the formation of fracture cracks, spalling was prone to form at the junction of aggregate and mortar, causing part of the surface of the concrete specimen to fall off, and the greater the impact load, the more obvious the spalling phenomenon.

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