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Gradation Optimization Design of Cement Stabilized Macadam Base by Discrete Element Method

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Abstract: The meso-structural stability of cement stabilized macadam mixture was evaluated by discrete element method. First, three two-dimensional discrete element models of typical gradation structures were established. A cyclic loading rate of 0.001mm/cyc was applied to the model top using a loading plate of 10cm and 20cm. Analysis was made on the mechanical response characteristics, stress transfer rate and main skeleton distribution rate of the mixture meso-structure, with meso-structure evaluation method proposed. Moreover, through different gradation design methods, meso-structure two-dimensional discrete element models composed of 14 target gradations were established for stability analysis. Finally, through laboratory tests, the feasibility of discrete element method for evaluating the meso-structure stability of cement stabilized macadam was verified. The results showed that the skeleton dense structure had the advantages of meso-structure stability and good resistance to external load and deformation. Through the discrete element method, the target gradation component was evaluated, with gradation group tested in laboratory, finding consistency between the meso-structure and macro characteristic evaluation, so the gradation optimization in this paper was effective.

1. Introduction

As a semi-rigid base, cement stabilized macadam is extensively used in the load-bearing layer of the highway asphalt pavement structure with its advantages of good board property, strong carrying capacity and good economic benefits [1]. In 2015, “Technical Specifications for Highway Pavement Base Construction” [2] raised strength requirements for the base, with 7d strength range increased from 2.5MPa~5MPa to 3MPa~7MPa. Meanwhile, adjustment was also made to gradation range of cement stabilized materials, with gradation smaller compared to the previous specification, so material cracking risk was more prominent. The properties of cement stabilized macadam mixture are greatly correlated with gradation type. A good skeleton dense gradation can give full play to the aggregate's extrusion strength, correspondingly reduce the cement dosage, improve the cracking resistance of the mixture, and strengthen durability of the base. Accordingly, gradation component design is an important link in the application of cement stabilized macadam base. Nonetheless, there are currently few researches on the meso-structure characteristics of gradation component, and even fewer researches on gradation optimization design of meso-skeleton structure characteristics. The discrete element method, which can reflect the inhomogeneity and discontinuity inside the material, has recently become one of the main methods for analyzing internal material structure, and has been gradually introduced into road engineering materials [3, 4]. As a kind of discrete granular cementing material, cement stabilized macadam is characterized by material heterogeneity, mechanical anisotropy and internal structure discontinuity. By breaking through the previous gradation optimization methods, this paper conducts in-depth research from numerical simulation of gradation meso-structure, and takes discrete element method to evaluate the skeleton structure of different gradation components, providing theoretical methods and engineering guidance for practical engineering projects.

2. Three Typical Gradation Mechanical Models and Numerical Simulation Analysis

2.1. Model Establishment

In this paper, discrete element 2D modeling calculation was adopted, which could enable better observation of the contact force chain during mixture loading deformation, and the plane renderings are more intuitive. The wall model with a width of 300mm and a height of 150mm was adopted, and the moving boundary wall method [5] was taken to generate gradation particles, so that particles were not generated outside the model, as is shown in Figure 1.

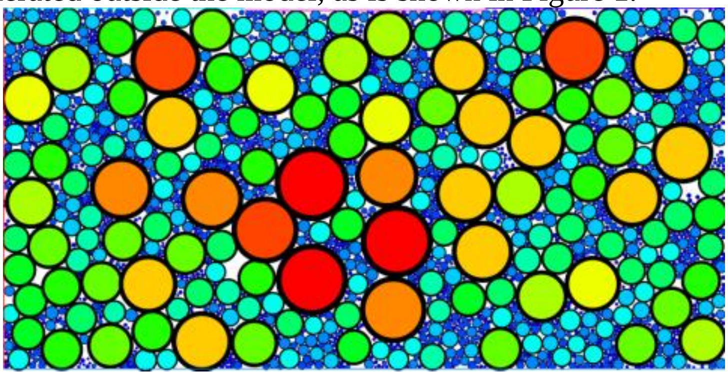

Figure 1: Schematic diagram of discrete element model

2.2. Model Parameter Setting

In this section, based on previous studies [6], contact adhesion was taken as the bonding model of cement stabilized macadam base to better approximate the actual mixture characteristics. In this paper, the mesoscopic contact adhesion strength was calibrated by applying unconfined compressive strength to the 150*150mm specimen. In the loading process, the deformation was detected with a dial indicator to compare the force value generated by different deformations. Adjustment was made to the contact adhesion strength of discrete element 150*150 model, and the data was comparatively fitted. When the contact adhesion strength was 1.414×104N, it basically met the requirement for the mixture model with 4% cement dosage. Specific model parameters are detailed as follows.

2.3. Stress Analysis and Evaluation Method for Typical Gradation Skeleton

In this section, three typical gradation structures commonly found in cement stabilized macadam mixtures were adopted: GK skeleton void structure, GM skeleton dense structure, and XF suspension dense structure. A 30cm*15cm discrete element model with the above three typical gradations was established to conduct numerical simulation analysis. In the static pressure cyclic loading test of 20cm loading plate, the displacement loading stopped when the deformation reached 5mm. During the loading, the deformation curve of the loading plate reaction with displacement and the deformation curve of the particle force on the bottom wall with displacement were monitored. The model was divided into 18 measuring circle regions to monitor the contact force change in each region. The gradation is shown as follows Table 1.

Table 1: Mesoscopic parameters of the discrete element model

Mesoscopic parameter	Unit	Value
Aggregate density	Kg/m^3	2700
Normal stiffness of aggregate	N/m	1×10^{10}
Tangential stiffness of aggregate	N/m	1×10^{10}
Loading plate stiffness	N/m	5×10^{11}
Aggregate friction coefficient	/	0.5
Friction coefficient between wall and aggregate	/	0.5

Table 2: Pass rates of three typical gradations

sieve pore(mm)	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18
GK skeleton void	100	87.7	60.8	46.8	41.1	26	11.7	5	3
GM skeleton dense	100	90.2	77.4	60.4	55.1	48.6	27.3	22.8	10.7
XF suspension dense	100	96	92.1	83.3	74.4	67.3	40	26.5	9.8

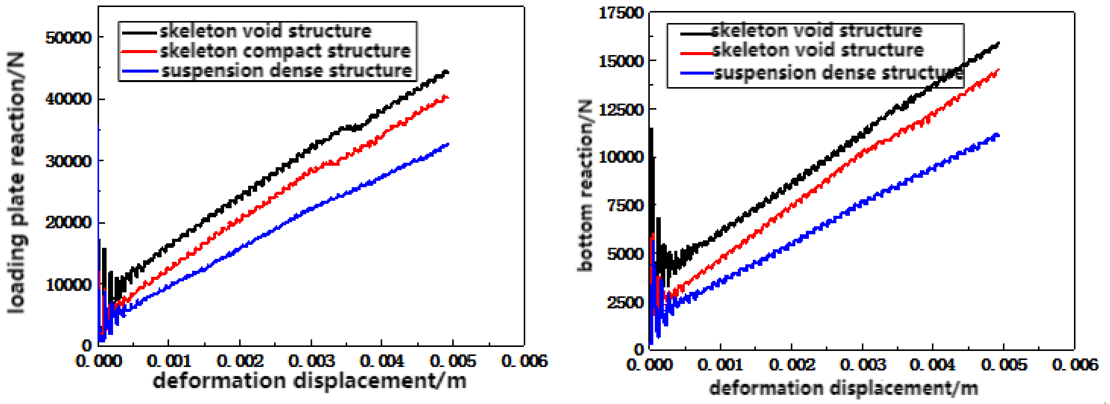

Figure 2: Relation diagram between loading plate reaction and bottom reaction under 20cm cyclic loading

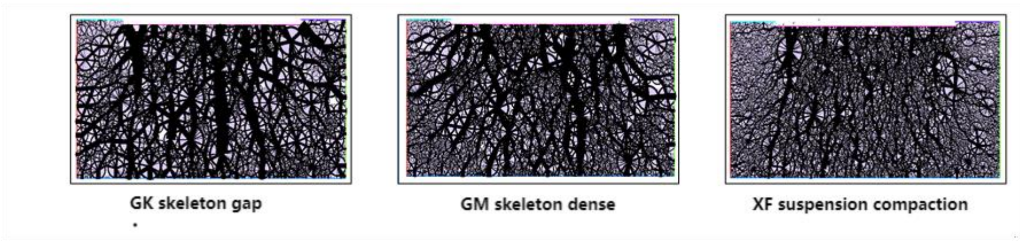

Figure 3: Stress transfer diagram of typical gradation skeleton

Figure 2 and Figure 3 show that, the black cylinder is the force chain for particle interaction generated when the loading plate applies pressure on the particles, and also the physical stress transfer path formed after the mixture is compressed. A thicker line means greater force chain value. The initial stress transfer diagram when the 20cm loading plate is cyclically loaded to 1mm shows that several main stress transfer paths have been formed in the skeleton void structure, and the stress path network of the overall skeleton structure has been initially formed with uniform distribution, demonstrating high-quality skeleton stability structure. The skeleton dense structure also forms several stress transfer paths, and the stress path network of the whole skeleton structure has a good skeleton stability structure. The suspension dense structure fails to form an obvious stress transfer path, but generates a small force chain with poor integrity. Both the stress transfer ability and the ability to resist external forces correlate with the stress generated by the intercalation between particles under mixture deformation. Namely, in the evaluation of meso-structural skeleton, the thicker the force chain between particles is, the stronger the resistance to deformation inside the mixture is. Generally speaking, GK skeleton void structure gradation has similar slope with the GM skeleton dense structure gradation, while XF suspension dense structure gradation has a low slope, with poor resistance to external forces. Thus, the skeleton structure effect was ranked in descending order as that of GK > GM > XF.

During the loading cyclic test in which three different gradation mixture models (30cm×15cm) were loaded on a 20cm loading plate at a rate of 0.001mm/cyc, the reaction changes between the loading plate and the bottom were monitored, with monitoring results shown in the following Table 3:

Table 3: Stress transfer rate of meso-structure of 20cm loading plate

Discrete element model	stress monitoring				
	Gradation type	Mean reaction of the loading plate/KPa	Mean bottom reaction/KPa	Maximum contact force inside the mixture/Pa	Stress transfer rate/%
30cm×15cm	Skeleton void structure	28898.70	14672.63	165104.01	50.7%
	Skeleton dense structure	22766.83	10796.30	112071.41	47.2%
	Suspension dense structure	21598.14	8845.23	110260.20	40.9%

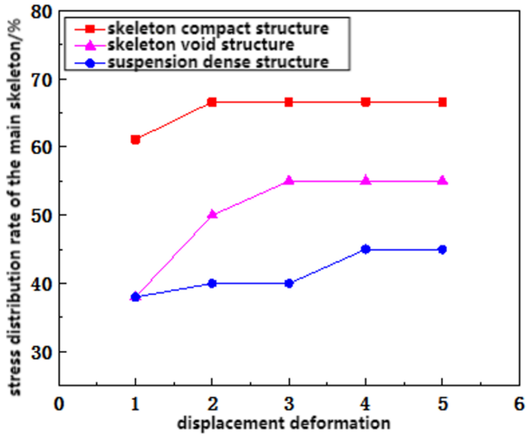

Figure 3: Relation between deformation displacement of different gradations and deformation distribution rate of the main skeleton

Figure 3 analyzes the stress distribution law of the main skeleton under different gradations during the loading process. The variation coefficient of contact force between particles in 18 measured circles was calculated under different degrees of deformation and displacement to evaluate the dispersion of force chain distribution inside the mixture. The stress distribution rate of the main skeleton is calculated as follows:

$$S_n = \frac{nA^{circle}}{A_c} \quad (1)$$

Where:

S_n——stress distribution rate of the main skeleton;

A_c——the total area of the monitored and measured circle;

n -- The number of measured circle areas greater than the average contact force

A^{circle}——single measured circle area.

Table 2 and Figure 3 reveal that GK skeleton void structure has the highest stress transfer rate, GM skeleton dense structure has moderate stress transfer rate, while XF suspension dense structure has the lowest stress transfer rate. Hence, both GK structure and GM structure demonstrate good stress transfer ability, while XF structure has no skeleton structure, with poor stress transfer effect. Therefore, for good particle skeleton structure, stress transfer rate can be used as one method for evaluating gradation skeleton level.

For the skeleton dense structure, the main skeleton stress distribution accounts for 66.6% of the entire model. During cyclic loading of skeleton dense structure, the highest main skeleton stress distribution is 55%. The suspension dense structure has the lowest main skeleton stress distribution of only 45% at the maximum. The higher the main skeleton stress distribution rate is, the better the macro mechanical performance of the mixture is. In addition, when the skeleton dense structure is cyclically loaded from 20cm to 2mm, the stress distribution rate of the main skeleton reaches the maximum, indicating that in the loading process, the internal skeleton structure effect of the mixture acts quickly and soon forms the physical transfer path, showing uniform skeleton structure stress distribution, and displaying the best mixture performance. Although GK skeleton void structure has a good skeleton structure, it lacks the filling of fine aggregate to further promote the stress transfer, so GK skeleton void structure has slightly smaller stress distribution than skeleton dense structure. The suspension dense structure has the lowest value, because too much fine aggregate greatly interferes with coarse aggregate and cannot provide sufficient stress transfer path. As a result, the suspension dense structure has poor integrity, with poor resistance to deformation and external force. In summary, the stress distribution rate of the main skeleton can be used as one index for evaluating gradation skeleton.

3. Gradation Component Design and Optimality Comparison of Skeleton Structure

3.1. Gradation Component Design

By referring to domestic and foreign research on gradation theory and design method, the C-B-3 gradation standard value in the detailed rules were used as the basis, and planning function value was taken to control the specific sieve value. 14 gradation groups were designed. JS-1 -- JS-4, JS-5 -- JS-8 and JS-9 -- JS-12 were the gradation design mainly to control the 19mm sieve pass rate, 9.5mm sieve pass rate, and 4.75mm sieve rate, respectively. Gradation design group ZD-1 (adopting coarse aggregate multilevel mixing method combined with vibration test and fine aggregate gradation design based on i method) was established after vibration multilevel mixing test [7-9], and target mix ratio gradation group XC-1 of Tonggu-Wanai expressway P4 project was taken as the control group. The gradation group is shown as follows Table 4:

Table 4: Gradation design of anti-crack cement stabilized macadam mixture

Sieve pore(mm)		31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.075
specification value	Upper limit	100	100	86	/	/	58	32	28	/	3
	Lower limit	100	90	68	/	/	38	22	16	/	0
	median value	100	95	77	/	/	48	27	22	/	1.5
JS-1		100	99.5	72.1	61.7	53.2	42.6	25.6	16.8	12.6	3.1
JS-2		100	99.4	70.3	60.5	52.5	42.6	25.6	16.8	12.6	3.1
JS-3		100	99.3	68.6	59.2	51.7	42.5	25.6	16.8	12.6	3.1
JS-4		100	99.3	69.3	58.8	50.2	39.7	25.5	16.8	12.6	3.0
JS-5		100	99.6	74.1	64.4	56.5	46.5	25.8	16.8	12.6	3.1
JS-6		100	99.7	75.2	66.8	60.0	51.3	25.9	16.8	12.6	3.1
JS-7		100	98.4	70.1	59.4	50.6	39.7	22.8	14.9	11.1	2.7
JS-8		100	98.4	70.3	60.1	51.9	41.6	24.7	16.1	12.1	2.9
JS-9		100	99.5	72.3	63.2	55.7	46.5	29.5	19.3	14.5	3.5
JS-10		100	99.6	74.3	65.8	59.0	50.5	33.3	21.9	16.4	4.0
JS-11		100	99.8	77.2	69.2	62.6	54.4	37.2	24.5	18.3	4.4
JS-12		100	99.5	72.9	62.4	53.6	42.7	25.6	16.8	12.6	3.0
ZD-1		100	99.4	71.1	60.8	52.2	41.7	25.6	16.8	12.6	3.0
XC-1		100	91.5	72.1	62.8	54.8	44.7	28.5	18.8	14.1	3.4

3.2. Optimality Comparison of Skeleton Structure

Particles of different sizes were generated according to the 14 designed gradation pass rates and placed in the discrete element numerical model of 30cm×15cm. 10cm, 20cm loading plates were used to apply load on the top of the model at a cyclic loading rate of 0.001mm/cyc until 5mm mixture deformation was reached, with speed recorded. During the loading process, optimality of skeleton structure with different gradations was compared based on internal stress of the mixture, particle force on the loading plate and the bottom. The transfer rates of different gradations are shown below:

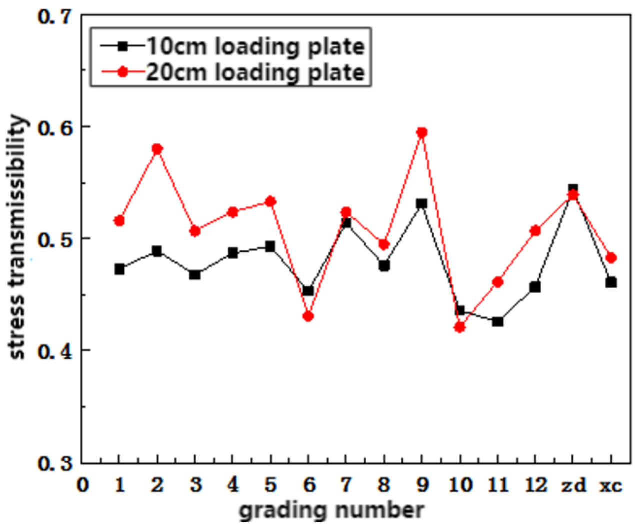

Figure 4: Stress transfer rate under different gradations

The stress transfer law differs to some extent between different gradation types. With the continuous filling of fine aggregates, the mixture gradually reaches denseness. For instance, JS-9 gradation group has optimal stress transfer rate, while the gradation groups JS-10 and JS-11 with continuously increased fine aggregates reveal fine aggregate interference to coarse aggregate, making the coarse aggregate unable to effectively form the stress transfer path, so the stress transfer rate gradually declines. In comparative optimality evaluation of skeleton structure with different gradations under 20cm loading plate, different gradation groups had an average transfer rate of 48.0%, with gradation groups JS-2, 4, 5, 7 and ZD-1 exceeding the average. Under 20cm loading plate, different gradation groups had an average transfer rate of 50.8%, with gradation groups JS-1, 2, 4, 5, 7 and ZD-1 exceeding the average, all of which demonstrated good stress transfer rate, as is shown in Figure 4.

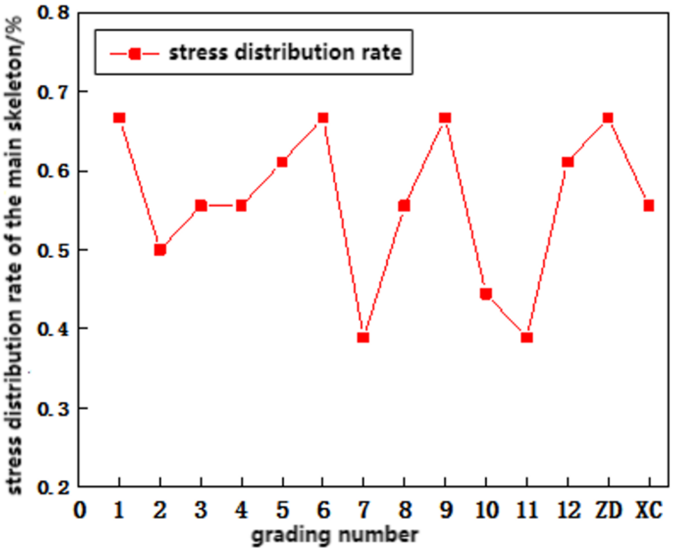

Figure 5: Stress distribution rate under different gradations

In cement stabilized macadam mixture, a greater stress distribution rate of the main skeleton reflects rich stress transfer path of the main skeleton, which indicates ability to transfer stress more effectively, so skeleton structure stability is stronger. The main skeleton stress distribution rate was analyzed for 14 groups of gradations, finding that JS-1, 5, 6, 9, 12 and ZD-1 had a main skeleton stress distribution rate of more than 60%. It is recommended that JS-5, 7, 9 and ZD-1 can be used as the base for stabilized macadam mixture based on discrete element gradation optimization method, as is shown in Figure 5.

3.3. Laboratory Test

Cement stabilized macadam mixture is used as the base material in highway engineering, with the cement dosage generally controlled between 3%-6% [7], while excessive cement dosage will easily cause shrinkage and cracking of the base. Thus, the design core of cement stabilized macadam mixture is to highlight cement stabilized strength characteristics and reduce shrinkage. In this section, the gradations derived from the meso-skeleton structure evaluation by the discrete element method in Section 2.2 were taken, including JS-3, JS-5, JS-10, ZD-1 and XC-1. After mixture of different dosages of cement to prepare specimens [10], 7d unconfined compressive strength tests were conducted in the laboratory, with test results shown below:

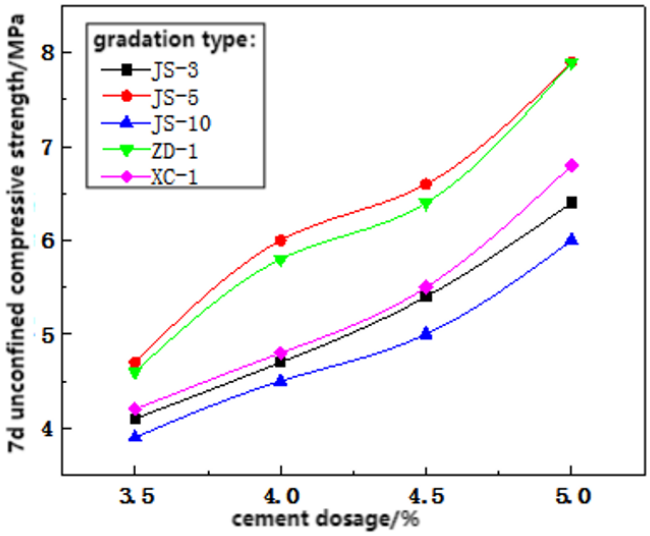

Figure 6: 7d unconfined compressive strength under different gradations

In Figure 6, the five groups of different gradations exhibit the same growth law with the increase of cement dosage. Under the same cement dosage, it can be seen that the 7d unconfined compressive strength is ranked in descending order as that of JS-5 > ZD-1 > XC-1 > JS-3 > JS-10. Seen from gradation, it is believed that in a good skeleton structure, stable skeleton is formed by the mutual intercalation of coarse aggregates, and enough fine aggregates are filled to form a good stress transfer path, so that skeleton stress transfer structure is formed rapidly between gradation aggregates, with the force transfer evenly distributed to form a more effective force transfer grid. The greater the participation rate of aggregate macadam is, the greater the resistance to external forces is and the higher the strength is. In this paper, meso-structure mechanical model was established for different gradation groups to evaluate the stress transfer rate of gradation, stress distribution rate of main skeleton, and dispersion of stress distribution, etc. It was found that the meso-skeleton structure had consistent optimality with the laboratory mechanical properties test. JS-5 and ZD-1 gradation groups were superior to other gradation groups, proving that discrete element numerical simulation evaluation has certain effectiveness in gradation optimization.

4. Conclusion

(1) Three typical gradations were established using discrete element method for numerical simulation analysis. A series of meso-structure gradation evaluation methods were obtained, such as stress transfer diagram analysis, stress transfer rate, stress distribution rate of the main skeleton, etc. The effect of meso-skeleton structure was verified, with that of GM skeleton dense structure > GK skeleton void structure > XF suspension dense structure.

(2) Certain differences were found in stress transfer law of different gradation types. In terms of stress transfer, as the loading displacement deformation increased, stress transfer paths were constantly formed between particles until a certain number was reached. A stable linear relationship was formed between the reaction force and displacement of the loading plate, which was the mechanical performance of the macroscopic loading process. Due to the great amount of coarse aggregate in the skeleton void structure, skeleton structure was easily formed, so its stress transfer rate was maximum. The suspension dense structure had discontinuous stress transfer grid and the force chain was relatively thin. Fine aggregate greatly interfered with coarse aggregate. The cracking resistance of the mixture was essentially the resistance to external force deformation of the

mixture. In terms of stress distribution of the main skeleton, the stress distribution rate of the main skeleton was used to characterize the stress distribution inside the mixture under local load. The skeleton dense structure had the best performance under the three typical gradations.

(3) Mesoscopic discrete element model was established based on 14 target gradation design groups. Analysis of the test results showed that the evaluation methods such as stress transfer rate and stress distribution rate of mesoscopic skeleton structure could be used to effectively distinguish the advantages and disadvantages of the gradation mesoscopic skeleton structure, and the numerical simulation results corresponded to the macroscopic mechanical properties in laboratory test. By using discrete element method, it is possible to evaluate and screen more levels of gradation, better solve the problem of low efficiency of traditional tests and improve the efficiency and economy in gradation design.

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