Study on Confined Compression Characteristics and Particle Crushing Law of Phyllite Waste Slag

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Abstract. The particle crushing effect of coarse-grained soil has been widely studied. This study conducted lateral compression tests under high-pressure conditions to study the compression characteristics and particle crushing laws of waste particles from tunnel excavation of phyllite. Samples with continuous and intermittent gradation were set up to analyze the physical parameters such as compression deformation law, gradation curve, crushing index, and plastic work before and after loading. The results show that the strain of each group of samples increases rapidly with stress during the loading process and then gradually stabilizes. The continuous group gradation shows good compressive bearing capacity. As the content of phyllite particles decreases, the overall deformation of the samples can be effectively reduced. Under high stress, the grading of each intermittent grading sample gradually converges to a continuous grading, with similar physical and mechanical properties. The fragmentation indicators applicable to the particles of waste rock in phyllite are B_r and B_g. Establishing a hyperbolic model to fit the plastic work and relative fragmentation rate B_r during the compression process, it was found that fitting the plastic work model can better characterize the fragmentation law of waste particles in phyllite. The research results can provide certain reference and guidance for further understanding the compression characteristics and particle fragmentation laws of soft rock waste materials such as phyllite, as well as for the filling of geotechnical engineering structures.

Keywords: Confined Compression; Phyllite; Compression Deformation; Fragmentation Characteristics; Particle Breakage

1 INTRODUCTION

With the implementation of China's "transportation power" and "western development" strategies, the construction of geotechnical structures in the western region has gradually moved towards mountainous areas. Phyllite particles are porous soft rock particles with obvious joint surfaces formed by metamorphism of shale, siltstone, and other materials. Currently, a large number of geotechnical structures have used Phyllite as filling

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material [1]. The reuse of waste materials from the excavation of phyllite in the mountain can reduce project costs and comply with the development concept of green environmental protection. Due to the low particle strength and dense pore distribution of phyllite, significant particle breakage will occur when used to fill geotechnical structures under the self-weight of the overlying soil and additional loads of the engineering structure, leading to excessive deformation and instability of the building. As a building filling material, it is easy to form a lateral compression state when subjected to external loads and surrounding constraints [2]. The study of the lateral compression deformation and particle fragmentation law of phyllite particles helps to grasp the fragmentation deformation mechanism of soft rock particle materials, and provides theoretical reference for the construction of geotechnical engineering structures in western mountainous areas.

Zeng K et al. [3] conducted triaxial compression tests on ten different gradations of coral sand and found that under the same external energy input, as the average particle size D50 increased and the non-uniformity coefficient Cu decreased, the relative fragmentation rate Br increased, while the curvature coefficient Cc had a relatively small impact on the fragmentation rate. Zhang T et al. [4] analyzed the particle fragmentation law of silica sand using high-pressure compression tests and found that when the confining pressure/axial stress is small, fragmentation occurs under smaller axial pressure. The yield stress decreases with the decrease of confining pressure/axial stress and the hyperbolic plastic work model can better describe the particle fragmentation law of silica sand. Shen J et al. [5] conducted lateral compression tests on calcareous gravel sand (CGS), and the results showed that compared to hyperbolic and Gunary models, the power function model can better predict the fragmentation pattern of CGS. When the non-uniformity coefficient increases, the fragmentation of CGS first increases and then decreases, and the degree of fragmentation decreases with the increase of relative density Dr. Huang et al. [6] conducted compression tests and discrete element simulations on spherical and angular rock particles, and the results showed that the sharper the angle, the greater the variation in the stress-strain curve during fragmentation, the greater the deviation between the crack propagation direction and the vertical direction, and the easier the particles are to break into more fine particles. Long Jiao et al. [7] measured the crushing characteristics of calcareous sand in the Nansha Islands with Hardin model. The results showed that the compression degree of calcareous sand can be effectively improved with the occurrence of particle crushing. The fitting effect of power function fitting plastic work and relative crushing Br is good, which can predict the occurrence of particle crushing. Sun Yue et al. [8] found that the plastic work and relative fragmentation rate of calcareous sand and quartz sand during lateral compression have a hyperbolic relationship. The use of a hyperbolic model can better predict the degree of particle fragmentation. When the pressure increases, the aspect ratio and sphericity of particles show a hyperbolic positive correlation with fragmentation rate. Sun Xiangjun et al. [9] studied the gradation changes of soft rock rockfill materials under triaxial compression and confining compression tests. The results showed that under low pressure, the particle breakage of soft rock rockfill materials gradually increased and then stabilized with the increase of confining pressure. The crushed gradation showed a trend towards the same gradation. Yu Bangyong et al. [10] conducted lateral compression tests on limestone of soft rock materials and analyzed the fragmentation of samples containing only continuous graded limestone components under high pressure. The results showed that an increase in Talbot index and particle fragmentation would lead to a decrease in the porosity of the samples.

In Summary:

(1) The existing research results on particle breakage are relatively sufficient for the study of calcareous sand and quartz sand, while there are few reports on the particle breakage characteristics and mechanisms of soft rock particle materials such as phyllite.

(2) For the study of soft rock particles, the research conditions are mostly low stress triaxial compression tests, and there is less discussion on the particle fragmentation law under high stress compression.

(3) For soft rock materials, current research mainly focuses on continuous graded samples with a single component, and there is relatively little research on the evolution law of the fragmentation rate of waste mixed soil and poor grading.

By conducting research on the lateral compression deformation and particle fragmentation laws of waste particles in phyllite, the influence mechanism of particle fragmentation mechanisms on macroscopic mechanical behavior of soft rocks such as phyllite can be revealed. This provides a reference for establishing a constitutive model of soft rock coarse-grained soil considering particle fragmentation conditions, and has important scientific significance for understanding the intrinsic mechanism and quantitative research of the structural mechanical behavior of soft rock particle materials. At the same time, it can better predict the stress and deformation problems of soft rock particles such as phyllite in practical engineering, predict the degree of soft rock particle breakage, prevent excessive deformation and structural instability of geotechnical engineering structures caused by particle breakage, and lay the foundation for further research and application of deformation calculation and analysis of soft rock rockfill dams, soft rock particle fillers, and improvement of phyllite roadbed fillers in related engineering practices.

2 TEST METHOD

2.1 Test Materials

The phyllite waste slag sample is made of block waste materials generated during the excavation of mountains and tunnels along the S44 Kang County to Lueyang Expressway, and its physical and mechanical parameters are shown in Table 1.

Table 1. Physical and mechanical parameters of waste slag from phyllite.

Density / $g \cdot cm^3$	Specific gr avity G_s	Average crushing value (%)	Maximum dry density after crushing d_{max} / $g \cdot cm^3$	Free swelling rate / %
2.735	2.735	29.1	2.407	0.04

From Table 2 we know the main minerals of this phyllite sample are chlorite, sericite, quartz, etc. Analyze the chemical composition of the phyllite sample using an energy spectrometer. Representative points and surfaces were selected for analysis, and the results are shown in the table below. The mineral crystals in the phyllite are fine, with strong sericite luster and fine sericite visible on the bedding planes.

Table 2. Composition of Phyllite.

Component	Fe_2O_3	SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	CO_3
Content（%）	7.35	48.28	26.95	1.55	8.42	1.00	4.33	0.70

The particle size of the waste slag collected on site is relatively large, with some large particles exceeding 500mm. In order to meet the filling requirements, the natural state of the waste slag of the shale is dried at 150 °C for 24 hours. After crushing the large particles with a jaw crusher, preliminary screening tests are conducted. Through preliminary screening, a total of 10 samples with a particle size range of 53-0.075mm are obtained for backup.

Control the maximum particle size to 53mm, and prepare mixed continuous grading group samples A1 (n=0.4) and A2 (n=0.8) according to the Talbol index (n) [11]. A1 is a small particle continuous grading group with a Talbol index of 0.4, and A2 is a large particle continuous grading group with a Talbol index of 0.8. A3 groups are equipped as uniformly graded samples for each particle group.

The formula for calculating the Talbol index (n) is as follows:

$$P_i = 100\left(\frac{d_i}{D}\right)^n \tag{1}$$

In the formula (1): n is the Talbol index, and D is the maximum particle size.

The filling materials for geotechnical engineering in mountainous areas usually use high excavation and deep filling methods for site leveling. The filling materials used are mostly a mixture of fine-grained soil and block stone materials that can be obtained locally, namely soil rock mixture [12].

Due to the similarity of physical and mechanical properties of calcareous sand to sandy soil, standard sand (ISO) was used in this study to replace sand mixed in phyllite [13]. Mixed groups B1, B2, and B3 of phyllite sand were configured according to 0%, 25%, and 50% sand content. At the same time, discontinuous mixing group C1 was set for comparative analysis. Standard sand (ISO) was prescreened to obtain a particle size of 0.6mm-0.3mm for later use. The grading schemes for each group of samples are shown in Table 3.

Table 3. Design of Grading Scheme for Waste Residues of Various Groups of Phyllite.

Grading scheme	The percentage of particle size by mass in each group /%										
(mm)	0.075-0.15	0.15-0.3	0.3-0.6	0.6-1.18	1.18-2.36	2.36-4.75	4.75-9.50	9.50-16.0	16.0-31.5	31.5-53.0	Standard Sand (ISO)

A1	2.32	3.06	4.03	5.17	6.97	9.30	12.17	11.66	19.28	18.79	0
A2	0.39	0.68	1.18	1.99	3.53	6.22	10.76	13.08	27.59	34.05	0
A3	0	0	0	0	0	25	25	25	25	0	0
B1	0	0	0	0	0	0	0	0	0	100	0
B2	0	0	0	0	0	0	0	0	0	75	25
B3	0	0	0	0	0	0	0	0	0	50	50
C1	0	0	0	0	0	50	0	0	0	50	0

2.2 Test Steps

The experiment used a steel compression drum and a YAW4306 electro-hydraulic servo press controlled by a motor as the loading equipment, as shown in Figure 1. The maximum loading pressure is 3000kN, and the stress and displacement during the experiment can be collected independently. The size of the loading container is 300mm (inner diameter) x 300mm (height) x 16mm (wall thickness), and the compression deformation measurement accuracy is 0.01mm. The inner diameter of the container (300mm) is greater than 5 times the maximum particle size of the sample (265mm), which can effectively eliminate size effects.

Fig. 1. Loading equipment and dimensions.

Before the start of the experiment, control the mass of each group of samples to be equal, with a total mass of 28Kg for each group of samples. Prepare small samples with a total mass of 7Kg for 10 groups of phyllite waste particles and standard sand (ISO) according to the preset grading percentage. Put the small samples into a sealed woven bag and mix evenly. Then, layer by layer fill a single total sample of 28Kg from 4 groups of small samples into the loading container, ensure that the surface of each layer of small samples is leveled after filling, and control the flatness of the sample end face according to the "Soil Test Method Standard" to ensure that the end face error is less than the specification requirements. Use a vibrating machine to compact the sample, and then load the samples at all levels.

In the confined compression test, the deformation of the specimen is limited by the surrounding rigid sidewall, and the relative motion between particles is weak. To eliminate the influence of strain rate on compression characteristics, this study uses the graded loading confined compression method. Before loading, Vaseline is applied to the sidewall of the container for smoothing treatment. During the loading process, a loading rate of 3KN/s is used, and the loading levels are divided into 0MPa, 3MPa, 6MPa, and 9MPa. Durning the loading process, read the loading pressure every 2mm displacement.

The criteria for determining the stable state of the specimen after compression completion in the confined compression test refer to references [14]-[15], and the "Standards for Soil Test Methods". That is, when the hourly deformation of the specimen is less than 0.01 mm, the stable pressure step can be completed, followed by unloading. After the experiment is completed, carefully remove the specimen, screen it, and obtain particle size distribution data to analyze the experimental results.

3 ANALYSIS OF EXPERIMENT RESULT

3.1 Analysis of Stress-Strain Curve

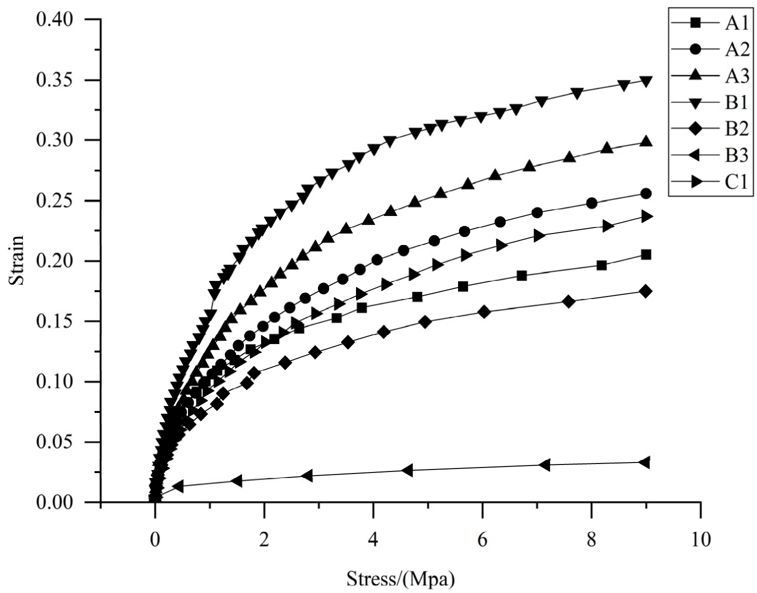


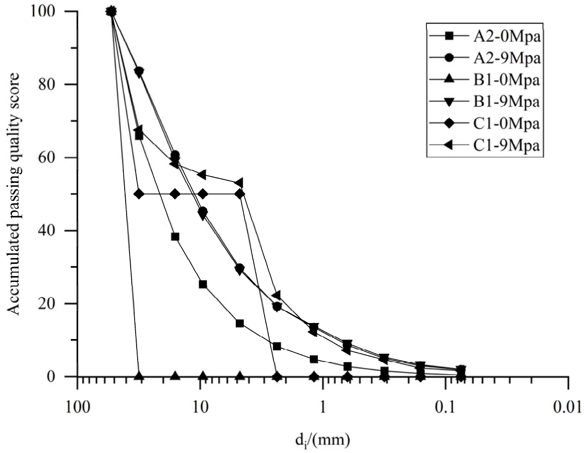
Fig. 2. Stress-Strain curve.

Figure 2 shows the stress-strain curves of each group of specimens under compression. As can be seen from the figure, the overall stress-strain behavior of each group of specimens shows that the strain rapidly increases with stress when the strain value is less than 0.1, and gradually flattens with loading when the strain value is greater than 0.1. When P = 9Mpa, the final strain value of B1 group is 0.35, and the final strain values of A2 and A3 groups with continuous gradation mainly composed of large particles are 0.26 and 0.30, indicating that better gradation continuity and wider gradation distribution can reduce the maximum strain value, when the strain value is 0.1, the stress of B1 group is 0.43Mpa, and the stress of A2 and A3 groups is 0.92Mpa and 0.67Mpa. The B1 group specimen has undergone significant deformation under low stress, and the strain growth rate of the continuous grading group is significantly lower than that of the discontinuous grading group. It is due to the fact that during the initial loading stage, only large-sized particles in the B1 group of samples bear the skeleton role in the particle group, bearing the full load. The contact points of particles inside the entire sample decrease, and the force transmitted by the contact points increases, making it easy for stress concentration to occur. Large particles quickly break, and the degree of adjustment of the position between particles due to pore space compression is large. However, the continuous and stable bearing structure of the particle grading inside the A2 and A3 groups has a stable bearing structure, the greater the stress required to achieve the same strain.

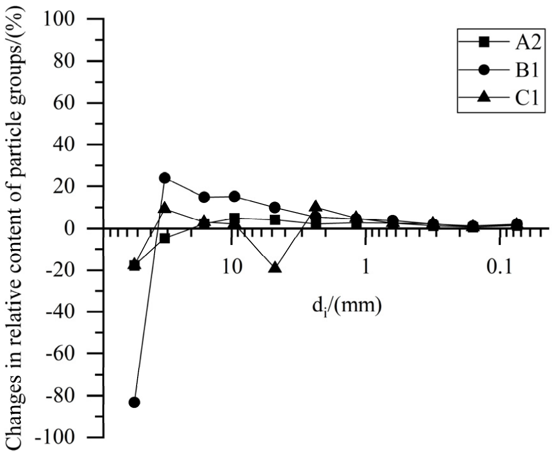
When P = 9Mpa, the strain value of continuous gradation A1 group is 0.21. When the strain value is 0.1, the corresponding stress value of A1 group is 0.93Mpa. It can be seen that the bearing capacity of good gradation A1 and A2 is better than that of poor gradation A3. In continuous gradation, the compression deformation of the sample with a wider distribution range of gradation is also smaller. When the gradation is continuous, the content of small particles of different sizes in A1, A2, and A3 groups gradually increases, small particles slip and fill under pressure, exhibiting a more stable load-bearing structure. With the increase of sand content, the strains of C1, B2, and B3 groups are 0.24, 0.18, and 0.03, respectively. The final strain values of C1, B2, and B3 groups are only 68.6%, 51.4%, and 8.6% of those of B1 group. This indicates that after the addition of calcareous sand, the frictional interlocking and embedding effects of carbonate sandstone in the particle group gradually increase, and the curve reaches the peak strain earlier and the peak strain gradually decreases. Fine sand particles with high hardness and friction angle have a certain inhibitory effect on the deformation of phyllite particles. The method of adding carbonate sandstone can improve the bearing capacity of soft rock waste to a certain extent.

3.2 Analysis of Gradation Curves Before and After the Experiment

The variation curves of the gradation and relative content of each group of samples before and after compression are shown in Figures 3 and 4:



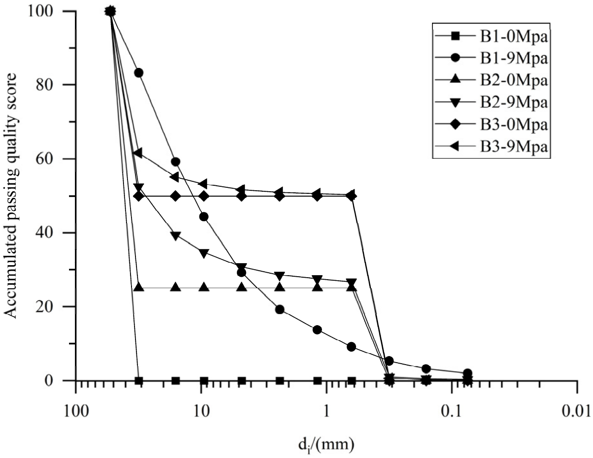
(a)



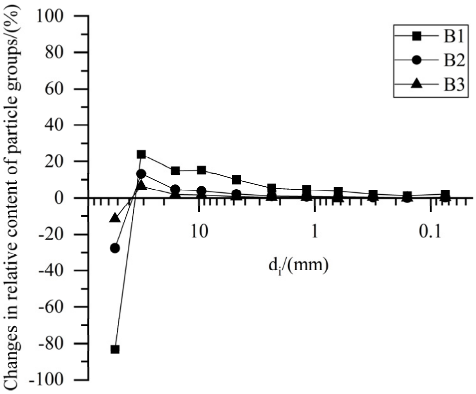
(b)

Fig. 3. The gradation changes of groups A2, B1, and C1 under the action of 9Mpa ((a) shows the gradation changes, and (b) shows the relative content changes of particle size).

From Figure 3 (a), it can be seen that when P = 9Mpa, the upward shift of the A2 curve in the continuous grading group is smaller than that in the intermittent grading group C1 and smaller than that in the single particle size grading sample B1 group. This is because the internal structural contact points of the continuous grading group A2 are more tightly connected, and when subjected to external loads, the force chain fully plays its role, with less local stress concentration. The overall bearing capacity of the particle group is good, and the amount of fragmentation is small. From Figure 3 (b), it can be seen that the inflection points of the relative content changes of A2, B1, and C1 groups first appeared at the particle sizes of 19.9mm, 35.3mm, and 37.8mm. A2 and B1 groups have 2 obvious inflection zones, while C1 group has 4 obvious inflection zones. At the same time, the maximum decrease in the content of the most granular group in B1 group is -83.25%, which is much greater than that of A2 group's -17.71% and C1 group's -19.22%. The range of fracture intervals in continuous group A2 is much larger than that of B1 and C1 groups, under high pressure, a single graded soft rock particle will experience significant fragmentation within the original grading range, while using continuous grading can significantly reduce the sudden decrease in particle size content within a certain range, and the overall curve of particle group content change is smoother. When the particle size is less than 3mm, all groups of samples enter a stable growth zone, which also indicates that the larger the particle size, the easier it is for the particles to break. Compared with single grading and intermittent grading, continuous grading exhibits lower crushing characteristics.



(a)



(b)

Fig. 4. The gradation changes of groups B1, B2, and B3 under the action of 9Mpa ((a) shows the gradation changes, and (b) shows the relative content changes of particle size).

As shown in Figure 4 (a), with the increase of sand content, the upward shift of the particle size distribution curve of soft rock under intermittent gradation can be significantly reduced. The B1, B2, and B3 groups each have only one inflection point of relative content change, with inflection points between 35-38mm. The most advantageous fragmentation range for the three groups of samples is 53-31.5mm, and the overall variation curve of particle content in B3 group is also the smoothest. The maximum reduction values of the maximum particle content in B2 and B3 groups are -27.55% and -11.63%, which are much smaller than those in B1 group samples. The range of fragmentation ranges for the three groups of samples is close. By adding other particles to the hard sandstone, the overall gradation and strength of the particle group can be improved. Small particles can initially fill the pores generated by compressive volume changes, helping to construct the overall force chain of the sample. In the later stage, it can play a good role in bearing capacity and effectively suppress the development of particle breakage.

The continuous gradation equation proposed in reference [16] is used to fit the gradation curves of each group of samples after loading, as shown in equation (2):

$$P = \frac{1}{(1-a)(\frac{d_{\max}}{d})^m + a} \tag{2}$$

Where P is the percentage by mass, and a, m are the fitting parameters.

From the fitting results, it can be seen that the fitting correlation coefficients of the continuous grading A1, A2, A3, and B1 groups are all higher than 0.99. With the increase of loading pressure, the fitting degree of the grading curves of each intermittent grading group sample also improves. The fitting results of the B2, B3, and C1 groups are shown in Figure 5. As the pressure increases, the fitting correlation coefficients of the continuous range also increase, indicating that the particle crushing effect causes the particle crushing of the intermittent grading test to transition to the continuous grading sample, At the same time, make the grading tend to be stable, and the structure in continuous grading is stable and uniformly stressed.

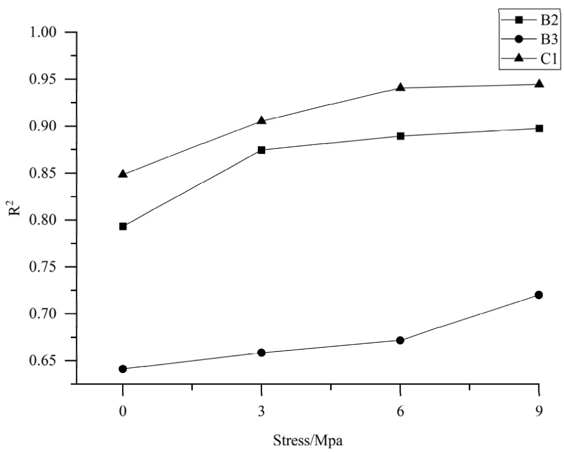


Fig. 5. Variation of correlation coefficients for fitting the grading equations of groups B2, B3, and C1.

4 PARTICLE BREAKAGE RATE ANALYSIS

4.1 Particle Crushing Index Analysis

In order to better measure the degree of fragmentation of tailings particles in the compression process, this study uses Hardin's relative fragmentation rate index B_r [17], which considers the fragmentation potential and has upper and lower limits (0-1), Marsa's fragmentation index B_g [18], which considers the difference between particle groups before and after, and Tyler's fractal dimension D[19], which is proposed in a logarithmic coordinate system, to measure the degree of particle fragmentation. The calculation formula is as follows:

$$B_r = B_t / B_p \tag{3}$$

In equation (3): B_t represents the total crushing amount, which means the area between the particle size distribution curves before and after crushing; B_p is the crushing potential, which means the initial gradation curve is related to 0 between the 0.075 particle size lines.

$$B_g = \Sigma \left| \Delta W_k \right| \tag{4}$$

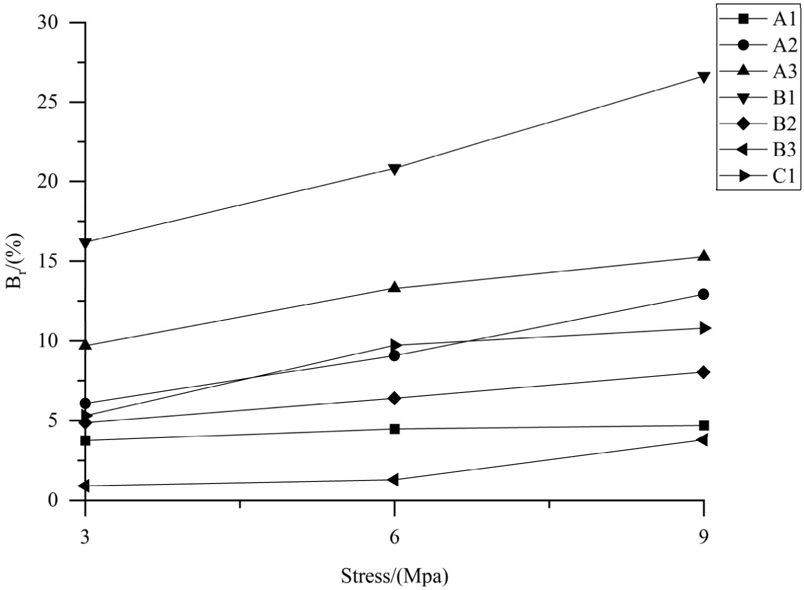
In equation (4): ΔW_k is the difference in percentage content of each particle component before and after particle crushing.

$$L_g\left[\frac{M\left(r<d_i\right)}{M_{\mathrm{T}}}\right]=(3-D)L_g\left(d_i / d_{\max}\right) \tag{5}$$

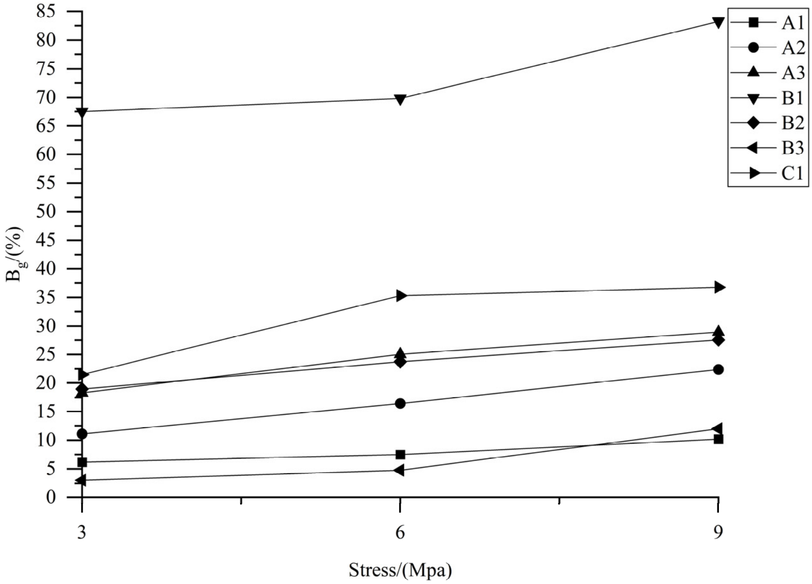
In equation (5), $M\left(r>d_i\right)$ represents the mass of particles with a particle size smaller than d_i; M_T is the total mass of particles; $d_{\max}$ is the maximum particle size within the particle group. Taking $L_g\left(d_i / d_{\max}\right)$ as the horizontal axis and $L_g\left[\frac{M\left(r<d_i\right)}{M_{\mathrm{T}}}\right]$ as the vertical axis, the slope of the line is 3-D, thus obtaining the fractal dimension D of samples with different gradations before and after the experiment.

4.2 Changes in Particle Fragmentation Index Under Different Stresses

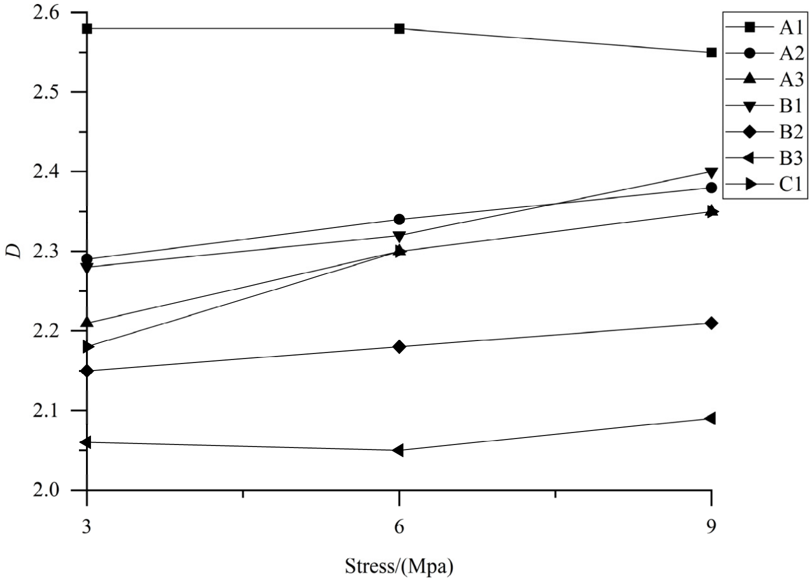
The relationship between the variation of particle breakage index under different stresses is shown in Figure 6:


A1
A2
A3
B1
B2
B3
C1
B_r/(%)
Stress/(Mpa)
0
5
10
15
20
25
30
3
6
9

(a)


A1
A2
A3
B1
B2
B3
C1
B_g/(%)
Stress/(Mpa)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
3
6
9

(b)



(c)

Fig. 6. Relationship between Particle Crushing Index and Stress Change((a) shows the relationship between *P* and B_r, (b) shows the relationship between *P* and B_g and (c) shows the relationship between *P* and *D*).

From Figures 6 (a) and (b), it can be seen that as the stress increases, the crushing rate of each gradation gradually increases. When the vertical pressure reaches its maximum value, the crushing rates Br of A1, A2, and A3 groups are 4.69%, 12.91%, 15.27%, and the crushing rates Bg are 10.22%, 22.39%, and 28.93%. It can be seen that the crushing rate of the continuous grading group is A3> A2> A1, and the maximum crushing rate of the A3 group is about 3-4 times that of the A1 group. It can be seen that the wider the distribution range of the continuous grading of the waste particles in the phyllite rock, the smaller the particle crushing rate. This also proves that using particles with continuous and excellent grading for filling engineering structures can effectively suppress the phenomenon of particle crushing.

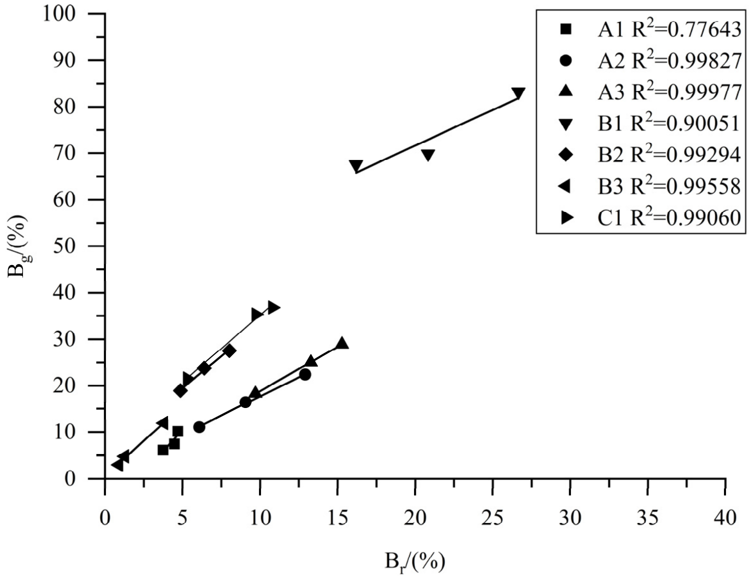
The A2, B1, B2, and B3 groups, which are mainly composed of large particles, still maintain a high crushing potential. The crushing curve is concave, while the crushing degree of A1, A3, and C1 groups, which are mainly composed of small particles, gradually slows down. The crushing curve is convex, indicating that large particles are more prone to crushing than small particles, and the crushing potential is also greater. Under the pressure of each group, the Br and Bg of continuously graded waste particles in Group A are both less than 35%. As the loading pressure increases, the Br and Bg of Group B1 and Group B2 both increases. Group B1 undergoes severe crushing in the early stage of loading, with the initial growth of Br and Bg accounting for 0.61 and 0.81 of the crushing rates under the maximum pressure. When the maximum loading pressure is reached, the crushing rate of Group B1 still has a high growth potential, its maximum crushing rate is also much greater than the maximum crushing rate of the continuous grading group sample. Profits by the uniform distribution of particles of different sizes within the continuous grading, during the initial stress, the pores are quickly squeezed, and the spatial position within the particle group is adjusted. Small particles can quickly fill the pores between the particle groups, and a complete force chain has been formed before some larger particles have undergone stress concentration. The overall compressive strength of the particle group is enhanced, and the conduction and distribution of overlying pressure are relatively uniform. As the pressure gradually increases, the directional arrangement of particle groups has been completed, forming a stable load-bearing structure. The strength and direction of the force chain have changed, and the main reason for deformation is local particle breakage, and the deformation is also relatively small. It can be seen that increasing the content of small particles has a good effect on suppressing the crushing amount and crushing development rate of waste particles in phyllite.

Comparing B3 and C1 under a stress of 9Mpa, it can be seen that the two groups of samples have the same content of large particles. By adding sand, the pure phyllite waste was improved into a mixed soil of phyllite. The Br and Bg of B3 group were only 0.35 and 0.33 times that of C1, indicating that through sand mixing and other means, the structural characteristics of the particle group were indirectly changed, and the anisotropy of the original single particle size waste particle group was increased. Due to its small volume, sand can play a structural filling role in the early stage of loading, reducing initial fragmentation. In the later stage of loading, due to its more rounded shape compared to sheet-like phyllite waste particles and excellent friction coefficient, it can wrap around the edges of phyllite waste particles to reduce the grinding and crushing of waste particles, the addition of high-strength particles such as calcareous sand through the replacement method can also effectively suppress the particle breakage phenomenon of soft rock waste.

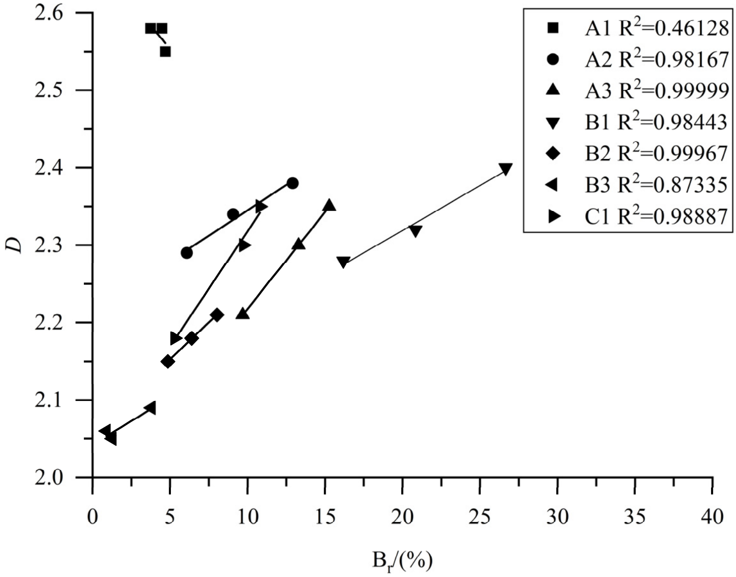
From Figure 6 (c), it can be seen that the variation of fractal dimension D is basically consistent with the variation pattern of Br and Bg. There were errors in the evaluation of some samples mainly composed of small particles, which will be discussed in the following text.

4.3 The Variation Pattern Between Different Particle Crushing Indicators

The relationship between the variation of particle fragmentation indicators with different gradations is shown in Figure 7:



(a)



(b)

Fig. 7. Variation relationship between particle breakage indicators((a) shows the relationship between B_r and B_g and (b) shows the relationship between B_r and D).

From Figure 7, it can be seen that there is a clear linear relationship between the relative fragmentation rates of Br-Bg and Br-D in each group of samples, and this linear relationship is fitted. It was found that the fitting effect between Br and Bg was good. Combined with Figures 7 (a) and (b), it can be seen that using Br or Bg can better predict and evaluate the particle breakage of waste particles in phyllite. However, for the A1, B3, and C1 groups of samples, which are mainly small in size, the fitting result between Br-D is poor. This may be due to the large variation in particle content due to the small particle size. When calculating the breakage rate and fractal dimension, it is assumed that the extremely small particles do not break, the change in the content of extremely small particles has a smaller impact on Br and Bg, but a greater impact on D. Secondly, there is a significant difference between the shape of small particles and the shape of large particles in phyllite, which leads to a stronger influence on the fractal dimension due to changes in the content of small particles within the particle group, resulting in errors, and this is also consistent with the research conclusion of Liu Yang et al. [20] on crushed stone ballast.

5 CALCULATION AND DISCUSSION OF PLASTIC WORK

In the lateral confinement compression test, plastic work is an excellent indicator for determining the load, deformation, and fragmentation laws of rockfill materials from the perspective of energy method. The analysis of particle group fragmentation laws using plastic work is to explain the process of particle fragmentation evolution from the perspective of energy dissipation. The calculation formula for plastic work is as follows:

$$W_{\mathrm{p}} = \int p d\varepsilon_{\mathrm{v}} - \int p d\varepsilon_{\mathrm{v}}^{\mathrm{e}} \tag{6}$$

In equation (6), $d\varepsilon_{\mathrm{v}}$ represents the total volumetric strain increment; $d\varepsilon_{\mathrm{v}}^{\mathrm{e}}$ represents the increment of elastic volume strain. Due to the fact that the elastic work of the waste slag of phyllite is relatively small compared to the total energy dissipation and can be ignored, the total energy dissipation is approximately the same as the plastic work. At the same time, there is basically no shear strain in confined compression. The plastic work can be simplified and calculated using equation (7) [21]:

$$W_{\mathrm{p}} = \int p d\varepsilon_{\mathrm{v}} \tag{7}$$

According to equation (7), it can be seen that according to the experimental results, the plastic work and crushing rate under different grading conditions are fitted, and it is found that the two exhibit a hyperbolic relationship. This article uses the hyperbolic function proposed by Jia et al. [22] to explore the relationship between the two:

$$B_r = \frac{W_p}{A + B \cdot W_p} \tag{8}$$

In equation (8), A and B are parameters that are related to the compression mechanical indicators of waste particles. Based on experimental data, corresponding fitting relationships are established, and the relationship between relative crushing rate and plastic work, as well as the relationship between fractal dimension and plastic work, are plotted as shown in Figure 8.

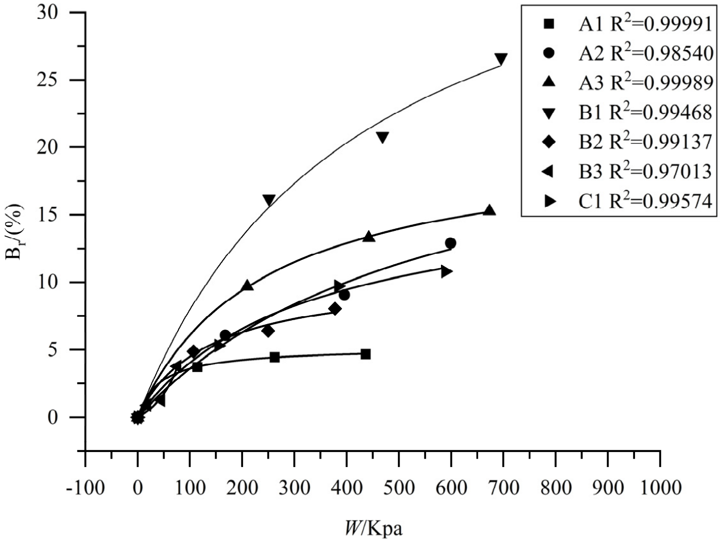


Fig. 8. Relationship between W_p and B_r.

The relative fragmentation rate under various mixing conditions shows a hyperbolic growth with the increase of plastic attack. For samples with different gradation and sand content of phyllite waste, the fitting correlation coefficients are all greater than 0.95, indicating that using a hyperbolic model can better estimate and predict the degree of fragmentation of waste samples with high accuracy. At the same time, for samples with high content of large particles and discontinuous grading of mixed soil, the fitting error is also very small, indicating that the model has wide applicability and can widely evaluate the particle crushing characteristics of phyllite waste under the condition of considering strain.

The maximum plastic work of the B1 group specimen can reach 695.16kPa, which is approximately 1.16 times that of the continuously graded A2 group specimen. At the same time, it can be seen that under the consideration of strain conditions, the plastic work of sand mixed groups B2 and B3 is only 377.69 kPa and 76.16 kPa, indicating that reducing the percentage of soft rock particles in the sample through methods such as overfilling can not only effectively reduce the particle breakage of the sample, but also have a significant effect on improving the deformation bearing capacity of the sample.

6 CONCLUSION

This article conducted lateral compression tests on waste materials of phyllite with different gradations, and obtained their compression and deformation characteristics under high pressure through comparative analysis. The variation range of particle group content and particle fragmentation law of single and continuous gradations were quantitatively obtained, and the applicability of different fragmentation indicators to waste materials of phyllite was discussed, through fitting, it was found that the hyperbolic model using plastic work has certain advantages in predicting its degree of fragmentation. The specific conclusions are as follows:

(1) The overall trend of stress-strain changes in the confined compression of phyllite waste slag is that the strain increases rapidly and then tends to stabilize. Compared with the intermittent graded sample, the continuous graded sample has better compressive bearing capacity and smaller final deformation. Its structure is more likely to form a stable load-bearing structure after being subjected to external forces. As the sand content increases, sand particles with higher hardness and friction angle can suppress the overall deformation of the sample, significantly reducing the final strain value of the sample. Under external loads, the sample is also more likely to reach a stable state.

(2) Continuous group gradation can form a good force chain transmission structure after being subjected to force. Small particles can fill the pores generated by compressive volume changes in the initial stage, which can effectively suppress the development of particle breakage. The relative content of particle groups in the most advantageous crushing interval is relatively small. Under the same pressure, using continuous group specimens can significantly reduce the crushing rate of the specimens. With the increase of experimental sand content, the overall grading and strength of particle groups can be improved, Inhibiting the development of particle breakage. With the occurrence of particle breakage, the intermittent group gradation will transition to the continuous group gradation.

(3) The fragmentation rates Br and Bg can accurately measure the degree of particle fragmentation in the waste slag of phyllite. However, when using the fractal dimension D, there is a large error. When using the plastic work considering the displacement of the sample, the fitting results between the plastic work and the fragmentation rate Br are good. The hyperbolic model can accurately characterize and predict the degree of particle fragmentation in the waste slag of phyllite, reducing the content of soft rock materials in the filling material through methods such as replacement can simultaneously reduce deformation and fragmentation.

Shortcomings of the paper and future prospects: Considering the significant differences in the shape of the phyllite samples, this study mainly considered the particle size in the sample configuration process without considering the influence of shape factors. Subsequent research can consider the different percentage of abandoned phyllite particles with different shape factors in the confined compression test for more detailed analysis.

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