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Experimental Study on the Force-Electric Coupling Characteristics of Coal Gangue during Uniaxial Compaction

Zequan He[1*], Zhongwei Wang[2] and Zhiwen Guo[2]

[1,2]State Key Laboratory for Geo-mechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou Jiangsu 221008, China.

****Corresponding Author:** **Zequan He,** State Key Laboratory for Geo-mechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou Jiangsu 221008, China.*

Abstract: *The dynamic changes of stress-strain-resistivity of bulk materials under uniaxial compression have good synchronization. In this paper, a two-phase electrode method is proposed to measure the resistivity of gangue under uniaxial compression. The resistivity change characteristics of solid backfill gangue compaction process under different proportioning conditions are studied. The results show that the resistivity decreases abruptly in the initial compaction stage, in the later stage of fracture and compaction and the stable stage of compaction, with the increase of compressive stress, the resistivity changes slightly and tends to be stable. In the initial stage of compaction, the resistivity of gangue samples with different proportions tends to decrease with the increase of proportions due to the material itself. In the later stage of stability, with the increase of the compression degree of the gangue sample, the imagination that the resistivity of the gangue increases with the increase of the proportion of the gangue is created. The above conclusions prove that it is feasible to study the mechanical properties of coal gangue bulk materials in compaction deformation by using resistivity characteristics, it also enriches the evaluation index of solid backfill effect of coal gangue.*

Keywords: *uniaxial compression; solid backfill; resistivity; backfill mining*

1. INTRODUCTION

With the rapid development of the national economy and the increase of energy demand, China's primary energy has long been dominated by coal. However, with the massive exploitation of coal resources, "three under" (under buildings, under railways, under water) coal pressure problem is becoming more and more prominent, seriously affecting the normal production of many mining enterprises. On the other hand, coal production is accompanied by the discharge of a large number of solid waste gangue, its traditional treatment is lifted from the underground to the surface of the accumulation, forming a unique surface feature of the coal mine "building" - gangue hills, occupying land, polluting the environment, endangering human safety [1]. In view of the above problems, China University of Mining and Technology has developed a solid filling mining technology, which transports solid filling gangue to the mine goaf through specific transport equipment and fills the goaf, so as to support the roof and control the movement and deformation of overburden. This technology can not only effectively solve the problem of "three under" coal pressure, but also play a very good role in dealing with the accumulation of solid waste in mines [2-3].

Different from the traditional caving method, when the gob roof is managed by solid filling mining technology, space left after coal mining is occupied by the solid backfill materials. Under the action of self-weight and mine pressure, overlying rock produces pressure on the solid backfill material, and the solid backfill body is gradually compacted. As a typical bulk material, the study of mechanical properties of the solid backfill materials in the process of compaction can provide theoretical basis for grasping the basic characteristics of filling and overburden deformation, and for understanding the basic law of overburden deformation in filling stope. A large number of scholars have done a lot of research on the compaction characteristics of solid backfill materials, and have obtained rich research results and practical experience. Y.J. Zang analyzed the strength and deformation characteristics of coal gangue bulk, and then analyzed the influence of water on the strength and deformation characteristics of coal gangue [4]. Through the compaction test, consolidation test, permeability test, CBR test and direct shear test, J.Q. He studied the influence of coal gangue on the engineering mechanical properties of coal gangue [5]. X.J. Deng carried out an experimental study on the pressure transfer characteristics of backfill materials with different particle sizes, the results show that the backfill materials with larger particle size have higher pressure transfer characteristics, while the backfill materials with smaller particle size have poorer pressure transfer ability [6].

According to the above concepts, it can be understood that the previous study on the compaction and filling characteristics of coal gangue filling materials is based on the compression deformation, and there is little research on the resistivity measurement and characteristic analysis of solid filling gangue. The study on the resistivity of filling gangue materials was carried out, and the characterization method of using resistivity characteristics to reflect the compaction process of gangue was put forward, which enriched the evaluation index of solid filling effect of coal gangue. Scholars at home and abroad have studied the resistivity characteristics of rock mass, soil and concrete. G.Y. Chen and Y.M. Lin studied the electrical effect of compressive stress on rock and proposed and verified the state equation of rock fracture law [7]. S. Kahtaman and T. Yeken tests show that uniaxial compressive strength and tensile strength of igneous rocks are linearly correlated with resistivity [8]. G.H. Liu carried out orthogonal experimental study on four factors affecting water content, pore water resistivity, saturation and soil resistivity, and concluded that the influence degree of these four factors decreased in turn [9]. L.X. Xiao tested the 24h resistivity and 24D compressive strength of different types of cement mortar respectively. Through data fitting, it is concluded that there is a linear relationship between them [10]. Ramezanianpour used cement、coarse and fine aggregate as basic materials, respectively, adding tuff, pumice, rice husk powder and metakaolin, and made 57 groups of samples according to different proportions. The resistivity and compressive strength of the samples were tested for 7 days and 28 days respectively, and the results showed that only cement was contained in the samples. The linear relationship between resistivity and compressive strength is relatively high [11]. G.Y. Zhang measured the resistivity of the grouting material with high content of fly ash in liquid state by using an electrode-less resistivity tester [12].

In this paper, the resistivity characteristics of gangue samples in the whole process of uniaxial compression are studied. Considering the influence of gradation on resistivity characteristics, the deformation of filling materials under compression is studied by means of universal press and resistivity testing device, the relationship between the deformation of backfill and resistivity is understood.

2. TESTING PROGRAM

2.1. Test Materials

The gangue samples in the filling materials come from the washing gangue discharged from the coal preparation plant in the gangue hill. The maximum diameter of the gangue is 30 mm. In order to ensure the integrity of the test sample, the sample was sealed to prevent the change of moisture content.

According to the relevant literature [13], the compaction rate of gangue was the smallest under the condition of original gradation (natural state). Therefore, this experiment adapt the natural state of washing and selecting gangue, and taken the washing and selecting gangue as the test sample before the test. The samples were divided into 5 groups, and the particle size of the original gangue was 0-30mm. In order to classify the original gangue in the next step, a special sieve was designed to classify the original gangue. The sizes of the sizes were 0-5mm, 5-10mm, 10-15mm, 15-20mm, 20-25mm and 25-30mm. Grading according to the theory of Tai Po:

$$P = 100(d / D)^n \tag{1}$$

P: the percentage of each particle size of the gangue, %;

D: the maximum particle size of the gangue, mm;

d: the current particle size of the gangue, mm;

n: the test index, n is 0.4-0.7;

According to the Thai wave formula, the value of n is 0.4-0.7, and the grade ratio of continuous graded gangue can be obtained as shown in **Table 1**.

Table1. *Grading of Continuous Graded Gangue*

n	P					
	0-5mm	5-10mm	10-15mm	15-20mm	20-25mm)	25-30mm
0.4	48.86	15.60	11.34	9.24	7.93	7.03
0.5	40.83	16.92	12.97	10.94	9.63	8.71
0.6	34.15	17.60	14.24	12.43	11.22	10.36
0.7	28.54	17.81	15.22	13.73	12.72	11.98

2.2. Test Device and Method

The test system includes: pressure system, compaction sleeve, electrode matching device and electric detector.

2.2.1. Pressure System

The pressure system is controlled by electro-hydraulic servo pressure testing machine with axial stress loading mode. The maximum axial compressive stress is 20MPa. The axial pressure is loaded according to 1KN/s speed. The test curve is displayed in real time and the test data is recorded automatically through the pressure control system.

2.2.2. Compaction Sleeve

The compaction sleeve includes three parts: plastic sleeve, steel sleeve and pedestal, as shown in **Fig 1**. The plastic sleeve and the base are fastened by dislocation to facilitate disassembly, and the outer side of the plastic sleeve is provided with steel sleeves. The inner part of the plastic sleeve is provided with a piston which is sliding and matching with the inner wall of the plastic sleeve, so that the piston can move up and down in the plastic sleeve. The piston is provided with a force transmission rod connected with a pressure system, and the plastic sleeve and the piston are provided with boreholes conducive to the derivation of the copper electrode line. The steel sleeve wall is drilled with screw holes, and the steel sleeve is fixed with the plastic sleeve by screws. In order to eliminate the friction between the piston and the cylinder wall during the test, when processing cylinders, the upper, bottom and cylinder walls must be polished. Taking into account the insulation factor, an insulating pad is placed on the part of the piston contacting with the material. According to the design of the compaction sleeve, the diameter of the cylinder is 200mm, the height is 175mm, and the thickness of the insulating cylinder is ignored.

Fig1. *Schematic Diagram of Compaction Sleeve*

2.2.3. Electrode Matching Device and Electric Detector

When studying the change of resistivity related parameters of gangue specimen under uniaxial loading, it is appropriate to calculate the resistivity related parameters during compression loading by using two-phase electrode method (by directly measuring the voltage drop at both ends of the sample). The thin copper plate with 2mm thickness is used as the electrode on the base， the diameter of the electrode is the same as that of the insulating sleeve or the diameter of the indenter of the loading device. as shown in **Fig 2**.

Fig2. *Schematic Diagram of Electrode Plate*

Then the conductive glue is applied on the electrode plate, and the sample is mixed evenly into the sleeve. Another copper plate electrode is placed after the surface is smooth, conductive glue is applied on the contact surface between the electrode plate and the sample. The insulating pad and piston are placed above the electrode plate, the base and the insulating pad and the side wall of the piston are engraved with appropriate grooves. The appropriate size of the groove is carved on the base, on the side wall of the insulation pad and piston. The conductor is embedded in the groove and exported out of the barrel, on the one hand, it acts as insulation, on the other hand, it also acts as a good protection for the conductor. As shown in **Fig 3**.

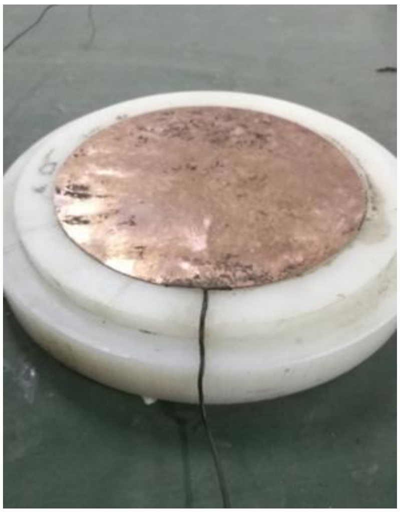

Fig3. *Schematic Diagram of Iinstallation of Traverse*

Then the upper and lower electrode lead is connected to the resistance tester. This test uses the resistance tester as shown in **Fig 4**. Through connecting the upper and lower electrode lead, the resistance R of the sample is measured directly. Then the resistivity data in the process of gangue compaction is obtained by formula：

$$\rho = R\frac{S}{\mathrm{L}} \tag{2}$$

S: the area of cylinder inner ring.

L: Compacting height

Fig4. *Resistance Measuring Device*

At the same time, the data acquisition system is opened. The measured values of axial pressure and displacement are converted into the values of stress and strain, and the values of resistance are converted into the measured values of resistivity by using the formula. Through data processing, the corresponding relationship between strain and strain under uniaxial load is achieved.

3. Test Results and Analysis

3.1. Analysis of Compaction Characteristics of Solid Filling Gangue

In order to measure the strain values produced by solid backfilling gangue specimens during compaction deformation, Defining the formula for strain ε :

$$\varepsilon=\Delta h/h \tag{3}$$

Δh ： Compressibility

h: sample height

The sifted gangue is evenly mixed according to the size distribution, 20 MPa axial pressure is applied to the mixed sample. The stress-strain curve of the compressed gangue is shown in **Fig 5**.

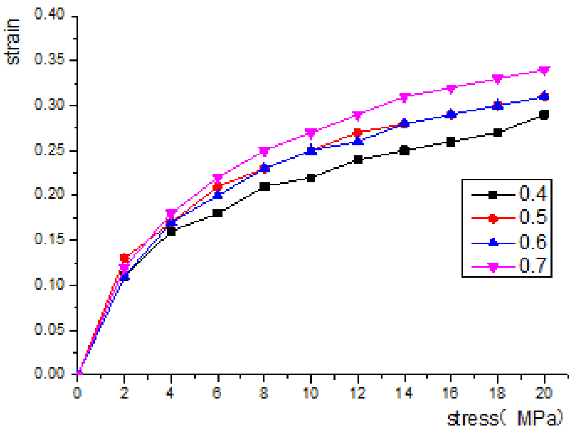

Fig5. *Stress-strain Curve of Gangue*

According to **Fig 5**, the strain of gangue increases with the increase of stress and the whole is logarithmic curve. According to the stress-strain curve, the compression process can be roughly divided into 3 stages:

In the initial compaction stage, under the action of axial stress, the gangue blocks are extruded each other and the gap decreases. Under the lower load, the strain growth rate of the specimen is small, and the deformation is easy. The larger strain is produced under the smaller stress.

In the stage of gangue crushing and compaction, with the increase of axial stress, the interaction force and extrusion degree of gangue become higher and higher. The larger particle size and harder gangue are crushed and fractured, the voids are further filled, and the volume shrinkage of the sample is obvious. The gangue is gradually compact, and the deformation is difficult, and the strain growth rate is smaller. Comparing with the first stage, the compaction process of gangue changes from micro-fracture to crushing and compaction, and the stress-strain curves show obvious concave characteristics.

In the stable compaction stage, when the axial pressure increases to a certain extent, most of the gangue is broken and deformed under the action of pressure. The gap between the gangue is pressed and filled. and the sample is pressed into an approximate whole structure. Even under high pressure, the compression increment is very small, and the pressure-strain curve shows a horizontal curve.

3.2. Resistivity Analysis of Solid Filling Gangue Compaction Process

The resistivity measurements of natural gangue specimens in compaction process were carried out under different particle size ratios. Two samples of each proportion are made to prevent errors. After processing the data, the electrical resistivity characteristics of solid filling gangue under different physical conditions are analyzed.

Fig 6 shows the compression stress resistivity curve of the sample with natural ratio of 0.4. It can be clearly seen from the diagram that resistivity decreases as a whole in the process of gangue compaction. In the beginning of pressurization, the resistivity is in a higher value, when the axial pressure increases gradually, the resistivity value decreases rapidly, and finally the resistivity tends to be stable.

According to the three stages of gangue compaction, the compressive stress increases from 0 to 25KN and the resistivity decreases from 3.0M.m to 0.25M.m in the initial compaction stage. The reason is that the pores between the particles are gradually closed, the gangue sample is compacted, the material contacts with the electrode plate better, the conductive environment is improved, and the resistivity is decreased.

In the later stage of fracture and stable compaction, the resistivity changes slightly with the increase of compressive stress. The compressive stress increases from 25KN to 308KN, and the resistivity changes from 0.25MΩ.m to 0.42MΩ.m. The reason is that the particles are further broken and the voids between the particles are filled with small particles. The contact between the material and the electrode plate is sufficient, and a stable equilibrium state is achieved, resulting in no obvious change in the resistivity at this stage.

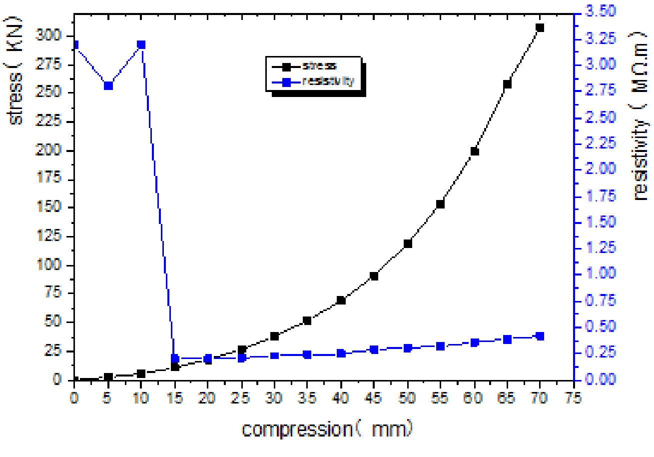

Fig6. *Compressibility-Stress-Resistivity Curve of Specimen with Natural Ratio of 0.4*

3.2.1. Influence of Particle Size Ratio on Electrical Resistivity Characteristics During Solid Fill Gangue Compaction

Considering the influence of particle size ratio on resistivity characteristics of gangue materials, the resistivity of gangue samples with different particle size ratio during compaction was measured and statistically analyzed, as shown in **Fig 7**. **Fig 7** shows that the initial resistivity of gangue samples with different proportions is different, but with the increase of axial pressure, they all show a downward trend, and finally remain stable. However, the decline trend of resistivity of 0.6 and 0.7 gangue samples during compaction is not obvious, especially for 0.7 gangue specimens.

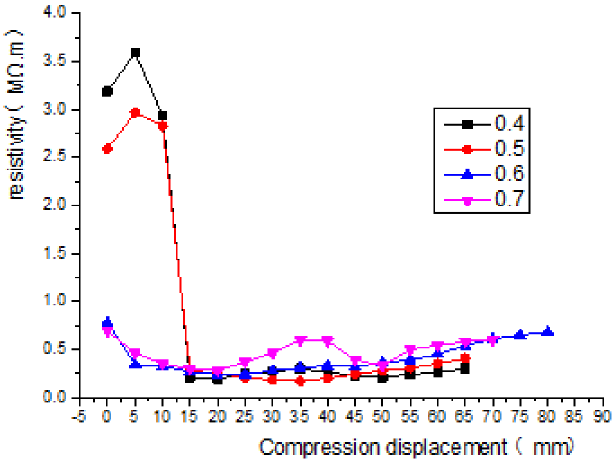

Fig7. *Resistivity diagram of different proportions of natural state*

In the initial stage, the resistivity values of the gangue samples decrease with the increase of the proportioning series. The reason is that gangue belongs to solid electrolyte, the resistivity is high ((generally more than 106Ω.m), and the current can hardly be transmitted through the skeleton, and is mainly transmitted through the solution between the pores. For different rate of gangue samples, the increase of the ratio corresponds to the increase of the interstitial voids between the particles, which is conducive to the conduction of the solution between the particles, and leads to the decrease of the resistivity. But with the increase of pressure, the gap between particles is gradually compressed, and the material is fully contacted with the electrode. The conductivity of the material itself occupies the dominant position and the conductivity increases, resulting in the resistivity shows a downward trend with the increase of pressure.

The above mentioned phenomena are found in gangue samples of 0.6 and 0.7. The reason for the analysis is that the ratio of large particle to gangue samples in material is much higher than that in the previous two groups. The dispersion of the material is larger in the early stage, and the uncertainties such as voids in the medium have more influence. As a result, the material contact with the electrode plate and other factors may not be as effective as the ahead two groups, the medium-term fluctuation is intense.

Fig 8 shows the resistivity contrast diagram of gangue samples with different proportions at the later stable stage (stress up to 20MPa). It can be found from the diagram that resistivity increases from 0.3MΩ.m to 0.68MΩ.m with increasing ratio. This is due to the decrease of fine particle content with the increase of the ratio. Even in the same compressive stress state, the pore of the sample with small proportion is easy to compress more fully, and the material contacts with the electrode more fully. As a result, the final conductivity is also higher than that of the larger proportion, which leads to the imagination that the resistivity increases with the increase of the ratio.

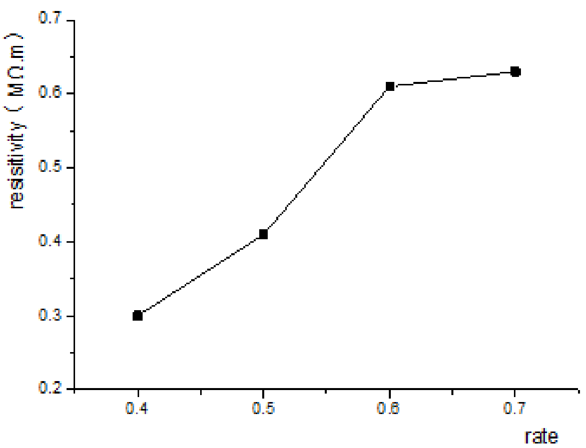

Fig8. *Resistivity curves of gangue samples with different proportions in stable stage*

4. CONCLUSIONS

On the basis of previous studies, the resistivity response characteristics of uniaxial compression solid backfill gangue samples were studied. The following conclusions are drawn:

The gangue specimen undergoes three stages of preliminary compaction, fracture compaction and overall stable compaction during uniaxial compression and the stress-strain curve is logarithmic.

The resistivity characteristics of gangue samples during uniaxial compression are closely related to the changes of particle breakage, void filling and compaction. In the initial compaction stage, the gangue samples are pressed, and the pores between the particles are gradually closed. The better contact between the material and the electrode plate improves the conductive environment, there is a sharp decline in resistivity. In the later stage of fracture and stable compaction, the particles are further broken and the voids between the particles are filled by small particles. The contact between the material and the electrode plate is sufficient, and a stable equilibrium state is achieved, resulting in no obvious change in the resistivity at this stage.

Considering the influence of particle gradation, the resistivity decreases gradually with the increase of the proportion due to the material properties of the gangue. As the pressure increases, the gap between particles is gradually compressed; resulting in an increase in pressure, the resistivity of gangue samples shows a downward trend. In the later stable stage (stress up to 20MPa), with the increase of the ratio, the pore of the sample with small ratio is easy to compress more fully, and the contact between the material and the electrode is more sufficient. As a result, the final conductivity is higher than that with large ratio, which leads to the imagination that the resistivity increases with the increase of the ratio.

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AUTHOR'S BIOGRAPHY

Zequan He, Master, is a graduate student in the Faculty of mechanics and civil engineering, China University of Mining and Technology. The tutor "Feng Ju" is an Associate Research Fellow at the State Key Laboratory of deep geotechnical and underground engineering, China University of Mining and Technology. Under the guidance of the tutor, the author mainly studied the mechanical characteristics of solid filling gangue, and participated in many national and enterprise projects.

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