# EXPERIMENTAL STUDY ON LATERAL COMPRESSION CHARACTERISTICS OF FLY ASH SLURRY FILLED WITH SEPARATE LAYER

by

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*The spatiotemporal evolution of multiple key layers overlying strata in thick coal seam has always been one of the key and difficult problems to be solved in the field of stratified filling, and the confined compression characteristics of fly ash slurry are the main influencing factors. In this paper, the lateral compression and viscosity test of filling materials were carried out, and the shear stress and plastic viscosity of filling materials were studied. The results show that the strain of fly ash in the initial stage of compaction accounts for 64.8% of the final strain. When the fly ash slurry is pressed, the stress increases exponentially with the strain, and the volume weight has a logarithmic relationship with the compaction stress. Both shear stress and plastic viscosity decrease negatively with the increase of water-cement ratio. When the ratio of fly ash to water to cement is controlled between 1.2 and 1.4 and the mass concentration is controlled between 41.7% and 45.5%, the slurry fluidity, pumpability and grouting efficiency are high.*

Key words: *separated pack, confined compression, fly ash slurry, uniaxial compression*

## Introduction

More than 90% of China's coal production comes from mining, and the huge mining intensity and scale make the ground collapse in coal mining area serious. According to the current production scale, the current reclamation rate of coal mining subsidence area is only about 35% [1]. Due to its special physical and chemical properties, fly ash has been applied in the fields of agriculture, construction and environmental protection [2].

Up to now, filling mining is an important technical means to liberate *three coal* resources. Academician Qian *et al*. [3] proposed that after the initial mining, before the key layer in the overlying strata was broken, the rock layer would bend and deform in the form of elastic foundation plate or beam structure, and then the lower part of the key layer would have unco-ordinated deformation, that is, the overlying strata separated. Guo [4] proposed a method to solve the development volume of the stratospheric space by quadratic integration. Ma [5] proposed

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that adjacent rock layers with a difference of more than 2 Pratt coefficients would produce separate layers with the progress of underground mining activities. Jia [6] proposed that the filling paste material with aeolian sand as aggregate has good pumping performance when the concentration is less than 72%. Wang *et al*. [7] proposed that the gelling compound formed by calcium oxide in fly ash was the main cause of grouting pipe-line blockage. Wang *et al*. [8] proposed that ultra-high water materials could be used as filling materials for off-bed grouting and water plugging in fracture zones.

To sum up, the previous studies on the grouting of overlying strata mainly focus on rock movement and grouting technology. The mechanical and flow characteristics of separated layer grouting filling materials need further study.

## Project profile

### *Engineering geological condition*

The test coal mine is located in Xiangyuan County, Changzhi City, Shanxi Province, The coal seam No. 3 of Shanxi Formation is mined by fully mechanized top coal caving with an average thickness of 5.5 m and an average burial depth of 620 m.

After the implementation of off-bed grouting, the rock interstice below the grouting level and the broken rock mass in the gob will be consolidated by high pressure slurry, and the rock interstice between the grouting level and the top of the caving zone can be ignored. The surface subsidence of the off-bed grouting working face is $S_b$, the mining height of the working face is $M$.

The surface settlement of the separate layer grouting face, $S_b$, is:

$$S_b = M - H_c\left(k'_p - 1\right) - \frac{\dfrac{WM\alpha}{W - H_1}}{\tan\beta} \tag{1}$$

where $\alpha$ is the injection-production ratio, $k'_p$ – the residual crushing coefficient of rock strata in caving zone, $H_c$ – the height of caving zone, $\beta$ – the full mining angle of the working face, $W$ – the width of the working face, and $H_1$ – the grouting level height.

It can be seen from eq. (1) that the main factors affecting the maximum surface subsidence are the mining height of the working face, the injection-production ratio, the height of the grouting layer and the width of the working face. Because the overburden pressure varies with the depth of off-bed grouting filling, the compaction degree of backfill also greatly affects the settlement reduction effect, so it is necessary to study the confined compression characteristics of fly ash slurry filling materials.

## Compaction characteristics of filling materials

### *Experimental equipment and scheme*

The main instrument used in the experiment is the slurry compression instrument, The specific operation flow of the slurry compressor is shown in fig. 1. First of all, the base with a guide tank is fixed on the mortar barrel, then the inner wall of the steel barrel is evenly coated with lubricating oil, the permeable plate is installed, and the filter screen is laid on the permeable plate. Then the fly ash slurry is added to the compressor, aligned with the piston, and the press is started.

The press used is an electro-hydraulic servo universal testing machine with a rated load of 100 kN. The change of axial pressure and displacement over time was recorded during the experiment.


**Figure 1. Compaction test flow; (a) install the permeable plate, (b) add fly ash paste, (c) compaction, and (d) remove cake**

## Experimental results and discussion

### *Strain-stress relation curve of fly ash*

After mixing the fly ash slurry with a water-cement ratio of 1.22 evenly, the axial pressure of 25 MPa is applied, and the stress-strain curve of the fly ash under pressure is shown in fig. 2.

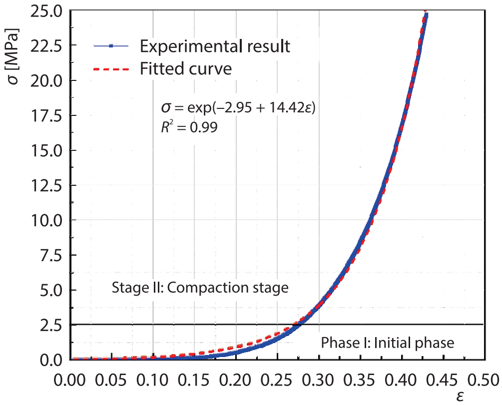


**Figure 2. Stress-strain relationship curve of confined compression fly ash**

It can be seen from fig. 2 that the strain of confined compressed fly ash increases exponentially with the increase of axial stress. The fitting equation is $\sigma = \exp(-2.95 + 14.42\varepsilon)$. When the stress is 0~2.5 MPa, the compaction of fly ash is in the initial stage, the strain growth rate is large, and the fly ash is easy to compress. When the pressure continues to increase, the fly ash is gradually dense and enters the compaction stage. At this time, the deformation is difficult and the strain growth rate slows down. In the whole compaction process, the maximum strain value of fly ash can reach 0.4256, and the strain in the initial stage accounts for 64.8% of the final strain.

### *Change law of stress and bulk density of fly ash*

The change curve of bulk density of fly ash with stress is shown in fig. 3.

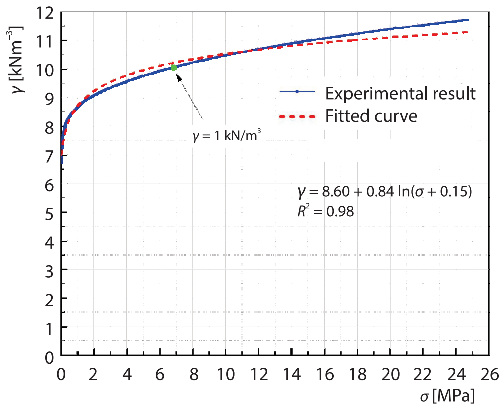


**Figure 3. volumetric weight-stress relationship curve of limited-compression fly ash**

As can be seen from fig. 3, the bulk weight of fly ash in the granular state is about 6.98 kN/m$^3$. With the increase of pressure, fly ash is gradually compacted, and the bulk weight also gradually increases. In the initial stage of stress from 0 to 2.5 MPa, the volume weight increases rapidly, and then enters the fly ash compaction stage, where the volume weight increases slowly. When the pressure reaches 6.48 MPa, the bulk density of fly ash is 10 kN/m$^3$, which is equal to that of water. During the compaction process of fly ash slurry, the volume weight and pressure increase logarithmically, and the fitting equation is $\gamma = 8.60 + 0.84\ln(\sigma + 0.15)$.

## Fly ash slurry flow characteristics

A large number of engineering practices show that excessive slurry concentration leads to increased viscosity, increased pumping energy consumption, and increased pipe-line clogging risk. If the slurry concentration is too small, the same injection amount of fly ash needs more water as a carrier, which reduces the grouting efficiency. The flow characteristics of grout affect the flow diffusion of grout for long distance pumping and grouting. Therefore, it is necessary to carry out experimental research on the flow characteristics of fly ash slurry.

### *Test material pretreatment*

In order to eliminate the influence of moisture absorption of fly ash on slurry viscosity test, it is necessary to pre-treat the fly ash collected on site. The processing steps are:
- Pulverize the fly ash that may be damp bound, as shown in fig. 4(a).
- The incomplete pulverized fly ash is screened with a 50-mesh sieve to make it free of gravel, as shown in fig. 4 (b).
- The dried pulverized and sifted fly ash is shown in figs. 4(c) and 4(d).

**Figure 4. Pretreatment of experimental materials; (a) experimental material crushing, (b) test material sifting, (c) experimental drying material, and (d) experimental material after drying**

### *Test equipment and scheme*

The flow characteristics of the fluid can be measured by a rotary viscometer, which is based on the principle of using a calibrated beryllium-copper alloy spring to drive the rotor in the fluid continuous rotation, and the drag force generated by the fluid on the rotor is measured by a torque sensor to measure the viscosity of the slurry.

Fly ash was configured into 14 kinds of slurry with different water-cement ratio, and 3 groups of tests were carried out for each water-cement ratio, with a total of 42 groups. The selected water-cement ratios are 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 3, 4, 5, 6, 7, and 8. The ash and water quantity required for the test are shown in tab. 1. In the viscosity test, a beaker with a diameter of 70 mm is used to stir the configured slurry evenly, and the lifting knob is rotated so that the viscometer rotor is slowly immersed in the slurry to be measured. When the scale line on the rotor connecting rod is level with the liquid level, measurement begins and data is recorded.

### *Experimental results and discussion*

Fly ash grout belongs to the Bingham fluid of non-Newtonian fluid. When the grout is at rest, the solid particles in it can form a temporary stable spatial network structure. Only when the applied external shear stress exceeds its cohesion, the slurry has the flow ability.

Slurry flow test measured the shear stress (laboratory temperature 15 °C, shear rate 28 $s^{-1}$) and plastic viscosity of fly ash slurry with different water-cement ratios. According to

**Table 1. Amount of ash and water used by each solution in viscosity test**

| Project | Water cement ratio | Water quality | Fly ash quality | Mass concentration | Water cement ratio | Water quality | Fly ash quality | Mass concentration |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.6 | 300 | 500 | 62.5% | 2 | 300 | 150 | 33.3% |
| 2 | 0.8 | 300 | 375 | 55.5% | 3 | 300 | 100 | 25% |
| 3 | 1 | 300 | 300 | 50% | 4 | 300 | 75 | 20% |
| 4 | 1.2 | 300 | 250 | 45.5% | 5 | 300 | 60 | 16.7% |
| 5 | 1.4 | 300 | 214.3 | 41.7% | 6 | 300 | 50 | 14.3% |
| 6 | 1.6 | 300 | 187.5 | 38.5% | 7 | 300 | 42.9 | 12.5% |
| 7 | 1.8 | 300 | 166.7 | 35.7% | 8 | 300 | 37.5 | 11.1% |

the test results, the change curves of slurry shear stress and plastic viscosity with water-cement ratio were plotted, respectively, as shown in fig. 5.

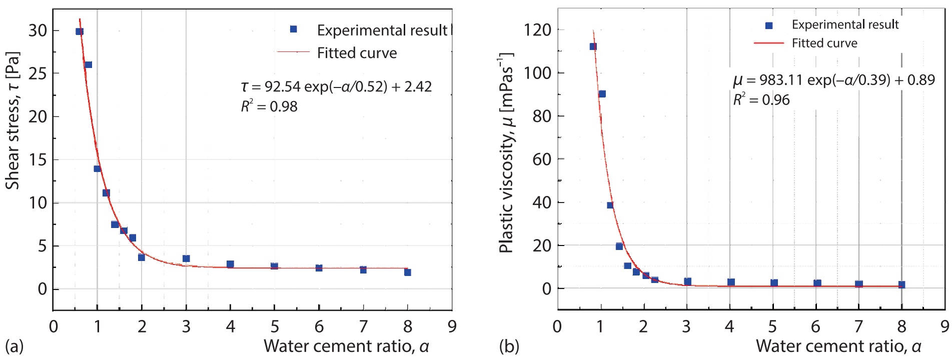


**Figure 5. Measurement results of coal slurry flow test; (a) curve of slurry shear stress with water-cement ratio and (b) curve of grout plastic viscosity with water-cement ratio**

It can be seen from fig. 5 that both the shear stress and plastic viscosity of the slurry decrease negatively exponentially with the increase of the water-cement ratio. When the water-cement ratio is less than 1.2, the growth rate of plastic viscosity is significantly larger, and when the water-cement ratio is greater than 1.4, the influence of the plastic viscosity on the water-cement ratio of slurry is significantly reduced. It is proved that when the water-cement ratio of grout is less than 1.2, the pump-ability and flow diffusion ability of grout become worse. When the water-cement ratio of fly ash slurry is between 1.2 and 1.4, the mass concentration is controlled between 41.7% and 45.5%, the slurry viscosity is small, the flow is good, the diffusion radius is large, and the grouting efficiency is high. At this time, the corresponding specific gravity of the slurry is 1.35-1.45, and the pump-ability and grouting efficiency are good, which can effectively control the surface settlement. Therefore, it is recommended to control the water-cement ratio of fly ash slurry in the project between 1.2 and 1.4.

## Conclusion

The physical and mechanical characteristics of the overlying rock and the compaction and flow characteristics of the fly ash grout are mainly measured, and the main conclusions are The strain of fly ash in the initial stage of compaction accounts for 64.8% of the final strain. When the fly ash slurry is pressed, the stress increases exponentially with the strain, and the fitting equation is $\sigma = \exp(-2.95 + 14.43\varepsilon)$. The bulk weight of fly ash in bulk is about 6.98 kN/m$^3$, and when the compaction stress is 6.48 MPa, the bulk weight of fly ash is 10 kN/m$^3$. In the compaction process of fly ash slurry, there is a logarithmic relationship between bulk density and compaction stress, and the fitting equation is $\gamma = 8.60 + 0.84\ln(\sigma + 0.15)$. Both shear stress and plastic viscosity decrease negatively with the increase of water-cement ratio. When the water-cement ratio of fly ash is controlled between 1.2 and 1.4 and the mass concentration is controlled between 41.7% and 45.5%, the slurry flow is good, the pump-ability and the grouting efficiency are high.

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