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Analysis of slag debris flow initiation based on laboratory tests of slag

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ABSTRACT
Accumulated slags and waste in mines are major physical resources for slag debris flow, which are potentially major disasters that threaten mine safety. Initiated by heavy rain, slag debris flow has happened in Ganjiang gully around Luanchuan county, China. Studies have been carried out to further understand the formation and initiation mechanism of slag debris flows. Slag samples with different fines content were collected from the gully and the slag strength and permeability were investigated by direct shear tests and by falling head permeability tests, respectively. The results indicate that the fines content has a significant impact on both the strength and permeability characteristics of slags. With the fines content increasing, both the strength and the hydraulic conductivity of the slag decrease. The strength of saturated slag samples is extremely weak, meaning that water will easily soften the slag. In addition, as the fines content increases, the hydraulic conductivity would decreases at an accelerated rate, down to a very small constant. Based on the current investigation, it can be concluded that two different types of slag debris flow would form in the specific conditions: shallow debris flows are mainly dominated by surface erosion, while deep debris flows are dominated by bottom tearing and suffusion erosion.
KEYWORDS: slag, debris flow, initiation, strength, hydraulic conductivity

1. INTRODUCTION

Mine debris flow is different from the natural debris flow, also referred to as slag debris flow, which mainly occurrs in the fragile ecological environment of mountainous and hilly areas. With the development of the mining industry, mine debris flow is quickly becoming one of the major reasons restricting mining and production safety. According to Xu (2007), as of the end of 2005, mine debris flows have occurred 247 times in the northwest region of China, killing 426 people and causing direct economic losses of $384 million. There is much research on general debris flow; however, research related to slag debris flow is currently lacking due to the particularity of the material resource and dynamic conditions.

Debris flow occurs in all regions with steep relief and at least occasional rainfall, and tends to occur on slopes that are geologically young, steep, and naturally only marginally stable, (Jakob, 2005; Anderson, 1995). The initiation of the debris flow is related to three issues of resources, water (rainfall), and underlying conditions. Cannon et al. (2008) specify the significant role of rainfall in the initiation of debris flow by using a rain guage and response data. Stoffel et al. (2011) studied the formation mechanism of debris flow in the Alps of Switzerland. Chen and Cui (2006) have carried out research on the formation process of debris flow through artificial rainfall experiments. Jakob et al. (2012) studied the formation mechanism of debris flow induced by rainstorms. Mergili (2012) developed a GIS model to simulate the initiation and movement of debris flows.

The related research on mine debris flow is mainly on the qualitative analysis of provenance characteristics, formation conditions, classification, and initiation mechanisms. Fang (2007) summarized the material sources of mine debris flow, and considered hydrodynamic conditions to be the external factor that triggers the initiation. Waste and dump induced debris flows were classified into 5 types according to their formation mechanism: dump outburst, bottom tearing, side eclipse, surface erosion, and other complex types (Ni, 2011). Deng (2009) analyzed the development characteristics and the initiation conditions of slag debris flow for one gully in a gold mining area. Cao (2008) classified slag debris flow into two types, slope flow and trench flow, and studied their initiation mechanisms.

Other studies have focused on the penetration characteristics of slag, and tried to analyze and predict the mechanisms of mine debris flow through the use of quantitative methods. However, the impact of slag strength and permeability characteristics on the initiation of slag debris flow is still poorly understood. This paper consists of two main parts. First, the shearing strength and permeability of the slag with different fines content taken from Ganjiang Gully, in Luanchuan county, are studied using laboratory tests. Second, based on the test results of the shearing strength and permeability characteristics of the slag as well as some previous initiation models

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of general debris flow, the initiation of slag debris flow is analyzed.

2. LABORATORY TESTS

Test samples were taken from the slag heaps in Ganjiang Gully, Luanchuan County, with the sample's dry density (ρd) being 1.90 g•cm-3, specific gravity (Cs) being 2.86, and field moisture (W) being 3.2%. Three remoulded samples were prepared for direct shear tests and variable head permeability tests. The grading curves of the slag samples were as shown in Figure 1.

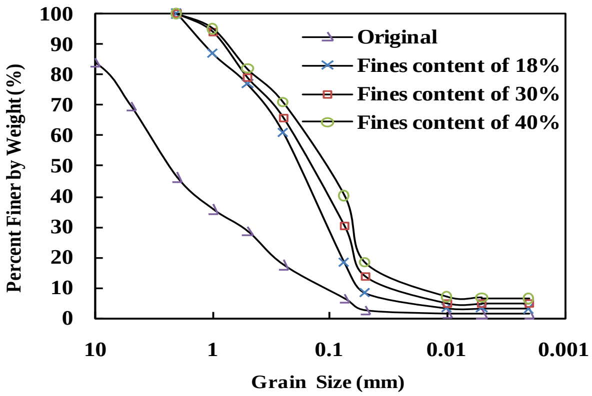

Figure 1: Grading curves of original and remoulded samples.

2.1 Direct shear test

Figure 2: The direct shear apparatus.

Direct shear tests were carried out to obtain the strength parameters of the slag samples. The three remoulded samples have different fines content of 18%, 30%, and 40%, with two different saturation of natural water contents: 50% and full saturation. The test was conducted in the strain controlled direct shear apparatus (Figure 2). The quick shearing test was applied at a rate of 0.8 mm/min, with the samples destructed in 3-5 minutes.

2.1.1 Shear Stress vs. displacement

The remoulded samples with fines content of 18% were chosen for explaining the variation of shear displacement as the shear stress increased under different saturations of 21%, 75%, and 100%.

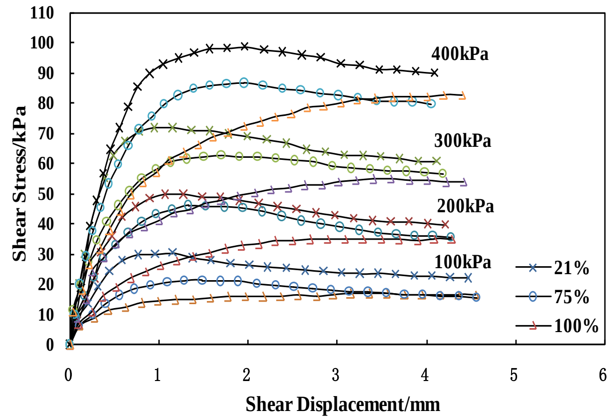

Figure 3: Shear stress vs. horizontal displacement under different saturation (21%/75%/100%).

As Figure 3 shows, the slag samples of 21% and 75% saturation were mostly destructed with the peak horizontal displacement between 3-5 mm, which proved to be strain softening. When the shear stress reached a peak, shear failure occurred, and the shearing strength continued to decrease, with the shear displacement going down to a certain value of residual strength. While under full saturation (100%), there were no significant peaks at different vertical pressure, which shows the characteristics of creep deformation and strain hardening.

In the shearing process, the particles rearrange on the shear plane with the effort of vertical stress, and the shear dilatancy occurs when the pore pressure builds up in the undrained condition. Fully saturated slag samples with high water content may have a certain plasticity flow, with fluctuating curves of stress-displacement. In addition, it can be seen that the corresponding peaks of the curve declined with increases in slag saturation level, and the shear stress of the saturated slag declined more sharply than the slag of 21% and 75% saturation, demonstrating that the slag strength is weaker in saturated states. Rainfall results in slags reaching a saturated state, which may accelerate the initiation of slag debris flow due to the deterioration of stability.

2.1.2 Slag Strength vs. Fines Content

Shear tests for three samples with different fines content of 18%, 30%, and 40% were conducted to investigate the relationship between slag fines content and the shear strength, as shown in Figure 4.

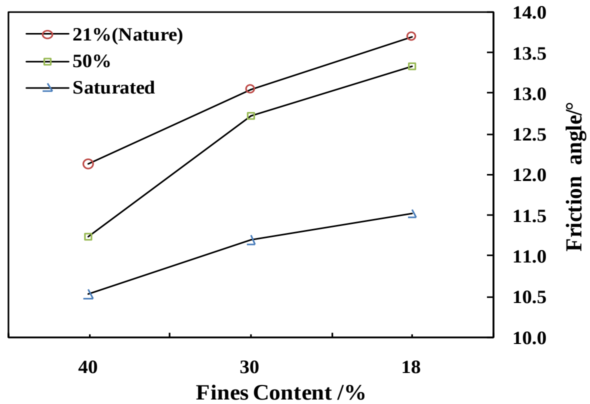

Figure 4: Relationship between fines content and φ.

Since the clay content of slag is very low, and the cohesion measured from the test by Xie (2013) is close to zero, in this study the tested slag was considered sandy soil, without considering the cohesion. The Mohr-Coulomb theory was employed to determine the shear strength of slag, using the following equation (1):

$$\tau = \tan \varphi \tag{1}$$

Where

φ is the internal friction angle;

τ is the shear strength.

In this study, friction angle (φ) is used to express the strength of slag samples. As Figure 6 shows, it can be seen that slag strength decreases with increases in fines content, with the three different slag samples all showing the same phenomenon. Strength of the slag samples with 40% fines content was 8.6%-15.6% lower than that of slag samples with 18% fines content. The fines content has a significant influence on the microstructure of the slag, and the increased fines content leads to weakening of the interactions between the coarse particles, causing a reduction of its shearing strength. In addition, it shows an obvious decrease when the saturation of slag with the certain fines content increases, and the inflection points of the curve are more apparent for the 50% and natural saturation levels. While the slag sample is in a saturated state, the friction angle declines to a minimum, since the water in the slag samples destroys the cementation of the particles of slag.

The results indicate that the particle gradation characteristics of slag have a limited effect on slag strength, while the saturation level shows a more important influence on shearing strength of slag.

2.2 Variable head permeability test

The South 55-type variable head permeameter was carried out to obtain the slag permeability characteristics, using three different fines content (18%, 30%, 40%) slag samples. In order to measure the saturated hydraulic conductivity, the cutting ring samples for testing are prepared and controlled at natural saturation levels.

In order to determine the saturated hydraulic conductivity, the slag in natural states are prepared to for testing using the vacuum saturation method. The following equation (Darcy Law) was used (2):

$$K = QL / Aht \tag{2}$$

Where

A=0.23758 cm^2;

L=4cm, represents Penetration Path;

Q, h and t are obtained from the test records.

The test results are listed in Table 1, and graphed in Figure 5.

Table 1: Results of variable head permeability test.

Fines Content	18%	30%	40%
Hydraulic Conductivity/$cm \cdot s^{-1}$	1.68E-04	7.22E-05	4.67E-05

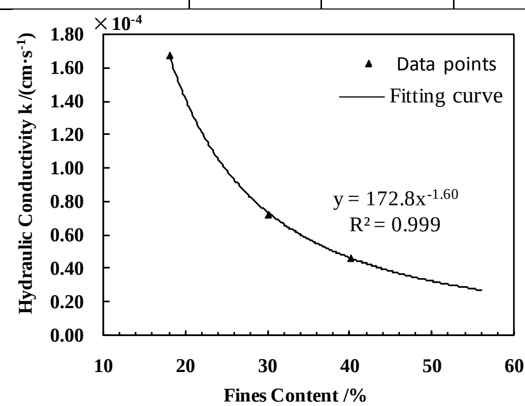

Figure 5: Fitting curve between fines content and hydraulic conductivity.

As shown in Table 1 and Figure 5, there is an apparent gap between the hydraulic conductivity of slag samples with different fines contents of 18%, 30%, and 40%. The gap between the slag samples of 18% and 30% fines content is much larger than that between the slag samples of 30% and 40% fines content. The fitting curve between fines content and hydraulic conductivity, according to the distribution of data points, is expressed as the following equation (3) with a correlation coefficient (R) of 0.999:

$$y = 172.8x^{-1.60} \tag{3}$$

In which, y=K×104, x=C×102, where K and C represent the hydraulic conductivity and fines content, respectively. Equation (3) can then be changed to the following equation (4):

$$K = 1.0903E-05C^{-1.60} \tag{4}$$

With increases in the fines content of slag samples, the hydraulic conductivity decreases, and the trend of decline is such that the difference gap of the hydraulic conductivity between the slag of 40% fines content and one of 30% fines content is larger than the gap between the slag of 18% fines content and the one of 30%.

Meanwhile, from the trend of the fitting curve, when the fines content of slag reaches a certain value, the decline of hydraulic conductivity gradually becomes weaker, and reaches an almost stable state with values of more than 40%. Kong (2011) and Wang (2012) have found similar sequences by studying the variation of hydraulic conductivity of sand. It can then be noted that the greater the hydraulic conductivity, the stronger the infiltration ability, therefore, the slag will more easily reach a saturated state under certain rainfall conditions.

3. ANALYSIS OF SLAG DEBRIS FLOW INITIATION

3.1 Initiation Models of General Debris Flow

As Liu (2002) summarized in his overview of foreign debris flow mechanism models, the primary classical debris flow initiation mechanism models that have been widely accepted include: Coulomb's particle flow model containing pore water pressure, the Johnson model (1970), the Takahashi model (1978), the general viscous plastic flow model put forward by Chen (1986), O'Brien's dilated plastic flow model (1993), and the mixed flow theory of momentum conservation equation applied for complicated debris flows as proposed by Verson (1997).

In addition, many researchers have developed diverse initiation mechanisms for debris flow with different types of solid content and formation, including:

1. Takahashi model

Takahashi (1991) proposed that the wash and erosion of the sediments in gully beds by water flow, resulting from rainfall or underground water, is the key factor causing the initiation of hydraulic debris flow. After rainfall, runoff with a depth of h develops and forms on the underground surface or on s brook with an inclination angle θ. The shearing force produced from water flow acting on deposits is τ, and the shearing resistance of deposits is τ_L. According to the relationship between τ and τ_L, the initiation of debris flow can be discussed. If the effect of flow velocity on the deposits with a certain depth is ignored, the total shearing force acting on the deposits can be calculated using the following equation (5):

$$\tau = g\sin\theta\left[C_*\left(\rho_m-\rho\right)a+\rho\left(a+h_0\right)\right] \tag{5}$$

Where

C_* is the volume concentration of deposits.

a is the layer thickness of deposits which is possibly sheared and move, m.

ρ_m is the soil density of debris, g/cm3.

ρ is for the density of water (containing a small suspended solids, ρ = 1), g/cm3.

g is the acceleration due to gravity, m/s^2.

h_0 is for the depth of surface flow, m.

The totally shearing force is made up of two parts, the solid material in the flow and the water, as shown in the equation.

The shear resistance τ_L of the deposits can be calculated using the following equation (6):

$$\tau_L = g\cos\theta\left[C_*\left(\rho_m-\rho\right)a+\frac{\rho_m d}{\cos\theta}\right]\tan\varphi \tag{6}$$

When $\tau > \tau_L$, it is believed that debris flow is likely to form and develop.

2. Sediment movement model

Xie et al. (1993) established the mechanical model for the initiation of deposits loosely piled up in gully beds, based on sediment movement theory. It is believed that loose deposits in gully beds is critical in debris flow initiation, and deposits containing a lot of water show the characteristics of saturated slurry. This is especially true for the deposits contracted with the bottom of the gully bed. For hydraulically driven debris flow, the flow initiation theory can be regarded as the sediment movement theory for bed material flow initiation.

3. Hydrodynamic model

Tang et al. (2001) proposed a mechanical model for the initiation of deposits piled up in gully beds based on hydrodynamic theory. This type of debris flow initiation model mainly considers that the debris flow is initiated by the fluid's drag force on the deposits. Therefore, it is called the drag-imitation model. The drag force is determined according to hydrodynamic theory, and it is a key factor influencing the initiation of deposits.

3.2 Analysis of slag debris flow initiation

Based on the findings above, the strength of slag samples is greatly influenced by slag saturation state, and is quite weak in a saturated state. Slag strength has shown little sensitivity to grain-size distribution characteristics. However, the hydraulic conductivity makes a significant difference because of the different fines content of slag. Therefore, slag debris flow initiation can be analyzed according to the strength and permeability characteristics of slag.

As Cui et al. (2003) studied, there is a direct relationship between soil saturation and rainfall, and with some initial rainfall, a slag pile reaches a certain saturation state. In addition, antecedent moisture content directly governs the hydraulic conductivity of partially saturated soils and also influences the strength characteristics of the slag. Generally, with ongoing rainfall, slag strength declines constantly. In contrast, its weight would be increasing, causing the stability of the slag pile to become worse, and eventually causing damage.

Secondly, judging from the experimental data, slag strength is lowest when its hydraulic conductivity has the minimum fines content of 40%, for conditions where the stability of the slag pile is worst. It should be noted that a value of 40% for fines content is already great, according to the analysis of the particle composition of slag material collected from different location.

Hereafter, if the fines content of slag, which is considered a quantitative evaluation factor, is high, the slag strength would be weak, while permeability and infiltration capacity would be also weak with a lower saturated velocity, that is, with a decreased velocity of slag strength. Generally in this case, such slag pile induced debris flow is initiated slowly, and with conditions of continuous rainfall, both surface flow and pore water pressure of the slag pile also increase constantly, and shallow debris flows mainly dominated by surface erosion may form easily. On the other hand, the lower the fines content of slag, the stronger the slag strength, and the slag pile would be more susceptible to damage in the same topographic and rainfall conditions. While, there is a large hydraulic conductivity among the slag pile and rainfall can quickly penetrate into the bottom of slag pile through the void in particles, due to the higher saturated velocity and the higher decreased velocity of slag strength, such slag piles induced debris flow generally initiates quickly. With ongoing rainfall, deep debris flows mainly dominated by bottom tearing and suffusion erosion may easily form, which would carry a larger amount of provenance and be more dangerous than shallow debris flows.

3.3 A Field Case of Slag Debris Flow

On July 22 to 24, 2010, impacted by the typhoon "chan had", heavy rain occurred around Luanchuan county in China, inducing a centralized outbreak of debris flow because of the torrential rains. The affected slag pile had been accumulating in Ganjiang gully, and had a lack of protection. The debris flow initiation induced by the slag pile was analyzed according to the strength and permeability characteristics controlled by the particle composition of the slag.

First, the fines content of slag pile in Ganjiang gully was between 20% and 30%, and the slag strength was relatively high. Correspondingly, due to the large hydraulic conductivity, the slag pile was in a saturated state within a short time during the heavy rainfall that occurred, and the slag strength decreased quickly. Therefore, as the heavy rain continued, runoff occurred and the hydrodynamic conditions were prepared for the initiation of debris flow. Finally, on July 24, 2010, the slag pile in the source area of Ganjiang gully experienced outburst, forming deep debris flows mainly dominated by bottom tearing and suffusion erosion. This was accompanied by shallow debris flows in the other partial area. The following picture is the slag left behind after the debris flow burst in Ganjiang gully, as shown in Figure 6.

Figure 6: Slag left behind after the debris flow burst.

In conclusion, when the slag debris flow in Ganjiang gully was evaluated, the main factors affecting the initiation of slag-induced debris flow were the fines content and permeability characteristic of slag, because particle size distribution is more sensitive to permeability characteristics than to slag strength.

4. CONCLUSIONS

Based on the current study's analysis of the slag debris flow in Ganjiang gully in Luanchuan county, the following main conclusions are obtained:

1) The fines content of slag is a significant factor not only for the slag's strength but also its permeability characteristics. With fines content increasing, both the strength and the hydraulic conductivity of the slag decrease. If the value of the fines content of the slag exceeds 40%, the hydraulic conductivity decreases constantly, with the acceleration of decline becoming more gradual, down to an almost stable state.

2) Considering the change in slag strength and permeability characteristics in conditions of continuous rainfall, two different types of debris flow can be induced: shallow debris flows, which are mainly dominated by surface erosion, and deep debris flows, which are mainly dominated by bottom

tearing and suffusion erosion. Fines content and the permeability coefficient are the main factors that affected slag debris flow in Ganjiang gully.

5. ACKNOWLEDGMENTS

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