An Experimental Study of the Influence of Strength and Permeability Characteristics of Slag on Debris Flow Initiation

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***Abstract* — Affected by heavy rain, slag debris flow has been happening in Ganjaing gully around Luanchuan area. In this paper we study the initiation and formation mechanism of slag debris flow in terms of slag strength and permeability characteristics. First, the shear strength and permeability characteristics of slag samples with different grain size distributions taken from the slag pile in Ganjiang Gully were studied by direct shear tests and falling head permeability tests. The results indicated that the shear strength of slag samples decreased modestly when the fine particle content and uniformity coefficient increased according to the tests on three groups of slag samples with different grain size distributions. The shear strength was rather less sensitive to particle size distribution of the samples when they are in saturated condition, and no peak values could be found in displacement-stress curves of direct shearing tests. With the increase of fine particle content, the hydraulic conductivity showed a moderate gradual decrease which meant that the reduction of hydraulic conductivity from group 1 to group 2 was somewhat more than that from group 2 to group 3. Secondly, comprehensively taking into account: i) the particle size distribution, ii) shearing strength, iii) hydraulic conductivity, and iv) the previous rainfall, the initiation mechanisms and complexity of slag induced debris flow was studied. It is concluded that both the fine particle content and hydraulic conductivity are primary factors that impact the initiation of slag debris flow in Ganjiang gully.**

Keywords - slag; fine particles content; saturation; strength characteristics; permeability characteristics; debris flow

I. INTRODUCTION

Mine debris flow affects mine construction and the sustainable exploitation of resources, and damages the natural environment of the mine [1].The mine debris flow becomes one of major reasons restricting the mining and production safety with the development of the mining industry, and the factitious accumulated slag are the main physical resources which cause the mine debris flow. There are many research on general debris flow [2-9], however, the related research on slag debris flow is fairly lacking due to the particularity of the material resource and dynamic condition.

Debris flow occur in all regions with steep relief and at least occasional rainfall [3], and it tend to occur on slopes that are geologically young, steep, and naturally only marginally stable [4]. Notoriously, the initiation of debris flow is related three questions of resource, water (rainfall) and underlying conditions, Cannon indicated the significance of the role of rainfall by using rain gage and response data, which is the most significant factor to induce the initiation. Then, A comprehensive account of the physics of debris flows has been presented by Iverson [6], and Rickenmann [7] has summarized some empirical relationships for debris flow to estimate the important parameters such as potential debris volume, mean flow velocity, peak discharge, and run-out distance, in order to design protective measures against debris flows.

However, the related research on mine debris flow are mainly on the qualitative analysis of provenance characteristics, formation conditions, classification and initiation mechanism. Fang [10] summarized the types of material source of mine debris flow, and considered hydrodynamic conditions be the external factor to trigger the initiation. Through statistical analysis of waste-dump -induced debris flows around Western Region in China, waste-dump-induced debris flows were classified to 5 types of dump outburst, bottom tearing, side eclipse, surface erosion and other complex types according to the formation mechanism by Ni [11]. Furthermore, Cao [13] has explored the initiation and cause mechanism of mine debris flow by analyzing the features of material and water source, Xu [14] took the slag as a source for straight ramp-start simulation test， the quantitative correlations of the grain composition，slope gradient and the critical water content were studied , which are the main influential factors of mine debris flow, and found that the slag is the most vulnerable to start when the content of the fine material in the slag reaches 28%.

In addition, some study are also focused on the penetration characteristics of slag, and tried to analyze and predict the mechanism of inducing mine debris flow by using of quantitative methods. However, it is still lack of research on the impact of slag strength and permeability characteristics to the initiation of mine debris flow. In the first part of this paper, the shearing strength and permeability of slag samples with different particle size distribution from Ganjiang Gully, in Luanchuan country, are studied by laboratory tests. Secondly, with the test results, the influence of shearing strength and permeability on the initiation of slag debris flow is analyzed, when the characteristics of slag samples have changed. In the end, a theoretical basis to study the mechanism, prediction and prevention for mine debris flow is proposed.

II. LABORATORY TESTS

A. *Testing Samples*

Test samples are taken from the slag heaps in Ganjiang Gully, Luanchuan County. The mean particle size of slag is fairly small and the natural moisture is lower in slag heaps. It is difficult to acquire undisturbed samples, Figure 1 is the original grading curve of slag samples. Therefore, three remolded samples are prepared for tests in this paper, as figure 2 showed. The samples are dried and sieved to obtain slag samples with different particle sizes before the tests, the slag samples with particle size lager than 2mm must be removed due to the limitation of test methods. The equivalent substitution method is used to deal with the oversized slag in order to not impact the properties of slag.

TABLE Ⅰ. NATURAL PHYSICAL INDEXES OF SLAG

(1-1)

Dry density ρ_d/g•cm^{-3}	Specific gravity C_s	Field moisture W/%
1.90	2.86	3.2

(1-2)

Slag grain composition/mm/%						
<10	<5	<2	<1	<0.5	<0.25	<0.075
92.16	77.10	58.00	52.72	48.13	41.97	18.91

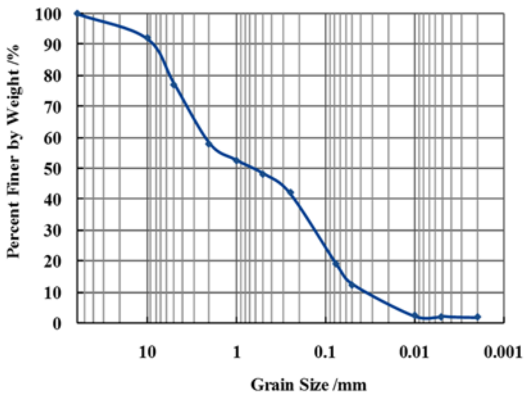

Fig 1. Grading curve of original slag.

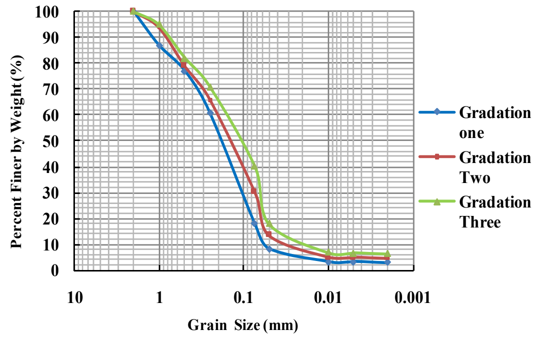

Fig 2. Grading curves of three remodeling samples.

B. *Testing programs [15]*

The purpose of this paper is to study the influence of shearing strength and permeability on slag debris flow. Therefore, direct shear tests and variable head permeability tests are carried out to obtain the strength parameters and hydraulic conductivity of the slag samples.

1) *Direct shear test*

The strain controlled direct shear apparatus(*Fig.3*) was conducted in test, and considering the feature of sudden outbreak of the debris flow, the quick shearing test was applied at a rate of t 0.8mm/min, and the samples were destructed in 3-5minutes.

Fig 3. The direct shear apparatus and broken samples.

The dry density of the slag samples was controlled to be in 1.90g/cm3 which was equal to that measured in field. As the figure 2 showed, the fine particles content of the prepared three groups are 18%, 30% 40%, respectively. The Group1 of 18% content fine particles was oversized and treated with the equivalent substitution method. And the group 2 and 3 are the samples in which the content of fine particles has been improved with the purpose of researching the influence of fine particles content on strength and permeability of slag. Figure 2 shows the grading curves of the three remodeling samples. In order to research the effect of saturation level on the strength of slag, three different saturation level of the samples (e.g. the natural water content, 50% and full saturation) are made for testing. The saturated slag samples are made from the natural sample by making a cutting ring sample, placing in a vacuum and saturated device, soaked for 2-4 hours with water, and preserved in water after taking out for enough time to ensure saturated.

2) Variable head permeability test

Fig 4. The apparatus of South 55-type variable head permeameter.

The South 55-type variable head permeameter(*Fig.4*) was applied, and three kinds of gradation of samples are prepared in the control index of fine particles content with the same proportion of data. Particularly, it is the saturated hydraulic conductivity of slag samples needed to be measured, and the influence of porosity and pore size is not considered. Therefore, the cutting ring samples of natural saturation are prepared. They are placed in the vacuum and saturated equipment to be fully saturated, and the saturating method is same with that mentioned above. Two readings methods are used,1): Record the time every 10ml falling of the piezometric head; 2): Read piezometric head by a certain time interval. And the permeability coefficients of three different grading slag samples can be calculated by comparing the two methods.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Variation of Slag Strength

Shear tests for the three samples with different fine contents of 18%, 30% and 40% were conducted to investigate the impact the impact of slag fine content and uniformity coefficient on the shear strength. Among them, the uniformity coefficient and the fine particles content can be used to represent the gradation characteristic.

Since the clay content of slag is very low and the cohesion measured from the test is close to zero [16], the tested slag was considered as the sandy soil, it will be only taking the variation of the friction angle into account without the cohesion in the study. The Mohr-Coulomb theory was employed to determine the shear strength of slag as the following equation (1):

$$\tau = \tan\varphi \qquad (1)$$

where φ=internal friction angle, τ=the shear strength, σ= the normal stress.

Figure 5 shows the relationship between friction angle and uniformity coefficient. It can be seen that the friction angle decreases with the increase of uniformity coefficient with a small quantity. It also decreases with the increasing of fine particles content from Figure 6, which presents the relationship between fine particles content and friction angle. Both of the results above indicated the impact of uniformity coefficient tand fine

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particles content of slag on the friction angle are almost consistent at the same saturation level, and it indicates that the increased slag fine particles content not only affects the uniformity coefficient, but also to some extent weakens the slag strength, because of the fine particles content have an significant influence on the microstructure of the slag, and the increase of fine particles content leads to weakening the interaction of the coarse particles which caused a reduction of its shearing strength.

In addition, the influence of saturation level of the slag on internal friction angle was studied. It showed an obvious decrease when the saturation level of the slag increased under the same gradation in both Fig. 5 and 6. And the curve inflection points are apparent at the state of the 50% and natural saturation levels, also the decline of friction angle increases slightly. It can be seen that when in saturated state, the friction angle declined to minimum and the uniformity coefficient and fine particles content showed a less impact on the friction angle since the cementation of the particles in slag is destroyed strength of slag is almost independent on particle gradation.

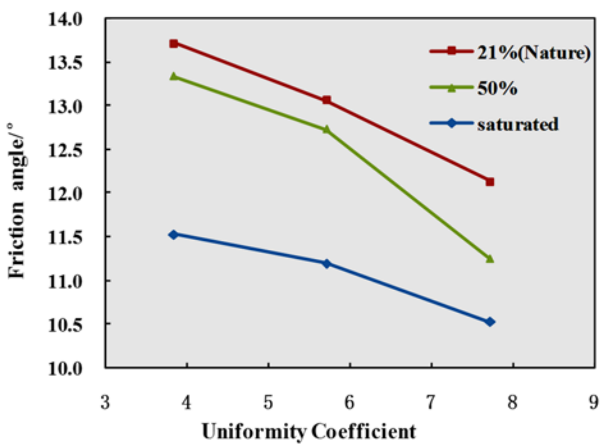


Fig 5. Relationship between Cu and φ.

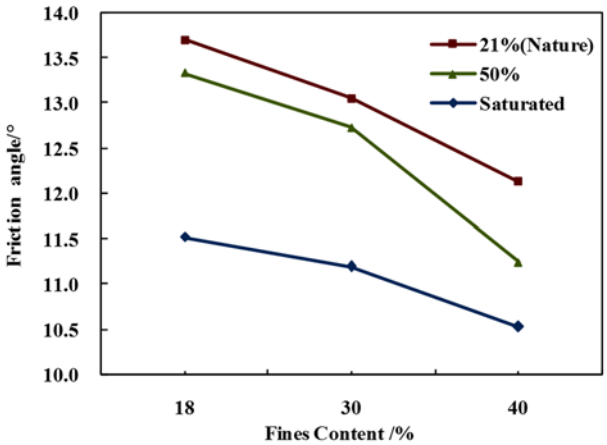
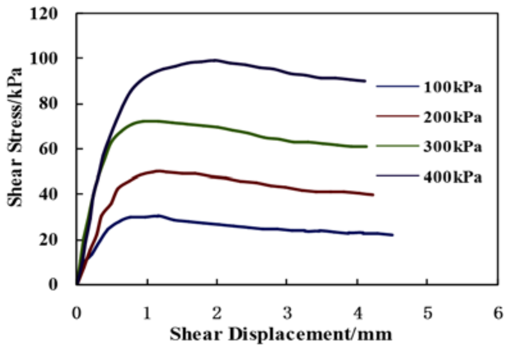


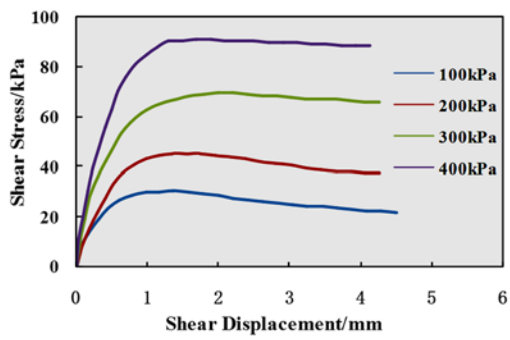
Fig 6. Relationship between fines content and φ.

B. Slag Shear Stress-displacement Under Different Saturation

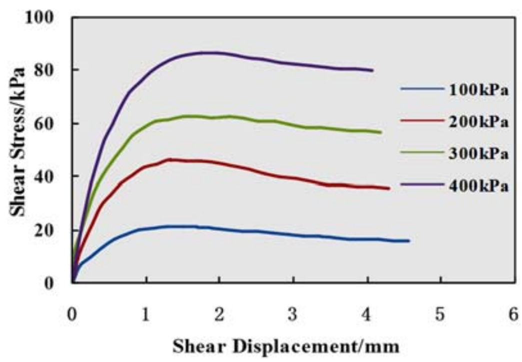
It can be found that the relationship between shear stress and displacement for different particle gradation of slag shows similar characteristics under different saturation. The gradation of group 1 was chosen for



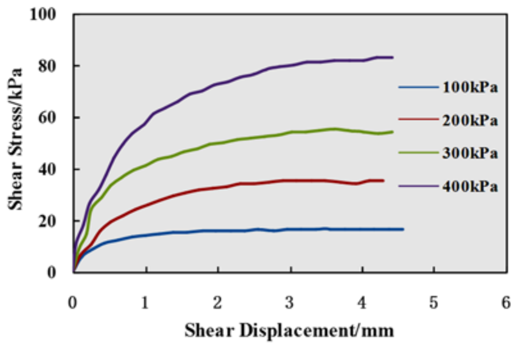
(a) Saturation of 21% (Nature)



(b) Saturation of 50%



(c) Saturation of 75%



(d) Full saturated state

Fig 7. Relationship between shear stress and horizontal displacement of different saturation of Grade one.

explaining the relationship between the shear stress and displacement as showed in Figure 7 (a, b, c, d).

Figure 7 (a, b, c, d) shows the variation of shear stress with displacement of slag samples under four different saturation levels. It can be seen that, under the first three saturation levels (a, b, c), the peak horizontal displacement of all slag samples are between 3 ~ 5mm, which proved to be strain softening, and the analogous results were received by studied the relationship between △l and τ of deep reconstituted soil in different water content of 17.2%, 21.3%,25.5%, 30.8% by Zhao [19]. While under full saturation, they have no significant peaks at different vertical pressure. However, once the horizontal displacement reaches 3mm, as shear displacement increases, the shear stress shows a slow growing trend, and the curve appears occasional fluctuations, showing strain hardening characteristics. The reason is that the first three of unsaturated specimens are prepared according to the saturation conversion, the water content is lower, and the slag particles get gradually compacted under the effect of vertical pressure.

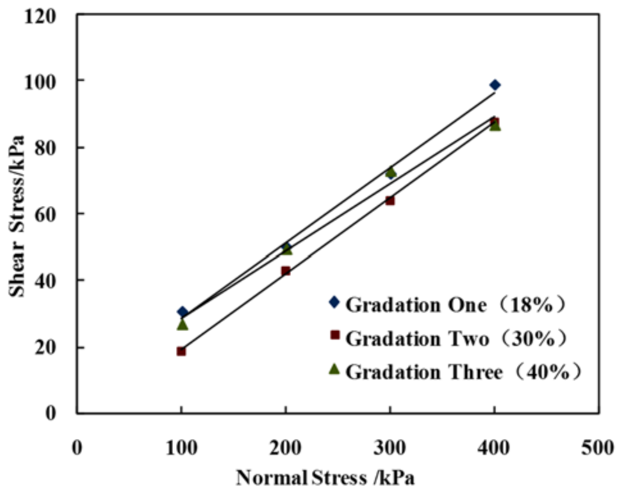
When the shear stress reaching a peak, the shear failure occurred and the shearing strength decreased maintained residual strength unchanged. However, the full saturated samples are prepared in process of soaking in water for three hours after saturated in vacuum saturation device. They reached to full saturation state and had higher water content. On the one hand, the quick shear testing method was applied, the samples were not consolidated, and the overall slag particle size is smaller, the particles rearrange on the shear plane with the effort of vertical stress in the shearing process. And the shear dilatancy occurs when the pore pressure built up in the undrained condition. On the other hand, when soil samples are in the saturated state, the water content are very high, then they may have a certain plasticity flow in the shearing process, which is the reason that the stress-displacement curves of the slag samples increased and fluctuated under the saturated state.

Secondly, it can be seen in Figure 7 that peaks of the curve corresponding declined with the increase of slag saturation level. Compared to the samples with natural water content, the shear stress of the saturated slag sharply declined at the same condition of horizontal and vertical stress, which shows the strength of the slag is very weak in saturated state. The previous rainfall will result in reaching to saturated state of the slag, deteriorating the stability, and accelerating the initiation of slag debris flow.

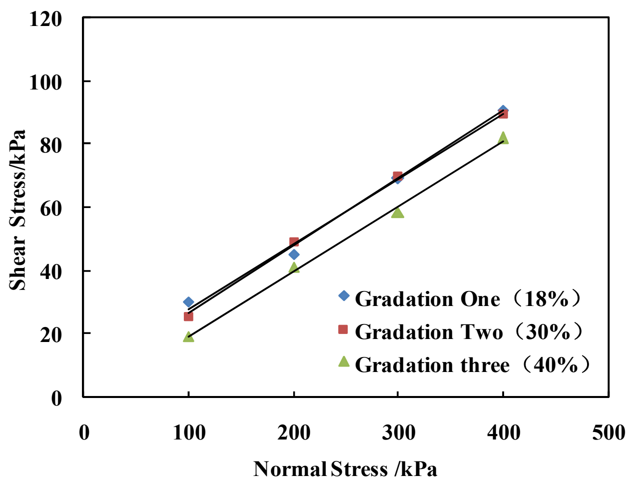
C. Mohr Strength Envelope Characteristics of Tested Slag

In this part, three different grain size distributions of the slag samples were tested to study the characteristics of Mohr strength envelope.

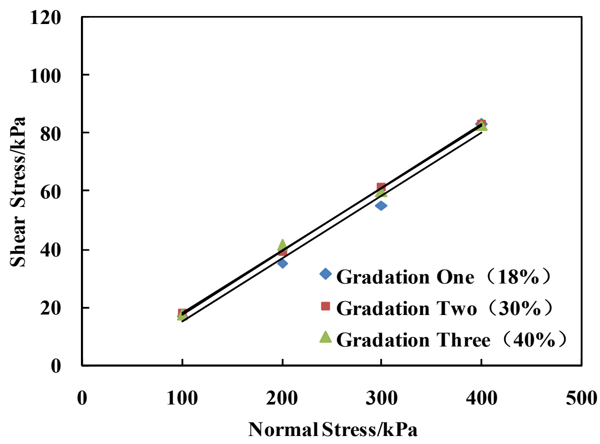
In direct shear tests, the stress applied to the slag is not high, when fitting Mohr-Coulomb envelope, linear function is adopted, and the results showed that it was similar to a straight line as showed in Figure 8 (a, b, c). The consequences of fitting strength envelope from the data of three different gradation slag samples at different saturated state are described. It can be concluded that all of the strength envelopes of slag samples under a, b, c three states with different particle gradation is not apparent different, especially for the saturated state (c), the strength envelope of slag soil almost coincides in three gradation conditions. However, the strength envelope at 50% saturated state is significantly lower than the other two. The conclusion indicated that the effect of the characteristics of particle gradation on slag strength is limited. However, the saturation level showed a more important influence on shearing strength by taking three figures (a, b, c) into account.



(a) Natural State



(b) Saturation of 50%



(c) Saturated state

Fig 8. Relationship of shear strength and fine particles content in different saturation

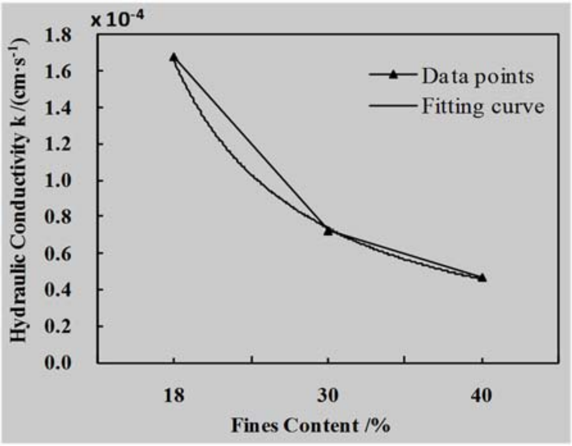
D. Slag Permeability Characteristics

In this part, three different partical size distributions of the slag samples were tested to study the Permeability characteristics.

In order to determine saturated hydraulic conductivity, the slag in natural state are prepared to test samples using vacuum saturation method. Three samples were prepared for each parallel experiments under different operation conditions, and two different counting methods are used separately in each experiments. According to Darcy law as the following equation (2):

$$K = QL/Aht \qquad (2)$$

In which, A=0.23758cm2; L =4cm , represents Penetration Path; Q, h and t are obtained from test measurement records, the acquired data with large discrete were rejected and the hydraulic conductivities under different conditions are calculated based on weighted average method. Figure 9 and 10 respectively showed the relationships between fine particles content, uniformity coefficient and saturated hydraulic conductivity.



Fig(9). Relationship between hydraulic conductivity and fine particles content of slag samples.

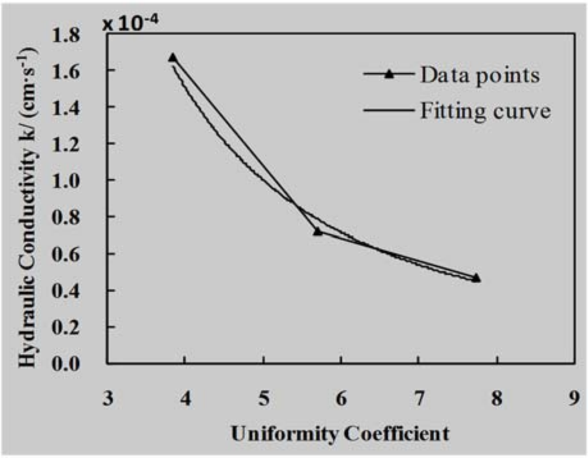


Fig 10. Relationship between slag hydraulic conductivity and Cu

There are apparent differences in hydraulic conductivity for three different particle size distribution as shown in Figure.9 and 10. The hydraulic conductivity of first gradation samples are particularly up to 1.68E-04(cm·s-1), and obviously larger than the other two in magnitude. Overall, with the increase of fine particles content and uniformity coefficient, hydraulic conductivity of slag samples decreases constantly, and the reduction from samples with 18% to 30% of fine particles content is significantly greater than that from samples with 30% to 40% of fine particles content.

Therefore, it is believed that the fine particles content is an important factor indeed affecting hydraulic conductivity of the slag, the reason can possibly be interpreted to that uniformity coefficient increases and the slag gradation has been simultaneously becoming well with the increasing fine particles content. Meanwhile, when the dry density is a certain value, the compactness of slag also increases as uniformity coefficient and fine particles content increasing. It will affect the slag porosity and pore structure, resulting in weakening its penetration properties eventually.

However, when the fine particles content reaches a certain value, the impact on slag hydraulic conductivity has showed a decreasing trend, and decline of hydraulic conductivity gradually becomes feeble, and even to an almost stability state with the value more than 40%, exemplified as the fitted curve drawn in fig.9. The previous research on the influence rules of fine particles content and uniformity coefficient versus hydraulic conductivity was reviewed. Kong [20] and Wang [21] have received the same sequence. They holds that hydraulic conductivity decreased in the form of acceleration reducing with the increase of fine particles content, and when the value of fine particles content have exceeded more than 25%, 30%, hydraulic conductivity of sand would gradually be a constant value. Hence, the hypothesis that there have been some similar characteristics between slag and sand has been proved due to the uniform sequence, and its strength parameters should be handled as sand.

In addition, by carrying out constant head permeability test, Yang (2012) found that permeability coefficient of tailings sands around gold fields in the Middle and Lower Yellow River, would be 1.37E-03(cm·s-1) to 4.2E-04 (cm·s-1)which slightly bigger than that measured in this paper for slag because of its larger mean particle size, and with both the two values more bigger than permeability coefficient of the material source in general debris flow [22]. So, it is considered that the significant difference of permeation properties between general debris flow and slag debris flow is the most important factor for the formation of debris flow around study area. Meanwhile, the greater the hydraulic conductivity, the stronger the infiltration ability generally, and saturation velocity of slag is also faster under the same rainfall condition.

IV. ANALYSIS OF THE INFLUNECE OF DEBRIS FLOW INITIATION VERSUS STRENGTH AND PERMEABILITY CHARACTRISTICS

Based on the findings above, strength of slag samples which is quite weak in saturated state, would be greatly influenced by soil saturation and it has showed little sensitivity to grain-size distribution characteristics which has greatly influence on the penetration characteristics of slag.

Firstly, there is a direct relationship between soil saturation and rainfall, and with some initial rainfall, the slag pile would have been reaching a certain saturation, even saturated state [23]. In addition, antecedent moisture content directly governs the hydraulic conductivity of partially saturated soils and also influences strength characteristics of a soil [24]. Generally, with the ongoing rainfall, the strength of slag would be declining constantly, but its weight would be increasing in contrast, thus stability of slag pile may become so worse and cause the damage eventually.

Secondly, just judging from the experimental data, slag strength is lowest while its permeability coefficient has been the minimum in fine particles content of 40% (Gradation 3), for the condition when the stability of slag pile is worst. It should be noted, the value of 40% for fine particles content is already great by analyzing the particle composition of slag material collecte from different location, and certainly this is also the reasons why we took the value of 40% as the largest proportion of fine particles content in particle analysis.

Hereafter, with fine particles content as a quantitative evaluation factor, strength and permeability characteristics of slag samples are comprehensively considered to analyze the influence for the initiation of mine debris flow. If the fine particles content of slag is high, its strength would be weak, while permeability and infiltration capacity would be also weak with a lower saturated velocity, that is, the decreased velocity of slag strength was slow. Generally in this case, such slag pile induced debris flow initiates slowly, and with the conditions of continuous rainfall, both surface flow and pore water pressure of slag pile have been also increasing constantly, and shallow debris flows mainly dominated by surface erosion may easily be formed. On the contrary, the lower the fine particles content, the stronger the slag strength, and slag pile would be more likely to damage in the same topographic and rainfall condition. While, there is a large hydraulic conductivity among 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 pile induced debris flow initiates quickly generally. And with rainfall going on, deep debris flows mainly dominated by bottom tearing and suffusion erosion may easily be formed, which would carry more amounts of provenance and be more dangerous than shallow debris flows.

Fig 11. The Site pictures of slag debris flow in Ganjiang gully.

In particular, when the slag debris flow in Ganjiang gully was evaluated regarding the particle size distribution as variable, fine particles content and permeability characteristic of slag are considered to the main factor which affect the initiation of slag-induced debris flow, because particle size distribution is more sensitive to permeability characteristic than to slag strength.

In fact, affected by the typhoon "can du", heavy rain and rainstorm have happened around Lunchuan area on July 22-24, and the torrential rains caused the centralized outbreak of debris flow in Luanchuan Country. In addition, the fine particles content of slag pile in Ganjiang gully has been between 20% and 30%, and the slag strength has been relatively high. Correspondingly, due to the large hydraulic conductivity, the slag pile would be saturated condition in a short time, and the slag strength decreased quickly with rainfall going on, therefore, slag pile in source area of Ganjiang gully happened to be outburst, which formed the deep debris flows mainly dominated by bottom tearing and suffusion erosion, and accompanied by shallow debris flows in partial area. The following pictures are taken from the regions of debris flow accumulation in Ganjiang gully, as Figure 11 showed.

V. CONCLUSIONS

Based on the experiment research for strength and permeability characteristics of slag located in Ganjiang gully in LuanChuan country, the following main conclusions are obtained:

A. Sensitivity of factors to slag strength: Saturation>particle size distribution, and there are almost no relationship between particle size distribution and strength of the slag under water-saturated state. Due to the plastic flow and shear dilatation in shear flow process, the displacement-strain curves of slag of saturated state under different vertical pressure did not show any obvious peak and stress fluctuation phenomena.

B. Fine particles content is the main factor affecting the hydraulic conductivity of slag, with the increase of fine particles content, the hydraulic conductivity decreases constantly in the form of acceleration reducing, and the decline of hydraulic conductivity gradually becomes feeble, and even to an almost stability state when the value of fine particles content have exceeded more than 40%.

C. Considering the change of slag strength and permeability characteristics in the conditions of continuous rainfall, two different types of debris flow would be induced, which are shallow debris flows mainly dominated by surface erosion and deep debris flows mainly dominated by bottom tearing and suffusion erosion. Fine particles content and permeability coefficient are the main factors which affecting slag debris flow of Ganjiang gully.

D. It is suggested to strengthen the monitoring of rainfall intensity and saturation of slag pile in Ganjiang gully, Luanchuan country, and take appropriate drainage measures to prevent debris flow from initiation occurring. Analysis of the influence of debris flow initiation versus strength and permeability characteristics in the paper can be further tested and verified by combining with model experiments and numerical simulation in the future.

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