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Laboratory experiments on the improvement of rockfill materials with composite grout

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Abstract. Dam deformation should be strictly controlled for the construction of 300 m-high rockfill dams, so the rockfill materials need to have low porosity. A method of using composite grout is proposed to reduce the porosity of rockfill materials for the construction of high rockfill dams. The composite grout is a mixture of fly ash, cement and sand with the properties of easy flow and post-hardening. During the process of rolling compaction, the grout admixture sprinkled on the rockfill surface will gradually infiltrate into the inter-granular voids of rockfill by the exciting force of vibratory roller to reduce the porosity of rockfill. A visible flowing test was firstly designed to explore the flow characteristics of composite grout in porous media. Then, the compressibility, shear strength, permeability and suffusion susceptibility properties of composite grout-modified rockfill are studied by a series of laboratory tests. Experimental results show that the flow characteristics of composite grout are closely related to the fly ash content, the water-to-binder ratio, the maximum sand size and the content of composite grout. The filling of composite grout can effectively reduce the porosity of rockfill materials, as well as increase the compression modulus of rockfill materials, especially for loose and gap-graded rockfill materials. Composite grout-modified rockfill tends to have greater shear strength, larger suffusion erosion resistance, and smaller permeability coefficient. The composite grout mainly plays the roles of filling, lubrication and cementation in rockfill materials.

Keywords: rockfill materials; composite grout; porosity; compressibility; shear strength; permeability; suffusion susceptibility

1. Introduction

The rockfill dam is one of the most promising dam types in dam construction, as it is characterized by favourable adaptability to dam foundations, full utilization of local materials, fast construction processes, low construction costs and low cement consumption (Sherard and Cooke 1987, Alonso and Cardoso 2009, Zhong *et al.* 2018). At present, a number of super-high rockfill dams are under construction, such as Lianghekou (295 m), Shuangjiangkou (314 m) and Rumei (315 m) rockfill dams in western China (Hua *et al.* 2011, Chen *et al.* 2018). The control of dam deformation is of great importance to the construction of rockfill dams, especially for 300 m-high rockfill dams (Langroudi *et al.* 2013). Large dam deformations will pose great threats to the safety and operation of rockfill dams (Zhou *et al.* 2016, Chen *et al.* 2016, Li *et al.* 2016).

Dam deformation includes deformation that occurs instantaneously upon applying the load and time-dependent deformation (creep deformation), both of which are largely dependent on the porosity of rockfill materials (Zhang *et al.* 2015). Porosity is an important parameter reflecting the density of rockfill materials and construction quality. Rockfill with lower porosity, i.e., higher density, will undergo less deformation under loading. Previous studies show that raising compaction standards is usually adopted to get lower porosity of rockfill materials, and the porosity of rockfill materials should be controlled within 18% when they are used in 300 m-high rockfill dams (Ma and Chi 2016). However, such a low porosity is difficult to achieve only by raising compacting standards.

Recently, a new method of using composite grout is proposed to reduce the porosity of rockfill materials for the construction of high rockfill dams. The composite grout is a mixture of fly ash, cement and sand with the properties of easy flow and post-hardening (Grzeszczyk and Lipowski 1997). As shown in Fig. 1, the composite grout admixture is firstly sprinkled on the rockfill surface before rolling compaction and gradually infiltrates into the inter-granular voids of rockfill materials under self-gravity. Then, in the process of rolling compaction, the composite grout further fills the inter-granular voids of rockfill materials under exciting force of vibratory roller, which is intended to reduce the porosity and increase the strengths of rockfill materials.

It should be noted that the rockfill with composite grout filling some of its inter-granular voids is still a kind of granular material and has the typical properties of earth-rock material. It is obtained by sprinkling composite grout on the surface of rockfill and let the composite grout fill the voids of rockfill by the exciting force of vibratory roller, which is essentially different from the so-called cemented sandy gravel or hardfill materials. Cemented sandy gravel or hardfill materials are obtained by mixing cement and

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well-graded gravels and their mechanical properties are more like concrete (Kongsukprasert *et al.* 2005). From this point of view, the proposed method in this paper maintains the advantages of fast construction process of rockfill dam, because it does not need the process of mixing cement and gravels in advance but instead sprinkling the composite grout during the spread and pavement of rockfill. On the other hand, the proposed method of using composite grout to reduce porosity of rockfill materials is relatively economical since the composite grout is composed of large volume of fly ash (with mass fraction exceeding 60%), which is a kind of industry waste and not expensive.

In order to explore the feasibility and effectiveness of the proposed method, a preliminary field test has been carried out at the downstream cofferdam of Wudongde hydropower station located in south-western China (Fig. 1). According to the preliminary results of the field test, rockfill materials with composite grout could succeed in getting much lower porosity of 17%, which is difficult to reach only by raising compaction standards (Changjiang Institute of Survey, Planning, Design and Research 2016). However, the influence factors controlling the effect of composite grout on porous mediums were still unclear. Besides, the basic physical/mechanical properties of composite grout-modified rockfill were different to be determined only via some expansive field tests.

In this paper, a visible flowing test was firstly designed to investigate the flow characteristics of composite grout in porous medium under exciting force. The influencing factors studied include fly ash content, water-to-binder ratio, maximum sand size and composite grout content. Then, the compressibility, shear strength, permeability and suffusion susceptibility properties of composite grout-modified rockfill were studied and compared with that of pure rockfill without composite grout. Based on the laboratory experimental results, the mechanism of the effects of composite grout on rockfill materials was further analyzed and summarized.

(a) Spreading the rockfill

(b) Sprinkling the composite grout

(c) Rolling compaction

Fig. 1 Procedures of using composite grout to reduce porosity of rockfill in Wudongde hydropower station

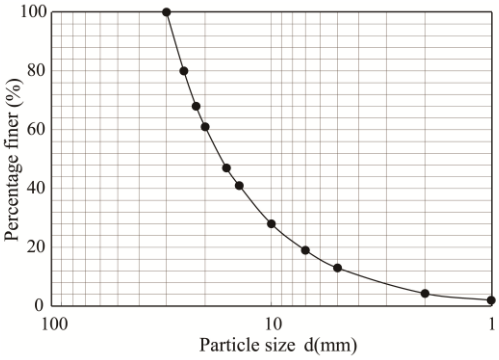


Fig. 2 Gradation curve of glass balls

2. Flow tests on composite grout

The porosity of rockfill materials can be reduced by composite grout on condition that the composite grout effectively fills the inter-granular voids of rockfill materials under the exciting force by vibratory rollers. As rockfill materials are porous mediums, the filling process is essentially the flow of composite grout in porous medium under exciting force, which is closely related to the flow characteristics of composite grout. To study the flowing characteristics of composite grout in the porous medium, transparent glass balls were used as an ideal porous medium. By observing the flow depths of the composite grout in the transparent glass balls, the effects of several influencing factors were investigated, such as the ratio of fly ash to cementitious materials (the sum of cement and fly ash) *F/B*, the water-to-binder ratio W/B, the maximum sand size dmax and the content of composite grout α (the ratio of the mass of grout content to the total volume of the specimen). The advantages of using transparent glass balls are as follows: 1) The flowing process of composite grout in the voids of porous mediums can be observed clearly and intuitively. 2) The voids characteristics of glass ball specimens are almost the same for each test, because the number of glass balls with different sizes can be precisely controlled.

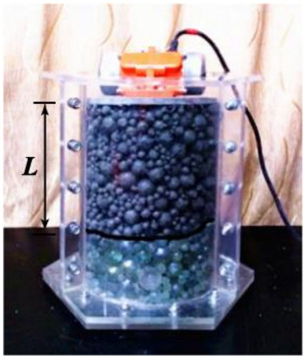
2.1 Materials and methods

The glass balls used in flow test have 11 different diameters, ranging from 1 mm to 30 mm. The gradation curve of glass balls is shown in Fig. 2. The composite grout is a mixture of Ordinary Portland cement (type I), Class F fly ash and river sand, containing 0.8% polycarboxylate superplasticizer (in mass fraction).

The flow tests were carried out in a transparent cylinder

(a) Putting glass balls into the cylinder

(b) Sprinkling the composite grout



(c) Applying exciting force

Fig. 3 Procedure of flow tests on composite grout in glass balls

Table 1 Experimental variables and their corresponding variations

Variables	Variations
Fly ash content *F/B*	0.60, 0.70, 0.80
Water-to-binder ratio *W/B*	0.42, 0.45, 0.50
Maximum sand size d_{max} (mm)	1.0, 2.0, 5.0
Composite grout content α (kg/m^3)	30, 40, 50, 60, 70, 80

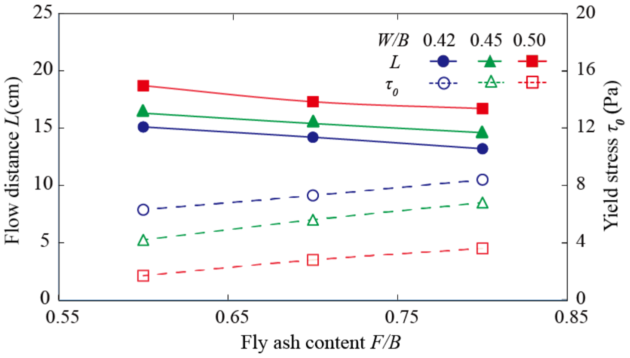


Fig. 4 The effects of fly ash contents and water-to-binder ratios (α=70 kg/m^3, d_{max}=2 mm)

with the dimension of 200 mm in diameter and 300 mm in height (Fig. 3(a)). In order to make the particle distribution of the whole sample as homogeneous as possible, the glass balls were firstly divided into five parts on average and further mixed thoroughly until achieving a uniform state. Then, the ball assembly was packed into the cylinder layer by layer with the total height of 200 mm and the overall density of 1.9 g/cm^3. Next, the prepared composite grout was sprinkled evenly on the specimen surface and gradually infiltrated into voids of glass balls under self-gravity (Fig. 3(b)). Finally, exciting force was applied on the top of the specimen by a small vibrator (Power: 30W, Frequency: 50Hz, Exciting force: 400N) to simulate the process of rolling compaction (Fig. 3(c)). The flow depth L of composite grout in glass balls, used to characterize the flowing effectiveness of the composite grout, was measured after one minute of vibration.

Flow tests were carried out under different conditions of fly ash content *F/B*, water-to-binder ratio *W/B*, maximum sand size d_{max} and composite grout content α. The variables of flow tests and their variations are shown in Table 1.

2.2 Results and discussions

(1) Effects of fly ash content and water-to-binder ratio

The effects of the fly ash content *F/B* and water-to-binder ratio *W/B* on flow depths of composite grout in porous mediums are shown in Fig. 4 (α=70 kg/m^3, d_{max}=2 mm). The yield stress was measured by a rotational viscometer. Researches (Senff *et al.* 2007, Mirza *et al.* 2002) show that the composite grout is homogeneous single-phase fluid when the sand size is small, which can be considered as Bingham fluid with yield stress. The flow of composite grout depends on the relation between shear stress and yield stress. When the shear stress is lower than the yield stress, the composite grout remains stationary, otherwise, it begins to flow. As shown in Fig. 4, with the increase of fly ash content, the yield stress increases and the flow depth decreases. With the increase of water-to-binder ratios, the yield stress decreases and the flow depth increases. This is in agreement with the results found by Ma *et al.* (2007), who studied the effects of fly ash content and shear ratio on the rheological characteristics of cement-fly ash paste.

(2) Effect of maximum sand size

When the sand size increases, the composite grout will transform from a homogeneous single-phase fluid to a suspension fluid composed of sand and cement paste. If granular blocking occurs, the composite grout will fail to fill the pores of glass balls. Roussel *et al.* (2009) claimed that granular blocking is a matter of probability and found the probability of granular blocking of a suspension crossing obstacles increase with the number of particles crossing the obstacles, their volume fraction and the ratio

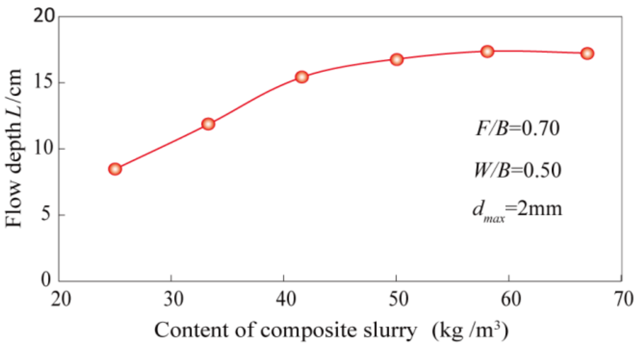


Fig. 5 Changes of flow depth with the composite grout content (F/B=0.70, W/B=0.50, d_{max}=2 mm)

between the diameter of the particles and the obstacle (see Eq. (1).

$$P = 6\Omega / \pi d^3 \phi^{0.85\delta^2/d^2} \tag{1}$$

where P is the probability of granular blocking, Ω is the volume of a suspension, d is the maximum diameter of particles in the suspension, ϕ is the volume fraction of the aggregate particles, i.e., sand, and δ is the width of obstacles.

Flow tests on maximum sand size d_{max}=1 mm and 5 mm were conducted (F/B=0.7, W/B=0.5), and the measured flow depths were 18.7 cm and 13.4 cm, respectively. Together with the previous experimental fact in Fig. 5 that the flow depth is 17.5 cm when d_{max}=2 mm, it can be concluded in the test that the flow depths of composite grout in glass balls decrease with the increase of maximum sand size. This suggests that the probability of blocking between inter-granular voids increases with the increase of sand sizes, which is in accordance with the granular blocking model proposed by Roussel *et al.* (2009).

(3) Effect of composite grout content

Fig. 5 shows the changes of flow depth with the composite grout content α (F/B=0.70, W/B=0.50, d_{max}=2 mm). It is apparent that the flow depth increases gradually as α increases from 30 kg/m^3 to 80 kg/m^3. However, the increase speed rate flow reduces upon the continued increase of composite grout content. This phenomenon can also be explained by Roussel's granular blocking model. The probability of granular blocking is low when the composite grout content is small, so the flow depth will increase greatly with increasing composite grout content. As the composite grout content increases to a certain extent, the probability of granular blocking is high, so the flow depth will not increase so rapidly and presents reduced increasing speed rate. Considering the commercial and cost factors, the content of 50~60 kg/m^3 may be more appropriate when using composite grout in reducing porosity of rockfill.

In summary, the flow characteristics of composite grout in porous medium are largely dependent on the fly ash content, the water-to-binder ratio, the maximum sand size, and composite grout content. The flow depths will increase with increasing water-to-binder ratios and decreasing fly ash contents and maximum sand sizes. There is a relative optimum value of the composite grout content.

3. Physical and mechanical properties of composite grout-modified rockfill

As aforementioned, the deformation of super-high rockfill dams, including instantaneous deformations and creep deformation, should be strictly controlled. Also, the shear strength, another important mechanical parameter of rockfill, is of great importance to the stability of dams. Herein, a new method of using composite grout is proposed to reduce the porosity of rockfill materials, thus increasing compression modulus and shear strength as well as decreasing deformation of high rockfill dams. However, the permeability and suffusion susceptibility of composite grout-modified rockfill should also be paid attention due to the fact that the composite grout may affect the seepage behaviour of rockfill materials in rockfill zone. Besides, whether the fine particles in composite grout filling in the voids of rockfill will be taken away by seepage force or not remains unclear. Therefore, to acquire a better knowledge of the basic physical and mechanical properties of composite grout-modified rockfill, a series of laboratory compression tests, direct shear tests and permeability tests were conducted. Preliminary discussions on compressibility, shear strength, permeability and suffusion susceptibility of composite grout-modified rockfill are presented in the following part.

3.1 Materials and sample preparation

Two different types of rockfill materials were used (denoted as, *Rockfill A* and *Rockfill B*), both of which are obtained from the construction site of a rockfill dam in southern China. *Rockfill A* is dolomite, with a saturated uniaxial compression strength of 50 MPa~60 MPa (medium hard rock), and *Rockfill B* is strongly-weathered dioritic porphyrite, whose saturated uniaxial compression strength is 5 MPa ~ 10 MPa (loose rock). In addition, two different kinds of gradations (denoted as, *Gradation 1* and *Gradation 2*) were taken into consideration. Fig. 6 shows the gradation curves of the tested rockfill materials. *Gradation 1* is well-graded (C_u=13.5, C_c=2.02), obtained on the basis of a dam's design gradation, while *Gradation 2* is gap-graded (C_u=30.2, C_c=0.48). Since gap-graded rockfill and loose rock rockfill are common during the construction of rockfill dam in China, it is meaningful to figure out how the composite grout affects the physical and mechanical properties of gap-graded and loose rockfill. Table 2 gives

Table 2 Rockfill materials with different types and gradations

Specimen No.	Rockfill type	Gradation	With/without composite grout
A1Y	Rockfill A	Gradation 1	with
A1N	Rockfill A	Gradation 1	without
A2Y	Rockfill A	Gradation 2	with
A2N	Rockfill A	Gradation 2	without
B1Y	Rockfill B	Gradation 1	with
B1N	Rockfill B	Gradation 1	without

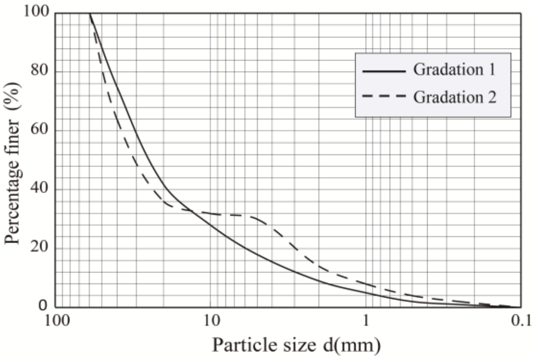
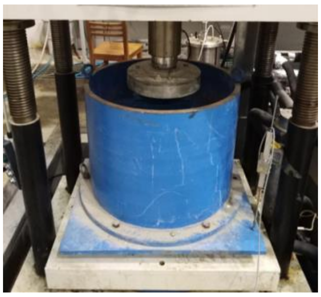


Fig. 6 Two gradation curves of rockfill materials

Table 3 Composition of the composite grout used in laboratory tests

Fly ash-to-binder ratio *F/B*	60%
Water-to-binder ratios *W/B*	0.5
Maximum sand sizes d_{max} (mm)	2
Mass fraction of polycarboxylate superplasticizer	0.8%
Contents of composite grout α (kg/m^3)	50



(a) Compression test

(b) Direct shear test

(c) Permeability test

Fig. 7 Apparatus of the laboratory experimental investigation

the details of the rockfill types and gradations of rockfill materials used in this paper and their notations. Compression tests involve rockfill with two different types and gradations, and rockfill used in permeability tests and direct shear tests are medium hard rockfill with good gradation (A1Y).

According to the experimental results of previous flow tests on composite grout, the flow characteristics of composite grout in rockfill materials may also be largely dependent on the fly ash content, the water-to-binder ratio, the maximum sand size, and composite grout content. The basic composition of the tested grout was selected as shown in Table 3.

For compression tests, the rockfill sample was designed to weigh 180 kg in mass and divided into five equal parts. Each part was carefully dropped into the conpression apparatus (600 mm in diameter and 300 mm in height, shown in Fig. 7(a)), and then the composite grout was sprinkled on the surface of each layer. Each layer was compacted by a vibrator (Frequency: 45Hz, Exciting force: 5 kN) for eight minutes. The total height of the specimen was measured after five layers were placed and compacted, and the density and void ratio of the specimen were calculated. Each specimen was placed for seven days before tested. At the beginning of confined compression test, a rigid compression plate was placed on the top of the specimen, and a pre-pressure of about 5 kPa was applied to ensure good contact between the plate and specimen. Then, vertical stresses of 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa and 3200 kPa were applied respectively, and the vertical displacements of the specimen were recorded.

For permeability tests and direct shear tests, the rockfill samples were designed to have dry densities of 2100 kg/m^3.

The preparation of the tested rockfill samples are the same as that of compression tests. Fig. 7 shows the apparatus of laboratory tests. The direct shear device has a inner diameter of 30 cm and a height of 40 cm.

3.2 Compressibility

The data of confined compression tests are plotted in Figs. 8 and 9 of void ratio, *e* versus the logarithm of vertical stress, $log\sigma_v$. The initial void ratio e_0 and void ratio e_i under vertical stress σ_{vi} can be calculated by Eqs. (2) and (3).

$$e_0 = \frac{\rho_w G_s (1+0.01\omega_0)}{\rho_0} - 1 \tag{2}$$

where *Gs* is the specific gravity of rockfill sample, ρ_w is the density of water, ρ_0 and ω_0 are the initial dry density and initial water content of the rockfill sample, respectively.

$$e_i = e_0 - (1+e_0)\frac{\Delta h_i}{h_0} \tag{3}$$

where e_i is the void ratio after a certain vertical stress σ_{vi} is applied, Δh_i is the height increment under vertical pressure σ_{vi}, and h_0 is the initial height of the rockfill sample.

It can be seen from Fig. 8 that, under the same vibrating compaction conditions (Frequency: 45Hz, Exciting force: 5kN), the initial void ratio e_0 of rockfill samples decreases from 0.272-0.277 to 0.231-0.234 after the composite grout is added. As the vertical stress increases, the curve transfers

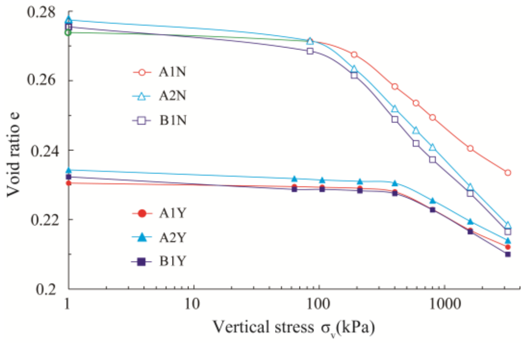


Fig. 8 Confined compression curves of rockfill with different types and gradations

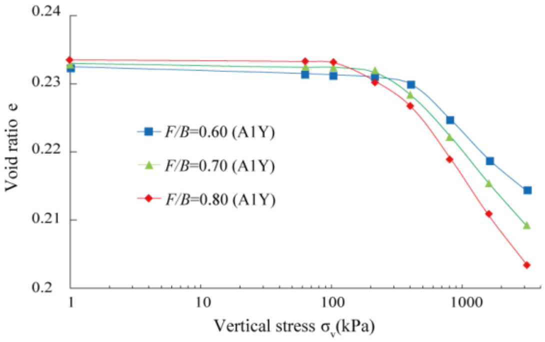
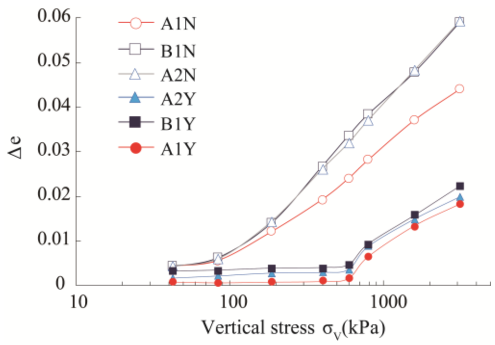
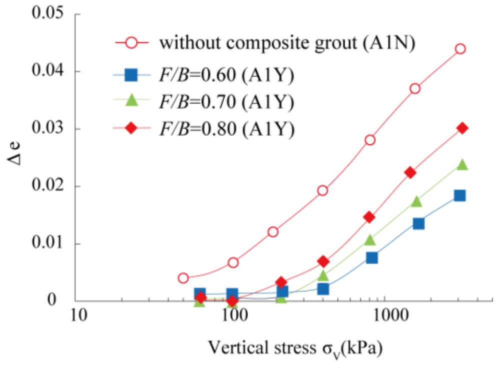


Fig. 9 Confined compression curves of A1Y rockfill with different *F/B* values

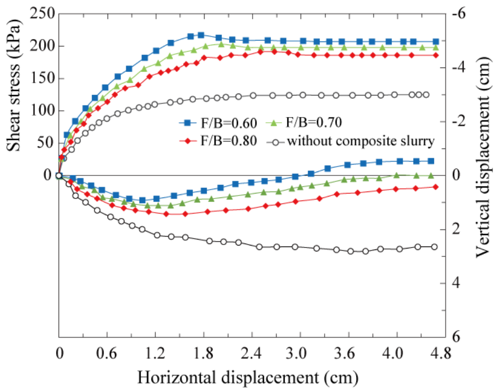


(a) Different rockfill types and gradations

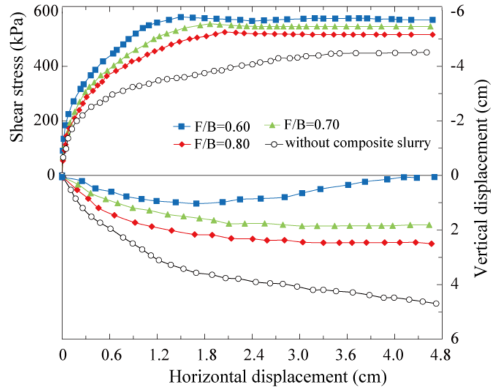


(b) Different *F/B* values

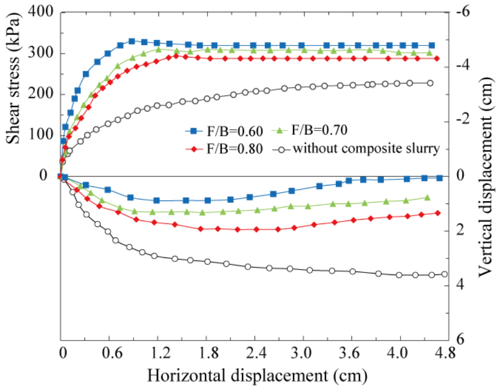
Fig. 10 Variation in void ratios with applied vertical stress for rockfill



(a) σ_v=100 kPa



(b) σ_v=200 kPa



(c) σ_v=400 kPa

Fig. 11 Shear stress-horizontal displacement and vertical strain-horizontal displacement curves of rockfill under different vertical stress

from a flat section to a steep section because of compression and particle breakage of the rockfill (Marsal 1967, Wang and Wong 2010, Hyodo *et al.* 2017, Li *et al.* 2016). The value of vertical stress corresponding to the sudden decrease of void ratio is much larger for rockfill with composite grout owing to the filling and cementation effects of composite grout. As presented in Fig. 9, with the decrease of fly ash content *F/B* in the composite grout, the stress value corresponding to the sudden decrease of void ratio increases. More precise stress values corresponding to the sudden decrease of void ratio can be derived if changes in void ratio are represented in terms of the applied stress (in log scale). In Fig. 10, the acceleration of changes in void ratio with stress is found at approximately 100 kPa and 600kPa for the composite grout-modified and pure rockfill, and for different *F/B* values of 80%, 70% and 60%, the corresponding stress values are about 100 kPa, 180 kPa and 300kPa, respectively. It can be explained by flow tests results that the composite grout fills the voids of rockfill better at lower fly ash contents. Besides, lower fly ash contents means higher cement contents, so the cementation effect of composite grout is more significant.

Compression modulus *Es* is usually used to reflect the ability to resist deformation of rockfill under the condition of no lateral deformation, which is defined as

$$E_s = \frac{d\sigma_z}{d\varepsilon_z} \tag{4}$$

where σ_z and ε_z are the vertical stress and vertical strain, respectively.

Compression modulus of rockfill under different stress ranges are calculated and listed in Table 4. As shown in Table 4, the filling of composite grout could effectively increase the compression modulus of rockfill. Compression modulus of well-graded and medium hard rockfill are bigger than those of gap-graded and loose rockfill. For the vertical stress in the interval of 1600 kPa-3200 kPa, it can be seen that the compression modulus for well-graded hard rockfill increases by 19.1 MPa, while for gap-graded and loose rockfill, the increments are 29.9 MPa and 21.8 MPa. It indicated that the effect of composite grout on increasing rockfill compression modulus is more obvious for gap-graded and loose rockfill.

3.3 Shear strength

Direct shear tests were conducted to investigate the strength behavior of composite grout-modified rockfill and the effect of the fly ash-to-binder ratio *F/B* in the composite grout was also taken into account. Fig. 11 shows the curves of shear stress-horizontal strain and vertical strain-horizontal displacement for pure and modified rockfill under different vertical stress.

It can be seen from Fig. 11 that with the increase of the vertical stress, the shear strength of rockfill will increase gradually. The addition of composite grout has great effects on the shear strength of rockfill. Under the same vertical stress condition, the composite grout-modified rockfill tends to have bigger shear strength. The initial slopes of the shear stress-horizontal displacement curves, i.e., the initial shear modulus of rockfill, are much bigger for composite grout-modified rockfill due to the cementation effect of composite grout. Besides, the shear strength of composite grout-modified rockfill decreases with the increment of F/B. This is mainly because composite grout with smaller *F/B* value will fill the voids of rockfill better, which is also reflected in the previous flow tests in Fig. 5 that the flow depth increases with the decrease of fly ash content.

From the relationship between horizontal displacement and vertical strain, it can be found that the composite grout changes the dilation characteristics of rockfill. Composite grout-modified rockfill will undergo more dilation during shear load and dilation increases with the decrease of *F/B* values, which is in agreement with the results found by Amini *et al.* (2014) when they studied the shear strength-dilation characteristics of cemented sand-gravel mixtures. It can be explained that the composite grout fills the inter-granular voids of rockfill materials and bond rockfill particles together, which on one hand makes the rockfill structure much denser, and also decrease particle breakage and particle rearrangements during shearing. Therefore, rockfill with composite grout will have more obvious dilation behaviour. It also can be seen that the shear stress-horizontal displacement curves of rockfill samples would transform from strain hardening to strain softening after composite grout is added, and this finding is in agreement with the described dilation behavior of samples.

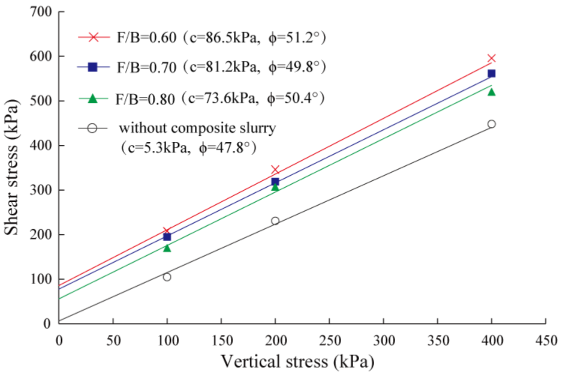


Fig. 12 Relationship between shear stress and vertical stress of rockfill with and without composite grout

Table 4 Compression modulus of rockfill with different types and gradations under different vertical stresses

Vertical stress (kPa)		100~200	200~400	400~800	800~1600	1600~3200
Compression modulus (MPa)	A1N	39.5	55.0	70.4	98.7	110.6
	A1Y	58.6	72.4	97.6	115.8	129.7
	Increment	19.1	17.4	27.2	17.1	19.1
	A2N	31.5	42.3	59.4	77.3	93.7
	A2Y	53.6	68.7	89.4	104.4	123.6
	Increment	22.1	26.4	30	27.1	29.9
	B1N	28.7	37.9	62.3	82.3	98.7
	B1Y	58.1	73.2	93.2	113.8	120.5
	Increment	29.4	35.3	30.9	31.5	21.8

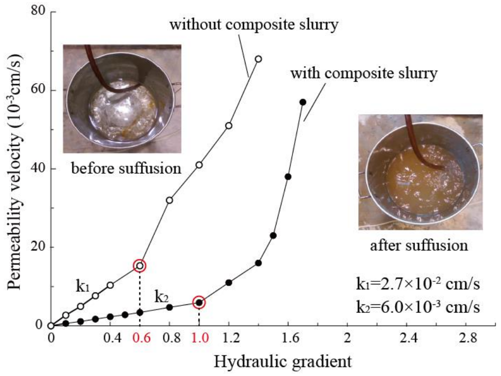


Fig. 13 Permeability velocity against hydraulic gradient for rockfill with and without composite grout

Data of peak shear stress versus vertical stress are plotted in Fig. 12 to obtain the cohesive strength *c* and internal friction angle ϕ of pure and composite grout-

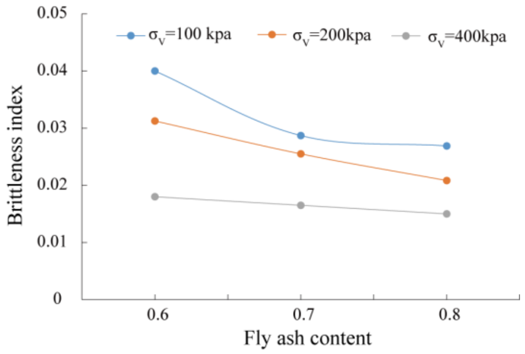


Fig. 14 variation of brittleness index of composite grout-treated rockfills with fly ash content

modified rockfill. As can be seen, the pure rockfill materials almost have no cohesive strength. While the filling of composite grout evidently improves the cohesive strength of rockfill owing to its cementation effects. It is also observed that composite grout-modified rockfill with smaller *F/B* values has greater cohesive strength. This is also attributed to the fact that the composite grout with smaller *F/B* value will lead to a longer flow depth along the inter-granular voids and thus fill the voids of rockfill better. The internal friction angle ϕ, however, did not show so obvious increase as the cohesive strength did.

3.4 Permeability and suffusion susceptibility

Permeability tests were carried out to investigate the permeability of rockfill materials with and without composite grout. In addition, the critical hydraulic gradient for initiation of suffusion erosion was measured.Suffusion in rockfill materials involves the transport of finer particles through the voids between the matrix of the coarser particles of the rockfill by seepage forces (Le *et al.* 2017). The measured permeability velocities are plotted in Fig. 13 in terms of applied hydraulic gradients. As shown in Fig. 13, when the applied hydraulic gradient is small, the permeability velocity is proportional to the hydraulic gradient, and the slope of the curve was permeability coefficient *k* according to Darcy law. The permeability coefficient *k* of rockfill with and without composite grout is 6.0×10^{-3} cm/s and 2.7×10^{-2} cm/s, respectively. It seems that the addition of composite grout may influence the seepage property of rockfill zone to some extent, however, this problem can be solved by setting some horizontal and vertical drainage bodies.

As the hydraulic gradient increases to a certain value, suffusion erosion may occur. With the increase of hydraulic gradient, shown in Fig. 13, the Darcy law is no longer valid and the permeability velocity has a sudden increase, which indicates that suffusion erosion occurs and fine particles are taken away within the matrix of coarse particles under seepage flow. The critical hydraulic gradients, which correspond to the initiation of suffusion erosion, are about 1.0 and 0.6 for rockfill materials with and without composite grout, respectively. It can be concluded that composite grout-modified rockfill has larger suffusion erosion resistance due to the cementation effect of composite grout, which played a role in bonding fine particles together against the seepage flow. Besides, the fine particles of composite grout filling in the voids of rockfill are not easy to be taken away out of the matrix of rockfill particles.

3.5 Brittleness

Because the added composite grout contains cement, the brittleness of rockfill materials will increase when the composite grout is added due to the nature of cement. The brittleness index I_B proposed by bishop (1967) is adopted to quantitatively describe the brittleness of rockfill materials, which is defined as

$$I_B = \frac{\tau_p - \tau_r}{\tau_r} \tag{5}$$

where τ_p and τ_r are the peak and residual shear stresses under a certain vertical stress.

Fig. 14 shows the brittleness index of rockfill materials with composite grout under different fly ash contents. It shows that the brittleness index of composite grout-treated rockfill materials is small, which indicates that the added composite grout does not increase the brittleness of rockfill materials significantly. It can also be observed that the brittleness index decreases with the increasing fly ash content in composite grout, and the specimen under higher vertical stress tend to have a relatively lower brittleness index.

4. Mechanism analysis of the effect of composite grout on rockfill

According to the previous laboratory experimental results, the filling of composite grout can effectively reduce the porosity of rockfill materials, thus increasing the compression modulus and the shear strength of rockfill. The effect of composite grout on rockfill can be summed up as filling, lubrication and cementation.

1) *Filling*.Composite grout fills the inter-granular voids of rockfill materials, which reduces the porosity of rockfill and makes rockfill more compacted, therefore rockfill with composite grout tends to have higher compression modulus. Besides, the filling composite grout wraps around the rockfill particles and functions as a kind of “cushion layers”, which can reduce particle breakage under high stress and decrease dam deformations.

2) *Lubrication*. Before hardening, the composite grout makes the rockfill particle surface moister and reduces friction during the process of rolling compaction.

3) *Cementation*. Composite grout contains cementitious materials like cement and fly ash, which have the property of post-hardening. The filling composite grout will not only bond the rockfill particles together but also restrain the particle rearrangements during loading, such as sliding and rotation.

5. Conclusions

A method of using composite grout is proposed to reduce the porosity of rockfill materials for the construction of super-high rockfill dams. Laboratory tests were conducted to investigate the flow characteristics of composite grout. Besides, the compressibility, shear strength, permeability, and suffusion susceptibility of composite grout-modified rockfill materials were studied. The conclusions are summarized as follows:

- The filling of composite grout can effectively reduce the porosity of rockfill materials, as well as increasing the compression modulus of rockfill materials, especially for loose and gap-graded rockfill materials.
- The flow characteristics of composite grout in porous medium are highly related to the fly ash contents, the water-to-binder ratios, the maximum sand sizes and the contents of composite grout. The flow depths of composite grout in porous medium increase with increasing water-to-binder ratios and decreasing fly ash contents and maximum sand sizes. There is a relative optimum value of the composite grout content.
- Composite grout-modified rockfill has greater shear strength than pure rockfill, and the composite grout significantly improves the cohesive strength of rockfill. The addition of composite grout increases the dilation behaviour of rockfill materials.
- Rockfill with composite grout tends to have larger suffusion erosion resistance due to the cementation effect of composite grout, and the fine particles of composite grout are not easy to be moved out of the matrix of rockfill particles by flow force.
- The composite grout mainly plays the roles of filling, lubrication and cementation in rockfill materials.

This study mainly provides a laboratory experimental understanding on the basic compressibility, shear strength, brittleness, permeability and suffusion susceptibility properties of composite grout-modified rockfill, as well as the mechanism of the effect of composite grout on rockfill. More studies need to be conducted to further investigate some dynamic properties of composite grout-modified rockfill, such as seismic ductility.

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References

Alonso, E.E. and Cardoso, R. (2010), “Behavior of materials for earth and rockfill dams: Perspective from unsaturated soil mechanics”, *Front. Arch. Civ. Eng. China*, **4**(1), 1-39.

Amini, Y., Hamidi, A. and Asghari, E. (2014), “Shear strength-dilation characteristics of cemented sand-gravel mixtures”, *Int. J. Geotech. Eng.*, **8**(4), 406-413.

Bishop, A.W. (1967), “Progressive failure-with special reference to the mechanism causing it”, *Proceedings of the Geotechnical Conference on the Shear Strength of Natural Soil sand Rocks*, Oslo, Norway.

Changjiang Institute of Survey, Planning, Design and Research. (2016), “Report of field roller compaction test on rockfill materials with composite grout”, Changjiang Institute of Survey, Planning, Design and Research, Wuhan, China.

Chen, S.K., He, Q.D. and Cao, J.G. (2018), “Seepage simulation of high concrete-faced rockfill dams based on generalized equivalent continuum model”, *Water Sci. Eng.*, **11**(3), 250-257.

Chen, S.S., Fu, Z.Z., Wei, K.M. and Han, H.Q. (2016), “Seismic responses of high concrete face rockfill dams: A case study”, *Water Sci. Eng.*, **9**(3), 195-204.

Grzeszczyk, S. and Lipowski, G. (1997), “Effect of content and particle size distribution of high-calcium fly ash on the rheological properties of cement pastes”, *Cement Concrete Res.*, **27**(6), 907-916.

Hua, J.J., Zhou, W., Chang, X.L. and Zhou, C.B. (2011), “Long-term deformation prediction of 300 m high rockfill dams”, *J. Sichuan Univ.*, **43**(3), 33-38.

Hyodo, M., Wu, Y., Kajiyama, S., Nakata, Y. and Yoshimoto, N. (2017), “Effect of fines on the compression behaviour of poorly graded silica sand”, *Geomech. Eng.*, **12**(1), 127-138.

Kongsukprasert, L., Tatsuoka, F. and Tateyama, M. (2005), “Several factors affecting the strength and deformation characteristics of cement-mixed gravel”, *Soil. Found.*, **45**(3), 107-124.

Langroudi, M.F., Soroush, A., Shourijeh, P.T., and Shafipour, R. (2013), “Stress transmission in internally unstable gap-graded soils using discrete element modeling”, *Powder Technol.*, **247**(10), 161-171.

Le, V.T., Marot, D., Rochim, A., Bendahmane, F. and Nguyen, H.H. (2017), “Suffusion susceptibility investigation by energy based method and stat”, *Can. Geotech. J.*, **55**(1), 57-68.

Li, L.K., Wang, Z.J., Liu, S.H. and Bauer, E. (2016), “Calibration and performance of two different constitutive models for rockfill materials”, *Water Sci. Eng.*, **9**(3), 227-239.

Li, S., Yu, S., Shangguan, Z. and Wang, Z. (2016), “Estimating model parameters of rockfill materials based on genetic algorithm and strain measurements”, *Geomech. Eng.*, **10**(1), 37-48.

Ma, H.Q. and Chi, F.D. (2016), “Major technologies for safe construction of high earth-rockfill dams”, *Eng.*, **2**(4), 498-509.

Ma, K.L., Feng, J., Long, G.C., Xie, Y.J. and Cheng, X.B. (2017), “Rheological characteristic and its mechanism of cement-fly ash paste”, *J. Railway Sci. Eng.*, **14**(3), 465-473.

Marsal, R.J. (1967), “Large scale testing of rockfill materials”, *J. Soil Mech. Found. Div.*, **93**(2), 27-43.

Mirza, J., Mirza, M.S., Roy, V. and Saleh, K. (2002), “Basic rheological and mechanical properties of high-volume fly ash grouts”, *Construct. Build. Mater.*, **16**(6), 353-363.

Roussel, N., Nguyen, T.L.H. and Yazoghli, O. (2009), “Passing ability of fresh concrete: A probabilistic approach”, *Cement Concrete Res.*, **39**(3), 227-232.

Senff, L., Labrincha, J.A., Ferreira, V.M., Hotza, D. and Repette, W.L. (2009), “Effect of nano-silica on rheology and fresh properties of cement pastes and mortars”, *Construct. Build. Mater.*, **23**(7), 2487-2491.

Sherard, J.L. and Cooke, J.B. (1989), “Concrete-face rockfill dam: i. assessment”, *J. Geotech. Eng.*, **113**(10), 1096-1112.

Wang, Z. and Wong, R.C.K. (2010), “Effect of grain crushing on 1d compression and 1d creep behavior of sand at high stresses”, *Geomech. Eng.*, **2**(4), 303-319.

Zhang, B.Y., Zhang, J.H., and Sun, G.L. (2015), “Deformation and shear strength of rockfill materials composed of soft siltstones subjected to stress, cyclical drying/wetting and temperature variations”, *Eng. Geol.*, **190**, 87-97.

Zhong, Q.M., Chen, S.S. and Deng, Z. (2018), “A simplified physically-based breach model for a high concrete-faced rockfill dam: A case study", *Water Sci*. *Eng*., **11**(1), 46-52.

Zhou, W., Li, S.L., Ma, G., Chang, X.L., Cheng, Y.G. and Ma, X. (2016), "Assessment of the crest cracks of the pubugou rockfill dam based on parameters back analysis", *Geomech*. *Eng*., **11**(4), 571-585.

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