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Original Article

Mechanical and hydraulic performance of sludge-mixed cement grout in rock fractures

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Abstract

The objective is to assess the performance of sludge mixed with commercial grade Portland cement type I for use in minimizing the permeability of fractured rock mass. The fractures were artificially made by applying a line load to sandstone block specimens. The sludge comprises over 80% of quartz with grain sizes less than 75 µm. The results indicate that the mixing ratios of sludge:cement (S:C) of 1:10, 3:10, 5:10 with water:cement ratio of 1:1 by weight are suitable for fracture grouting. For S:C = 3:10, the compressive strength and elastic modulus are 1.22 MPa and 224 MPa which are comparable to those of bentonite mixed with cement. The shear strengths between the grouts and fractures surfaces are from 0.22 to 0.90 MPa. The S:C ratio of 5:10 gives the lowest permeability. The permeability of grouted fractures with apertures of 2, 10, and 20 mm range from 10^{-16} to 10^{-14} m^2 and decrease with curing time.

Keywords: rock fracture, grouting, permeability, sludge, cement

1. Introduction

The increasing amount of the water treatment sludge from the Metropolitan Waterworks Authority of Thailand (MWA) has called for a permanent solution to dispose the sludge from the Bang khen Water Treatment Plants. The MWA report (2007-2009) indicates that the plant produces sludge with a maximum capacity of 3.2×10^6 m^3 per day. The sludge has been collected from the water treatment process. The increasing rate of the sludge is about 247×10^3 kg per day. One of the solutions is to apply the sludge to minimize groundwater circulation in rock mass. Groundwater in rock mass is one of the key factors governing the mechanical stability of slope embankments, underground mines, tunnels, and dam foundations. A common solution practiced internationally in the construction industry is to use bentonite mixed with cement as a grouting material to reduce permeability in fractured rock mass (Papp, 1996; Akgün and Daemen, 1999). Knowledge and experimental evidences about the permeability of the sludge-mixed cement in fractured rock under varied stress conditions are rare. The objectives of this study are to assess the performance of sludge mixed with the commercial grade Portland cement for reducing permeability in saturated fractured rock under various stresses in the laboratory and to compare the results with those of the bentonite-mixed cement in terms of the mechanical and hydraulic performance.

2. Grouts preparation

The grouting materials used in this study are (1) sludge with particle sizes less than 75 µm, (2) commercial grade bentonite, and (3) commercial grade Portland cement type I for mixing with the sludge and bentonite. The fractures in sandstone collected from Phu Kradung formation were

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artificially made by applying a line load to induce a splitting tensile crack. Two shapes of the sandstone samples are 152.4×152.4×152.4 mm blocks and 100 mm diameter cylinder with 100 mm in length. Bentonite is from American Colloid Company.

Sludge and bentonite were tested for the Atterberg's limits, specific gravity, and particle size distribution. The equipment and test procedure follow the ASTM standards (D422, D854). The results are summarized in Table 1. Figure 1 shows the particle size distributions of the sludge used here.

3. Basic mechanical properties of grouting materials

The basic mechanical properties of the mixtures were determined to select the appropriate proportions of sludge-to-cement ratios. The sludge-mixed cement ratios (S:C) of 0:10, 1:10, 2:10, 3:10, 4:10, 5:10, 6:10, 8:10, and 10:10 by weight were prepared with water-cement ratios (W:C) of 0.8:1, 1:1 and 1.25:1. The bentonite-mixes cement ratios (B:C) are 0:10, 1:10, 2:10, 3:10, 4:10, and 5:10 by weight with water-cement ratios (W:C) of 1:1 and 4:1. Mixing of all grouts was accomplished using a blade paddle mixer as suggested by ASTM standard (C938). The mixtures were placed in a 54 mm PVC mold. They were cured under water at room temperature (ASTM C192). Viscosity measurement follows, as much as practical, the ASTM standard (D2196). The results are shown in Figure 2.

The procedure for determining the grout permeability is similar to the ASTM standard (C938, C39). The water flow tests were conducted at 3, 7, 14, and 28 days of curing. The mold has an inner diameter of 101.6 mm with a length of 152.4 mm. The prepared specimen was sealed between two acrylic platens with the aid of O-ring rubber and epoxy coating. Inlet port was installed at the end of the mold and connected to a water pressure tube compressed by nitrogen gas at about 13.8 kPa. Air bubbles were bled out before measuring the permeability. The outlet port was installed at the other end and connected to a high precision pipette for measuring the outflow. The coefficient of permeability is computed from the flow rate based on the Darcy's law. The results are presented in Figure 3.

Table 1. Atterberg's limits and specific gravity of sludge and bentonite.

Atterberg Limits	Bentonite (%)		Sludge (%)	
	SUT*	ACC**	SUT*	TU***
Liquid limit	357	478	55	69
Plastic limit	44	28	22	42
Plasticity index	313	449	23	28
Specific gravity	-	-	2.56	-

*SUT = Suranaree University of Technology Laboratory,
**ACC = American Colloid Company Technical Data,
***TU = Thammasat University Laboratory.

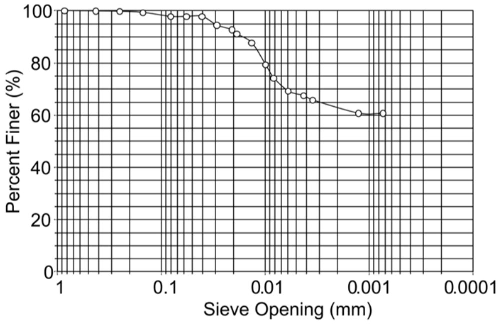

Figure 1. Grain size distribution of water treatment sludge.

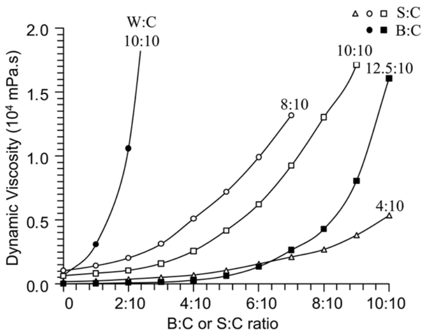

Figure 2. Dynamic viscosity of S:C and B:C for different W:C ratios.

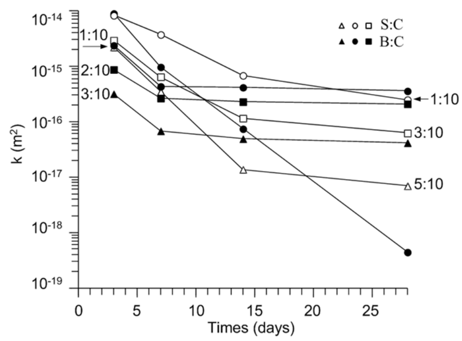

Figure 3. Intrinsic permeability as a function of time for pure cement (C), B:C, and S:C with W:C = 1:1.

4. Uniaxial compressive strength of grouting materials

The uniaxial compressive strength, elastic modulus, and Poisson's ratio of the grouting materials were determined. The results indicate that the suitable mixing ratios for the S:C are 1:10, 3:10, 5:10 and for the B:C are 1:10, 2:10, 3:10 with the W:C of 1:1 by weight. These proportions yield the lowest slurry viscosity of 5 Pa·s and the highest compressive strength. Preparation of these samples follows, as much as practical, the ASTM standard (C938, C39, D7012). All specimens were cured for three days before testing. During the test, the axial deformation and lateral deformation were monitored. The maximum load at the failure was recorded. The compressive strength (σ_C), Poisson's ratio (ν), and elastic modulus (E) are determined. The results of the S:C and B:C mixtures indicate that the chemical reaction between cement and water with the large casts were better than with the small ones. Figure 4 shows the uniaxial compressive strength for the S:C and B:C with W:C = 1:1. The uniaxial compressive strength and elastic modulus for the specimens with the diameter of 101.6 mm are summarized in Table 2. The maximum compressive strengths for the S:C and B:C are similar.

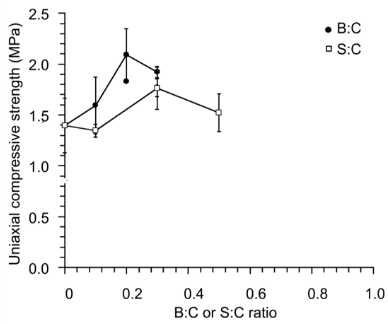

Figure 4. Uniaxial compressive strengths for B:C and S:C with W:C = 1:1.

5. Shearing resistance between grout and fracture

The maximum shear strengths of grouting material in sandstone fractures were determined by direct shear testing. The test procedure is similar to the ASTM standard (D5607). Three-ring shear test equipment was used. All specimens were cured for three days before testing. Laboratory arrangement for the three-ring shear test equipment is shown in Figure 5. The constant normal stresses used were 0.25, 0.5, 0.75, 1.0, and 1.25 MPa. The shear stress was applied while the shear displacement and dilation were monitored for every 0.2 mm of shear displacement. The failure modes were recorded. The test results are presented in the forms of the shear strength as a function of normal stress in Figure 6. The angles of internal friction and cohesion for all mixtures are similar.

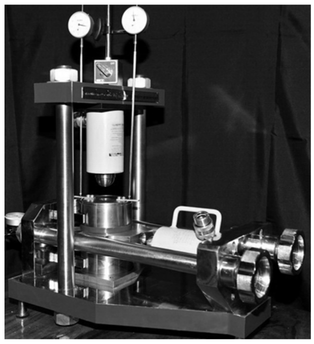

Figure 5. Laboratory arrangement for three-ring direct shear test.

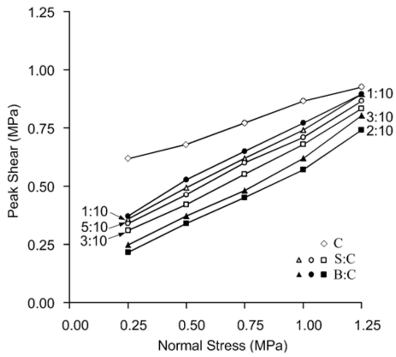

Figure 6. Normal stress and peak shear stress.

6. Permeability testing of fractures

The objective of this task is to assess the permeability of rock fractures under varying normal stresses. The fracture permeability is used to compare with the permeability of grouting materials for both sludge and bentonite mixtures. Constant head flow tests were performed. The normal stresses are from 1 to 4 MPa. The experimental procedure is similar to Obcheoy *et al.* (2011). Five specimens were prepared and tested. The injection hole at the center of the upper block is 12 mm in diameter and 101.6 mm in depth. The tests were conducted by injecting water into the center hole of the rectangular block specimen. The laboratory arrangement of the constant head flow test is shown in Figure 7. Water

Table 2. Mechanical properties of grouting materials.

Type	Mix ratio	Number of Samples	Average density (g/cm^3)	Poisson Ratio ν	σ_c (MPa)	E (MPa)
C	0:10	5	0.83 ± 0.01	0.18	1.40 ± 0.27	212
B:C	1:10	5	1.35 ± 0.04	0.17	1.59 ± 0.28	193
B:C	2:10	5	1.38 ± 0.04	0.14	2.09 ± 0.26	275
B:C	3:10	5	1.33 ± 0.02	0.16	1.92 ± 0.05	228
S:C	1:10	5	1.91 ± 0.06	0.15	1.35 ± 0.06	190
S:C	3:10	5	1.81 ± 0.07	0.21	1.77 ± 0.21	224
S:C	5:10	5	1.79 ± 0.06	0.16	1.52 ± 0.19	261

volume and time were recorded. Both tend to decrease exponentially with the normal stress. The permeability results (k) are plotted as a function of the normal stress (σ_n) in Figure 8. The equivalent hydraulic aperture (e_h) for the radial flow, hydraulic conductivity between smooth and parallel plates (K), and intrinsic permeability (k) are calculated by (Tsang, 1992; Indraratna and Ranjith, 2001) :

$$e_h = \left\{ \frac{6\mu q}{\pi \Delta P} \ln\left(\frac{r}{r_0} \right) \right\}^{\frac{1}{3}} \tag{1}$$

$$K = \gamma_w \frac{e_h^{\,2}}{12\mu} \tag{2}$$

$$k = \frac{e_h^{\,2}}{12} \tag{3}$$

where μ is the dynamic viscosity of the water (N·s/cm^2), q is water flow rate through the specimen (cm^2/s), ΔP is injecting water pressure into the center hole of rectangular blocks of the specimen, r is radius of flow path (m), r_0 is radius of the radius injection hole (m). γ_w is unit weight of water (N/m^2). The results indicate that the intrinsic permeability of the fractures is less than 1.4×10^{-9} m^2.

7. Permeability of grouting materials in rock fractures

The permeability of sludge- and bentonite-mixed cement in artificial fractures was determined. The testing method is similar to that described above. The grouting materials were injected into the fractures. The fracture apertures are 2, 10, and 20 mm. The grouting materials were cured for three days. Figure 9 shows the laboratory arrangement. Constant head flow tests was performed. The constant head ranges between 13.8 and 551.7 kPa. The constant normal stresses are 0.25, 0.5, 1.0, and 1.25 MPa. The results indicate that the normal stress could reduce the permeability of grouting materials in sandstone fractures. The intrinsic permeability (k) is calculated from the measured flow rate (Q) as follows (Indraratna and Ranjith, 2001) :

$$K = \frac{Q}{2\pi L H_c} \ln\left(\frac{2mL}{D} \right) \tag{4}$$

$$k = \frac{K\mu}{\gamma_w} \tag{5}$$

where K is hydraulic conductivity, Q is flow rate of water flow through the mixture, m is square root of the ratio between the conductivity perpendicular and parallel to the hole (in this case, m is equal to 1), L is the thickness of grouting material in fracture apertures, D is diameter of the injection hole at the center of the upper block, H_c is the constant head used for the test, μ is dynamic viscosity (891×10^{-6} kg/(m×s)) at temperature of 25°C, γ_w is unit weight of water (997.13 kg/m^3). Figure 10 shows the intrinsic permeability of grouting materials in fracture apertures for twenty-one samples.

8. Discussion and Conclusions

The sludge is classified as elastic silt with over 90% of its particles smaller than 0.047 mm. This study aims to determine the minimum slurry viscosity and appropriate strength of the grouting materials. The results indicate that the suitable mixing ratios for sludge-to-cement (S:C) are 1:10, 3:10, and 5:10, and for bentonite-to-cement (B:C) are 1:10, 2:10 and 3:10, with water-cement ratio (W:C) of 1:1 by weight. For the sludge these proportions yield the lowest slurry viscosity of 5 Pa·s and the highest compressive strength. For S:C of 3:10, the compressive strength and elastic modulus are 1.22 MPa and 224 MPa which are similar to those of the B:C. The direct shear test results indicate that the shear strengths at the interface between the grout and sandstone fractures varying from 0.22 to 0.90 MPa under normal stresses ranging from 0.25 to 1.25 MPa. Permeability of the grouting materials measured from the one-dimensional

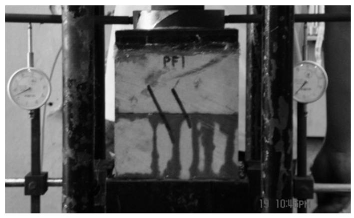

Figure 7. Laboratory arrangement for permeability testing of fractures.

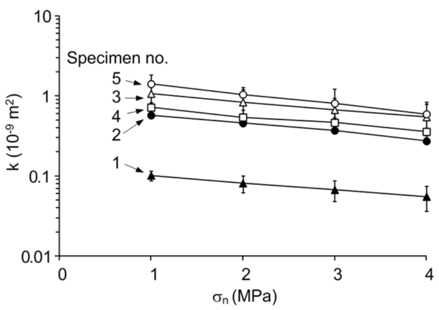

Figure 8. Intrinsic permeability (k) as a function of normal stress (σ_n) for fracture in Phu Kradung sandstone.

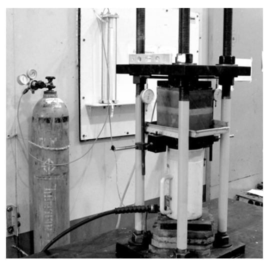

Figure 9. Permeability testing of grouting materials in rock fracture aperture 20 mm.

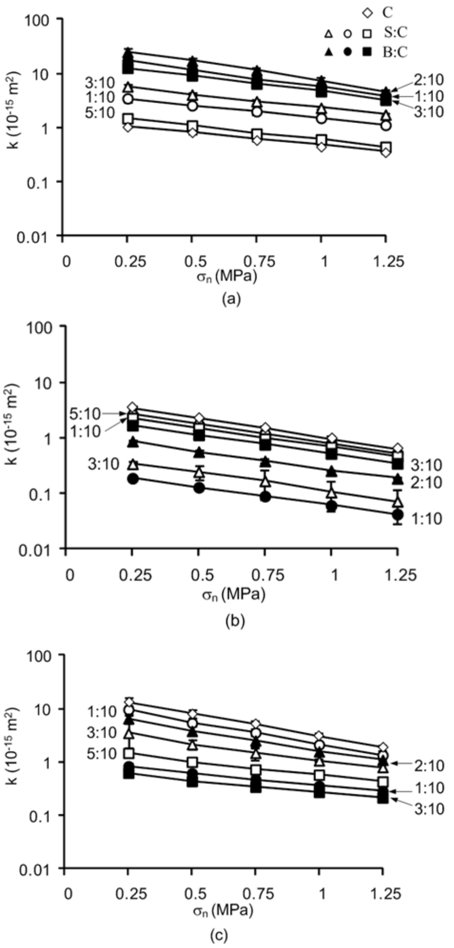

Figure 10. Intrinsic permeability (k) values as a function of normal stress (σ_n) for a fracture apertures of (a) 2 mm, (b) 10 mm, and (c) 20 mm in Phu Kradung sandstones.

flow test with constant head is from 10^{-17} to 10^{-15} m^2 and decreases with curing time. The mixture with the S:C of 5:10 by weight gives the lowest permeability. The permeability of the grouts measured by radial flow test in fractures with apertures of 2, 10, and 20 mm ranges from 10^{-16} to 10^{-14} m^2. The S:C mixtures have the mechanical and hydraulic properties equivalent to those of the B:C mixtures which indicates that the sludge can be used as a substituted material to mix with cement for rock fracture grouting purpose. Such applications can also minimize the disposal cost of the sludge and reduce the environmental impact due to the landfill construction.

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