Journal of the Faculty of Environmental Science and Technology.
Okayama University
Vol.14 No1,pp.23-28, March 2009

Laboratory Investigation of Ethanol/Bentonite Slurry Grouting into Rock Fractures: Preliminary Results

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During underground space development, groundwater seepage mostly occurs which may seriously affect the stability of deep excavations as well as retard progress of construction. For smooth progress of work, effective construction and operation of a disposal facility for high level radioactive waste (HLW), it is important to control seepage into excavations by sealing off fractures or fissures and excavation disturbed zones (EDZ) to control groundwater inflow during the construction phase of such a facility. In this study, a series of experiments were conducted on ethanol/bentonite slurries in the laboratory with the aim of determining the effect of a hydrophilic solvent such as ethanol on the hydraulic and injection characteristic of bentonite slurry for the sealing of fissures to control ground water seepage during the construction phase of a repository. Preliminary results revealed ethanol/bentonite slurry as an effective grouting material capable of penetrating micro fractures (100μm or less) and with the permeability of the grouted medium being as low as 10E-7cm/s. The results also show that the effectiveness and efficiency of grouting is dependent on the type of injection and fissure size. Dynamic injection was observed to be efficient as it was able to inject high dense slurry.

Key words: *Dynamic injection, permeability, swelling, bentonite, clay*

1 INTRODUCTION

In the construction phase of a repository for high level radioactive waste (HLW) disposal, tunnels and shafts are excavated as temporal means of transport for the installation or construction of engineered barrier systems. Substantial amount of water inflow into the facility is anticipated during the construction and operation periods. In such situations, it is desirable to minimize or arrest the inflow, not only for facilitating progress of construction and smooth operation of the facility after construction, but also to prevent deterioration of the quality of the *in situ* rock as a natural barrier. Apart from the existing naturally occurring fractures, fissures or joints, excavations can weaken the surrounding zone formation (herein called, weak excavation disturbed zone, EDZ) resulting in high permeability of the zone. All these serve as flow paths to groundwater seepage. In underground construction, groundwater seepage is one of the underlying issues that can hamper the smooth, effective and efficient construction progress. Seepage control is therefore an important phenomenon in underground construction. For effective operation of a repository, a good work must be done during the construction phase. In order to fulfill the basic requirement of a geological disposal system, and to prevent tunnels and fractures from becoming preferential flow paths or conduits for groundwater flow, these discontinuities must be properly sealed. This will ensure dry tunnel and comfortable environment to allow for smooth construction work and ultimately effective operation of a repository.

High quality or effective sealing can be accomplished by grouting with the most appropriate method and materials that can penetrate the very tiny fissures, have a hydraulic conductivity as low or lower than the *in situ* rock and have a swelling potential that will contact and seal fractures very well. The increased demand for efficiency when sealing tunnels or underground space facility by grouting has led to the need to seal narrow fractures (Funehag, 2005). Sealing narrow fractures is dependent on the ability of the grout to penetrate into the fissures. Grout penetration into fissures more than 100μm is not much of a problem. Once the grout enters the fissure or fracture, sealing takes place after gelling depending on the binding property of the grouting material. However, for injection of grout through fissures less than 100 μm, penetration of grout is limited, depending on the grain sizes of grout materials, mixing ratio and injection type. Successful grouting programme can be accomplished if grout slurry is able to penetrate the narrow fissures and effectively seals them.

More conductive or open fractures are mostly sealed by cement–based materials. These materials have been used extensively in the past for rock grouting in tunnels and other underground facilities, however, for penetrability into narrow fractures, cement grouts have their limitations and are therefore rendered less useful for low permeable rocks. Though they have the advantages of being strong and erosion-resistant, cement-based materials are chemically unstable, brittle and have low

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self-healing capacity. They also react with groundwater to produce hyper alkaline leachate (Metcalfe and Walker, 2004), which can affect the host rock thereby destroying its integrity that is essential for assuring long-term durability. An alternative to cement-based grout is clay-based or bentonite. Bentonite has been considered as one of the most promising materials for seepage barrier grouting for long durability (Asada et al., 2003). The importance of bentonite as a good sealing material has been discussed in many literature (e.g. Chegbeleh et al., 2008a; Hussain. 1999; Alawaji, 1997). It has the following desirable properties: - high swelling capacity, self-healing capacity and high chemical stability under common temperature and geochemical conditions. However, at the desired density of water/bentonite slurry, the viscosity is too high to allow enough quantity of bentonite to be injected into small fractures (Asada, 2003 as cited in Takase et al., 2006). In order to increase bentonite content in the slurry and still have a low viscosity, the use of ethanol as a substitute for water was considered. Ethanol is a hydrophilic solvent with a low dielectric constant and therefore has the tendency to suppress the swelling of bentonite. Ethanol suppresses the swelling of bentonite with a corresponding decrease in viscosity thereby allowing more bentonite to be injected into the fissure. Once the slurry is injected into the fissure the concentration of ethanol begins to decrease by diffusion and dispersion. This causes a possible increase in the viscosity of the slurry and hence produces the sealing effect.

While experiments are ongoing for subsequent examinations of findings, preliminary results are presented in this paper. In this study, grout slurry of various viscosities was injected into a synthetic fracture to investigate the penetrability/groutability of grout into a fracture of aperture 100μm or less. Both static and dynamic injections were performed to determine the effect of injection type on grout injection efficiency. Flow test was first carried out to measure the viscosity of ethanol/bentonite slurry (EBS) at various levels of ethanol concentrations (0%, 40%, 50% and 60%) for conditions of shear rate ranging between 1 and 15 1/s to determine the effect of ethanol on the flow properties. Permeability tests were also carried out to determine the sealing effect of ethanol/bentonite slurry as a grouting material. Only the permeability of 80μm grouted fracture was determined for L/S = 8 as experiments are ongoing for more determinations.

2 MATERIALS

2.1 BENTONITE

The main grouting material used in this study was bentonite from the Wyoming state of USA. The grain–size distribution curve and other physical properties of the clay are given in Fig. 1 and Table 1 respectively. According to the Unified Soil Classification System proposed by Casagrande (1948) and U.S. Army Corp of Engineers (1953) as stated in Kasenow (2001), the clay is poorly sorted or well graded as the coefficient of uniformity, Cu > 6.

2.2 HYDROPHILIC SOLVENT

A stock solvent of ethanol concentration, 95% obtained from Japan and diluted with water to various levels of concentrations (40%, 50% and 60%) was used for mixing with bentonite at different liquid-solid ratios L/S by weight ,w/w (10, 8 and 6).

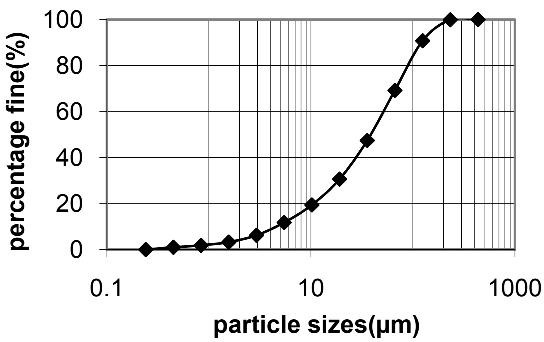


Fig.1 Grain size distribution curve of bentonite

Table 1 Physical properties of bentonite

Property	Bentonite
Specific gravity (g/cm³)	1.59
Effective particle size,De or D_{10} (μm)	4.90
Average particle sizes (μm)	40.0
Coeffient of uniformity Cu	11.1

3 LABORATORY EXPERIMENT

3.1 VISCOSITY OF ETHANOL/BENTONITE SLURRY

Prior to the injection of grout, the viscosities of ethanol/bentonite slurry (EBS) at various levels of ethanol concentrations (0%, 40%, 50% and 60%) and at L/S mixing ratios of 10, 8, and 6 were measured for shear rate ranging from 1 to 15 1/s using viscometer TVB–10M to characterize the type of fluid and the effect of ethanol concentration on the viscosity of the slurry

3.2 INJECTION INTO FRACTURE MEDIUM

3.2.1 DEVICE ASSEMBLY

The device set up for fracture injection is made up of a grout tank with an agitator, a dynamic grout pulser, dynamic control system, air compressor, Pressure transducers, artificial fracture or fissure medium consisting of an upper acrylic plate and a lower steel plate with a steel spacer (60-100μm thick) sandwiched between them to form the fracture channel. The plates have dimensions 2cm x 20cm x 40cm each and the channel width and length are respectively 4cm and 25cm; and a monitoring system. The outline of the device is shown in Fig. 2.

3.2.2 GROUT INJECTION

Grout was injected dynamically or statically with injection pressure from compressor. The grout pulser when activated creates pulses by rapid closing and opening of a rubber tube through movement of pistons. This sets in dynamic injection mode. The frequency of pulsation was varied to obtain optimum frequency. Injection is in static mode when the grout pulser is not activated.

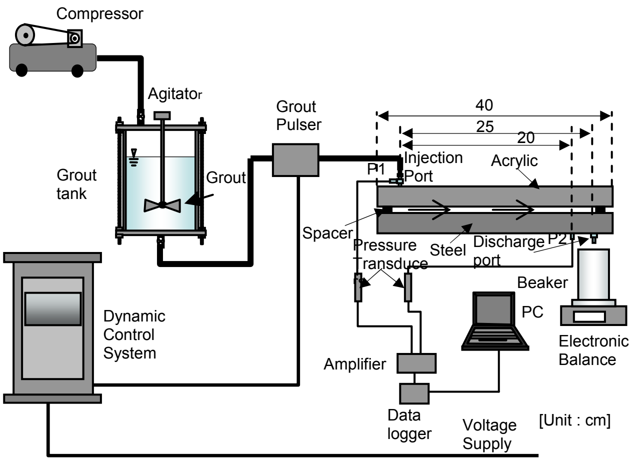


Fig.2 Outline of fracture device, after Chegbeleh et al. (2008b)

Grout slurry was prepared by mixing different concentrations of ethanol with bentonite using a high speed shearing mixer (1100rpm). EBS ratios of 10, 8 and 6 were used. This was poured into the grout tank and the agitator activated to stir the slurry to keep bentonite particles in suspension during the injection process. After setting the initial conditions of injection (adjustment of pressure) in static mode, grout was injected into the fissure through the inlet port at an injection pressure in the range of 200–600kPa. The mass of the grout flowing along the channel of the fissure was measured by an electronic balance over the injection period through the outlet port. Pressure distribution along the channel was also measured by the pressure transducers. In dynamic injection mode, the same procedure was followed but with the grout pulser activated and the frequency of pulsation adjusted to optimum (0-7Hz).

3.3 PERMEABILITY TEST

After determining grout penetrability into fracture apertures of various sizes, constant flow rate parallel plates permeability device was designed to measure the permeability of grouted fracture. In this device the parallel plates with spacer of different thickness sandwiched between them form the fracture. Grouts of different mixing ratios were then injected into the fracture medium and the permeability determined using water. The outline of the permeability test device is shown is Fig.3.

4 RESULTS AND DISCUSSIONS

It is important to have first hand information about the relationship between the grouting material and injection medium when planning a grouting programme. A detailed discussion on grouting/injection medium relation is provided by John et al. (1961). They indicated that for effective grout injection to take place, the pore or aperture size of the grouting medium should be at least three times the effective maximum grain diameter of the grouting material:

$$D_p \geq 3D_e \quad (1)$$

where D_p is the effective pore diameter or aperture size of the medium to be grouted and D_e or D_{10} is the effective maximum grain size of the grouting material. From the particle size distribution curve (Fig.1) and results in Table 1, the effective grain sizes ($D_e = D_{10}$) of the grouting material (bentonite) is 4.9μm. The fracture apertures considered in this study range from 60 to 100μm. If the aperture sizes are considered to be D_p, then the D_p for the fractures is more than $3D_e$ (14.7μm) indicating that grout penetration into fracture of aperture sizes (60-100μm) is possible as confirmed by the results of grout penetration into fractures (Table 2). Inability to penetrate could be due to high viscosity of the slurry.

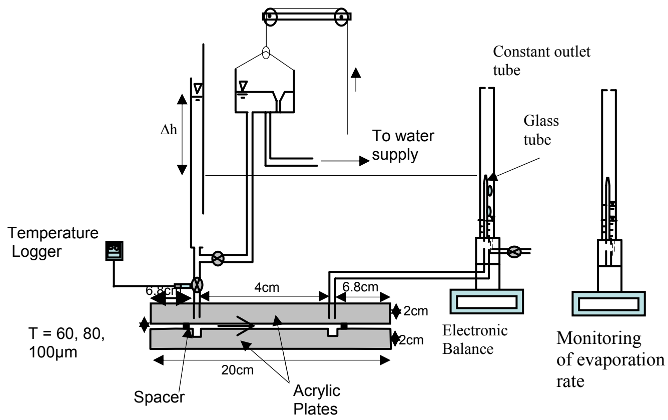


Fig.3 Outline of permeability test device

Figure 4 shows the relation between the shear rate and the viscosity. As the share rate of the rotating spindle of the viscometer increases, the viscosity deceases. This indicates that the viscosity depends on the shear rate. This is a characteristic of a non–Newtonian fluid which implies that the slurry's viscosity changes with time. This therefore means that under stable condition in the injection process, the rate of migration front of the slurry along the fracture will slow down due to increase in viscosity through non – Newtonian behavior.

From the viscometer test, the viscosities of 0% ethanol/bentonite slurries (i.e. water/bentonite mixtures) were too high (thick pastes) and were over the full scale range of the viscometer. These pastes could not be injected into the fractures. Generally, the slurry has very low fluidity in the case where the liquid phase of the slurry is 100% water. However, with the introduction of ethanol, fluidity of the slurry was enhanced as the viscosity was observed to decrease. The very high viscosities of the slurries with 100% water in the liquid phase confirm the high swelling capability of bentonite when in contact with water.

Figure 5 shows the relationship between viscosity and the concentration of bentonite in the slurry. The results indicate a sharp increase in the viscosity as the concentration of ethanol in the liquid phase decreases from 60% to 40% for a given mixture. The ethanol concentration of 40% for L/S = 6 was highly viscous and could not also be measured by the viscometer as it exceeded its full scale range. It could not also penetrate apertures of sizes 80 and 60μm as shown in Table 2. However, for L/S = 8 and 10 with the same 40% ethanol concentration, the slurry was fluidic and could be injected into narrow fractures. A critical ethanol concentration of 40% was, however, set as the limit to achieve sufficient groutable viscosity. Also, a maximum ethanol concentration of 60% was used based on the Japanese legislation for fire prevention which stipulates that any liquid in which the concentration of ethanol exceeds 60% must be treated as flammable material (Ishii et al., 2006). Though the concentration of slurry with L/S = 6 was high, the introduction of 60% ethanol concentration offered the slurry less viscous and fluidic, making it possible to be injected into narrow fissures. This indicates that the suppression of the swelling behavior of bentonite is dependent on the ethanol concentration.

High concentration of EBS, e.g. L/S ratio of 6 was able to be injected into a 100μm synthetic fracture by dynamic and even static injection with ease. Easy penetration with static injection was possible due to the low viscosity of the slurry as a result of the addition of ethanol. With dynamic injection, penetration was easier. Apart from the low viscosity, the pulsation in dynamic injection improves fluidity as bentonite particles are vigorously agitated. This prevents clogging at the interface between the fracture and injection hole. Settlement of particles in the fracture is also prevented due to the pulsation, thereby allowing more grout to flow through the channel.

The cumulative mass for dynamic injection is more than that of static injection Fig. 6. This confirms that dynamic injection suppresses the occurrence of clogging and is more efficient than static injection. From Fig. 6 (a and b), the injection efficiencies for dynamic and static injections are respectively 0.9g/s and 0.09g/s; and 0.6g/s and 0.05g/s confirming that dynamic injection is more efficient than static injection. It also suggests that it is easier injecting low dense slurry into a given fracture than high dense slurry.

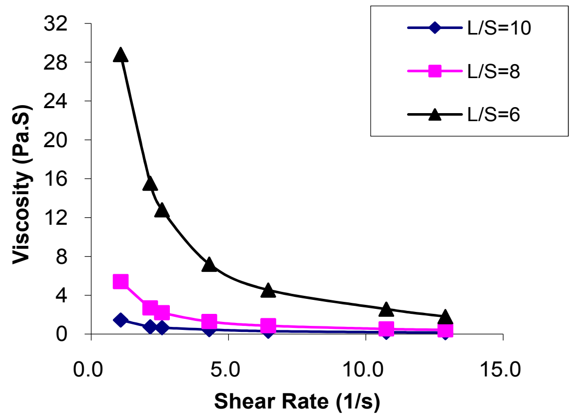


Fig.4 Viscosity versus shear rate for 50% EBS

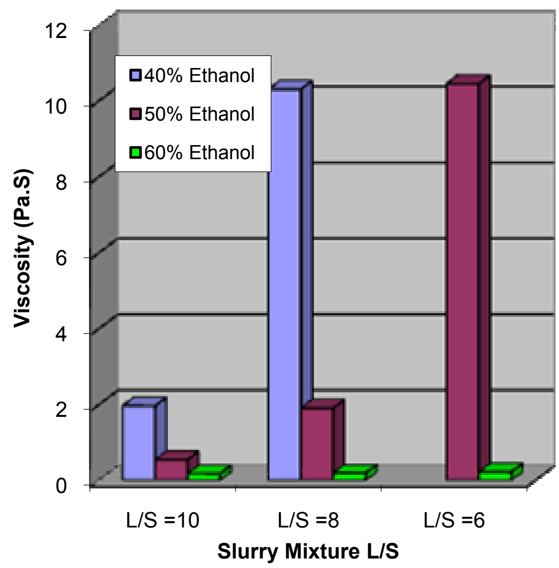


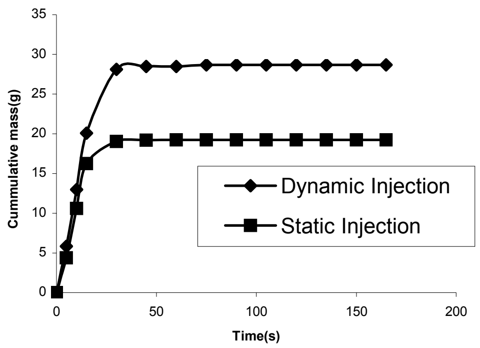
Fig.5 Relationship between viscosity and mixing ratio of slurry

Table 2 Grout penetration through various fracture apertures

Slurry	Ratio L/S	Grout Penetration through apertures (µm)					
		Static			Dynamic		
		100	80	60	100	80	60
40% Ethanol / Bentonite	10	Y	Y	N	Y	Y	N
	8	Y	Y	Y	Y	Y	Y
	6	Y	N	N	Y	N	N
	10	Y	Y	Y	Y	Y	Y
	8	Y	Y	Y	Y	Y	Y
	6	Y	Y	Y	Y	Y	Y
60% Ethanol / Bentonite	10	Y	Y	Y	Y	Y	Y
	8	Y	Y	Y	Y	Y	Y
	6	Y	Y	Y	Y	Y	Y

Y: Yes (Grout Penetration is positive)

N: No (Grout penetration is negative)



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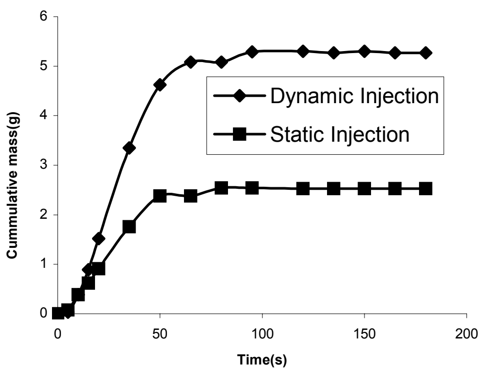

b

Fig.6 Relation between cumulative mass and time of injection into fracture (100µm) under dynamic and static injection for (a) L/S = 10 and (b) L/S =8

From the permeability test result of 60% ethanol/bentonite slurry and L/S = 8 injected into a fracture of aperture size 80µm, the permeability was determined to be 5.6 E-07 cm/s using water which is quite low for effective sealing.

5 CONCLUSIONS

Based on the results of laboratory investigation on the injection of EBS at various levels of ethanol concentrations and at different L/S mixing ratios into synthetic planar fracture, the following conclusions can be drawn:

(1) The injection of EBS into a synthetic fracture is a demonstration of the possibility of injecting the slurry into a small fracture for effective sealing of the fracture.

(2) The measured viscosity of the slurry is dependent on the ethanol concentration and the shear rate which is a characteristic of a non-Newtonian fluid. The viscosity of the slurry with 60% ethanol decreases many folds compared with the slurry of 0% ethanol as its viscosity was too high and could not be measured.

(3) Grout penetrability is enhanced by the effect of ethanol concentration. A high concentration of EBS, L/S ratio of 6 could easily be injected into 100µm fracture medium by both dynamic and static injections.

(4) Ethanol suppresses the swelling effect of bentonite and allows more dense slurry with low viscosity to be injected.

(5) Dynamic injection can inject grout with higher concentration into narrow fissures than static injection for a given time. The injection efficiency (amount of injected grout per unit time) of dynamic injection was observed to be more than that for static injection. This signifies that dynamic injection is more efficient than static injection.

(6) The permeability of 80µm fracture injected with 60% ethanol/bentonite slurry of L/S = 8 was determined to

be 5.6E-07cm/s, which is reasonably low for effective sealing.

In summary, ethanol/bentonite slurry is an effective grouting material capable of injecting into narrow

ACKNOWLEDGEMENTS: The first author wishes to express his profound gratitude to the Centre of Excellence (COE) for the financial support during which time this research was carried out.

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