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PROPERTIES OF COMPACTED BENTONITE-AGGREGATE MIXTURES AS BACKFILL IN SALT AND POTASH MINES

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อหาคุณสมบัติเชิงกลศาสตร์ของเบนทอไนต์ผสมกับวัสดุมวลรวมและน้ำเกลือโซเดียมคลอไรด์กับแมกนีเซียมคลอไรด์โดยใช้วิธีการบดอัด การเฉือนและการกด ส่วนผสมนี้จะนำมาใช้เป็นวัสดุถมกลับใน ช่องเหมืองเกลือและเหมืองโปแตช วัสดุมวลรวมประกอบด้วย ดินตะกอนประปา กรวดทรายและเกลือหินบดโดยมีขนาดระหว่าง 0.425 ถึง 6 มิลลิเมตร อัตราส่วนผสมระหว่างเบนทอไนต์ต่อวัสดุมวลรวมอยู่ระหว่าง 30:70 ถึง 100:0 โดยน้ำหนัก ผลการศึกษาระบุว่าปริมาณสัดส่วนของเบนทอไนต์ที่ลดลงสามารถเพิ่มความหนาแน่นและลดปริมาณน้ำเกลือที่จุดสูงสุดได้ ซึ่งเป็นจริงสำหรับน้ำเกลือทั้งสองชนิด ค่าความเค้นยึดติดและค่าความยืดหยุ่นของส่วนผสมที่มีเม็ดละเอียดจะมีค่าสูงกว่าส่วนผสมที่มีเม็ดหยาบ ซึ่งคุณสมบัติเชิงกลศาสตร์นี้จะเพิ่มขึ้นตามปริมาณส่วนผสมของเบนทอไนต์ ส่วนผสมที่ใช้น้ำเกลือโซเดียมคลอไรด์จะให้ค่าความหนาแน่นและค่ากำลังเฉือนใกล้เคียงกับส่วนผสมที่ใช้น้ำเกลือแมกนีเซียมคลอไรด์ ผลที่ได้จากการศึกษานี้สามารถนำมาใช้กำหนดปัจจัยและเกณฑ์การคัดสรรของวัสดุถมกลับในช่องเหมืองเกลือและเหมืองโปแตช

ABSTRACT

Compaction, direct shear and compression tests have been performed to determine mechanical properties of compacted bentonite-aggregate mixtures with saturated sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) brines for use as backfill materials in salt and potash mine openings. The aggregates include sludge, sand, crushed salt and gravels. Their grain sizes range from 0.425 to 6 mm. The mixing ratios of the bentonite-aggregate mixtures are from 30:70 to 100:0 by weight. The results indicate the decease of the bentonite weight ratio can increase the dry density and decease the optimum brine content, which holds true for both mixing fluids. The cohesions and friction angles increase with increasing aggregate contents and angularity. The compressive strengths and elastic moduli of the mixtures containing finer particles are higher than those with coarser ones. They also increase with the bentonite weight ratio. Higher bentonite contents allow larger dilation of the mixtures under loading, and hence reflecting as higher Poisson's ratio. The specimens mixed with NaCl brine show dry densities and shear strengths similar to those mixed *with $MgCl_2$ brine. The results can be used as initial installation parameters and material selection of backfills emplaced in salt and potash mine openings.*

KEYWORDS: Sludge, Sand, Crushed salt, Gravel, Magnesium brine, Sodium brine

1. Introduction

Thailand mining regulations require that the abandoned salt and potash mine openings be sealed, primarily to reduce the long-term surface subsidence and to minimize waste products obtained from ore processing plants. In addition the sealing materials should be chemically compatible with the surrounding rock [1]. Bentonite has long been extensively used as sealing material due to its low permeability, desirable swelling, self-healing and longevity in nature [2]. A mixture of bentonite and ballast material is also considered as sealant for mine opening because it decreases shrinkage potential, increases the bearing capacity of the sealant, and minimize creep or settlement [3]. Compacted bentonite-based materials have been proposed as possible sealing and sealing materials in geological repositories for the high-level radioactive waste disposal in several countries [4]. Butcher [5], Borgesson, et al. [6] and Johannesson and Nilsson [7] recommend that the compacted bentonite-crushed salt weight ratio of 30:70 should be used as backfilling in the underground openings.

For salt and carnallite mines, a recent experimental study by Theerapun et al. [8] suggest however that the presence of NaCl brine as mixing fluid in backfill can dissolve the surrounding carnallite in potash mine opening, and hence reduces the mechanical performance of support pillars and mine roof and floor. The carnallite and halite (rock salt) are however insensitive to $MgCl_2$ brine. The $MgCl_2$ brine is a toxic waste product obtained from the processing of carnallite ore extraction in Thailand. Disposal of the $MgCl_2$ brine and crushed salt by returning them to the abandoned mine openings not only minimizes the long-term surface subsidence, but also prevents the environmental contamination from these materials.

Most of the researchers above have concentrated their efforts on permeability of the bentonite mixtures. The mechanical properties of the bentonite-mixed with aggregates however have rarely been investigated. The objective of this study is to determine the mechanical performance of compacted bentonite-aggregates mixtures under various weight ratios. The NaCl and $MgCl_2$ brines are used as mixing fluid. The efforts primarily include compaction, direct shear and uniaxial compressive strength tests on the compacted mixtures. The findings can be used as initial installation parameters for the abandoned salt and potash mine openings.

2. Test Materials

The aggregates used in this study are sludge, sand, crushed salt and gravels. The construction grade bentonite is used to mix with each type of the aggregates. The sludge is obtained from dewatering plant of Bang Khen Water Treatment Plant located in Bangkok Metropolis. The chemical compositions of the bentonite and sludge are determined by X-Ray fluorescence (XRF), as shown in Table 1. The crushed salt is prepared from Middle member of Maha Sarakham formation, northeastern Thailand. The salt is crushed by hammer mill to obtain grain sizes ranging from 4 to 6 mm. Sand (1-2 mm) and gravel (4-6 mm) are collected from Khok Kruat District, Nakhon Ratchasima province. The particle size distributions of these aggregates are shown in Figure

1. Based on the Power [9] classification system the sand and crushed salt are classified as angular to sub-angular with spherical shape. The gravel is classified as sub-rounded to rounded with sub-discoidal shape. The bentonite has specific gravity of 2.50.

Two types of saturated brines are prepared from pure NaCl and $MgCl_2$ mixed with distilled water in plastic tank and stirred continuously. The dry densities of NaCl and of $MgCl_2$ are 2.16 and 2.32 g/cc. Under saturation the proportion of NaCl and

Table 1 Chemical compositions of tested bentonite and sludge

Compositions	**Weight (%)**		**Compositions**	**Weight (%)**	
	Bentonite	**Sludge**		**Bentonite**	**Sludge**
SiO_2	48.27	52.37	Rb_2O	N/D	0.01
Al_2O_3	12.78	23.47	SrO	N/D	0.01
Fe_2O_3	27.40	6.33	Y_2O_3	N/D	<0.01
Na_2O	1.23	0.22	ZrO_2	N/D	0.03
MgO	1.87	0.96	Nb_2O_5	N/D	<0.01
CaO	N/D	0.79	BaO	N/D	0.01
K_2O	1.81	1.55	Cr_2O_3	0.02	0.02
TiO_2	4.62	0.79	Cl	0.09	0.07
P_2O_5	1.40	0.34	Co_3O_4	0.07	N/D
SO_3	0.09	0.55	Nio	0.02	N/D
MnO	0.26	0.22	CeO_2	0.05	N/D
CuO	0.02	0.01			
Total				**100**	**100**

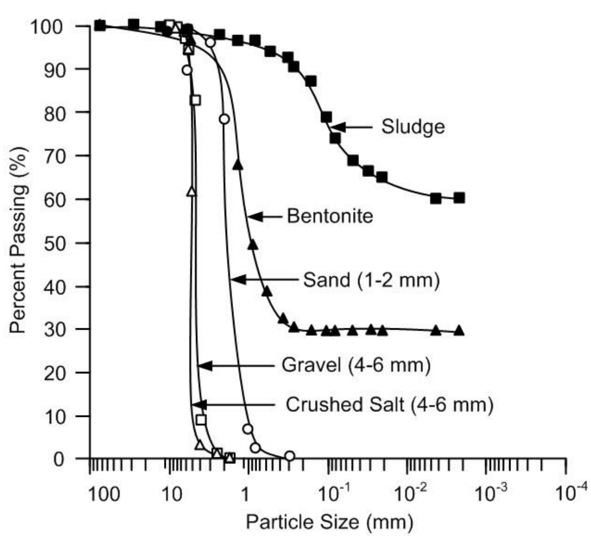

Figure 1 Particle size distributions of tested materials

$MgCl_2$ to water are about 39% and 57% by weight, respectively. The properties of NaCl brine are: density = 1.20 g/cc, pH = 8.9 and viscosity = 3.3 cP. The $MgCl_2$ brine has density = 1.31 g/cc, pH = 7.1 and viscosity = 10.5 cP.

3. Test Apparatus and Method

The three-ring mold [10] is used in this study for the compaction test. The test method and calculation follow the ASTM standard practice [11]. The mixing ratios of the bentonite-aggregates vary from 30:70 to 100:0 by weight. The brine content after compaction is calculated by [12]:

$$W_B = \frac{[100 + S_B] \times \left[W_1 - W_2 - (\frac{W_i}{100})(W_2 - W_{can}) \right] \times 100}{100(W_2 - W_{can}) - S_B(W_1 - W_2)} \tag{1}$$

where W_B is brine content (%), W_i is initial water content (about 8-9 %), W_{can} is weight of container (g), W_1 is weight of wet mixture and container (g), W_2 is weight of dry mixture and container (g), and S_B is solubility of NaCl and $MgCl_2$ in dissolved water (%). As suggested by Butcher [5], Borgesson et al. [6] and Johannesson and Nilsson [7] that for effective compaction the bentonite weight ratio for the mixtures should not be less than 30%. This is primarily to prevent bridging and voids occurring between aggregates particles. As a result, the bentonite weight ratio used here is 30% and greater.

4. Compaction Test Results

Figure 2 shows the maximum dry densities and optimum brine contents as a function of bentonite-aggregate weight ratio mixed with NaCl and with $MgCl_2$ brines. The results clearly show that by increasing the bentonite content, the optimum brine content increases while the dry density decreases. This holds true for all types of aggregate. This is due to the fact that the aggregate densities are greater than that of the bentonite. Coarser aggregate particles tend to have higher dry density than those of the finer ones. The specimens mixed with NaCl brine have lower dry densities than those with $MgCl_2$ brine. This is because $MgCl_2$ brine has higher density than NaCl brine. This behavior can be explained in context of diffuse double layer. With the addition of $MgCl_2$ brine, diffuse double layer tends to depress; this allows particles to come closer that increasing density [13], as shown in Figure 3. The microstructure of the bentonite mixed with $MgCl_2$ brine shows large amounts of leafs placed very closely to each other, and thus creating compact orientated layers of smectite particles. The bentonite mixed with NaCl brine contains more granular particles, which is characterized by large open-air voids.

5. Shear Strength Results

The direct shear tests are performed on the compacted mixtures under optimum brine contents determined above. The applied normal stresses are 0.2, 0.4, 0.6 and 0.8 MPa. The compacted mixtures with coarser grains show greater shear strengths than those with the smaller ones. Based on the Coulomb criterion the cohesions and friction angles of the compacted mixtures under their optimum brine contents can be calculated, as shown in Figure 4. It is clear that increasing the bentonite weight ratio significantly decreases the cohesions and friction angles of the mixtures. The mixtures with angular shape (rushed salt) tend to show larger cohesion and friction angle values, as compared to those with the rounds shape (gravel). The cohesion of coarser mixing particles (e.g. gravel and crushed salt) is lower than those of the finer particles (e.g. sludge). The friction angle of coarser particles is however higher than that of the finer particles. This may be due to the greater frictional resistance of the grain surfaces for the coarse materials. The cohesions and friction angles of the specimens mixed with NaCl brine tend to be the same with those mixed with $MgCl_2$ brine.

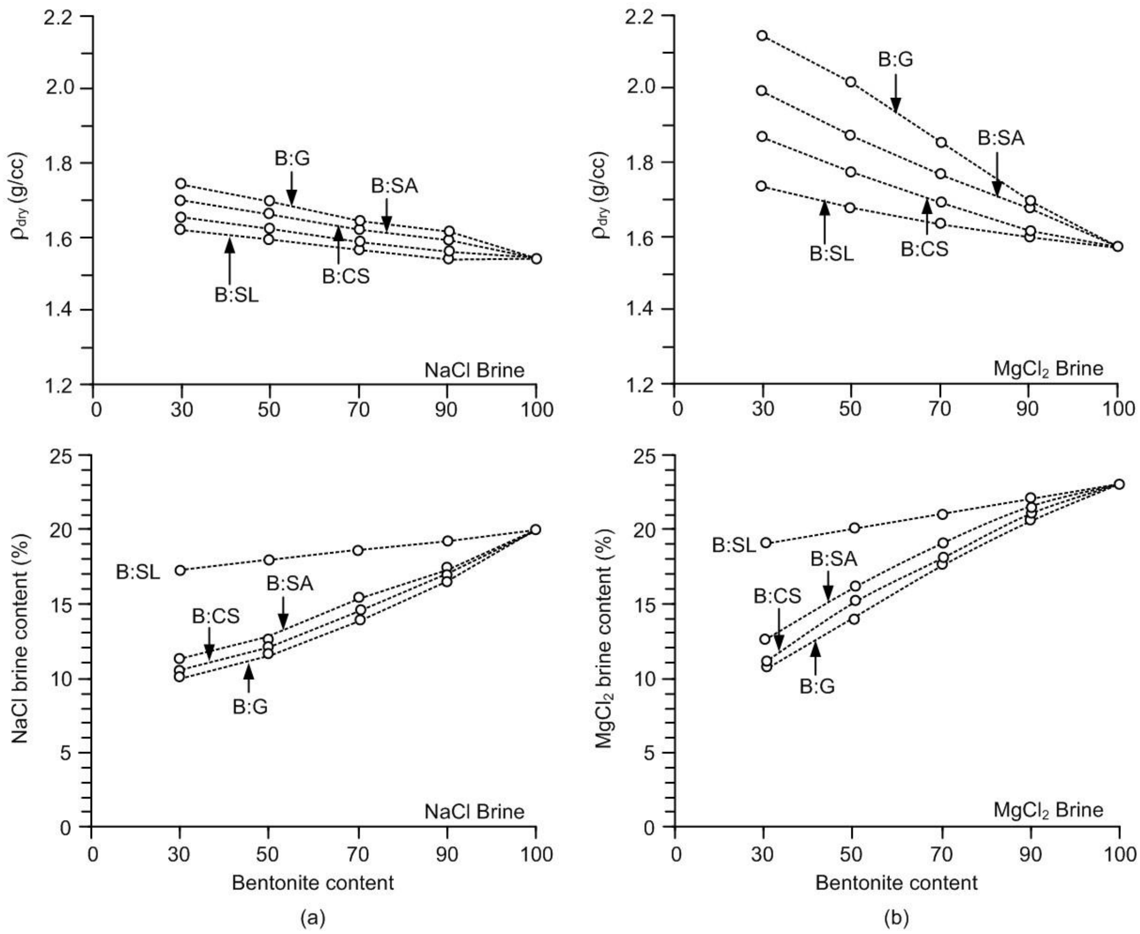

Figure 2 Maximum dry densities and optimum brine contents as a function of bentonite content mixed with NaCl brine (a) and with $MgCl_2$ brine (b)

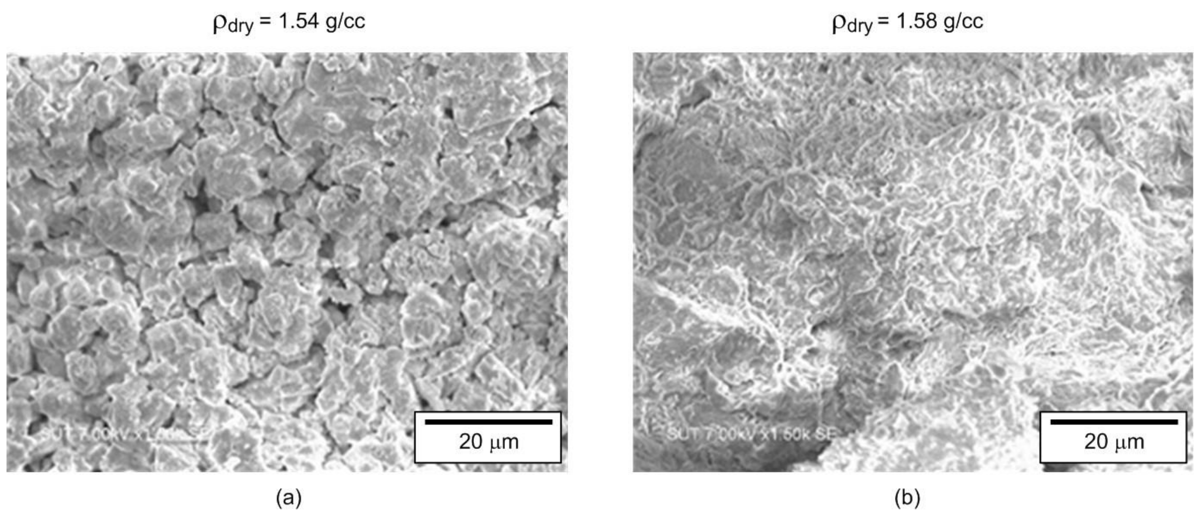

Figure 3 SEM images of compacted pure bentonite mixed with NaCl (a) and $MgCl_2$ (b) brines

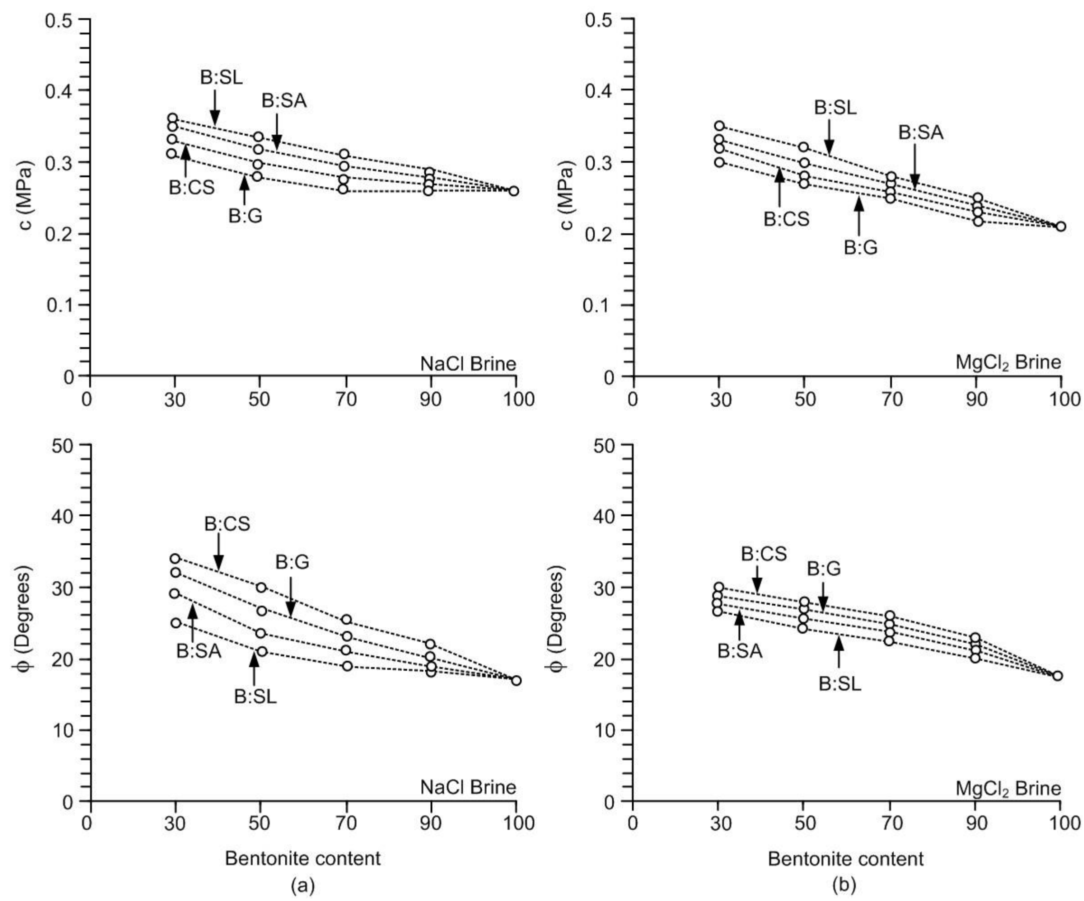

Figure 4 Cohesions and friction angle as a function of bentonite content mixed with NaCl brine (a) and with $MgCl_2$ brine (b)

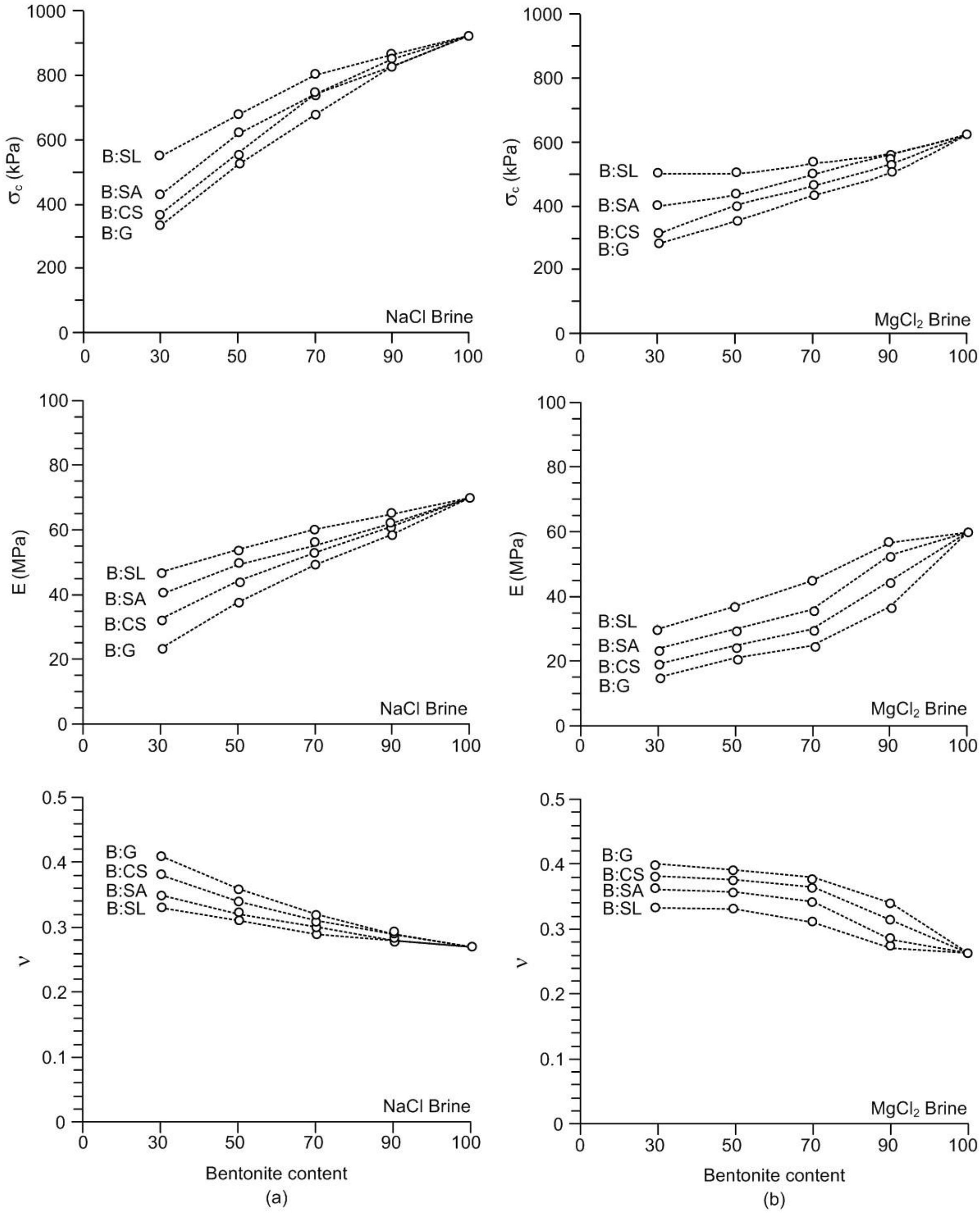

Figure 5 Compressive strengths, Elastic moduli and Poisson’s ratios as a function of bentonite content mixed with NaCl brine (a) and with $MgCl_2$ brine (b)

6. Compression Test Results

The compressive strength and elastic parameters of the compacted mixtures under their optimum brine contents can be determined by pushing the specimen out of the three-ring mold. The specimen ends are trimmed to obtain flat and parallel surfaces. The length-to-diameter ratios are about 2.0-2.2. The compressive strengths of the specimen are determined by axially loading under constant rate of 0.5-1 MPa/second until failure. Neoprene sheets are used to minimize the friction at the interfaces between the loading platen and the specimen surfaces. The axial and lateral displacements are monitored. The compressive strength, elastic modulus and Poisson's ratio are determined in accordance with the ASTM standard practice [14]. Figure 5 shows the results for all mixtures as a function of bentonite weight ratio. The mixtures with higher bentonite content give greater strengths and stiffness than those with the lower bentonite content. The Poisson's ratio, however tends to decrease with the bentonite weight ratio. This is probably because the increase of bentonite content can densify the mixtures, and hence increases their strength and stiffness. The mixtures with finer aggregate particles (e.g. sludge and sand) tend to show higher strengths and elasticity than those with coarser particles (e.g. gravels). The Poisson's ratios of the coarser particles are greater than those of the finer ones. This is because bentonite can effectively fill the small void spaces present between the individual fine particles in comparison to relatively larger void spaces between the coarse particles. The specimen mixed with NaCl brine gives greater strength than those mixed with $MgCl_2$ brine. This is primarily because the NaCl brine can recrystallize easier and quicker than the $MgCl_2$ brine. The recrystallization process of NaCl brine can increase the strength of the mixtures. The difference of the recrystallization behavior between the two solutions observed here agrees with the experimental evidence obtained by Sander and Herbert [15].

7. Discussions and Conclusions

Compaction, direct shear and compression tests have been performed to investigate mechanical properties of compacted bentonite-aggregate specimens mixed with saturated sodium and magnesium brines for use as backfill materials in salt and potash mine openings. The results indicate that the maximum dry densities and the optimum brine contents depend largely on the particle sizes of the aggregate and the bentonite contents. The coarser particles (gravels) show higher dry density and lower optimum brine contents than the finer ones. The decease of bentonite contents can increase the dry density and decease the optimum brine content. This agrees well with the test results obtained by Kaya and Durakan [16] and Soltani-Jigheh and Jafari [17]. Within the range of the normal stresses used here (0.2 to 0.8 MPa) the shear behavior of the mixtures relations can be well described by the Coulomb criterion. The mixtures with coarser particles show higher friction angles and lower cohesions. These shear parameters decrease with increasing bentonite content. The strengths and elastic moduli however increase with the bentonite content. The mixtures containing finer particles show higher strength and stiffness than those of the coarser particles. The specimens mixed with NaCl brine have higher dry density and strengths than those mixed with $MgCl_2$ brine. For the openings in pure rock salt all these mixtures can be used as backfill materials. For carnallite mine openings, the magnesium brine is recommended for mixing with backfilling material the openings [8]. Selection of the types and contents of aggregates also depends on site-specific conditions and availability of the materials. Bentonite, even construction-grade type, generally costs more than the aggregates. Crusted salt and sludge are considered as waste products and are relatively inexpensive as compared to sand and gravel.

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References

[1] Fuenkajorn, K. and Daemen, J. J. K. *Sealing of boreholes and underground excavations in rock*. London: Chapman and Hall, 1996.

[2] Ouyang, S. and Daemen, J. J. K. Performance of bentonite and bentonite/crushed rock borehole plugs. *Sealing of Boreholes and Underground Excavations in Rock*. Springer, Netherland, 1996, pp. 184-224.

[3] Dixon, D. A. et al. A study of the compaction properties of potential clay-sand buffer mixtures for use in nuclear fuel waste disposal. *Engineering Geology*, 1985, 21 (3-4), pp. 247-255.

[4] Wang, Q. et al. Long-term effect of water chemistry on the swelling pressure of a bentonite-based material. *Applied Clay Science*, 2014, 87, pp. 157-162.

[5] Butcher, B. M. *The advantages of a salt/bentonite backfill for waste isolation pilot plant disposal rooms*. Sandia Report for the United States Department of Energy. California, 1993.

[6] Borgesson, L. et al. Influence of soil structure heterogeneities on the behavior of backfill materials based on mixtures of bentonite and crushed rock. *Applied Clay Science*, 2003, 23 (1-4), pp. 121-131.

[7] Johannesson, L. E. and Nilsson, U. *Geotechnical properties of candidate backfill materials for the deep repository*. Swedish Nuclear Fuel and Waste Management Co. SKB Technical Report, 2006.

[8] Theerapun, C. et al. Effects of backfill compositions on integrity of underground salt and potash mines. *Research and Development Journal of the Engineering Institute of Thailand under H.M. the King's Patronage*, 2017, 28 (2), pp. 15-22.

[9] Power, M. C. *Comparison charts for estimating roughness and sphericity*. AGI Data Sheets, American Geological Institute, Alexandria, VA, 1982.

[10] Sonsakul, P. and Fuenkajorn, K. Development of three-ring compaction and direct shear test mold for soil with oversized particles. *Research and Development Journal of the Engineering Institute of Thailand under H.M. the King's Patronage*, 2013, 24 (2), pp. 1-7.

[11] American Society for Testing and Materials. D1557: 2012. *Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3))*: Annual Book of ASTM Standards, Philadelphia, PA, 2012.

[12] Fuenkajorn, K., and Daemen, J. J. K. *Borehole closure in salt*. Technical Report, prepared form the U.S. Nuclear Regulatory Commission, Washington, D.C. by the University of Arizona, 1988.

[13] Singh, S. and Prasad, A. Effect of Chemicals on Compacted Clay Liner. *Electronic Journal of Geotechnical Engineering*, 2007, 12.

[14] American Society for Testing and Materials. D2938: 1995. *Standard test method for unconfined compressive strength of intact rock core specimens*: Annual Book of ASTM Standards, Philadelphia, PA, 1995.

[15] Sander, W. and Herbert, H. J. NaCl crystallization at the $MgCl_2$/NaCl solution boundary a possible natural barrier to the transport of radionuclides. *Mineralogical Magazine*, 1985, 49, pp. 265-270.

[16] Kaya, A. and Durukan, S. Utilization of bentonite-embedded zeolite as clay liner. *Applied Clay Science*, 2004, 25 (1-2), pp. 83-91.

[17] Soltani-Jigheh, H. and Jafari, K. Volume change and shear behavior of compacted clay-sand/gravel mixtures. *International Journal of Engineering and Applied Sciences*, 2012, 4, pp. 52-66.