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Estimation of pore pressure for unsaturated-saturated bentonite sand mixture

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ABSTRACT

To investigate thermal hydration mechanical chemical couple phenomena is an important issue of the high-level radioactive waste disposal and a key indicator of artificial barrier system. Major objectives of the thermal and mechanical site characterization include the status of the environmental. Several research reports are aimed at the barrier layers for heating from radioactive waste disposal. This study appears the occurrence of the pore pressure under heat conditions for bentonite and bentonite-sand mixture material, which are completely undrained condition and unexhausted condition. It is considered that mechanics of pore pressure in macro-micro void structure due to heating-cooling repetition. A thermal chamber is used in heating method, which have high specification with accurate controlling sensitivity. The maximum temperature is 80 degrees Celsius temperatures. The prepared specimens are unsaturated specimens and saturated specimens, and silica sand are mixture into three different bentonites that various dry densities are required. Two different solutions are prepared for saturated specimen, which are distilled water and salinity water with concentration of 3.5 %. The specimens are placed into a thermostat oven, and heating application is applied isotropic conductivity. The obtained results are significant as followings; The measured pore pressures are obviously with increment of temperature, and the sand mixture ratio is small influence factor. Also, large por fluid pressures are produced for saturated condition that indication of small pore fluid pressure is verified for unsaturated specimen comparison with saturated specimen.

Keywords: bentonite; gas; heating; pore pressure.

1. Introduction

1.1. Background

The concept of high-level radioactive disposal (HLW) repository generally have an engineering barrier system and artificial barrier system. These barrier system (Castellanos et al., 2008, Bosch et al., 2023) have been established using compacted bentonite layer and compacted blocks, which are cove around the radioactive waste canister (Sellin and Leupin, 2013). After construction of the engineer barrier system, one of components, the compacted bentonite becomes gradually hydrate from host rock at deeply underground. The effort of hydration provides as hydro-mechanical couple phenomena, and have often thermal property (Chen et al., 2019, Samper and Montenegro 2020) such as heating from canister or produce chemical impact due to chemical components including ground water.

In addition, the swelling pressure of compacted bentonite after abortion is critical parameter affecting of estimation safety. Particularly, thermal-hydration-mechanical-chemical (Castellanos et al., 2008, Chen et al., 2017) couple phenomena are key feature and significant function, which is recognized in the barrier engineering. Estimation of swelling pressure for compacted bentonite including sodium type and calcium type have been studied that some functions such as dry density, compaction water content, saline solution, alkaline solution and heating temperature (Balmer et al 2017) are elicited through ling time on experimentalities and large-scale investigation.

1.2. Previous researches

Horseman et al., 1999 conducted out controlled flow-rate gas injection experiments using compacted samples of KBS-3 specification MX80 buffer bentonite. By simultaneously applications of a confining pressure and backpressure, the specimens are isotopically consolidated and fully saturation under promotion of effective stress conditions with injecting gas. Ingoing and outgoing gas fluxes are monitored. All of tests exhibit a conspicuous threshold pressure for breakthrough, fractionally larger than the sum of the swelling pressures and the backpressures. Birgersson et al., 2008 mentioned that gas migration in saturated bentonite is motivated by the fact for storage of high-level radioactive waste. These containers usually contain iron to some degree and in case of possible anaerobic corrosion of this iron, hydrogen gas is produced. If this gas production is fast in comparison to the diffusive transport capacity through the buffer, a gas pressure build-up is expected. Vardon et al., 2014 focused on the generation of gases due to progress such as anoxic metal corrosion and water radiolysis. It is mentioned that gases have the potential to migrate through the repository system and may be detrimental to the engineered barrier system by damaging the physical fabric of the buffer material through the

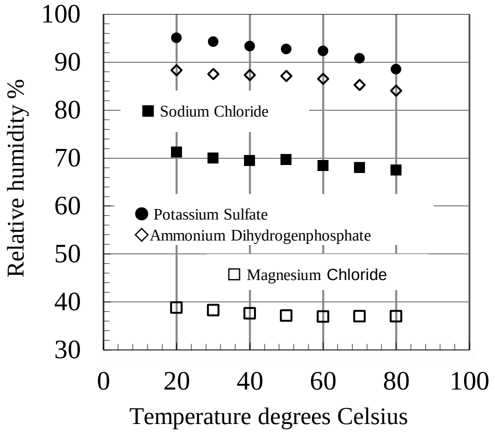

Figure 1. Reduction of relative humidity by heating.

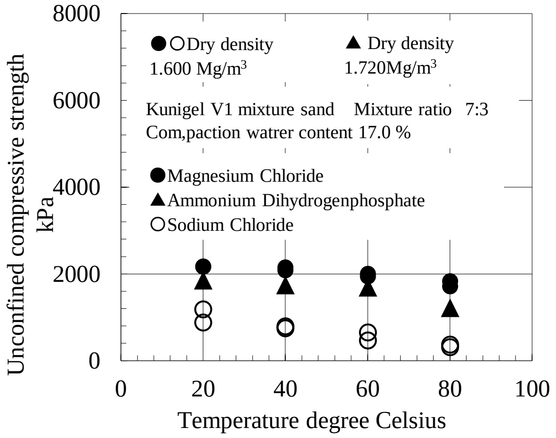

Figure 2. Reduction of unconfined compressive strength.

build-up of pressure. They have established a model of gas conductivity is presented to simulate the transport of gas in conjunction with coupled thermo-hydro-mechanical-chemical processes. Suggested models include a boundary condition linking the corrosion behaviour to gas generation and water supply.

Ahusborde et al., 2015 presented the results of gas migration as benchmark studies that compares a number of numerical models applied to a specific problem in the context of hydrogen flow and transport in a nuclear waste repository. The processes models are two-phase (i.e., water and hydrogen) immiscible compressible two-component transient flow in a heterogeneous porous medium under isothermal conditions. Cui et al., 2021 verified that ensure the performance efficiency and long-term operational safety of the engineering barrier in deep geological repositories. It is of great importance to investigate gas migration behaviour in the saturated bentonite subjected to decay heat generated by the nuclear waste. Cui et al., 2021 are successful to measure the influences of multi-step thermal cycles on variations of the effective gas permeability, gas breakthrough pressure and microstructure of the bentonite specimens. A temperature range of 20–60 degrees Celsius that the effective gas permeability increases with heating, while decreases with cooling. The effective gas permeability decreases for the specimen tested under a constant injection pressure of 1.52 MPa after experienced one to three thermal heating cycles.

Kim et al., 2023 reports that gases originated from the final SNF (i.e., spent nuclear fuel) disposal site are mobile in the barrier and they may also affect the migration of radioactive nuclides generated from the SNF. However, researches relate to gas migration coupled movement in the multi-barrier medium have been little in the world. Kim et al., 2023 mentioned that properties of gas generation and migration in the SNF disposal environment through previous researches. Kim et al., 2023 were summarized on the hydrogeological evolution stage of the SNF disposal site. The variation in the gas permeability of unsaturated GMZ bentonite caused by coupled thermo-mechanical effects is essential in evaluating the long-term safety of deep geologic repositories. Liu et al., 2023 conducted out gas permeability tests using samples containing different water contents in order to investigate the influence of different confining pressures and heating processes. Samples with different water contents were obtained by equilibrating at different relative humidity (RH). The obtained results show that the gas permeability of the unsaturated GMZ bentonite varies under coupled thermo-mechanical effects. Then, gas permeability generally decreases according to temperatures. When the temperature reaches 80 degrees Celsius, a sudden increment of gas permeability occurs with high relative humidity (94.7% and 97.3%) as gas pressure pushes out moisture.

2. Purpose of this study

2.1. Heating application on hydro-mechanical properties

This study has investigated the heating efforts to hydration and mechanical properties associated to the thermal-hydration-mechanical-chemical couple phenomena before prepared six experimental test series. It is measured the changing of relative humidity according to increment of temperature in the closed chamber. The steel mould is prepared that some salt solutions are installed in order to create relative humidity changing. Whole the mould was placed in thermostat oven, in which temperatures are controlled a range from twenty degrees Celsius to 80 degrees Celsius. Variations of salt solutions are used to verify relative humidity ranges, and the results is described as shown in Fig. 1. All of chemical substances have common tendency which is reduction with increment of temperatures regardless of relative humidity. Regard to mechanical properties such as unconfined compressive strength and deviator stresses, unsaturated specimens and saturated specimens for Kunigel V1 with sand mixture have measured as shown in Figs 2 and 3. The unsaturated specimens with high suctions created by vapor pressure technique using some salt solutions indicate the reduction of unconfined compressive strengths according to increment of temperatures (i.e., from 20 degrees Celsius to 80 degrees Celsius). Heating actions produce the disturb the soil void structure and contact point friction.

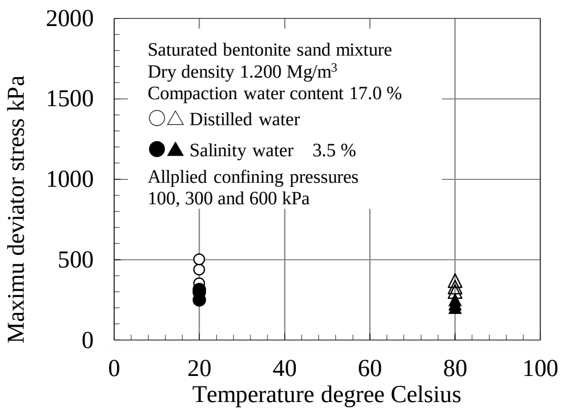

Figure 3. Reduction of shear resistance.

In case of application of lateral confining pressure, triaxial compression tests conduct out saturated bentonite sand mixture specimens, the specimens are soaked due to either distilled water or salinity water with a content of 3.5 %. Three different later confining pressures (i.e., 100, 300 and 600 kPa) are supplied into the triaxial chamber, and are measured the effort on heating application comparison with 80 degrees Celsius. The reduction of maximum deviator stress refers about 30 %. Above mentioned, it is evidenced that the influence of high temperature (i.e., 80 degrees Celsius) due to heating application produced the change of mechanical properties, and causes the disturb of surface at soil particle together.

2.2. Investigation points for this study

To investigate thermal-hydration-mechanical-chemical couple phenomena is an important issue of the high-level radioactive waste disposal system. Major objectives of interpretation for thermal and mechanical site characterization include the status of the environmental and safety conditions. Several research reports are aimed at the barrier layers for heating from radioactive waste disposal.

This study focuses on the pore pressures under heat conditions for bentonite and bentonite-sand mixture, which are completely undrained condition and unexhausted condition. Considering occurrence mechanics of pore pressure in macro-micro void structure due to heating and heating-cooling repetition. A thermal chamber is used in heating method, which has high specification with accurate controlling sensitivity. The maximum temperature is 80 degrees Celsius. The prepared specimens are unsaturated specimens and saturated specimens, and silica sand are mixture into three different bentonites that various dry densities are required. Two different solutions are used for saturated specimens, which are distilled water and salinity water with concentration of 3.5 %. The specimens are placed into a thermostat oven, and heating application is applied in the isotropic conductivity. The obtained results are significant as followings; the measured pore pressures are obviously increase with increment of the temperatures, and the influence of sand mixture ratio is not so much. Also, large pore fluid pressures are produced for saturated condition that indication of small pore fluid pressure is verified for unsaturated specimens comparison with saturated specimens.

3. Test procedure

3.1. Soil materials

In previous research experimental studies and large-scale investigation underground, two different bentonites are commonly used, and are sodium bentonite and calcium bentonite in the world. Each bentonite is selected corresponding to majority research subjection. This testing program has the purpose such as interpretation of pore fluid pressures under isotropic heating effort for unsaturated conditions and saturated conditions. Considering, Kunigel V1, (Ohkubo at al., 2008, Nikol Kochmanová and Tanaka 2011, Ruan et al., 2022, Ruan et al., 2022), Kunibond (Tanaka et al., 2010, Fujita et al., 2011, Ruan et al., 2022) and bentonite GX (Wiebe et al., 1998), (Nazir et al., 2021). Kunigel V1, Kunibond and bentonite GX are often used for experimental studies in order to define thermal-hydraulic-mechanical- chemical couple phenomena. These bentonites require to mixture sand that the sand is silica sand.

3.2. Soil specimens

All specimens are statically compacted, and have a diameter of 38 mm and a height of 76 mm through all of six series in testing programs. The statically compaction process use a hydraulic oil jack, which has a capacity of 70 MPa. Before compaction, three kinds of soil materials have spray to approach various required water contents that are 8.0 %, 17.0 % and 20 % in this testing program. The soil materials have stored during 24 hours with the required water content. The prepared specimen has small size, and the ratio height of dimeter is just 2.0 that is certainly for investigation of mechanical properties such as shear strength through unconfined compression tests. The dry densities have a range from 0.800 Mg/m^3 to 1.600 Mg/m^3 for six testing series.

3.3. Heating method

All of specimens in the developed stiffness steal mould is placed into the thermal chamber, which is installed the circulation system in the chamber. The circulation system for the chamber room is possible to make steady temperature controlling, and it applies the isotropic heating conductivity to the specimens. The thermal chamber has a specification as following; the size is 600 mm in wide, 600 in depth and 430 mm in height and the volume is 154 cm^3. The temperature controlling range is from 60 degrees Celsius to 260 degrees Celsius, the sensitivity is plus and minus 0.1 degrees Celsius. The temperature distribution in the chamber is plus and minus 1.0 degrees Celsius when the regulated temperature is settled to 100 degrees Celsius. In previous works, the variation of temperature is calibrated, and when the target temperature is 80 degrees Celsius, the centre position in the chamber approach to 80 degrees Celsius till 20 minus.

The developed stiffness steal mould is located on the stainless shelving plate, is has a capacity of 15.0 kg for loading due to placing for some test specimens. The

Figure 4. Position for installing of pressor sensor.

Figure 5. Pressor sensor (PHL-A-3MP-A).

side of thermal chamber has some holes at lateral surfaces, are useful to pass through some cables installed pore pressure sensor. Then, the cable is possible to connect the data logger. The data logger system transfer to the PC, and the data sets are saved in stability. The data logger system consists of TC 32K and switch box (CSW 5B 05), and made in Tokyo Measurement Instruments Laboratory Co., Ltd.

3.4. Developed steal mould

Thermal performance is significant key factor to relevance the phenomena of bentonite sand mixture, and it is possible to create the pore fluid pressure. The produced pore fluid pressures effort on the mechanical properties for bentonite sand mixture. In order to measure the pore fluid pressures, an improved steel mould is used in this study. The developed stiffness steal mould (Fig. 4) has a specification is mentioned that a height is 75 mm, and the outside diameter is 70 mm and the thickness is 16 mm. The material is SUS 304 that the thermal conductivity is 16.3 W/m℃, the specific heat is 0.50 J/g℃, Young's modulus is 193 kN/mm^2 and the coefficient of thermal expansion is 17.3 10^{-6}/℃ for a range from 0 degree Celsius to 100 degrees Celsius. Two holes are prepared at lateral surface for encourages of the pressure sensors that located portion is 18 mm distance from the top surface and bottom surface. The hole with a dimeter of 19 mm is produced and the depth is 12 mm. In addition, a porous stone is installed, which has a diameter of 4.0 mm an da thickness of 5.0mm. The surface of

Figure 6. Connected steal mould with pressure sensor.

porous stone at internal side contact to the specimen. The void structure in porous stone is relatively large and is rough for remaining good air pressure transfection. An O-ring is located between the porous stone and the pressure receiving surface when the setting the pressure sensor at the hole, and prevent completely the leakage of the air fluid and water fluid.

3.5. Pore pressure sensor used in this study

This testing measures the changing of pore pressure for the specimen under heating application that the heating produces 80 degrees Celsius at least in the thermal chamber. The pressure sensor with high temperature resistance is required that PHL-A-3MP-A (Fig. 5) made in Kyowa Electronic Instrument CO., Ltd is used, and are installed on the upper and lower portions of the lateral surface in the stiffness steal mould (Fig. 6). The specification show that a capacity is 3.0 MPa, a rated output is 2.0 mV/V, a temperature tolerance is minus 40 degrees Celsius to 150 degrees Celsius, a sensitivity is plus and minus 20.0 %. A connector plug is detailed for maintaining correct performance from minus 25 degrees Celsius to 85 degrees Celsius. A hysteresis is plus and minus 0.2 %, and repetition is less than 0.2 %. The heating and cooling in repeat are performed when the steal mould is empty. The controlling temperature range a from 20 degrees Celsius to 80 degrees Celsius. The pressure sensors has accurate performance. During all of testing series, the pressure sensors often checked the inspections for certifications. Also, a pressure is measured for distilled water only, the measured pressure indicates about 600 kPa, and recognized reproducibility.

3.6. Test programs

3.6.1. Test series No.1

This testing program consist five different test series including unsaturated condition and saturated condition for three different bentonite materials. Heating application produce 80 degrees Celsius. This study has the explanation for five test series as following.

The samples with Kunigel V1 sand mixture are prepared that required dry densities have a range from 0.800 Mg/m^3 to 1.600 Mg/m^3, with compaction water content of 17.0 % and degree of saturations show between 19.2 % to 65.6 % having a wide range. The mixture rate is 7 to 3 in Test series No.1.

The steal mould cover using plates with some small holes for saturation process, and submerge into water bath. The water bath completely closed, and vacuum application is applied to the specimen that is possible to approach to saturation condition. Two different solutions are propagated that one is distilled water and another one is salinity water, and the salinity water has a concentration of 3.5 % corresponding to natural sea water. Achieving saturation condition, upper portion and bottom portion replace cover plated with no holes and create perfect undrained conditions.

The heating application that from 20 degrees Celsius to 80 degrees Celsius is applied to unsaturated specimens and saturated specimens with the different solutions.

3.6.2. Test series No.2

Kunibond with sand mixture material is used for pore pressure investigation in Test series No. 2. The specimens are compacted with water content of 20.0 %, and the targeted dry densities are 0.800 Mg/m^3, 1.00 Mg/m^3, 1.200 Mg/m^3, 1.400 Mg/m^3 and 1.600 Mg/m^3, and corresponding degree of saturations are 22.6 %, 31.5 %, 42.8 %, 57.4 % and 77.2 %. After placed into the thermal chamber at 20 degrees Celsius, controlling temperature of 80 degrees Celsius is set up. The checking of pore pressure (i.e., gas) at the end of test, that is 20 degrees Celsius.

3.6.3. Test series No.3

The similar testing is conducted for bentonite GX for measurement of pore pressure, that has no sand mixture in Test series No.3. The statically compaction is able to produce the high density and the water content is 20 %.

The targeted dry densities are 0.800 Mg/m^3, 1.00 Mg/m^3, 1.200 Mg/m^3, 1.400 Mg/m3 and 1.600 Mg/m^3 in order to provide the influence of dry density. The calculated degree of saturations has as following: 22.6 %, 31.5 %, 42.8 %, 57.4 % and 77.2 %. After completely cove the steal mould using two plates, the steal mould installed into the thermal chamber at 20 degrees Celsius. Taking initial pore pressure value, the thermal chamber has an operation with the subjection of 80 degrees Celsius. The maximum pore pressure is estimated remaining 80 degrees Celsius. After test, it is duty that pressure sensor have calibration under cooling process.

3.6.4. Test series No.4

Testing procedure is similar to Test series No.3 in Test series No.4, and have one difference that is compaction water content is 8.0 % associated to be same dry density. The specimens have 9.1 %, 12.6 %, 17.1 %, 23.0 % and 30.9 % in degree of saturation.

3.6.5. Test series No.5

The bentonite GX with no sand mixture is used in Test series No.5. The specification of specimens is different with Test series No.3 and No.4 that water content is 17.0 %, and saturated specimens are observed. The dry densities are 0.800 Mg/m^3, 1.00 Mg/m^3, 1.200 Mg/m^3, 1.400 Mg/m^3 and 1.600 Mg/m^3 for unsaturated specimens. The saturated specimens have a range from 1.00 Mg/m^3 to 1.400 Mg/m^3, and are three different dry densities. All of specimens regardless unsaturated

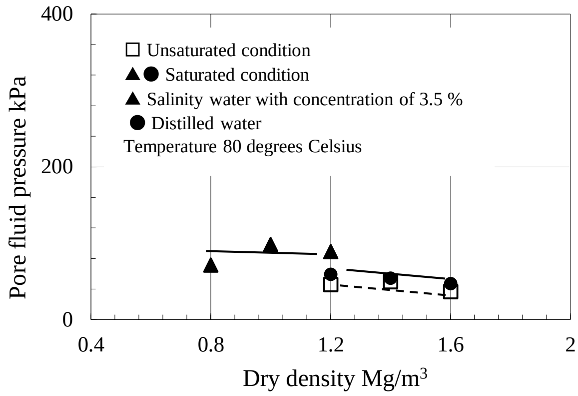

Figure 7. Kunigel V1 with sand mixture.

condition and saturated condition have the aim to 80 degrees Celsius on heating action.

3.6.6. Test series No.6

The bentonite GX with no sand mixture with water content of 8.0 % is statically compacted, and a target dry density is 1.500 Mg/m^3 with degree of saturation 29.6 %. The specimen in the steal mould received isotropic heating under undrained and un-exhaust condition that the controlling temperatures were 40, 50, 60 and 80 in degrees Celsius. The controlling temperature is 80 degrees Celsius, and increase directly from 20 degrees Celsius to 80 degrees Celsius on first process. Subsequently, the cooling application is applied to the specimens that temperature process product from 80, 60, 50 and 40 in degrees Celsius. When equilibrium with 40 degrees Celsius, once again, increment of temperature is produced that is from 40 degrees Celsius to 80 degrees Celsius. Thus, the heating history is considered to occurrence of pore pressure.

4. Test results

4.1. Pore fluid pressure for unsaturated bentonite materials

Kunigel V1 mixture silica sand, and statically compacted with water content of 17.0 % for variation of dry densities. Also, saturated specimens are prepared, when absorb waters are distilled water and salinity water. All of specimens have 80 degrees Celsius due to isotropic heating in the thermal chamber as shown in Fig. 7. The pore fluid pressures in unsaturated condition with variation of dry densities are lower than the pressures for saturated condition. It is common that reduction of pore fluid pressures occupied in increment of dry densities for saturated specimens. The void structure is saturated that cause the large growing of pore fluid pressures. Then, the difference of pressures according to variation dry densities with coincident of water content for unsaturated specimen depend of degree of saturations that is ratio of air volume to total volume. Considering the influence of chemical components, saturated specimens under salinity water with concentration of 3.5 % have large in 30 kPa comparison with the distilled water. It is verified the effort of chemical components that is increment of fluid pore pressure.

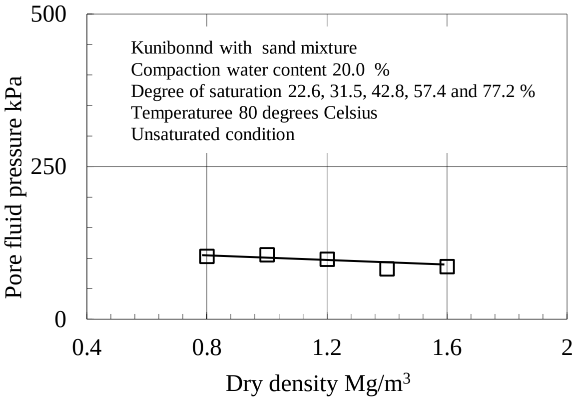

Figure 8. Kunibond with sand mixture.

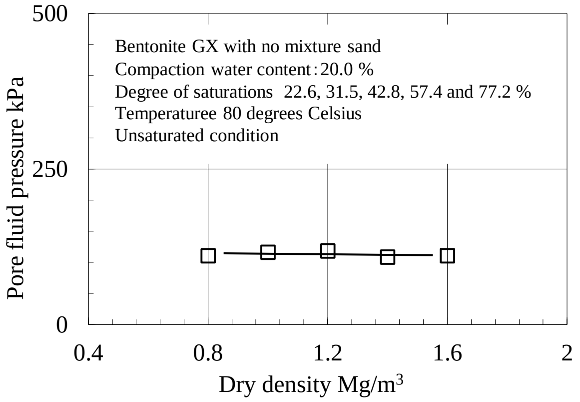

Figure 9. Compacted GX with water content of 20 %.

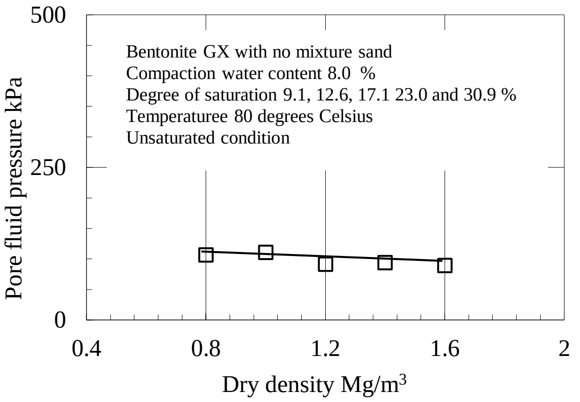

Figure 10. Compacted GX with water content of 8.0 %.

Kunibond and bentonite GX such as the different materials are used, and measured pore fluid pressures in unsaturated condition. The Kunibond mixture sand and bentonite GX has no mixture sand. Two different materials are common that are water content of 20 %, and established degree of saturations are close, respectively. Kunibond sand mixture specimens indicate the reduction of pore fluid pressure with dry density as shown in Fig. 8 that 102.7 kPa in the dry density of 0.800 Mg/m^3 decrease to 85.9 kPa in the dry density of 1,600 Mg/m^3. Compacted water content is 20 .0 %. The applied temperature is 80 degrees Celsius. Bentonite GX is statically compacted with both water content of 20 % and 8 %, and required dry densities have a variation as following; from 0.800 Mg/m^3 to 1.600 Mg/m^3.

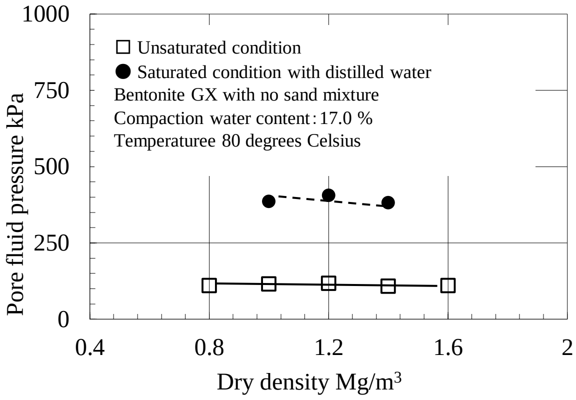

Figure 11. Increment of pressure due to saturation.

Specimen has no sand mixture. Measured pore fluid pressures are shown in Figs 9 and 10 that the pressures describe around 110 kPa, and the influence of dry density is slightly that smoothly reduction is recognized.

4.2. Increment of pore fluid pressures due to saturation

Unsaturated specimens compare to saturated specimen using bentonite GX, which have no sand mixture, and compacted at water content of 17 %. The measured pore fluid pressures shown in Fig. 11 are around 110 kPa through a range from 0.800 Mg/m^3 to 1.600 Mg/m^3 when the specimens are unsaturated condition. It is verifying that the influence of dry densities is not so much. The relationship between dry density and pore fluid pressure is similar with the pore fluid pressures above mentioned in Figs. 6 and 7. Saturated specimens are promoted under distilled water and subsequently, the heating produces to 80 degrees Celsius. Required dry densities are correspond to some unsaturated specimens. Saturated specimens having no air void indicate further pore fluid pressures that are over 380 kPa, and are close to four times against to unsaturated specimens. Air void spaces being that cause the decrease of pore pressure in the hydraulic mechanism. It is necessary to remine a long period according to 80 degrees Celsius at constant.

4.3. Influence of heating and cooling applications

This study exhibits the changing pore fluid pressure under heating and cooling in repetition, and bentonite GX specimen is prepared with a dry density of 1.500 Mg/m^3, compacted water content of 8.0 % and degree of saturation of 29.6 %. A beginning of heat action is from 20 degrees Celsius to being 80 degrees Celsius. Subsequently, cooling stage have from 80, 60 50 and 40 degrees Celsius. Repetition is applied to the specimen, and the specimen with 40 degrees Celsius approaches to 80 degrees Celsius through 60 degrees Celsius. Measured pore fluid pressure is 90.8 kPa in virgin heating as shown in Fig. 12. After occurrence of 90.8 kPa, a temperature in control panel could adjust to 60 degrees Celsius. A displayed pressure in the data logger gradually reduce, and taking equilibrium at 54.1 kPa. Two temperatures are remined, which are 50 and 40 degrees Celsius in cooling

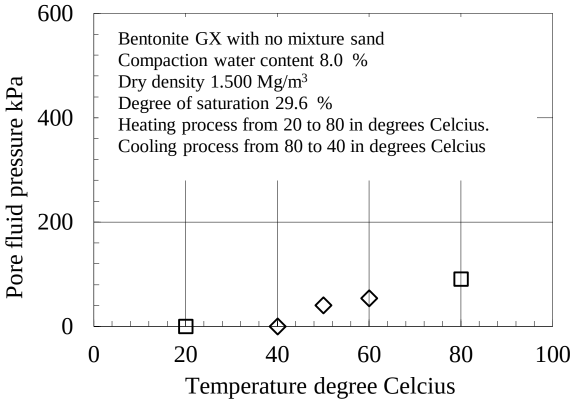

Figure 12. Heating and cooling process for GX.

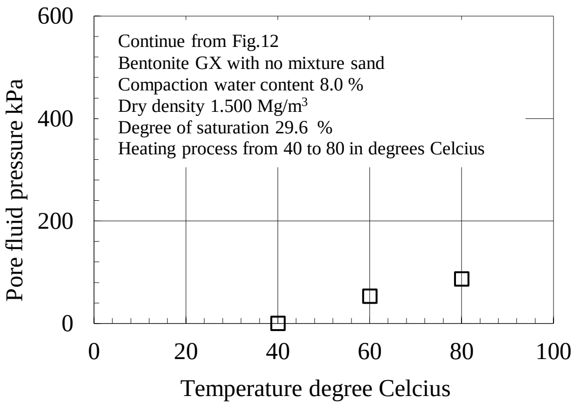

Figure 13. Heating application repetition for GX.

process that each evaluated pore fluid pressure is 40.8 kPa and 0.0 kPa. Heating application is continued, and temperature increase from 40 to 80 degrees Celsius through 60 degrees Celsius. The specimen with a pressure of zero have a reproduction that 53.2 kPa and 86.4 kPa in the pore fluid pressures to 60 and 80 degrees Celsius, respectively as shown in Fig. 13. As a like this result, increasing of temperature specimen is significant factor that large pore fluid pressure is produced, and its tendency is similar to repetition in heating and cooling.

5. Conclusions

This study focuses on established the pore pressure under heat conditions for bentonite and bentonite-sand mixture, which are completely undrained condition and unexhausted condition, and consider the occurrence mechanics of pore pressure in macro-micro void structure due to heating and heating-cooling repetition. A thermal chamber is used in heating method, which have high specification with accurate controlling sensitivity. The obtained summaries are verified as following:

(1) The three different compacted bentonites are prepared that the required temperature is 80 degrees Celsius, which are Kunigel V1, Kunibond and bentonite GX. The compacted specimens are unsaturated condition, and measured pore fluid pressures are less than 100 kPa while a dry density has a range from 0.800 Mg/m^3 to 1.600 Mg/m^3. The influence of dry density, compaction water content and degree of saturation are slightly.

(2) It is however, compassion between unsaturated condition and saturated condition that is verified significant different.

(3) The heating application and cooling application is repeated in continue. After heating and cooling process applied for one-time, unsaturated specimen indicate the occurrence large pore pressure.

References

Ahusborde, E., Amaziane, B., and Jurak, M. 2015. “Three-dimensional numerical simulation by upscaling of gas migration through engineered and geological barriers for a deep repository for radioactive waste.” Geological Society, London, Special Publications, 415(1), pp. 123-141.

Balmer, S., Kaufhold, S. and Dohrmann, R. 2017. “Cement-bentonite-iron interactions on small scale tests for testing performance of bentonites as a barrier in high-level radioactive waste repository concepts.” Applied Clay Science. 135, pp. 427-436. https://doi.org/10.1016/j.clay.2016.10.028

Birgersson, M., Åkesson, M. and Hökmark, H. 2008. “Gas intrusion in saturated bentonite – A thermodynamic approach.” Physics and Chemistry of the Earth, Parts A/B/C. 33, S248-S251. https://doi.org/10.1016/j.pce.2008.10.039

Castellanos, E., Villar, M. V., Romero, E., Lloret, A. and Gens, A. 2008. “Chemical impact on the hydro-mechanical behaviour of high-density FEBEX bentonite.” Physics and Chemistry of the Earth, Parts A/B/C. 33, S516-S526. https://doi.org/10.1016/j.pce.2008.10.056

Chen, Y. G., Jia, L. Y., Li, Q., Ye, W. M., Cui, Y. J. and Chen, B. 2017. “Swelling deformation of compacted GMZ bentonite experiencing chemical cycles of sodium-calcium exchange and salinization-desalinization effect.” Applied Clay Science. 141, pp. 55-63. https://doi.org/10.1016/j.clay.2017.02.016

Chen, Y. G., Dong, X. X., Zhang, X. D., Ye, W. M. and Cui, Y. J. 2019. “Cyclic thermal and saline effects on the swelling pressure of densely compacted Gaomiaozi bentonite.” Engineering Geology. 255, pp. 37-47. https://doi.org/10.1016/j.enggeo.2019.04.016.

Cui, L. Y., Ye, W. M., Wang, Q., Chen, Y. G., Chen, B. and Cui, Y. J. 2021.” Influence of cyclic thermal processes on gas migration in saturated GMZ01 bentonite.” Journal of Natural Gas Science and Engineering. 88. https://doi.org/10.1016/j.jngse.2021.103872

Fujita, T., Sugita, Y., and Toida, M. 2011. “Experimental studies on penetration of pulverized clay-based grout.” Journal of Energy and Power Engineering. 5.

Horseman, S.T., Harrington, J.F. and Sellin, P. 1999. “Gas migration in clay barriers.” Engineering Geology. 54. 1–2, pp. 139-149. https://doi.org/10.1016/S0013-7952(99)00069-1

Bosch, J. A., Qiao, Y., Ferrari, A. and Laloui, L. 2023. “Thermo-hydro-mechanical analysis of the complete lifetime of the bentonite barrier in the FEBEX in-situ test.” Geomechanics for Energy and the Environment. 34. https://doi.org/10.1016/j.gete.2023.100472

Kim, D., Jeon, S., Kim, S.-O., Wang, S. and Lee, M. 2023. “Review for Mechanisms of Gas Generation and Properties of Gas Migration in SNF (Spent Nuclear Fuel) Repository Site.” Economic and Environmental Geology. 56. 2, pp. 167-183.

Liu, J., Ni, H., Shao, J., Li, X., and Hong, Y. 2023. “Gas permeability evolution of unsaturated GMZ bentonite under thermo-mechanical effects.” Engineering Geology, 313.

Nazir, M., Kawamoto, K., and Sakaki, T. 2021. “Properties of granulated bentonite mixtures for radioactive waste disposal:A review.” GEOMATE Journal. 20. 81, pp. 132-145.

Nikol Kochmanová, N and Tanaka, H. 2011. “Influence of the Soil Fabric on the Mechanical Properties of Unsaturated

Clays" Soils and Foundations. 51. 2, pp. 275-286. https://doi.org/10.3208/sandf.51.275

Ohkubo, T., Kikuchi, H. and Yamaguchi, M. 2008. "An approach of NMR relaxometry for understanding water in saturated compacted bentonite." Physics and Chemistry of the Earth, Parts A/B/C. 33. S169-S176.

Ruan, K., Komine, H., Ito, D., Miyoshi, K. and Gotoh, T. 2022. "Hydraulic conductivity and X-ray diffraction tests of unsaturated bentonites with a multi-ring and their predictions by pores distributions." Engineering Geology. 306. https://doi.org/10.1016/j.enggeo.2022.106738

Ruan.K., Wang, H., Komine, H. and Ito, D. 2022. "Experimental study for temperature effect on swelling pressures during saturation of bentonites." Soils and Foundations. 62. 6. https://doi.org/10.1016/j.sandf.2022.101245

Samper, J., Mon, A. and Montenegro, K. 2020. "A coupled THMC model of the geochemical interactions of concrete and bentonite after 13 years of FEBEX plug operation." Applied Geochemistry. 121. https://doi.org/10.1016/j.apgeochem.2020.104687.

Sellin, P. and Leupin, O. X. 2013. "The use of clay as an engineered barrier in radioactive-waste management–a review." Clays and Clay Minerals, 61. 6. pp. 477-498.

Tanaka, Y., Hasegawa, T., and Nakamura, K. 2010. "Modeling hydraulic conductivity and swelling pressure of several kinds of bentonites affected by salinity of water." In International Conference on Radioactive Waste Management and Environmental Remediation. 54532. pp. 9-18.

Vardon, P. J., Thomas, H. R., Masum, S. A., Chen, Q. and Nicholson, D. 2014. "Simulation of repository gas migration in a bentonite buffer." Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics. 167. 1. pp. 13-22.

Wiebe, B., Graham, J., Tang, G. X., and Dixon, D. 1998. "Influence of pressure, saturation, and temperature on the behaviour of unsaturated sand-bentonite." Canadian Geotechnical Journal, 35. 2. pp. 194-205.