https://doi.org/10.1051/e3sconf/202454401004

A device to measure apparent swelling pressure of compacted bentonite using extremely thin specimen

Hailong Wang[1#]

[1] *Waseda University, Global Center for Science and Engineering, 3-4-1 Ohkubo, Shinjuku-ku, Japan*
[#]*Corresponding author: whlxy2002@aoni.waseda.jp*

ABSTRACT

As a candidate material proposed for the geological disposal of the high level radioactive waste, bentonite has been studied extensively in terms of its engineering properties. One of the properties is the pressure generated during wetting compacted bentonite under rigorously confined condition. This pressure is designated apparent swelling pressure (p_s) herein. On the other hand, due to the extremely low hydraulic conductivity (e.g. 10^{-9}-10^{-14} m/s) of compacted bentonite, it is often very time consuming to measure p_s. For instance, test duration is typically 1-2 month for a specimen with thickness (h_{sp}) of 20 mm, and 1-2 weeks for h_{sp}= 10 mm. Though testing duration can be reduced by using thinner specimens, it becomes difficult to control measurement accuracy. Recently, the author reported a series of datasets obtained with newly developed testing method using h_{sp}= 2 mm specimens to measure p_s, by which testing duration was reduced to 1-2 days and data repeatability was also extraordinarily good. In this paper, the author made further developments on such testing techniques and introduced a device to measure p_s for h_{sp}= 0.4 mm specimen, by which testing duration can be reduced to 1-2 hours. The p_s measured by this device on a bentonite was compared with previous database, which implies that data repeatability is very good in generally, though the data scattering is observed for h_{sp}= 0.4 mm specimens.

Keywords: compacted bentonite; apparent swelling pressure; apparatus; thin specimen.

1. Introduction

The high-level radioactive waste generated during nuclear fuel recycle is considered to be permanently disposed in the geological disposal system, in which the waste will be isolated in a multi-barrier system under the deep ground (e.g. more than several hundred meters) for more than 10 thousand years. Fig. 1 illustrated a conceptual configuration of the barrier system in the Japanese project. The buffer material is one of the barriers, which is made by compacting bentonite-sand mixture into blocks and is placed between the other two barriers, the metal container and the host rock. The buffer material, which is unsaturated condition initially, absorbs ground water and generates a swelling pressure under the disposal condition. This pressure is desigated the "apparent swelling pressure" (p_s) to distinguish from the pressure between montmorillonite crystalline layers. Generation of p_s can firmly fix the buffer material, metal container and the host rock as a whole body, which is important for the safe design of the disposal system.

Extensive works have been conducted to study p_s for both pure bentonite or bentonite-sand mixing under various conditions (e.g. Pusch 1980; Komine and Ogata, 1994; Delage, Howat, and Cui 1998; Villar and Lloret 2008; Lee et al. 2012; Chen et al., 2016; Watanabe and Yokoyama 2021). The consolidation apparatus was often used to measure p_s, where vertical loading was adjusted to restrain swelling deformation during wetting, and recent year, new apparatuses have been developed that the specimen was confined rigidly (Sridharan et al. 1986, Tang and Cui 2011). However it is often very expensive to conduct such tests since p_s generally increase exponentially and easily exceeds 10 MPa so that testing apparatuses have often to be designed cumbersomely, and it takes very long time due to the extremely low permeability of the compacted bentonite (say, less than 10^{-12} m/s). In past studies specimen diameter (ϕ) was normally 20-60 mm and height (h_{sp}) was 10-30 mm (Villar and Lloret 2008; Lee et al. 2012; Maeda et al. 1998; Suzuki et al. 1992; Namikawa and Kanno 1997; Suzuki and Fujita 1999; Sasakura et al. 2002; Komine et al. 2009). Suzuki and Fujita (1999) and Tanai et al. (2010) examined effects of the height diameter ratio (h_{sp}/ϕ) and specimen dry density (ρ_d) on p_s and suggested that h_{sp}/ϕ should be kept low (e.g. ≤ 0.5) especially for relatively dense specimens to reduce the sidewall friction effect of the specimen ring on p_s. However even for h_{sp}= 10 mm, wetting duration normally takes 1-2 weeks for Na type bentonite (i.e. bentonite with the exchangeable cation of sodium mainly), though Ca type bentonite (i.e. with the exchangeable cation of calcium mainly), may be a bit faster. For h_{sp}= 20 mm case, a test may take 1-2 month. Attempt was made to use h_{sp}= 5 mm specimens by Komine and Ogata (1994), in which testing duration was reduced to several days. Specimen height reduction is not only an issue of properly preparing the specimen, it is also a challenge for measurement accuracy, such as dry density (ρ_d) or water content (w) etc. Recently, Wang et al. (2022a, 2022b, 2022c) developed a system to measure p_s for specimen with h_{sp}= 2 mm and ϕ=28 mm, in which, to ensure the measurement accuracy, length and mass measurements of specimens were accurated to 1 µm and 0.1 mg, respectively. Their results shown extremely good repeatability for powder material, and the testing duration was reduced to 1-2 days.

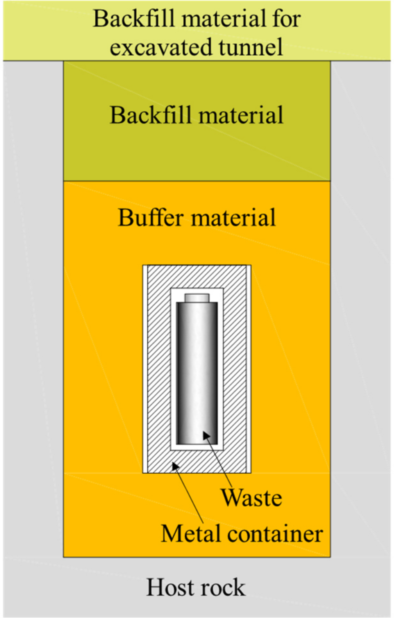


Figure 1. Conceptual configuration of the geological disposal system.

Though it is less urgent to develop technique to reduce specimen height further for directly wetting the compacted specimen by water or solutions, specimen size is still too large in case that it was wetted by water vapor, which is important to examine p_s under different humidity (i.e. suction) condition. For instance, it easily took a month to achieve equilibrium for a specimen with h_{sp}= 7 mm (Likos and Wayllace 2010). It also took at least 2 weeks for h_{sp}= 2 mm specimen based on the author's experience. Under such a condition, the author attempt to reduce specimen height to 0.4 mm in this study using newly developed techniques. Since these techniques are still under development, p_s measured by wetting the specimens with water is discussed in this study.

2. Material, apparatus and methodology

The commercial bentonite Kunigel V1 (K_V1), a candidate material for use in the Japanese geological disposal project, was used for all tests conducted in this study. The physical properties of K_V1 are summarized in Table 1. Note that all properties were obtained on the same batch of K_V1 though some were reported by previous studies, and in this study, the saome batch was also used.

Fig. 2 shows the apparent swelling pressure apparatus and the specimen preparation device. The apparatus mainly includes two stainless plates to fasten the specimen, a stainless porous metal with a pore size of 2 µm for water passage and a pressure sensor (measurement capacity: 20 MPa). The specimen with a thickness of ~0.4 mm and diameter of 6.45 mm is sandwiched between the pressure sensor and the porous metal. To measure p_s of the specimen, water droplet was injected in the opening above the porous metal to wet the specimen. Note that it was not sealed between the sensor and metal plate 1 so that pore air could escape from gaps between them during wetting. To reduce possible specimen deformation during wetting, four M6 bolts were used to fix the two metal plates, and the bottom surface of metal plate 2 was polished with a roughness of less than 0.5 µm.

Table 1. Physical properties of K_V1

Properties	**Value**
Specific gravity (G_s)[a]	2.8±0.03
Room water content (w_0) [b]	5.2-7.1%
Montmorillonite content (C_m) [c]	53%
Main accessory minerals[d]	Quartz, Feldspar, Plagioclase, Calcite
Content of particles size <5 µm[d]	73%
Liquid limit (L_L)[e]	505%
Plastic limit (P_L)[e]	45%
Cation exchangeable capacity (CEC)[e]	71.9 meq/100g
Extractable cations[e] Unit: meq/100g	Na^+ : 53.8 Ca^{2+}: 35.5 Mg^{2+}: 1.6 K^+ : <1.0

Note, [a]: reported by Wang et al. (2022a); [b]: for specimens in this study under relative humidity: ~50% and temperature: ~23 °C ; [c]: reported by Wang et al. (2022c); [d]: reported by Wang et al. (2020); [e]: reported by Shirakawabe et al. (2021)

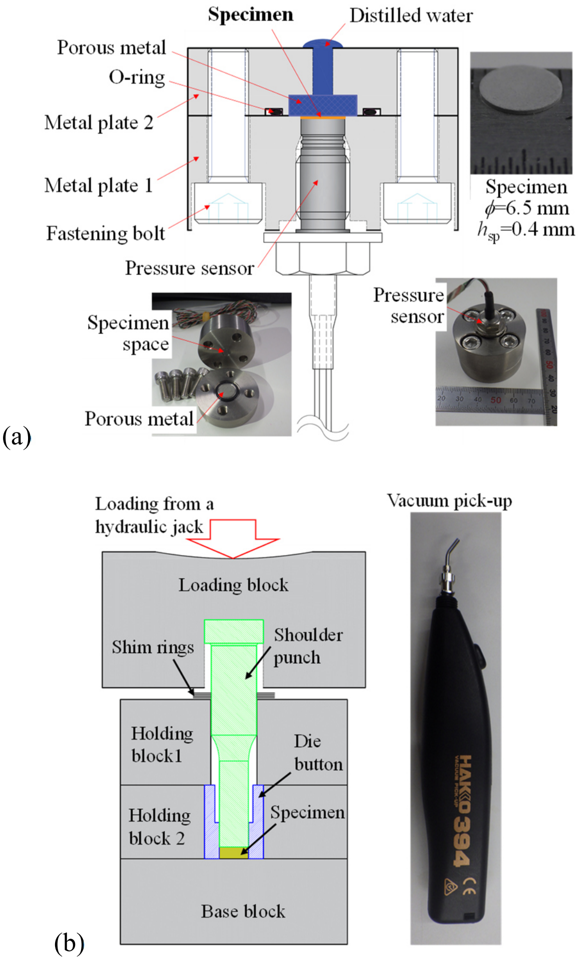


Figure 2. (a) Apparent swelling pressure aparatus; (b) Specimen preparation devices.

The specimen preparation device consists of mainly four blocks. The shoulder punch (tip diameter: 6.40 mm) and the die button (bottom inner diameter: 6.45 mm) are common tools for the metal stamping. These tools are manufactured by very stiff steel usually to an accuracy of 0.01 mm. The die button was glued to the holding block 2 and bentonite powder was poured into the inner space of it. Then the shoulder was inserted into the inner space, after which static loading from a hydraulic jack was applied to compact the material for 2 minutes. Several shim rings were placed between the loading block and holding block 1, by which the thickness of compacted specimens could be adjusted to a 0.01 mm level. After compaction, the specimen was pushed out and its mass was measured to 0.01 mg and its thickness was measured to 1 μm. To handle this tiny and fragile specimen, a vacuum pick-up was used instead of using hand. Even so, sometimes the specimen cracks and has to be prepared again. Note that the bottom inner diameter of the die button is slightly smaller than that of metal plate 1, so that the specimen can be easily placed into the hole above the pressure sensor. The dry density (ρ_d) of the specimens after wetting was calculated based on material initial water content, specimen mass and thickness and inner diameter of metal plate 1 (not inner diameter of button because the specimen swells in the metal plate 1).

In total, 35 tests were conducted as summarized in Table 2. Specimens with ρ_d less than 1.5 Mg/m^3 were not largely prepared because they were too weak to be handled. Since not many data are available for relatively dense specimen from past studies for comparison, specimens with ρ_d higher than 1.8 Mg/m^3 were not tested.

Table 2. Test programs in this study

Dry density ρ_d (Mg/m^3)	Water content after wetting w_f (%)	Equlibrium swelling pressure p_{eq} (MPa)	Degree of saturation S_r (%)
1.462	38.7	1.13	118
1.513	32.0	1.51	106
1.521	33.3	1.37	111
1.552	32.0	1.96	111
1.560	31.8	1.79	112
1.561	31.2	2.17	110
1.581	28.5	3.34	103
1.586	28.8	2.24	106
1.588	29.5	2.95	108
1.594	31.7	2.10	117
1.607	28.2	2.81	106
1.608	29.1	2.70	110
1.611	27.9	3.04	106
1.613	28.5	3.00	108
1.620	28.1	2.91	108
1.622	28.0	3.78	108
1.624	28.6	2.86	111
1.634	30.8	1.47	121
1.635	26.6	2.98	104
1.645	30.6	2.76	122
1.647	28.0	2.45	112
1.654	27.4	3.13	111
1.656	28.0	3.62	113
1.662	26.1	3.26	107
1.678	23.8	4.47	100
1.678	31.3	2.47	131
1.680	26.3	4.34	110
1.681	24.6	4.64	103
1.683	25.1	3.84	106
1.698	26.3	4.48	114
1.728	24.4	5.34	110
1.752	19.8	5.54	93
1.754	25.7	5.00	121
1.763	26.5	4.66	126
1.769	24.1	5.74	116

3. Test results and discussions

Fig. 3 shows typical time histories for specimens with different ρ_d. It can be seen that, regardless of ρ_d, p_s first increases to a peak, then drops and increases again to finally reach an equilibrium. These are very typical behaviours for compacted bentonites as observed by many researchers (e.g. Pusch, 1980; Komine and Ogata, 1994; Villar and Lloret 2008; Lee et al. 2012; Wang et al. 2020). These behaviours were explained Wang et al. (2022a) in Fig. 4, where montmorillonite particle is symbolled by a spring with arrows and the arrows indicate inter-particle force. Initially, the skeleton of non-swelling particles maintains its initial configuration and p_s increases due to swelling of montmorillonite. When p_s reaches a certain magnitude, some particles may move to less stressed positions that results in p_s reduction (i.e. reduction of inter-particle force). When stress environment inside a specimen becomes uniform, further swelling of montmorillonite causes p_s to increase again until it reaches an equilibrium. For most tested specimens, the p_s equilibrium was technically achieved after a wetting period of 0.5 h, which is significantly shorter than the period required for the thickness of specimens typically used.

For some tests initially conducted, the time histories were chaotic as shown in Fig. 5. Initially, water droplet injection as shown in Fig. 2a was not used, rather, the apparatus was turned over and placed in a water cup. Although the water level in the cup was higher than the position of the specimen, apparently water could not smoothly enter into the water path, taking much longer testing time to reach the equilibrium. On the other hand, it was noticed that if the fine porous metal could not be well dried before the test, p_s, after inserting the specimen, gradually increased by absorbing water vapor from the porous metal. As a result, the abnormal p_s, time histories were observed in Fig. 5b. Nevertheless, it seems that the equilibrium can be achieved eventually. In this study, the equilibrium swelling pressure (p_{eq}) was defined as the last measured p_s value before terminating tests.

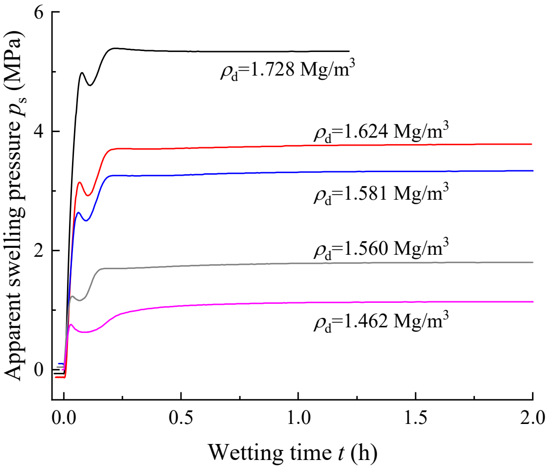
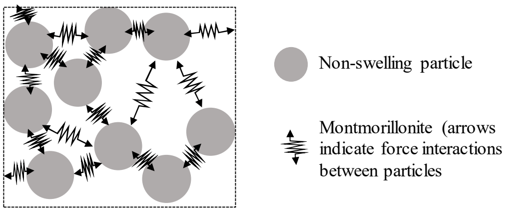
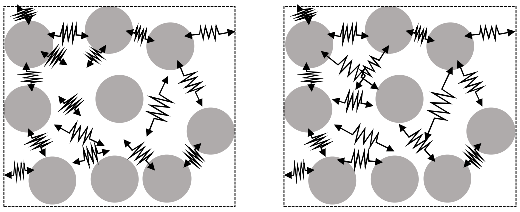


Figure 3. Typical time history of h_{sp} =0.4 mm specimen.



(a) p_s from 0 to p_{p1}: increases due to swelling of montmorillonite



(b) p_s from p_{p1} to p_v: reduction due to movement of particles resulting in reduction of inter-particle force

(c) p_s from p_v to p_{ei}: re-increase due to further swelling and limited movement space

Figure 4. Schematic illustration on behaviors of compacted bentonite after Wang et al. (2022a) with permission.

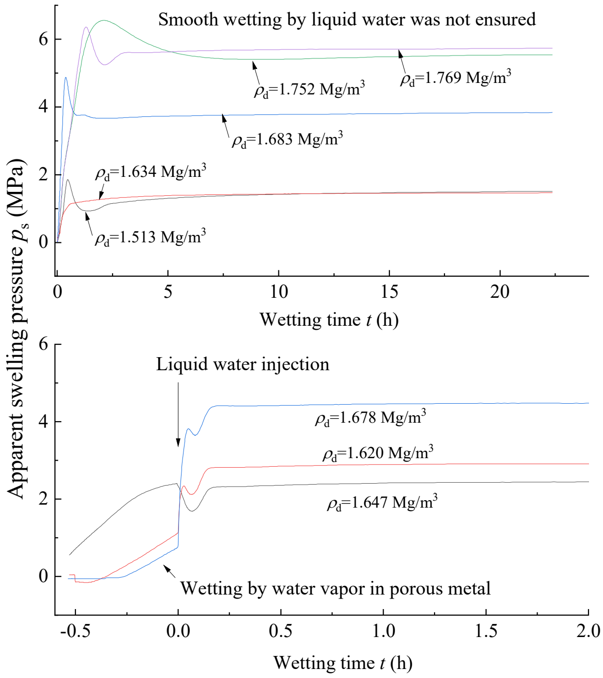


Figure 5. Some typical examples for specimens being not wetted normally.

Fig. 6 compares the relation between p_{eq} and ρ_d obtained in this study and that measured by Wang et al. (2022b) on specimens with thickness from 2 to 10 mm. It can be seen that data in this study are generally consistent with those of Wang et al. (2022b), however, the scatter is larger. Fig. 7 shows an example of data scattering of specimens with ρ_d of ~1.6 Mg/m^3. It can be seen that the time histories of p_s are very similar, although the final equilibrated p_s may change significantly. One reason causes scattering would be the variation of montmorillonite content (C_m) in the specimens. C_m of K_V1 is only 53% so that montmorillonite in these tiny specimens may differ (only about 25 mg material was used for a specimen). A second reason could be the ρ_d measurement error. Even using a scale balance with resolution of 0.01 mg for the mass measurement and a micrometer to 1 μm resolution for the diameter and thickness measurements, ρ_d only has 3 the significant figures. There were also some sources that would cause undetectable specimen deformation, such as porous metal compression, penetration of specimen into porous metal or other spaces. These sources are either negligible or measurable for relatively larger specimens (e.g. Wang et al. 2022b), however, they can hardly be accurately estimated in the current study.

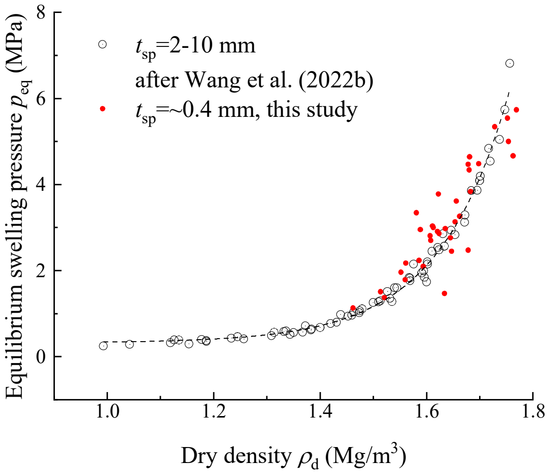


Figure 6. Relation between dry density and equilibrium swelling pressure.

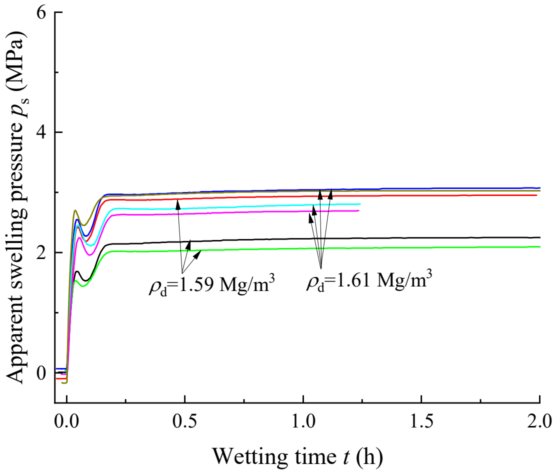


Figure 7. Time history of specimens at ρ_d of ~1.6 Mg/m^3**.**

It was found that, though the wetting duration changes significantly with specimen height, the time scale can be well normalized by a time coefficient $\lambda = h_{sp}/\sqrt{t}$ proposed by Wang et al. (2022b). This proposal is based on the water movement characteristics, i.e. water diffusion, in bentonite (See Wang et al. 2020 for more details). Fig. 8 reproduces the relationship between ρ_d and λ at some particular points, i.e. peak, valley and initial equilibrium points as defined in Fig. 8c. Note that Fig. 8, λ was calculated with the time corresponding to the particular points for different h_{sp} specimens. It can be seen that regardless of h_{sp}, λ are very close for h_{sp} of 2 to 10 mm. Silimarly data obtained in this study were added to Fig. 8, where although data of some abnormal p_s time histories (e.g. Fig. 5) were excluded.

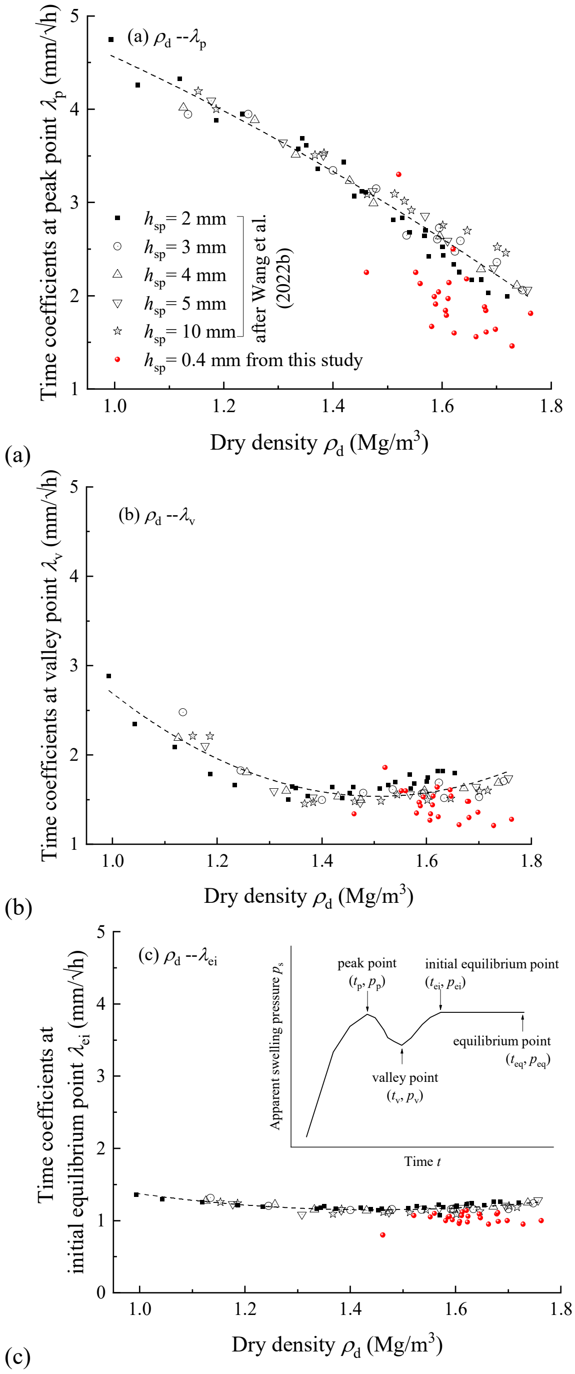


Figure 8. Relation between dry density and time coefficient at (a) peak, (b) valley and (c) and the initial equilibrium modified from Wang et al. (2022b) with permission.

Fig. 8 suggests that λ data for h_{sp} = 0.4 mm distribute on the lower bound of other data, which implies that, if the p_s time history of specimens with different height and similar dry density was drawn with the normalized time scale λ, these feature points will be achieved at a smaller λ (or longer time).

4. Conclusions

Apparent swelling pressure (p_s) was defined, in this study, as the pressure generated by wetting compacted bentonite specimens when their deformation was rigidly confined. Testing techniques to measure p_s with specimen height of 0.4 mm and diameter of 6.5 mm were described in this study. It was found that the wetting duration of such tiny specimens by water takes about 1-2 hours, significantly shorter than in currently available techniques employing thicker specimens. Although some technical challenges were solved to conduct the tests and care were taken, the data repeatability is still relatively low compared to some past techniques. Nevertheless, the general characteristics of p_s history was confirmed to be the same as that of much thicker specimens.

Acknowledgements

This work was performed as a part of the activities of the Research Institute of Sustainable Future Society, Waseda University, and supported by JSPS KAKENHI Grant Number 22K04320, Waseda University Grant for Special Research Projects (Project number: 2023C-171), and Kajima Foundation. The author expresses his deep gratitude to all those mentioned above.

References

Chen, Y. G., Zhu, C. M., Ye, W. M., Cui, Y. J., Chen, B. "Effects of solution concentration and vertical stress on the swelling behavior of compacted GMZ01 bentonite", Applied Clay Science, 124–125, pp. 11–20, 2016. https://doi.org/10.1016/j.clay.2016.01.050

Delage, P., Howat, M., Cui, Y. J. "The relationship between suction and swelling properties in a heavily compacted unsaturated clay", Engineering Geology, 50 (1–2), pp. 31–48, 1998. https://doi.org/10.1016/S0013-7952(97)00083-5

Komine, H., Ogata, N. "Experimental study on swelling characteristics of compacted bentonite", Canadian Geotechnical Journal, 31(4), pp. 478–490, 1994. https://doi.org/10.1139/t94-057

Komine, H., Yasuhara, K., Murakami, S. "Swelling characteristics of bentonites in artificial seawater", Canadian Geotechnical Journal, 46(2), pp. 177-189, 2009. https://doi.org/10.1139/T08-120

Lee, J., Lim, J., Kang, I., Kwon, S. "Swelling pressures of compacted Ca-bentonite", Engineering Geology, 129–130(1), pp. 20–26, 2012. https://doi.org/10.1016/j.enggeo.2012.01.005

Likos, W.J., Wayllace, A. "Porosity evolution of free and confined bentonites during interlayer hydration", Clays and Clay Minerals, 58(3), pp. 399–414, 2010. https://doi.org/10.1346/CCMN.2010.0580310

Maeda, M., Tanai, K., Ito, M., Mihara, M., Tanaka, M. "Mechanical properties of the Ca exchanged and Ca bentonite: swelling pressure, hydraulic conductivity, compressive strength and elastic modulus", Japan Nuclear Cycle Development Institute, Japan, PNC-TN8410 98-021 (in Japanese), 1998. Available at: https://jopss.jaea.go.jp/pdfdata/PNC-TN8410-98-021.pdf, accessed on Sep. 24, 2022.

Namikawa, T., Kanno, T. "Consolidation property of buffer material", Japan Nuclear Cycle Development Institute, Japan, PNC-TN8410 97-051 (in Japanese), 1997. Available at: https://jopss.jaea.go.jp/pdfdata/PNC-TN8410-97-051.pdf, accessed on Sep. 24, 2022.

Pusch, R. "Swelling pressure of highly compacted bentonite". Division Soil Mechanics, University of Lulea, KBS technical report, KBS PROJ. 15:05. (1980). Available at: https://inis.iaea.org/collection/NCLCollectionStore/_Public/12/605/12605438.pdf, accessed on Sep. 24, 2022.

Sasakura, T., Kuroyanagi, M., Okamoto, M. "Studies on mechanical behavior of bentonite for development of the constitutive model", Japan Nuclear Cycle Development Institute, Japan, JNC TJ8400 2002-025 (in Japanese), 2002. Available at: https://jopss.jaea.go.jp/pdfdata/JNC-TJ8400-2002-025.pdf, [accessed on July 05, 2019].

Shirakawabe, T. , Wang, H. , Goto, S., Yamamoto, S., Komine, H. "Study of thermal history effect on water movement in unsaturated bentonite". Journal of Japan Society of Civil Engineers, Ser. C (Geosphere Engineering), 77(2), pp. 103-117, 2021. https://doi.org/10.2208/jscejge.77.2_103

Sridharan, A., Rao, A., Sivapullaiah, P. "Swelling Pressure of Clays", Geotechnical Testing Journal, 9 (1), pp. 24–33, 1986. https://doi.org/10.1520/GTJ10608J

Suzuki, H., Fujita, T. "Swelling characteristics of buffer material", Japan Nuclear Cycle Development Institute, Japan, JNC TN8400 99-38 (in Japanese), 1999. Available at: https://jopss.jaea.go.jp/pdfdata/JNC-TN8400-99-038.pdf, accessed on Sep. 24, 2022.

Suzuki, H., Shibata, M., Yamagata, J., Hirose, I., Terakado, K. "Mechanical experiments of buffer material", Japan Nuclear Cycle Development Institute, Japan, PNC-TN8410 92-057 (in Japanese), 1992. Available at: https://jopss.jaea.go.jp/pdfdata/PNC-TN8410-92-057.pdf, accessed on Sep. 24, 2022.

Tanai, K., Kikuchi, H., Nakamura, K., Tanaka, Y., Hironaga, M. "Survey on Current Status of Laboratory Test Method and Experimental Consideration for Establishing Standardized Procedure of Material Containing Bentonite", Report of Collaboration Research between JAEA and CRIEPI, Japan, JAEA-Research 2010-025 (in Japanese), 2010. Available at: https://doi.org/10.11484/jaea-research-2010-025, accessed on Sep. 24, 2022.

Tang, A. M., Cui, Y. J. "Modelling the thermomechanical volume change behaviour of compacted expansive clays", Géotechnique, 59(3), pp. 185–195, 2009. https://doi.org/10.1680/geot.2009.59.3.185

Villar, M. V., Lloret, A. "Influence of dry density and water content on the swelling of a compacted bentonite". Applied Clay Science, 39(1–2), pp. 38–49, 2008. https://doi.org/10.1016/j.clay.2007.04.007

Wang, H., Shirakawabe, T., Komine, H., Ito, D., Gotoh, T., Ichikawa, Y., Chen, Q. "Movement of water in compacted bentonite and its relation with swelling pressure", Canadian Geotechnical Journal, 57(6), pp. 921-932, 2020. https://doi.org/10.1139/cgj-2019-0219

Wang, H., Komine, H., Gotoh, T. "A swelling pressure cell for X-ray diffraction test", Geotechnique, 72 (8), pp. 675-686, 2022a. https://doi.org/10.1680/jgeot.20.00005

Wang, H., Ruan, K., Harasaki, S., Komine, H. "Effects of specimen thickness on apparent swelling pressure evolution of compacted bentonite", Soils and Foundations, 62(1), 101099, 2022b. https://doi.org/10.1016/j.sandf.2021.101099

Wang, H., Ito, D., Shirakawabe, T., Ruan, K., Komine, H. "On swelling behaviors of a bentonite under different water contents", Geotechnique, online first, 2022c. https://doi.org/10.1680/jgeot.21.00312

Watanabe, Y., Yokoyama, S. "Self-sealing behavior of compacted bentonite–sand mixtures containing technological voids", Geomechanics for Energy and the Environment, 25, 100213, 2021. https://doi.org/10.1016/j.gete.2020.100213