Graduate School of Creative Science and Engineering
Waseda University

博士論文審査報告書
Doctoral Dissertation Review Report

論　文　題　目
Dissertation Title

Evaluation of underground environment effects on hydraulic properties and swelling pressure of bentonites in HLW disposal

高レベル放射性廃棄物処分におけるベントナイトの浸透特性と膨潤圧に及ぼす地下環境の影響評価

申　請　者
(Applicant Name)
Kunlin RUAN
阮　坤林

Department of Civil and Environmental Engineering　Research on Geotechnical Engineering

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This thesis focuses on the swelling pressure and hydraulic properties (i.e., hydraulic conductivity and water diffusivity) of bentonites, which have been selected as the candidate of buffer material in the deep geological disposal project for dealing with the high level radioactive waste. In this thesis, the disposal underground environment effects on swelling pressure and hydraulic properties of bentonites are taken into consideration. A new multi-ring is applied to the swelling pressure device for obtaining swelling pressure, hydraulic properties and X-ray diffraction (XRD) profiles of bentonites during saturation simultaneously. The underground environment effects on swelling pressure and hydraulic properties are discussed on these results. This thesis aims to contribute to the understanding of swelling pressure and hydraulic properties from a new dual pore system, which can be quantified by the basal spacing from XRD tests. Based on the experimental observations, the suggestions for the application of bentonites to the deep geological project are proposed.

The thesis has been undergone the department preliminary screening on 23rd June 2022 and has been revised on 18th July. The revised thesis has been inspected from 19th July to 26th July 2022. The thesis has been accepted by the department meeting on 28th July 2022 and the Graduate School of Creative Science and Engineering Steering Committee on 29th September 2022. The doctoral dissertation defense has been held on 15th November 2022. The research ethics course has been taken by the applicant before the acceptance and the check on the doctoral dissertation in terms of plagiarism by electronic tools has been finished.

The thesis is organized into eleven chapters. The contents of the chapters and their evaluations are as follows:

Chapter 1 briefly introduces the background of the issue addressed in this thesis, as well as a review of previous studies. The objective, organization and innovation of the thesis are given.

Chapter 2 illustrates the materials used in this thesis. The physical parameters of the materials and their testing methods are interpreted.

Chapter 3 details the new multi-ring and the development of the swelling pressure device. The experimental methodology and the testing procedure are explained.

Chapter 4 proposes an easy equation for calculating water diffusivity with a new parameter χ and water distribution during saturation. Furthermore, hydraulic conductivity is achieved from water diffusivity. This is of great significance in engineering as the hydraulic conductivity during saturation of bentonite can be quickly obtained. A convex shape for hydraulic conductivity under wetting and a swelling pressure evolution curve with peaks and valleys are observed. A new dual pore system is proposed as: (1) micro pore (inter-layer pores), and (2) macro pore (pores exclude inter-layer pores). The micro pore is considered to be the main factor controlling the swelling pressure, while the macro pore is assumed to be the paths for water to flow. Hydraulic conductivity and swelling pressure developing patterns are interpreted reasonably well with the new dual pore system.

Chapter 5 assesses the dry density effect on swelling pressure and hydraulic conductivity during saturation of bentonites. It is found that swelling pressure increase with dry density and hydraulic conductivity decreases as dry density rises. The relations between basal spacings and swelling pressures are explained from the aspect of fabric unit evolutions during saturation. The macro pore is compressed with the dry density increases, so hydraulic conductivity is decreased as the result.

Chapter 6 evaluates the Na^+ concentration effect on swelling pressure and water diffusivity during saturation by XRD. The testing results show that with the increase of concentration, swelling pressure decreases, and water diffusivity increases. The reduction of swelling pressure is expected to be attributed to the competition between the rise of inter-layer swelling from smaller basal spacing and the negative effect from the increase of osmotic suction.

Chapter 7 indicates the movements of water and Na^+ in compacted bentonite with XRD. By combining degree of saturation and percent of salt intrusion together, it is discovered that Na^+ moves much slower than water during saturation. According to the XRD investigation, it is considered that the micro pore is filled with the water at the initial stage of saturation and then gives Na^+ a moving path.

Chapter 8 shows the salt solution effects on swelling pressure and water diffusivity of bentonites. The salt types of saturation liquid have opposite impact on swelling pressure and water diffusivity of different cations bentonites. These phenomena originate from the competition between cation exchange, the change of basal spacing and the variation of osmotic suction.

Chapter 9 details the temperature effect on swelling pressure and water diffusivity of bentonites. The effect of temperature on swelling pressures of different grain sizes is found to be inconsistent. Swelling pressure of powder bentonite is found to increase as temperature rises, but it decreases in higher temperature conditions for granular bentonite. Temperature effect on swelling pressures for different grain size bentonites are closely related to the competition of inter-layer swellings, inter-particle swellings, free water expansion and thermal expansion of minerals. In case of water diffusivity, the results indicate that, regardless of the grain size, water diffusivity increases as the temperature rises. This phenomenon can be explained from the increase of macro pore as temperature grows.

Chapter 10 reveals the initial water content and specimen preparation method effects on swelling pressures with another separate series of XRD experiments. The initial water contents of bentonite are achieved by spraying water and controlling relative humidity. The results of XRD show that the effect of initial water content on basal spacing of saturated specimen is limited, which explains to some extent that the saturated microstructure of bentonite is not affected by initial water content, thereby inducing similar equilibrium swelling pressure. The complementarity of inter-layer swellings and inter-particle swellings brings a limited effect of specimen preparation methods on equilibrium swelling pressure.

Chapter 11 concludes the experimental observations and the applications of the findings in practical field. The limitations and recommendations of this study are also addressed, along with future directions for research.

This dissertation investigates the underground environment effects on swelling pressure and hydraulic properties of bentonites in high level radioactive disposal by new experimental devices and testing methodology. The proposed equations can quickly and easily obtain hydraulic properties during saturation, which is of great significance in the practical engineering. Academically, the new dual pore system explains the underground environment effects on swelling pressures and hydraulic properties during saturation reasonably well.

The referees recognize that this dissertation devotes the development of geotechnical engineering and geoenvironmental engineering and meets the given requirements of a doctorate (Doctor of Engineering).

December 2022

Principal Referee:

Prof. of Waseda Univ. Dr. of Eng. (Waseda University) Hideo Komine

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Sub Referees:

Prof. of Waseda Univ. Dr. of Eng. (Waseda University) Hirokazu Akagi

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Prof. of Waseda Univ. Dr. of Eng. (Waseda University) Atsushi Yamazaki

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Prof. of Waseda Univ. Dr. of Eng. (Tohoku University) Mitsuyoshi Akiyama

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Assoc. Prof. of Waseda Univ Dr. of Eng. (The University of Tokyo) Hailong Wang

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