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Thermo-Hydro-Mechanical Column Test on Compacted Bentonite Buffer: Experimental Setup Development and Preliminary Results

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Abstract. Compacted smectite clays/bentonites are being used as buffer material in deep geological repository (DGR) considered as suitable solution for isolating high level radioactive waste. In the DGR, the compacted smectite clay undergoes coupled thermal, hydraulic and mechanical (THM) loading conditions. This paper presents a state-of-the art experimental setup developed to study THM behavior of buffer material and results obtained from THM experiment. The equipment was designed at IIT Patna and commissioned by HEICO Ltd. Various sensors were attached to cylindrical soil sample (15×10 cm) to find out change in various properties such as soil moisture tension, temperature and swelling pressure at pre-selected locations with time. All these sensors were connected to the data logger for monitoring the results. Thermal and thermo-hydraulic tests were conducted in two stages. In the first stage, temperature was applied with gradual increment up to 90 °C from bottom of soil sample. In the second stage, after attaining the uniform temperature at particular depths, water was supplied from top of soil sample through the top of sample. In the first stage of the experiment, test results showed that the temperature at various locations equilibrated within about 14 hours, thereafter, there was no significant variation in temperature was noted. Swelling pressure showed an increasing trend during the coupled thermal and hydraulic loadings. In accordance with experimental findings, THM behaviour of smectite clays, which serve as a buffer material in deep geological repositories,can be assessed using reliable data from a newly developed column device.

Keywords: Smectite clay, column test setup, geological repository, temperature, swelling pressure

1 Introduction

The study on coupled THM behaviour of smectite clays/clay-sand mixture in deep geological repository system is gaining much importance, and researchers are more interested in understanding the transfer of heat, water, salts, as well as development of swell- ing pressure due to coupled thermal and hydraulic loading. Smectite/bentonite clays possess superior properties such as high swelling, cation exchange capacity, and self-sealing [1]. Due to these properties, smectite clays are being used as a buffer or engineered backfill materials for underground constructions in deep geological repository systems [2-4]. Hazardous radioactive wastes (HRW) generated by nuclear power plants are sealed in metal canisters before being buried in deep underground constructions in hard rocks to remain isolated. As a result of weathering or tectonic movement of the earth's crust, cracks may develop in host rocks or containers, promoting the transfer of HRW from the containers, and causing contamination of surrounding soils and groundwater. In order to prevent such failures, multi-barrier DGR system is designed.

Unsaturated compacted bentonite blocks, placed in multi-layers between the canisters and host rocks in deep repository systems are exposed to high-temperature transfer from the core of canisters and water/salt migration from the host rocks [5]. As a result, water ingress takes from host rock. Compacted bentonite acts as a barrier due to its very low hydraulic conductivity and penetrates through cracks because of its high swelling and self-sealing ability [1]. Coupled THM behaviour of buffer material had been investigated by conducting full-scale field tests or laboratory tests such as mock tests or prototypes [6-8]. A new column THM cell was designed with controlled boundary conditions (water pressure and temperature) to understand the flow of water, heat, and development of swelling pressure in unsaturated compacted clays/bentonite-sand mixture from the experience and knowledge gained by performing a series of THM tests by using a column device as described in [9-12]. The purpose of this paper is to introduce the newly developed column Thermo-Hydro-Mechanical (THM) test setup and the preliminary test results obtained by it. The THM test was conducted on smectite clay by compacting it in layers to attain uniform dry density at its natural moisture content in two stages, under constant volume conditions by applying temperature and water pressure simultaneously. During the tests, temperature and swelling pressure were measured. After dismantling, the tested soil sample is cut into circular discs for water content measurement.

2 Development of THM column test setup and its components

2.1 THM column test setup

To comprehend the THM behaviour of compacted Na-smectite clay in deep geological repositories, a new THM laboratory scale column (20×10 cm) experimental setup with sensors has been developed. The schematic of THM setup is shown in fig. 1. The column THM cell was designed to mimic the hydration of buffer material from host rock at one end and heating of buffer material by nuclear wastes at another end, simulating the conditions of the geological repository system in laboratory. The main components of the THM column setup includes a rigid hollow cylindrical cell made of stainless steel and Teflon (inside heat insulating material), a top cover plate, and a bottom base plate. The THM mould is fixed with top and bottom base plates with screws of 12 mm diameter. Additionally, a separate hydration system is designed for supply of water through controlled pressure during thermal and thermos-hydraulic tests on soil.

2.2 Bottom base plate and top cover plate

The cylindrical cell was based on a bottom plate with fixed heating coil at the center and top cover plate containing an opening for water supply. A base plate at bottom and a cover plate made of stainless steel consist of a heating system and water inlet, respectively. The electrical heater is made of heating coils fastened to bottom base plate and is used for heating the soil sample during the test. The heater's temperature is controlled by a thermocouple attached to the temperature regulator.

2.3 Cylindrical THM mould

A hollow cylindrical THM cell is made of two materials, the inner part is fabricated with Teflon covered by a stainless-steel casing at outer. Teflon is 1 cm thick, 10 cm internal diameter, and 20 cm height. The metal casing is 1 cm thick, 11 cm internal

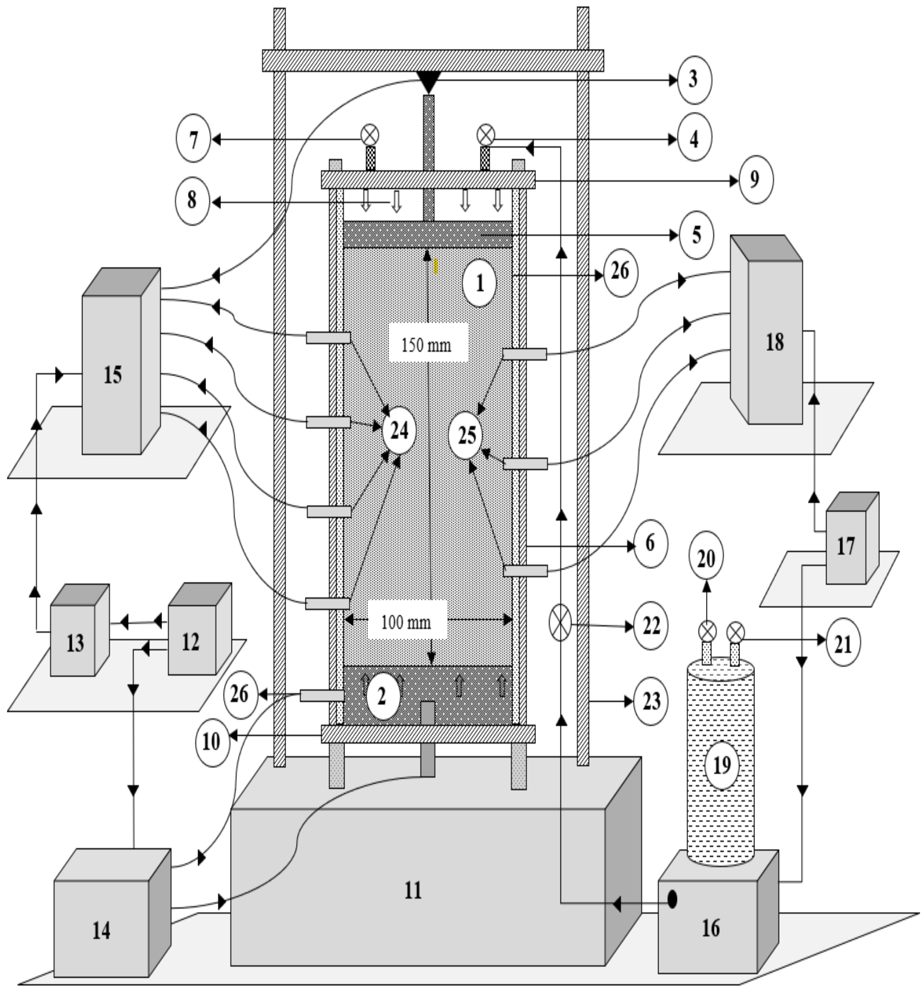

Fig. 1. Schematic of column THM test setup, compacted soil sample and position of sensors

1. Soil sample; 2. Electric heater; 3. Load cell; 4. Water inlet; 5. Porous load plunger; 6. Steel cylindrical mould; 7. Air valve; 8. Water circulation; 9. Top base plate; 10.

Bottom base plate; 11. Digital load frame; 12. Power source; 13. Voltage regulator device; 14. Temperature regulator; 15. Data logger for temperature probes and load cell; 16. Hydraulic pressure machine; 17. Power source; 18. Data logger for relative humidity; 19. Glass cylindrical mould for water storage; 20. Air valve; 21. Water valve; 22. Hydraulic pressure regulator; 23. Rigid steel frame; 24. Temperature probes (4 no's); 25. Relative humidity probes (3 no's); 26. Thermocouple (temperature regulator for heater); 27. Teflon (Heat insulating material).

diameter, and 20 cm in height to ensure rigidity and mechanical support for Teflon. Holes are pre-drilled on cylindrical mold at 7.5, 11, 14.5, and 18 cm depths for inserting the temperature sensors. During the thermal and thermo-hydraulic tests on sodium smectite clay, the soil was compacted to 15 cm in height and 10 cm in diameter. The remaining 5 cm at the top is used for placing porous steel load plunger and for water circulation.

2.4 Hydration system

De-aired and de-ionized water was injected into the soil sample by means of a hydration system. It is built with a closed glass cylindrical mould of 20-liter capacity and a motor with a steady pumping capacity of 1.1 MPa. A pressure regulator device is used to deliver the pre-determined water pressures on top of soil sample. Refer to fig.1.

3 Sensors

3.1 Temperature sensors

Total 4 no's of RTD (resistance temperature detector) temperature probes made of platinum were used for measuring the temperature of soil. RTD is a temperature sensing device that works on the principle that the resistance of a metal changes as the temperature changes. The electrical pulse that passes through the probe, generates a particular resistance with temperature change in soil. Resistance recorded by the sensing probe is transferred to the data logger for analog output. RTD sensors are covered with stainless steel for corrosion resistance and to protect from mechanical impact. The temperature probe (50×0.6 mm) has a cable with four wire connections for connecting it to the data logger. These sensors can measure a temperature range from 0 ℃ to 100 ℃ with an accuracy of ±0.5 ℃ over 12 volts power supply.

3.2 Load cell

A strain-gauge column type load cell (measuring capacity 100 kN) is used to measure the axial load/stress exerted by soil sample at top. It is fixed between a rigid frame and steel plunger to maintain constant volume for the soil sample during thermal and hydraulic loadings. Plunger attached to porous stainless-steel plate is placed over the soil sample to transfer axial load to load cell. Load cell is connected with a voltage regulator device (constant power supply of 10-12 volts) connected to the data logger for analog output.

4 THM test procedure

To study the THM behavior of unsaturated sodium smectite clay, the thermal and thermo-hydraulic test on sodium smectite clay was performed by statically compacting to a targeted dry density of 1.65 g/cc with its natural moisture content of 12 %. Soil sample with height of 15 cm and diameter of 10 cm was compacted in three layers in a cylindrical mould by using universal compression machine to achieve uniform dry density. In order to compact each layer 78 kN load was applied. Compacted soil sample was kept in vacuum desiccator for 3 days to attain uniform moisture content before commencement of THM test and the test was performed at constant volume condition in two stages [10]. Throughout the test, the surrounding environment temperature was maintained constant at 26 °C by an air conditioner. Physico-chemical properties of soil were determined by following IS code and ASTM standards. The physico-chemical properties of compacted soil sample are presented in Table 1.

In the first stage, temperature was applied by heater from bottom of soil sample with gradual increment up to 90 °C and at room temperature at top. Thermal variations along the depth of soil sample and stress generated at top due to only thermal loading were recorded by sensors. Temperature of heater was controlled by the thermocouple attached to temperature regulator device. In the second stage, de-aired water was injected by a hydraulic pressure machine from top of soil sample through top inlet. Temperature (90 °C) at bottom is maintained constant during second stage of test. Water was injected continuously with a constant pressure of 25 kPa after about15 hours from starting the test. Results were monitored from the data logger. After discarding the specimens by extruder, tested soil sample was cut into pieces for calculating water content at various depths [13].

Table 1. Physico-chemical properties of sodium smectite clay

Material characterization		Chemical properties (% by total weight)	
Clay content (%)	67	Oxygen (%)	41.25
Silt content (%)	32	Silicon (%)	25.03
Sand content (%)	1	Aluminum (%)	14.25
Liquid limit (%)	197	Ferrous (%)	8.12
Plastic limit (%)	38	Sodium (%)	7.36
Shrinkage limit (%)	11.5	Others (%)	3.99
Free swell index (%)	390	pH	7.82

5 Results and discussions

5.1 Temperature variation with depth

Temperature sensors were inserted into soil sample at pre-selected depths by drilling the compacted specimen with minimal disturbance. Initially, a seating load of 0.1 MPa was applied on load cell to have proper contact between the porous steel disc and soil sample.

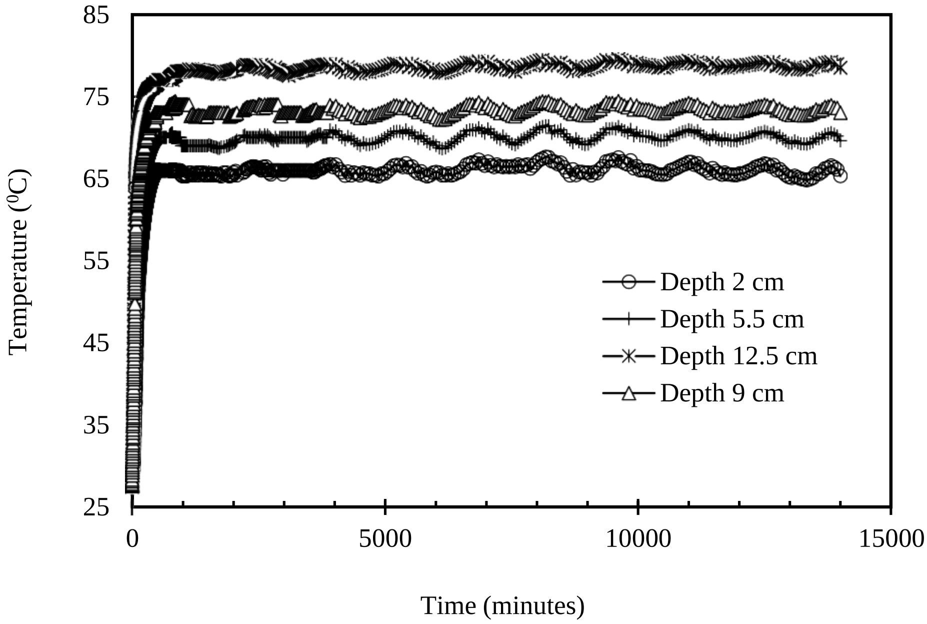

Fig. 2. Temperature profile at different locations from heater during THM experiment.

According to experimental findings in first stage of test, temperature equilibrium at specific depths was noted to reach within 14 hours from starting of test. Once thermal equilibrium was reached, no appreciable variation in temperature was noted, as illustrated in fig. 2. As the soil sample was compacted to a higher density, thermal conductivity increases and attains thermal equilibrium quickly [14,15]. Heat flux is constant at thermal stability; thus, temperature remains constant at particular depths.

During the second phase, there was a marginal decrement in temperature for a short period and increases thereafter. The decrease in temperature was due to the application of cool water (25 °C) or opening of air and water valve for water supply. As the soil sample was compacted in an unsaturated state, it absorbs water and thus increases the density and thermal conductivity. This phenomenon helped in increasing the temperature and re-attaining thermal equilibrium quickly. The variation of temperature with height of sample over the elapsed time is shown in fig. 3.

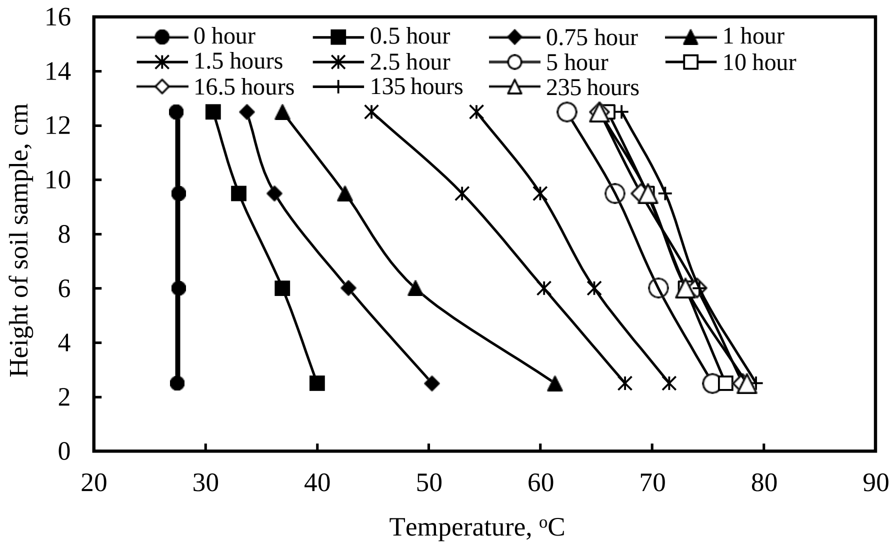

Fig. 3. Temperature profile at different time from starting the test during THM experiment.

5.2 Swelling pressure

From the fig. 4, it can be observed that there was a marginal increment in swelling pressure during the first stage of test. This increment in swelling pressure may be the combined effect of material stress and soil sample due to thermal loading. In the second phase of test, during coupled thermal and hydraulic loading, swelling pressure showed marginal decrement initially and thereafter showed an increasing trend. Initial decrease in swelling pressure might be due to the escape of heat from the vents opened for application of water or particles rearrangement. Later with absorption of water by voids present in soil filled with water, swelling pressure showed an increasing trend. Akesson et al. [6], Wang et al. [16] concluded that the development of swelling pressure upon external hydration is significantly influenced by pore structures in smectite rich clays, includes both macro and micro pore.

When water is injected to soil sample, water molecules penetrate through the open voids (macropores), and interact with the electrical double layers representing the osmotic potential and then move into the interlamellar space (micropores), representing matric potential [17]. This helps in increasing the thickness of double diffuse layer and expansion of microstructures. As the test was conducted in a confined THM cell with constant volume conditions, swelling pressure induced at top due to the ingress of water in free voids and interlamellar pores of smectite clays.

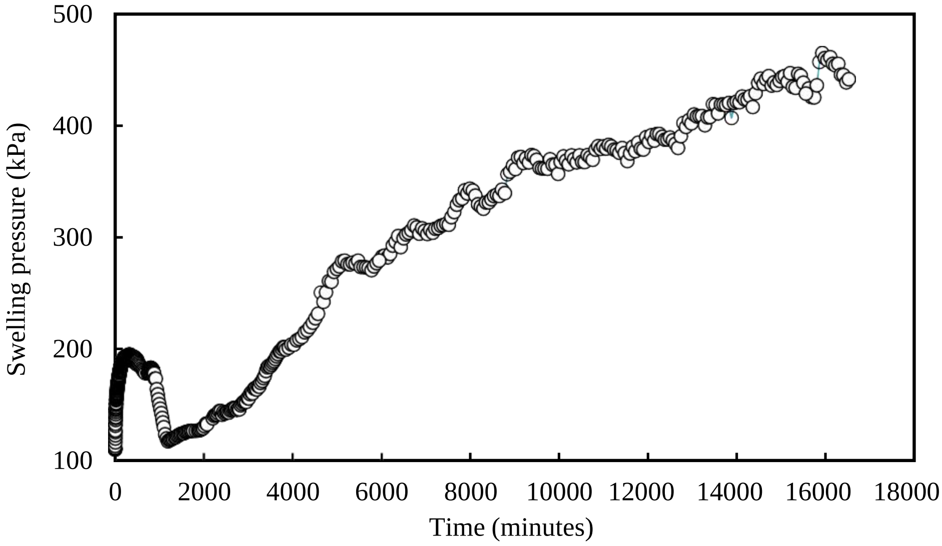

Fig. 4. Swelling pressure measured at the top end of the specimen during THM experiment.

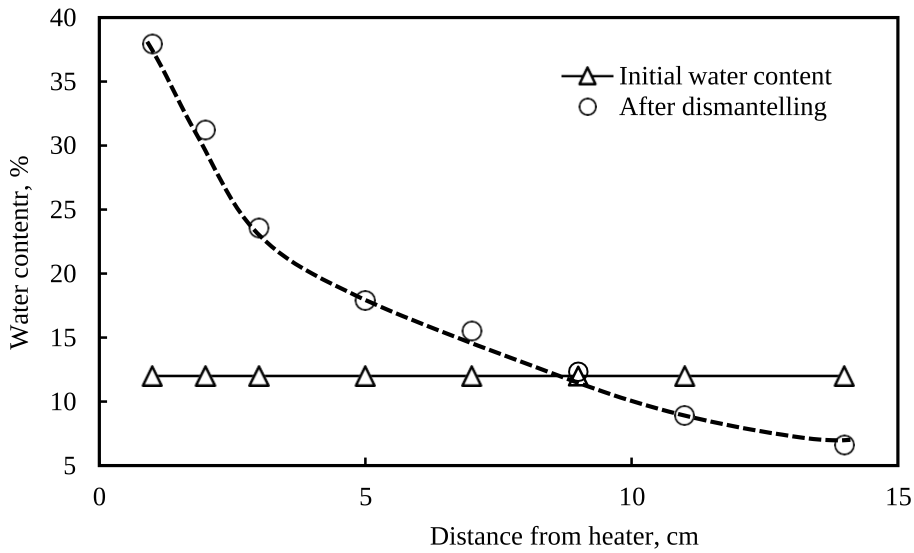

Fig. 4. Water content at different depths after dismantling sample.

After dismantling the test, tested soil sample was extracted by extruder with minimal disturbance. The extracted soil sample was cut in circular discs, packed in a polyethene bags for water content. Water content profile with depth of soil sample is illustrated in fig. 5.

Jadda and Bag [18] concluded that the free water expelled due to breakage of diffused double layer does exert any pressure on surrounding particles. Thus, at the end of test, swelling pressure showed a decreasing value. Moreover, expansion of microstructures due to water absorption causes the volumetric reduction of macro pores, reducing available space for flow of water and vapor through the soil; thus, swelling pressure showed a decreasing trend at end.

6 Conclusions

A new THM column cell along with sensors were designed at IIT Patna and commissioned in a factory. The cell can be used to apply thermal and hydraulic loading from bottom and top of soil samples simultaneously to mimic the environment of deep geological repository. The main components of THM cell along with different types of sensors are presented in this paper. A series of trail tests were conducted on bentonite powder by compacting in layers at pre-selected dry density with its natural moisture content to calibrate the device and find leakage of THM device along with sensors. It was found that the column test device can be used for studying THM behavior of compacted smectite clays.

The thermal and thermo-hydraulic test was conducted on compacted smectite clay in two stages. In the first stage of the test, thermal loading caused a minimal increase in swelling pressure and thermal equilibrium at specific depths reached faster. The moisture migrated from heater end moved toward cold end and condensed resulting in swelling pressure was developed. However, the amount of swelling pressure developed was not higher due to limited quantity of water availability.

As soon as water supplied in the second stage of test, there was a marginal reduction in temperature over the depths due to lower temperature of water supplied. In the course of coupled thermal and hydraulic loading, swelling pressure was noted to increase continuously over the elapsed time due supply of water from top of the sample. The developed THM cell provided the good results on compacted soil sample representing the conditions of deep geological repository.

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