A novel thermo-hydro-mechanical column-device for testing compacted expansive soils

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ABSTRACT: In the frame of phenomenological investigations for expansive soil as a key component of multilayer-engineered barrier system at nuclear waste repository, an innovative column type-testing device is designed and implemented at Ruhr-Universität Bochum, Germany. The instrumentation and measurement methods facilitate the precise control over the applied thermal and thermo-hydraulic gradient with transient measurements of key state parameters, such as temperature, suction, water content and total stress in both radial and axial direction. This paper presents the technical overview of design philosophy, constructional features, measurement methods and instrumentation for newly designed column-testing device. The temperature induced artifacts in system response and measurement methods under non-isothermal testing conditions are discussed in detail. The calibration studies showed that an increase in the applied temperature affects the water content measurement using the Time Domain Reflectometry technique and the total pressure measurement using pressure transduces in embedded position. Additionally, system compliance tests are suggested to quantify the temperature-induced anomalies in system response.

1 INTRODUCTION

At the deep geological repository for the disposal of high-level radioactive waste at several hundred meters below the surface, compacted buffer blocks are subjected to radioactive decay heat from canister-end. Whereas initially, unsaturated blocks may subject to hydration from the host-rock. Depending upon the available volume constraint, the applied thermal and hydraulic gradient result into volumetric changes in terms of shrinkage or swelling. The physical modeling of buffer emplacement at repository using small-scale experimental approach can be portrayed by imitating the in situ thermal and hydraulic gradient across the sample with some fundamental design requirements such as

- The device must fulfill the conservation laws. Hence, a closed system should be designed with air/water tight constructional joints.
- The device must imitate the field emplacement conditions. Hence, it should maintain the constant volume testing condition and one-dimensional heat flow and under applied thermal and hydraulic gradient.
- The device should able to measure the transient evolution of key state parameters in a precise and efficient manner under non-isothermal testing conditions.

Considering the reported literature on the prototype buffer heating experiment, the resulting swelling pressure is measured at the opposite end of the heating face, whereas, the transient profile of radial swelling pressure, soil total suction, and water content were not reported. Recently Schanz et al. (2013) designed a column-type testing device to apply the thermal and hydraulic gradient along the length of the tested sample. The device was equipped with water content, temperature, relative humidity and the resulting swelling pressure.

Recently, with certain advancements in the design, instrumentations, and material, an innovative column type-testing device is designed and implemented at Ruhr-Universität Bochum, Germany. The instrumentation and measurement methods facilitate the precise control over the applied thermal and thermo-hydraulic gradient with transient measurements of key state parameters, such as temperature, suction, water content and total stress in both radial and axial direction. In this paper, the temperature induced artifacts in system response and measurement methods under non-isothermal testing conditions are discussed in detail. System compliance tests are suggested to quantify the temperature-induced anomalies in system response and measurement methods. Additionally, the temperature induced shift in the sensor measurements is discussed with the relevant calibration procedure.

2 MATERIALS AND METHODS

2.1 *Development of column-testing device*

The newly designed column-testing device has four main assembling components namely, top /bottom boundary control units, Polyvinylidene fluoride (PVDF) sample rings, monitoring sensors/instrumentation, and confining cell with the rigid frame structure. The schematic diagram and pictorial view of assembled column-testing device are shown in Fig. 1.

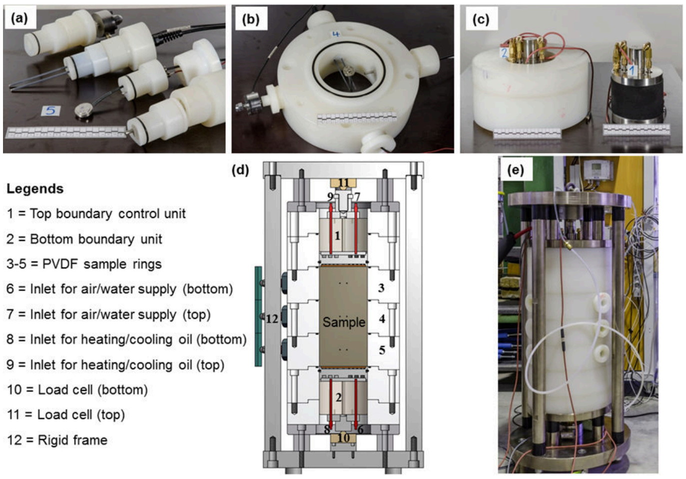


Figure 1. Technical and constructional features of newly designed column-testing device, (a) sensors, (b) PVDF sample ring with sensors, (c) top/bottom boundary control unit (d) schematic view of assembled column-testing device, and (e) pictorial view of the column-testing device.

2.1.1 *Top/bottom boundary control units*

The top/bottom boundary control units are designed to apply the repository relevant thermal/hydraulic gradient at sample extremities. These units are identical in the design and encapsulated within PVDF rings having 10cm thickness and thermal conductivity as low as 0.13 W/mK. To apply the thermal gradient along the sample height with a precision of 0.1°C, two thermostats are deployed separately for heating (Huber CC-202C) and cooling (Huber Ministat 230). For hydration, water is supplied externally to sintered stainless-steel plates having contact with soil sample at both the ends. The integrated design of temperature control unit with sintered stainless-steel plate ensures the thermal equilibrium between the supplied water and targeted temperature. During the hydration under constant volume condition, the sample exerts swelling pressure at both the ends and resulting total stress is transferred to load cells by these boundary control units. During the validation and compliance tests, it was observed that the inter-facial friction affects the load transfer mechanism due to the volumetric thermal expansion of top/bottom boundary control units. Later, the volumetric thermal expansion of top and bottom boundary control units were measured and corresponding changes were made in the design to diminish the effect of temperature dependent interfacial friction on load transfer mechanism.

2.1.2 *PVDF sample rings*

In newly designed column-testing device, the majority of assembling components are made of PVDF. Total 07 identical PVDF rings having 10cm thickness are used. Out of total 07 PVDF rings, 04 rings are used for encapsulating the top/bottom boundary control units. Whereas remaining 03 rings with 15cm inner diameter and 10cm height are used for compacted soil blocks. Hence the overall size of the compacted soil sample is 15cm diameter and 30cm height after assembling. The provision of peripheral O-ring connections with PVDF tightening screws ensures the air/water tight joint between two consecutive rings with adequate thermal isolation. During the assembling process, these 03-PVDF sample rings are installed over the bottom boundary control unit one after another using O-rings and PVDF tightening screws. For installing sensors, each PVDF sample ring has four installation points at the same level (5cm). Hence, the existing column-testing device has three measurement sections along sample height i.e., at 5cm, 15cm and at 25cm after assembling as a single unit. The respective sensors are installed with specially designed PVDF adapter to minimize the heat loss and any possible disturbance to sensor's electronics.

2.1.3 *Monitoring sensors and instrumentations*

The existing column-type device is instrumented to monitor the spatial and temporal distribution of temperature, relative humidity, water content and swelling pressure at three sections along the length of the sample (Fig. 2a). The technical specifications and other relevant information about the existing sensors and instrumentations can be found in Table 1.

Table 1. Technical specifications of sensors and instrumentation for newly designed column-testing device.

Parameter	Nos	Sensor	Measurement range
Temperature	08	Pt-100	-40 to 200°C
Relative humidity	03	Vaisala HMT337	0-100%RH, 0-80°C
Water content	03	IMKO PICO-32	0-100% at 0-60°C
Radial total stress	03	OMEGA (LCM203)	5KN
Axial total stress	02	OMEGA (LCM402)	10KN
	02	KYOWA-BEC 1MPa	1MPa at 0-60°C
Thermostats	02	Huber Ministat 230 (for cooling) and CC-202 for heating	Cooling up to 5-35°C and heating upto 20 to 95°C
Data acquisition	01	Graphtech-820	20 measurement channels

2.1.4 *Stainless steel confining cell and rigid frame*

The newly designed column-testing device has an outer SS confining cell and rigid frame to ensure the constant volume test conditions. The outer jacket is designed to restrain the possible volumetric thermal strains of PVDF sample rings at elevated temperature. The outer confining cell has three PT100 sensors to monitor the room temperature. The investigations pertaining to functionality check for assembled column-testing device are discussed in next section.

3 SYSTEM COMPLIANCE TESTS

Prior to core experimental investigations, system compliance tests were conducted as a functionality check for different assembling components of existing column-testing device. The main objective of system compliance tests was to validate the design philosophy against the above-mentioned prerequisites and to quantify possible artifacts under applied thermal and hydraulic gradient.

3.1 *Compliance test for air/water tight joints*

To check for air/water tight construction joints, the entire column was assembled as a single unit with a 30cm long wooden dummy between top and bottom boundary control units to provide mechanical stability. During the installation of the the test setup, the sensor dummies were placed at their respective positions in PVDF sample rings. As per the testing procedure, initially, the cell was subjected to two cycles of loading unloading under 0.5 MPa compressed air pressure. During the loading phase, the applied pressure was kept constant for one hour and the top and bottom load cell response was monitored. In the second stage, the temperature at the top was raised up to 80°C, while the temperature at the bottom was kept constant at 20°C for 24 hours. Once the thermal equilibrium achieved, the column was subjected to a single cycle of loading unloading with 0.5 MPa compressed air pressure.

The schematic diagram of the test setup is shown in Fig. 2. The test result is shown in Fig. 3. At room temperature, there was no dissipation of applied air pressure, which indicates that the joints are airtight and the top/bottom load cell transfer the applied air pressure to load cells. During the constant heating from the top at 80°C, the vertical load cells measure the thermal stresses induced by the volumetric thermal expansion of different components under volume-constrained condition. Later, the applied stress due to the volumetric thermal expansion of column-testing device assembled with a wooden dummy, steel dummy, dry sand and saturated sand were compared.

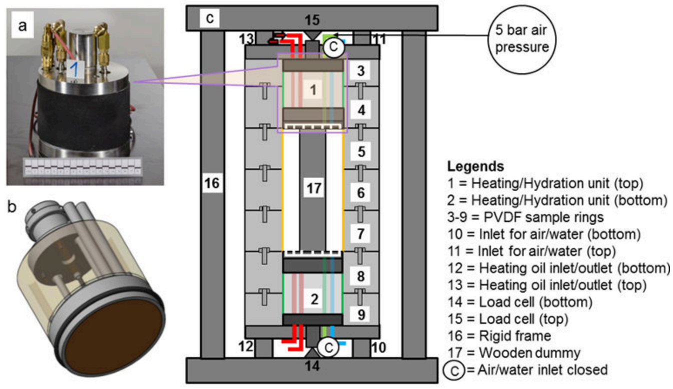


Figure 2. Schematic diagram of test setup for air/water tight construction joints, (a) top/bottom boundary control unit, (b) schematic view of top/bottom boundary control unit, and (c) test set up to validate the air/water tight joints.

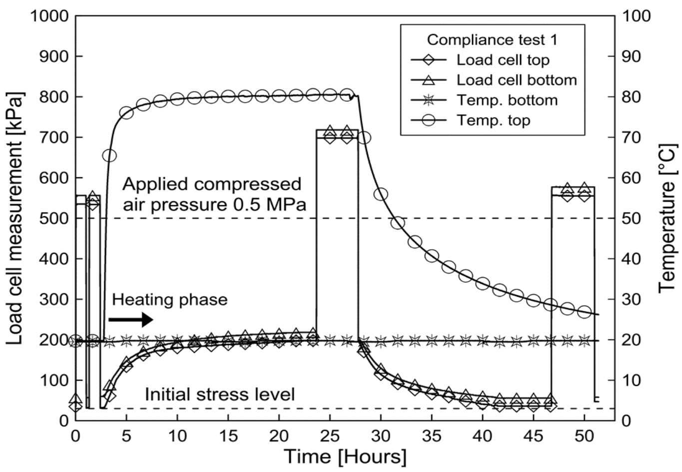


Figure 3. Test results for air/water tight joints under 0.5 MPa compressed air pressure.

3.2 *Compliance test for volumetric thermal expansion*

A test was conducted to quantify the volumetric thermal expansion of existing column-testing device. The schematic diagram of test set up is shown in Fig. 4. The device was assembled with a cylindrical SS L316 dummy (length 30cm and diameter 10cm). The dummy was placed between the top and bottom boundary control units for mechanical stability. In next step, the annular gap between PVDF sample rings and steel dummy was filled with water from the bottom end. A burette was attached at the top end and the water-level was observed for more than 48 hours to ensure zero occluded air bubbles condition inside the cell. Once water level became constant, the burette was detached from the top and two parallel-burettes were connected to the bottom end. Thereafter, the column was heated from top-end at 80°C and the temperature at bottom-end was kept constant at 20°C. During the heating phase, the water levels in the parallel burette system were recorded at every 5 minutes interval during the working hours of laboratory. The thermal gradient was applied until the water level in the parallel-burette system reaches a stable value. The test results are shown in Fig. 5.

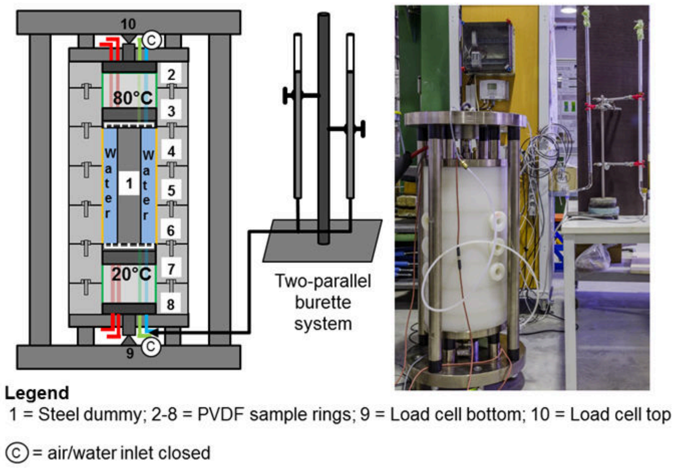


Figure 4. Schematic diagram of test setup for quantifying the volumetric thermal expansion of newly designed column-testing device.

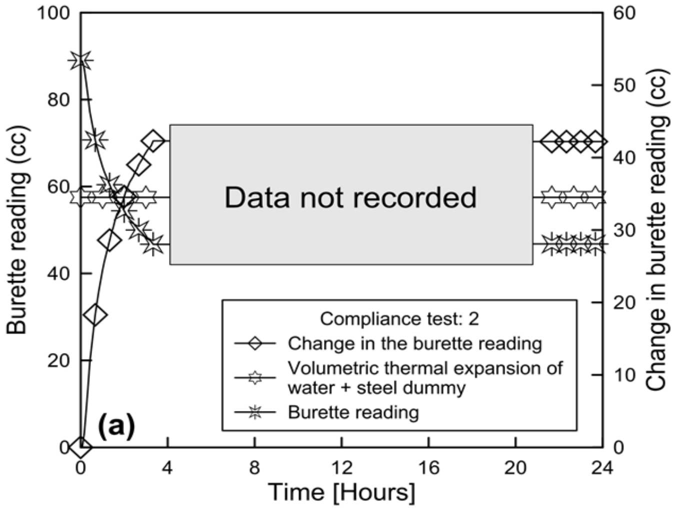


Figure 5. Test results for quantifying the volumetric thermal expansion of column.

During the heating-phase, the water level in the parallel-burette system initially increases due to volumetric thermal expansions of water/steel dummy, which expels the water from the annular gap. Whereas the volumetric thermal expansion of various assembling components accommodates water inside the cell and decreases the water level gradually. After 48 hours, the water level attains a constant value under above-mentioned competing effects. Initially, during the heating, the temperature of the water inside the column increases from room temperature to an average value of 50°C (top 80°C and bottom 20°C). At this stage, the volumetric thermal expansion of the cell can be determined by the following relationship,

$$\Delta X^{b} = \Delta V_{W}^{T} + \Delta V_{ss}^{T} - \Delta V_{Col}^{T} \tag{1}$$

Where, ΔX^{b} = change in the water level in parallel burette system; ΔV_{W}^{T} = volumetric thermal expansion of water; ΔV_{ss}^{T} = volumetric thermal expansion of steel dummy, and ΔV_{W}^{T} = volumetric thermal expansion of column.

As shown in Table 2, the cumulative volumetric thermal expansion of column-testing device under applied thermal gradient is 28.59 cm^3, which is approximately 0.53% of total available volume for a soil sample. Although the reported volumetric thermal expansion is quite low, an outer confining cell made by SS-L316 steel is designed to ensure the isochoric testing condition during the hydration process.

Table 2. Calculation for volumetric thermal expansion of newly designed column-testing device.

Material	Volumetric thermal expansion coefficient α, (1/°C)	Total volume at room temperature V, cm^3	Change in total volume ΔV^T, cm^3
Steel--dummy	4.80×10^{-5}	2850.99	6.84
Water	5.22×10^{-4}	2450.44	63.95
Test setup	-	-	42.2
Column internal volume	-	5301.4	28.59

3.3 *Compliance test for relative humidity chambers*

In existing column-testing device, the VAISALA HMT 337 sensors are installed in a closed-chamber made by PVDF, which allows the vapour transfer between soil pores and the small-space inside the chamber through a sintered opening (Fig. 6b and c). A perfect vapour and thermal equilibrium between soil pores and the available space in closed-chamber is the prerequisite for measuring the RH with the closed-chamber concept. In this regard, the volume of closed-chamber is kept as small as possible and RH sensors are selected with a heating option with a separate probe for measuring the relative humidity and temperature. The heating option prevents the condensation on the sensor at higher relative humidity levels (>95%). With the accurate temperature measurement, the ambient dew point can be calculated for higher relative humidity environment. The measured ambient temperature with separate Pt100 probe provides the compensation for calculating relative humidity and other humidity parameters. Hence, the additional Pt100 sensor was inserted into the compacted soil sample to measure the precise soil temperature.

The functionality of RH closed-chambers is verified under non-isothermal testing conditions. The schematic diagram of a test set up is shown in Fig 6a. Initially, the column was assembled with a wooden dummy (length 30 cm and diameter 8 cm) between the top and bottom boundary control units. The temperature at the top boundary control unit was raised up to 80°C, whereas the bottom-end was kept constant at 20°C for 48 hours. In the second stage, the heating was stopped at the top-end. The response of the RH sensors installed at three sections is shown in Fig. 7.

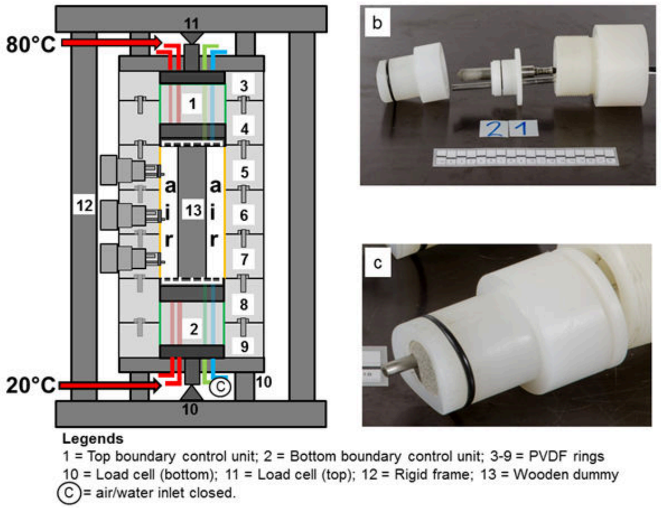


Figure 6. Schematic diagram of test setup for validating the functionality of relative humidity chambers, (a) test setup, (b) relative humidity measurement with the closed-chamber concept, and (c) closed-chamber with the extended Pt100 sensor.

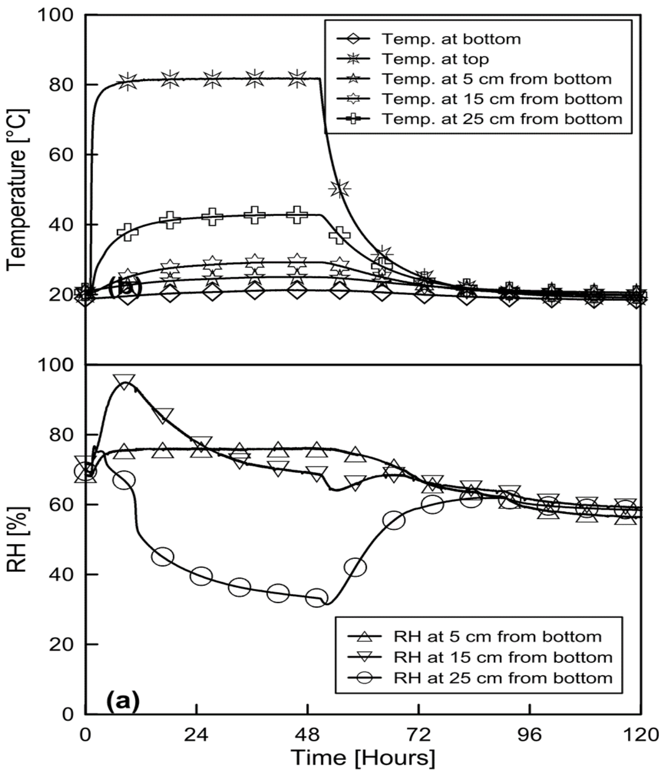
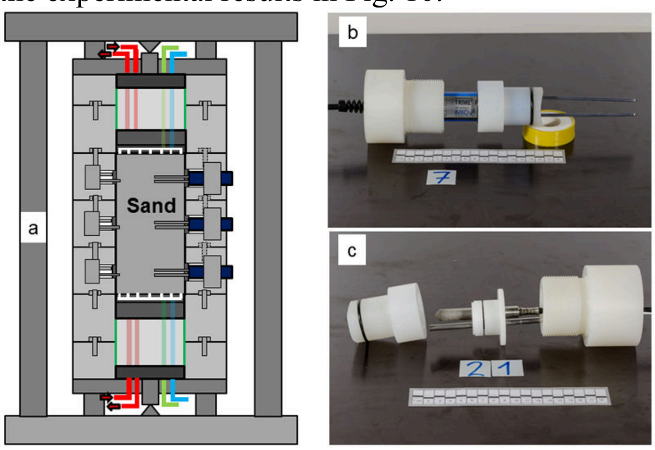


Figure 7. Test results for compliance test 3, (a) transient profile of RH values along the sample height, and (b) temperature profile at three different sections along the height of the sample.

During the heating-phase, RH value close to heating-end increases up to 77% within first 2 hours and later decreases continuously with increasing temperature. This initial rise in RH value close to heating-end is due to temperature induced vapour migration. Later, RH value decrease under the influence of elevated temperature, Hence, after attaining a peak value (77%), relative humidity continuously decrease up to 30%. The RH sensor located at 15cm shows similar trend with a prolonged effect of temperature induced vapour migration, where the relative humidity increases gradually up to 95% within 8 hours and then decreases continuously with increasing temperature. The sensor located near the bottom end shows a continuous increase in relative humidity value during the entire heating phase. Which indicates the insignificant effect of elevated temperature on saturated vapour pressure. During cooling phase, the relative humidity values at top section increase continuously with time. Whereas at the middle section, the relative humidity first increases and then decreases. The sensor located near the bottom end shows a continuous decrease in relative humidity with time.

3.4 *Compliance test with fine-sand*

A test was performed with fine sand to validate the one-dimensional heat flow condition and to evaluate the measurement quality of TDR sensors and relative humidity sensors under transient hydration process. The schematic diagram of test setup is shown in Fig. 8. Initially, the assembled column is filled with oven dried fine sand. The thermal gradient was applied at the sample extremities by raising the temperature at the top to 80°C and by maintaining 20°C at the bottom. In the hydration phase, the sand-column was hydrated from the bottom at room temperature under capillary action. The complete saturation of sand column was achieved in three stages. After getting the full saturation, the sand column was heated from the top-end at 80°C and the temperature at bottom end was kept at 20°C. The thermal gradient at two extreme ends was applied for more than 75 hours. The test results for hydration phase is shown in Fig. 9. The applied ramp type hydraulic loading features are captured quite well by both TDR sensors and RH sensors. Later, the temperature distribution at steady state conditions was compared with the analytical solution for one-dimensional heat flow through dry and saturated sand column is implemented in finite element code LAGAMINE developed by University of Liege using the thermal conductivity of dry fine sand as 0.15 W/(mK) and saturated fine sand as 2.75 W/(mK). The simulation results are compared with the experimental results in Fig. 10.



Dry sand test Case 1 (Heating): $T_{(top)}$ 80°C and $T_{(bottom)}$ 20°C
Dry sand test case 2 (Cooling): $T_{(top)}$ 20°C and $T_{(bottom)}$ 20°C

Figure 8. Schematic diagram of test setup with dry sand (a) test setup with RH chambers and TDRs, (b) installation of TDR with PVDF sensors adapter, and (c) RH chamber.

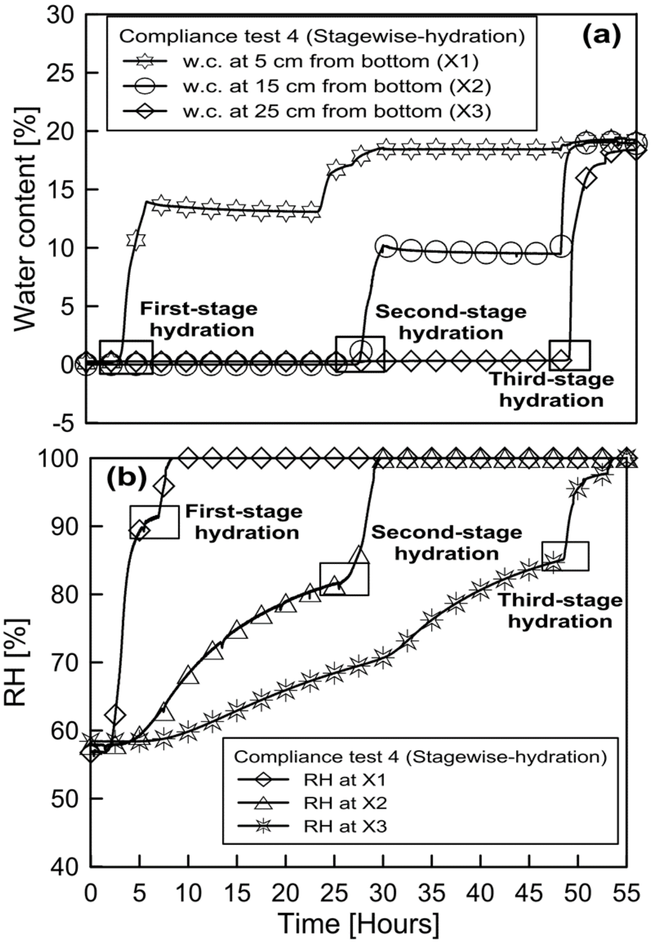


Figure 9. Test results for hydration phase of fine sand, (a) transient profile of relative humidity at three different sections along the height of sample, and (b) temperature profile at three different sections along the height of the sample.

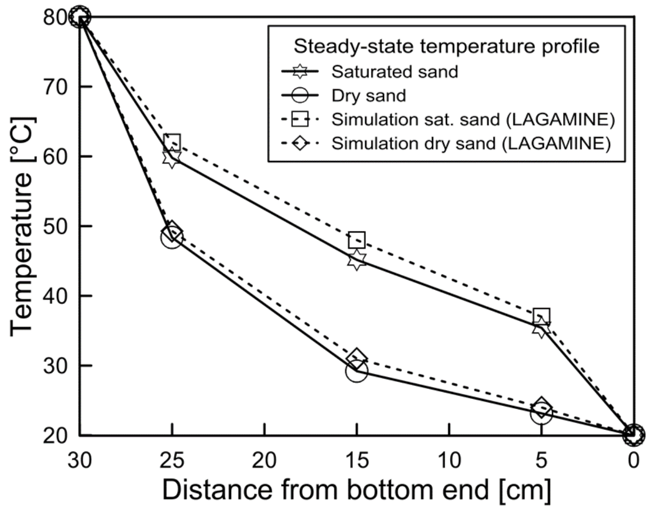


Figure 10. Test results for one-dimensional heat flow condition with dry and fully saturated sand.

4 TEST RESULTS AND DISCUSSION

To ensure the reliability of experimental data and correct interpretation, system compliance tests were performed. System compliance tests were conducted to validate the design philosophy and to quantify temperature-induced anomalies in the system response.

- In compliance test for air/water tight construction joints, the assembled column did not show any kind of leakage under applied 0.5 MPa compressed air pressure at room temperature and also at elevated temperature (top-end 80°C and bottom-end 20°C).
- In compliance test 2, the volumetric thermal expansion of column was quantified as 28.59 cm^3. Which is around 0.53% of total volume. Hence, an outer confining cell made by stainless steel was designed to ensure the constant volume testing condition.
- In compliance test for relative humidity chambers, trial tests were carried out with various arrangements to measure RH and temperature. The appropriate choice of RH sensor and isolation from outside environment significantly affect the measurements. The closed-chamber concept to measure the RH was validated under non-isothermal testing conditions.
- In validation test for 1D heat flow condition with dry sand and saturated sand, the test results agree well with the analytical solution for 1D heat flow. During the ramp type hydraulic loading to hydrate the sand-column in stage wise manner, the RH sensors and TDR probes efficiently capture the characteristics features.

5 CONCLUSIONS

The newly designed column-testing device promises a large area for study transient behaviour of unsaturated soil under coupled THM boundary conditions. It enables to study transient water retention characteristics of partially saturated soil under non-iso thermal testing conditions. The application of embedded total pressure transducers in combination with soil water retention curve at same measurement section will further emphasize the role of transient boundary conditions on water retention behaviour of compacted expansive soils. The paper also highlighted the temperature-induced disturbance in system response and measurement methods. System compliance tests are discussed in detail to quantify the temperature induced disturbance and a possible shift in the sensor measurements as a forerunner of core experimental investigations.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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