Changing and equilibrating water content of triaxial test specimens without suction control

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ABSTRACT: Testing of unsaturated soil specimens often involves moisture equilibrium through one of various means of suction control. This generally requires a long period of equilibration at the beginning of such a test. Going through a portion of this period by adjusting water content in a controlled manner beforehand, rather than imposing a matric suction value, could decrease the total time each specimen occupies the suction-controlled test setup. Additionally, the capability to control water content of a specimen homogeneously would be beneficial in the absence of suction control, when identical specimens have to be tested at different water content values. In order to devise the most efficient methods of adjusting water content in both drying and wetting regimes, 5cm diameter triaxial test specimens of a very low plasticity silt, and a high plasticity clay were subjected to a variety of procedures that do not require any specialized equipment. These trial procedures include combinations of soaking, evaporation, rotation against gravity, weight measurement, thermal gradient application, and sealing the specimen in nylon bags, for various durations. Any sealed specimen would eventually reach moisture equilibrium; this study's focus is the minimum duration required to reach such a state of homogeneous water content, which is found to happen in a matter of days. Spatial distribution of water content was checked in both axial and radial directions at the end of every trial, by dividing each specimen into 32 pieces and determining their water contents.

1 INTRODUCTION

The most widespread techniques for controlling suction can be summarized in three different approaches. First and most common technique is axis translation technique. In this technique, positive air pressure and positive water pressure are applied into the specimen's pores. Since matric suction is equal to the difference between air pressure and water pressure, matric suction control can be achieved by elevating both pressures to different levels. High air entry porous materials are used for preventing intrusion of air into water pressure system. Such setups can apply suctions as high as 1500 kPa.

Another technique used for controlling matric suction is osmotic control (Delage et al., 1998). In this technique matric suction is controlled by means of a semi-permeable membrane and an osmotic solution (commonly polyethylene glycol-PEG). Delage et al. (1998) reported that values of suction up to 10 MPa could be obtained using this technique. The detailed description of application of osmotic technique in unsaturated soil testing could be found in the study reported by Monroy (2005).

The third technique is vapor equilibrium (Blatz et al., 2008). In this technique, the specimen is placed in a sealed container together with an ionic solution. Total suction is created as a function of the relative humidity of the environment in the container based on thermodynamic principles. Very high suction values ranging from 4MPa to 600MPa can theoretically be created using this technique (Murray & Sivakumar, 2010). However, strict temperature control is required during testing since relative humidity is very sensitive to temperature changes.

All of the aforementioned methods have their advantages and disadvantages (Ng & Menzies, 2007). Independent of which method is used to control suction, suction equalization is essential in unsaturated soil testing (Ng & Zhou, 2005). Usually a long period of time is needed to achieve suction equilibrium in an unsaturated specimen. This can be several days to months, depending on the controlling method and soil type (Lloret et al., 2003). Such a long equalization time of suction in the specimen is one of the main difficulties in unsaturated soil testing, limiting the quantity of tests that can be performed in a single test setup.

Separating the suction equalization stage from the test and doing it in a separate setup (or multiple parallel setups if needed) could greatly reduce total time of a test program. This idea may appear to be more suitable for water content controlled tests (Thu et al. 2006), but is equally viable in preparation to suction controlled tests. Before deformation, bringing suction in a homogeneous specimen to a single constant value is almost identical to bringing its water content to a single constant value. In this study, the authors aim to adjust water content of specimens using simple procedures and equipment in a relatively short period of time, to be followed by suction (or water content) controlled test. Such an approach can be beneficial to increase test result output of unsaturated soil mechanics researchers, and perhaps make their theories more accessible for geotechnical engineering practice since it provides a way to perform constant water content tests without employing suction control techniques for extended periods and occupying costly equipment.

2 MATERIALS

A silt from Mersin, Turkey and Ankara clay were used in the study. The index properties and soil water characteristic curves of two soils are illustrated in Table 2, Fig. 1 and Fig. 2. Properties of Mersin silt are given by Ahmadi-Naghadeh (2016), whereas Ankara clay properties were determined during this study. The equation form proposed by van Genuchten (1980) was used to fit experimental SWCC data in Fig. 1, ignoring volume change.

$$w = w_r + \left(w_s - w_r\right) \Big/ \left(1 + \left(\psi / a\right)^n\right)^m \qquad (1)$$

where w is gravimetric water content, w_r and w_s are residual and saturated gravimetric water contents, respectively.

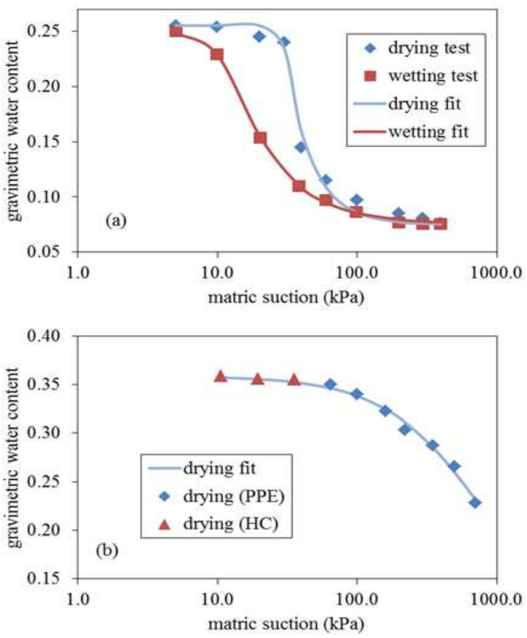

Figure 1. SWCCs of studied soils; (a) Mersin silt, (b) Ankara clay (PPE: pressure plate extractor, HC: Hanging column).

Table 1. List of SWCC fitting parameters.

	w_r	w_{sat}	a	n	m
Silt drying	0.075	0.255	28.5	120.6	0.02
Silt wetting	0.075	0.250	11.1	4.6	0.28
Clay drying	0.100	0.359	955.8	1.2	1.3

Table 2. The index properties of studied soils.

	Mersin Silt	Ankara Clay
Specific gravity	2.73	2.77
Liquid limit, (%)	25	66
Plasticity index, (%)	5	37
USCS classification	ML	CH

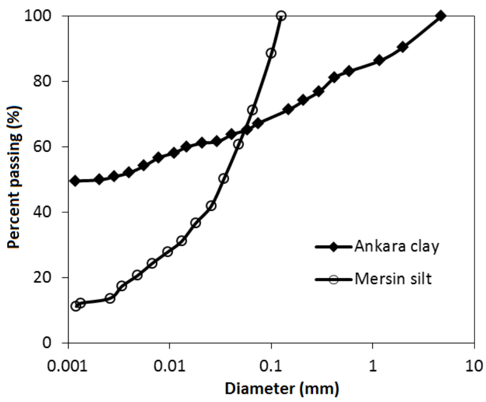

Figure 2. Grain size distribution curves.

3 TEST PROCEDURES AND RESULTS

Specimens were statically compacted in three layers inside a cylindrical hollow plastic mold by means of a hydraulic jack. A variety of procedures are devised and tried in stages for wetting and drying of triaxial test specimens (10cm in height and 5cm in diameter). The attempts at increasing water content of specimens are based on the capillary absorption phenomenon. In case of decreasing water content, specimens were dried by exposing them to open air. Resulting distribution of water content within specimens is not homogeneous after such procedures. Therefore, for both cases, process of equilibrating water content in the specimen as a following stage is required to diminish the differences in the water content distribution within the specimen. Any specimen would come to equilibrium after a sufficiently long period of equilibration process. The main concern in these trials is the time that is required for achieving homogeneous distribution of water content within specimen after proposed operations. Specimens were separated into pieces and water content of each piece was determined in order to evaluate the distribution of water content values within the specimen. First, specimens were divided into four or more disc-shaped slices by using a spatula to determine the distribution of water content along the vertical direction. Then each disc was divided into eight portions as shown in Fig. 3. Into each soil disc, two thin metal rings (diameters are approximately 10mm and 35mm) are inserted to prevent mixture of different parts in radial direction. Then each soil ring is separated into pieces in the hoop direction by using a 5mm spatula. Water content measurements are recorded to nearest 1%. The difference of water contents between each piece and mean value being less than 1% was considered as acceptable error margin in this study.

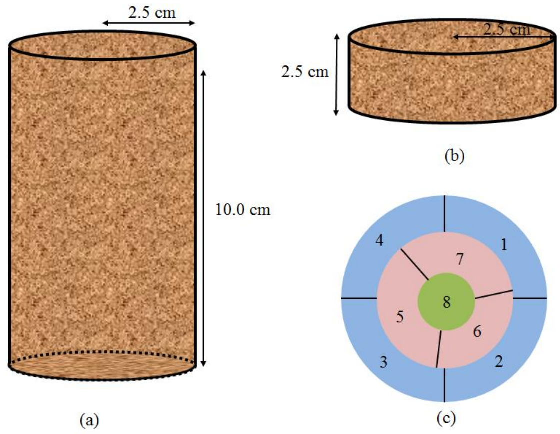

Figure 3. Dimensions of triaxial specimens (a), dimensions of disc-shaped slices after dividing specimen (b), plan view of the pattern which is followed during partition of one of disc-shaped slice, colors denote distance of radial groups from center (c).

3.1 *Wetting by Capillary Soaking*

Three different procedures were tried for increasing water content of specimens. First attempt is placing triaxial test specimen into a basin filled with water. In this case, specimen is not extruded from its mold after compaction. The bottom of the mold is covered with filter paper to prevent loss of material in water. The basin is filled with water up to a level slightly less than the mold's height. Specimen takes water in only through the bottom of the mold; creating a wetting front that rises inside the specimen. After a certain time, depending on the soil type and difference between initial and desired values of water content, the mold is removed from the basin and sealed in a nylon bag for water content equilibration. At the end of this procedure, water content values within the specimen vary along the specimen's height, (higher at the bottom and less at the top). During water content equilibration, water moves to dryer parts of the specimen due to difference in capillary potential.

Gravimetric water content of Ankara clay sample in air-dry condition was 7%. The initial dry densities for all prepared specimens were in the range of 1.46 to 1.52g/cm^3. The swelling of specimen caused by increase in water content was permitted. Specimen was kept in this condition until wetting front reached the specimen's mid-height. It was found by trial and error, that the duration of two hours is adequate for this soil. To determine water content variation at the end of wetting, one of the specimens was extruded from its mold and divided into ten disc-shaped slices immediately. Other specimens were sealed in nylon bags for water content equilibration for various times. Specimens were not turned over during water content equilibration; thus, mass transfer was only caused by capillary absorption against the direction of gravity.

This procedure did not yield useful results because too much time was required for water content equilibration stage (see Fig.4-a). The error margin of water content values within specimen became acceptable (<1%) after 55 days water content equilibration.

An attempt to accelerate the upward flow during water content equilibrium was by application of a thermal gradient in the direction in the first 3-21 hours of the water content equilibration stage. By placing the sealed specimen on a warm plate, an almost constant gradient of approximately 1.8°C/cm was generated (calculated value based on continuous temperature measurements at three points along the height). However, this modification did not improve the procedure (Fig. 4-b), as it created too much flow, and added a second location with large gradient of water content to the system.

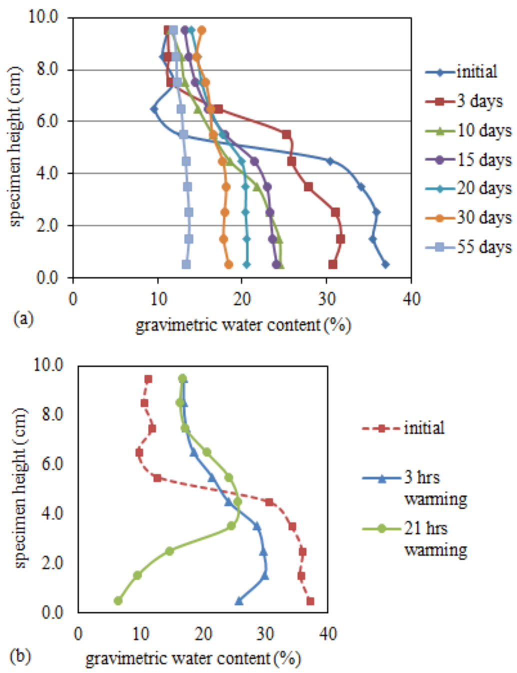

Figure 4. The distribution of water content within the Ankara clay specimens for different equilibration durations (a), results for equilibration with thermal gradient (b).

As a result, the time required to obtain a homogeneous distribution of water content is impractical. Thus, this method is not tried with another soil type.

3.2 *Wetting by Lateral Spraying*

The second procedure involves reducing the distance covered by the water during water content equilibration stage. To do this, specimen was wetted throughout the specimen's lateral surface by means of a sprayer, by the following procedure:

- The required amount of water to achieve desired water content is calculated by using Equation 2,

$$\Delta m_w = m_{T_0} / (1 + w_0) \times (w_f - w_0) \quad (2)$$

where, Δm_w is the required mass of water that should be added to the specimen to achieve the desired water content, m_{T0} is the initial total mass of the specimen, w_0 is the initial water content of the specimen and w_f is the desired water content after spraying.

- The specimen is placed on a plate. The plate helps avoiding unfavorable stress concentration and prevent damage to the specimen when carrying or changing position. Another plate is also placed upon the top of the specimen in order to moisten the specimen through only its lateral surface; otherwise, the upper part of the specimen would be excessively moistened and water content would differ in the axial direction. In this study, transparent plexiglass discs are used for this purpose (Fig.5).
- Before starting spraying, initial weight of specimen and plates are recorded.
- The sprayer nozzle is aligned horizontally at the mid-level of the specimen. The flow coming out of sprayer should be in the form of mist; stream flow erodes specimen surface. Also, sprayer nozzle should be at a distance of about 0.50 m away from the specimen, to create a uniform mist.
- Specimen should be moisturized uniformly from all horizontal directions. The transparent top cap may allow the operator to observe moistened parts of the specimen, if wetting front is visible.
- Droplets of water accumulate on the base plate and create a water pond around the base of the specimen. This water should be regularly removed by means of a paper towel to prevent loss of material from specimen and localized excessive wetting.
- Total weight of the specimen and plates is frequently measured to check whether the required amount of water has been added or not. Note that water on the surface of the plates should be drained with paper towel before measuring the weight.
- When the specimen reaches the desired water content, it is sealed in a nylon bag. It is more reliable to use multiple nylon bags. Then, the sealed specimen is left for water content equilibration.

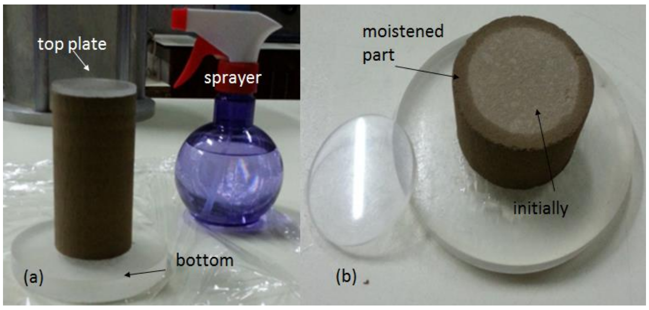

Figure 5. Equipment (a), the top view of specimen immediately after spraying (b).

Mersin silt was used and dry densities of specimens prepared by compaction were in the range of 1.50 to 1.58 g/cm^3. The water content was increased from an initial value of 5% during compaction to about 13% at the end of water content equilibration (Fig. 6). The maximum error for the water content became 0.9% (Fig. 6-a) and 0.8% (Fig. 6-b) after 1 day and 2 days water content equilibration, respectively.

When Ankara Clay specimens are sprayed, their expansive nature resulted in deformation and cracks propagating radially with the moisture.

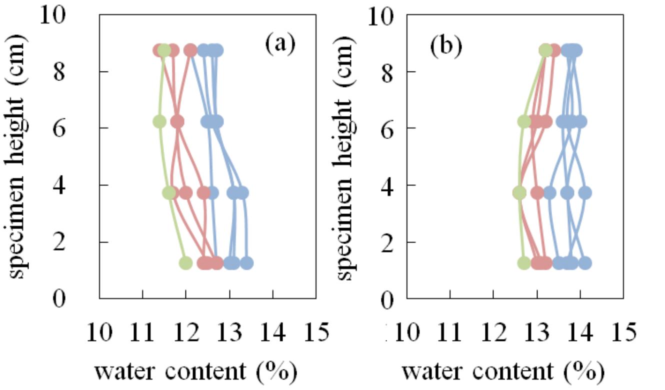

Figure 6. Water content distribution of Mersin silt specimen, that was moistened with a sprayer, followed by 1 day of equilibration in nylon bag (a), or by 2 days for equilibration (b).

3.3 *Wetting by Radial Soaking*

This procedure is developed to counter swelling that was observed in lateral spraying. The specimen was wetted throughout the specimen's lateral surface by means of a perforated mold (holes that are approximately 2mm in diameter were drilled at four different elevations in vertical direction, with 60° intervals around perimeter) made of relatively rigid (1 cm thick) poly-vinyl chloride (PVC). Thus, distribution of water content values differs in radial direction, not in vertical direction. In this method, the bottom surface of the mold is closed by means of a lid to permit water entry to the specimen only through its lateral surface. A filter paper was placed throughout the mold's inner lateral surface to provide uniform water flow to the specimen and to prevent intrusion of swelling soil in holes of the mold. The filter paper also helps specimen extrusion. It is important to note that the water level in the basin should be close to the specimen's height during wetting; otherwise, distribution of water content also differs in vertical direction, prolonging water content equilibrium stage duration. The volume change in the vertical direction can be prevented by covering top surface of the specimen with a rigid plate that lightly touches the specimen. Then, this plate is loaded more than the expected swelling pressure load, and this load is transferred to a support frame to avoid excessive load application upon specimen or mold (Fig. 7). Separate Ankara clay specimens were submerged for 30 and 50 minutes and Mersin silt specimen was submerged for 3 minutes.

The results show that wetting the specimen through its lateral surface reduces the required water content equilibration stage duration remarkably.

Overall water content of the specimen that remained in basin for 30 minutes increased from 7% (water content of air-dry soil) to 17%. The maximum variation of water content from the mean value within the specimen was 11.9% initially (Fig. 8-a) and decreased to 1.9% after 2 days (Fig. 8-b). The variation was still 2.5% (Fig. 8-c) after 5 days of water content equilibration. Another specimen was soaked for 50 minutes and its water content increased to 19%. The maximum variation of water content from the mean value became 3.4% after 3 days of equilibration (Fig. 9-b), down from the initial variation of 10.4% at the end of soaking (Fig. 9-a). The water content of Mersin silt specimen increased to 16.4% from 1% and the maximum variation from the mean water content was 0.5% after 5 days of equilibration (Fig. 8-c).

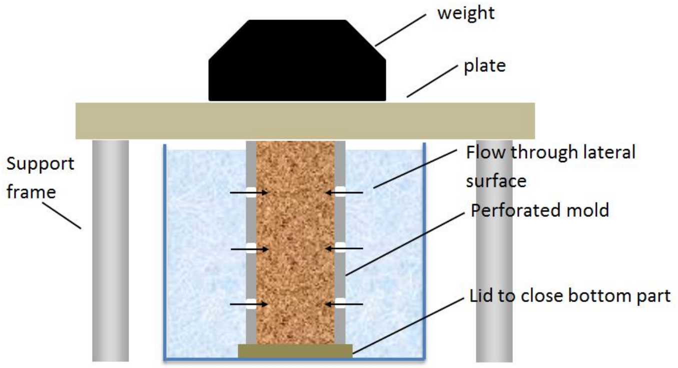

Figure 7. Sketch of radial soaking method.

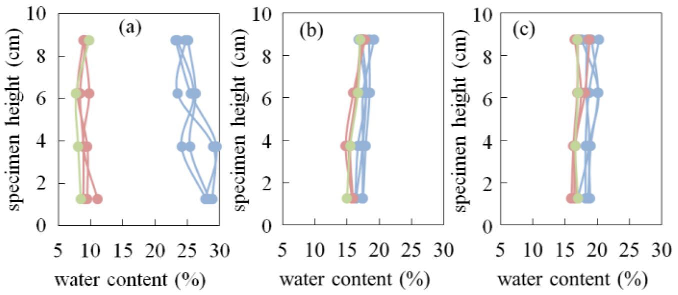

Figure 8. Water content distribution of Ankara clay specimen that remained in basin for 30 min. (a), followed by 2 days of sealed equilibration (b), 5 days of sealed equilibration (c).

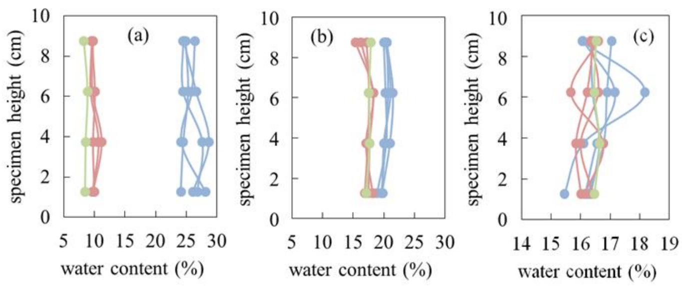

Figure 9. Water content distribution of Ankara clay specimen that remained in basin for 50 minutes (a), followed by 3 days of water content equilibration sealed in nylon bag (b), (c) Water content distribution of Mersin silt specimen that remained in basin for 3 minutes followed by 4 days of equilibration.

The maximum variation values for water content within Ankara clay specimens are higher than the acceptable error of 1% and it did not significantly decrease even if the water content equilibration duration was extended, water contents of inner parts are consistently less than outer parts. For this method, outer parts that are wetted by soaking experience drying whereas inner parts experience wetting during equilibration. The hysteretic nature of soil water characteristic curve results in larger water content in case of drying (of outer parts) compared to the wetting of inner parts, at the equilibrium suction. This effect can be minimized by keeping the specimen in water for a short period (e.g. in seconds) then waiting for equilibration (e.g. in hours) to prevent excessive saturation of outer parts.

3.4 *Drying by Evaporation*

Water content of the specimen decreases due to evaporation when it remains in open air. Water content inside the specimen is higher than that of the outer parts just after drying. Therefore, the specimen is sealed in nylon bags for water content equilibrium

It was noticed that the rate of evaporation is higher at the upper parts of specimen although the top surface of specimen is covered with plexiglass cap. It can be considered that the elevation head difference may cause this variation; however, it was shown that this effect is negligible (see Fig.6, Fig.8, Fig.9). At first, the reason of this variation was considered to be evaporation through the little gap between specimen's top surface and the top plate. When the specimen was placed on a perforated, elevated platform to expose bottom surface of specimen directly to atmosphere; however, the same variation was again observed. The authors speculate that this variation emerge due to endothermic nature of evaporation, which cools the moist air around the specimen. This cool moist air travels down due to convection resulting in higher relative humidity at the bottom part, decreasing the rate of evaporation at that location. To overcome this problem, a step of turning the specimen upside down for half of the drying duration was incorporated into the procedure.

Ankara clay sample was mixed with water and compacted in the mold to prepare specimens at high water content (28.2%). The dry densities of these specimens were in the range of 1.51 to 1.52 gr/cm^3. The specimen was placed in open air for two days and another two days in nylon bags for water content equilibration (Fig.10). All but one of the specimens were turned over after the first day of drying to avoid water content difference along vertical direction. There is significant variation of water content along vertical direction (Fig. 10-a) unless specimen is overturned (Fig. 10-b). Overall water content of specimen decreased to 14%. The maximum variation for not-turned-over specimen and turned-over specimens were 5.4% and 2.4%, respectively. This variation decreased to 1.5% after water content equilibration (Fig. 10-c). Mersin silt specimens were prepared at initial water content of 22.3% and initial dry density of 1.50g/cm^3. They are placed in open air for eight hours and fourteen hours and overturned at the half-time of drying. Overall water content of specimens were decreased to 18.3% and 15.6%, respectively after one day water content equilibration stage and maximum variation of water content became 0.3% in both cases (Fig 11).

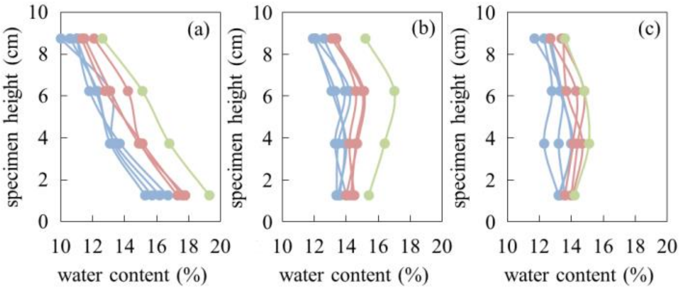

Figure 10. Water contents within Ankara clay specimen, that remained in open-air for 2 days without turning over (a), that remained in open-air for 2 days with turning over (b), followed by 2 days for equilibration for turned over specimen (c).

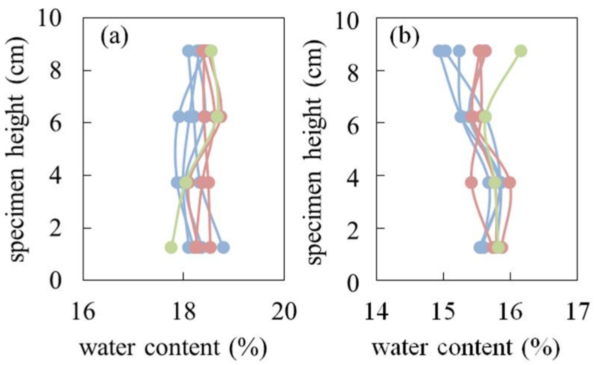

Figure 11. Water contents within Mersin silt specimen, that remained in open-air for 8 hours with turning over (a), that remained in open-air for 14 hours days with turning over (b).

4 CONCLUSION

Practical and rapid methods for adjusting water content of triaxial test specimens were investigated and several procedures were proposed. Two different soils (CH and ML) were used during trials. The capillary soaking method did not yield useful results. The most important factor affecting duration for water content homogenization appears to be the flow distance. For low-plasticity specimens, changing water content through its lateral surface is shown to be a viable way to obtain homogeneous distribution of water content in a short period of time. Using a sprayer to moisten the specimen in the radial direction resulted in acceptable homogeneity. High-plasticity specimens are successfully wetted inside a rigid, perforated mold that restricts radial and vertical strains to prevent localized swelling of the specimen. This process can be applied in multiple stages to reduce hysteresis effects.

For lowering the water content to a homogeneous value, leaving specimens to evaporate in open-air resulted in success, only if the specimen is turned upside down halfway through the process.

Specimens are sealed in nylon bags during the water content equilibration stage that follows either drying or wetting procedures. It becomes possible to bring specimens to moisture equilibrium at various water contents in less than one week for several scenarios.

Such simplified procedures could be incorporated into conventional laboratory methodology, if unsaturated soil mechanics is to become more accessible for geotechnical engineering practice.

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REFERENCES

Ahmadi-Naghadeh, R. 2016. Hydro-mechanical behaviour of unsaturated isotropically reconstituted specimens from slurry and compacted specimens. PhD thesis, METU, Ankara.

ASTM D2216-10. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, West Conshohocken, PA, 2010.

Blatz, J.A., Cui, Y.J. & Oldecop, L. 2008. Vapour equilibrium and osmotic equilibrium technique for suction control. *Geotechnical Geology Engineering* 26(6): 661-673.

Delage, P., Howat, M.D. & Cui, Y.J. 1998. The relationship between suction and swelling properties in a heavily compacted unsaturated clay. *Engineering Geology* 50: 31-48.

Lloret, A., Villar, M.V., Sanchez, M., Gens, A., Pintado, X. & Alonso, E.E. 2003. Mechanical behaviour of heavily compacted bentonite under high suction changes. *Geotechnique* 53(1): 27-40.

Monroy, R. 2005. The influence of load and suction changes on the volumetric behaviour of compacted London clay. PhD thesis, Imperial College, London, UK.

Murray, E.J. & Sivakumar V. 2010. Unsaturated Soils: A fundamental interpretation of soil behaviour. Wiley, NY.

Ng, C.W.W. & Zhou, R.Z.B. 2005. Effect of soil suction on dilatancy of an unsaturated soil. Proc. 16th International Conference Soil Mechanics and Geotechnical Engineering Osaka, Japan, 2, 559-562.

Thu, T., Rahardjo, H. & Leong, E. 2006. Shear strength and pore-water pressure characteristics during constant water content triaxial tests. *Journal Geotechnical and Geoenvironmental Engineering*. 132(3): 411-419.

Van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44: 892-898.