COMPARISON OF CENTRIFUGE AND MERCURY INTRUSION POROSIMETRY (MIP) TEST TO DETERMINE SOIL WATER RETENTION CURVE

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ABSTRAK

Soil water retention curve (SWRC) is a key property for analysing water flow in unsaturated soil profile. SWRC is usually determined by time-consuming laboratory experiment, such as using pressure plate and temp pressure apparatus. Centrifuge and Mercury Intrusion Porosimetry (MIP) techniques are two potential laboratory techniques that can be applied to determine SWRC. Both techniques require shorter test duration than others and they also cover a broad range of matric suction. This paper compares the SWRCs obtained from those techniques. Four materials with different particle size and pore space characteristic were used in this study. Two soils are classified as fine-grain soils (i.e. K-7 sand and Zeolite) and the other two are classified as coarse-grain soils (i.e. Kaolin clay and Commercial Diatomite). Based on the pore space characteristics, K-7 sand and Kaolin clay are grouped into single-porosity soils, while Zeolite and Commercial Diatomite are dual-porosity soils. Comparison are made between SWRC from Centrifuge and MIP tests. For fine-grain soils, the SWRC from both techniques do not show coherency. Volume change of the specimen is the main factor that make different between the results of Centrifuge and MIP test. The other important result is that the shape of SWRC cannot be predicted from the single- or dual-porosity grouping, but it depends also on the soil particle size. Fine-grained dual-porosity soils may exhibit only unimodal SWRC but, larger particle size of dual-porosity soils are more likely to exhibit bimodal SWRC. For single-porosity soils, it presents single SWRC.

Keywords: soil water retention curve, unimodal curve, bimodal curve, single-porosity soils, dual-porosity soils, Centrifuge test, MIP test

1. INTRODUCTION

Soil water retention curve (SWRC) is very important parameter in Unsaturated Soil Mechanics. It performs well when it is used to estimate the other properties of unsaturated soils, such as hydraulic conductivity (Fredlund *et al.*, 1994), shear strength (Fredlund *et al.*, 1996; Vanapalli *et al.*, 1996) and volume change (Fredlund and Morgenstern, 1976). SWRC shows the amount of water within the soil pore when a certain value of negative pore water pressure (matric suction) is applied. The amount of water within soil pore can be represented by water content, volumetric water content or degree of saturation. SWRC highly depends on the particle size distribution of soils. High matric suction is associated with fine-grained soils and low matric suction is associated with coarse-grain soils. Many methods has been proposed to determine SWRC. Laboratory test is considered to be the most accurate method to determine SWRC. Many laboratory test methods has been proposed to determine SWRC, however, the accuracy of each methods depend on the approach or technique of measurements. Some laboratory test methods directly apply matric suction and take record on water content of specimen to present SWRC. Pressure plate apparatus and tempe pressure cell are well known apparatuses to use that techniques. The other apparatuses can be used to determine SWRC indirectly. They apply (or measure) the other parameter that is believed to have correlation with parameter used to draw SWRC. Centrifuge apparatus does not directly apply matric suction, but it uses angular velocity to correlate with matric suction. Mercury Intrusion Porosimetry (MIP) test uses mercury and air as fluids to measure pore size distribution. The pore size distribution can be correlated with matric suction. Both direct and indirect determination of SWRC from laboratory tests have each advantages and disadvantages.

Laboratory test procedure to determine SWRC should be easy and effective in both cost and time. Centrifuge and MIP test are two of laboratory test method that fulfil those requirements. This paper discusses about the performance of Centrifuge test and MIP test to determine the SWRC. Four specimens with different particle size and pore characteristics were used in this study. Those specimens were subjected to both Centrifuge and MIP test. The SWRC obtained from both techniques are compared and discussed in details.

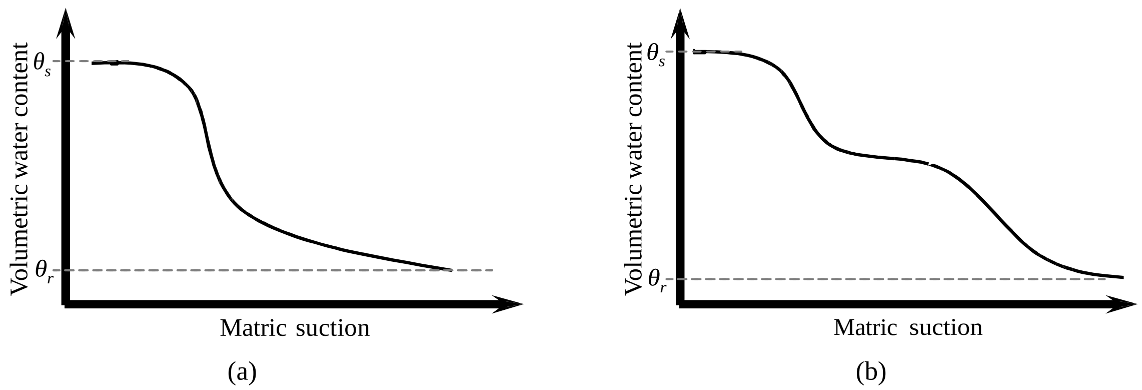

Figure 1. Typical shape of SWRC: a) unimodal curve and b) bimodal curve

2. THEORETICAL BACKGROUND

SWRC shows the relationship between the volumetric water content (or water content or degree of saturation) and the associated matric suction of a soil specimen. The volumetric water content is plotted in normal scale, while matric suction is in logarithmic scale. Generally, SWRC is depicted as single S-shape curve or unimodal curve. However, some soils may has bimodal or multimodal shape SWRC. Figure 1 shows the typical shape of SWRC. The upper limit of SWRC is the saturated volumetric water content (θ_s) and the lower limit is the residual volumetric water content (θ_r). Typically, SWRC has unimodal curve and bimodal curve. The shape of the curve depends highly on the pore diameter distribution and pore space characteristic. Pore space of soils can be grouped into interaggregate pore space and intraaggregate pore space (Burger and Shackelford, 2001). Interaggregate pore is defined as pore space that exist among soil particles. Unlike interaggregate pore space, intraaggregate pore is located inside of the soil particle. Depending on the type of pore space, soil can be grouped into single- and dual-porosity soils. Single-porosity soils are a group of soils that only have interaggregate pore space. Dual-porosity soils have both interaggregate pore space and intraaggregate pore space.

Soil water retention (SWR) test is basically conducted by giving pressure to air in order to intrude to soil pore which is initially saturated with water. The air is then flowing into the soil specimen replacing the volume of water which is already inside of the soil pore. The given pressure and the associated amount of water retained inside of soil pore are then plotted into a semi-logarithmic curve. Series of tests are required to obtain several plots to draw SWRC. Pressure plate and tempe pressure cell apparatus accommodate that method to determine SWRC. This method requires long duration to complete series of test depends on how much data are desired and how large the particle of the soils are. Fine-grain soil tends to take longer time than coarse-grain soil because hydraulic conductivity of fine-grain soil is much smaller than coarse-grain soils. Hydraulic conductivity property affects the flow of water out of the soil pore. Centrifuge and MIP test are two of most promising methods that expected to cover demerit of previous methods. Centrifuge test and MIP test were selected in this study because both of these methods are capable of establishing broad range of suction value in SWRC. Procedure of these tests are easy to conduct and they do not require long duration to complete the whole test.

Centrifuge test can be used to determine SWRC indirectly. Matric suction is not applied directly by giving air pressure during the test, but it uses correlation of angular velocity to the matric suction. Gardner (1973) proposed an equation to calculate matric suction based on angular velocity that is presented as follows:

$$\psi = \frac{\rho \omega^2}{2}\left(r_1^2 - r_2^2\right) \tag{1}$$

In Eq. (1), ψ is the applied matric suction, ρ is density of the pore fluid, ω is angular velocity, r_1 is the radial distance to the free water surface and r_2 is the radial distance to the midpoint of the soil specimen. In this test, specimen is rotated with a certain angular velocity. During the rotation, water are flowing out of the specimen. Thus, the amount of water inside of specimen reduces. One test is complete when no more water flowing out of the specimen. Series of tests are required to draw SWRC smoothly.

MIP test is generally used to measure pore size distribution of material. It uses mercury to determine the pore diameter. Pore space is initially fully filled with air. Mercury is intruded into pore space by using a certain pressure. The volume of air inside pore space reduces because it is replaced by the volume of mercury. The volume of

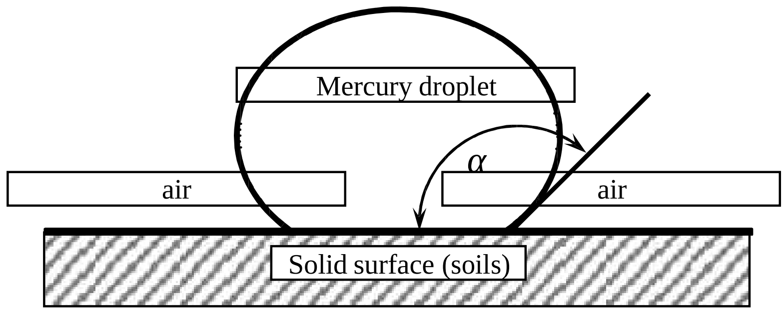

Figure 2. Mercury and air interaction on a solid surface

intruded mercury indicates the volume of pore space larger than a certain diameter which can be correlated with the pressure given to the mercury. The correlation is presented as follows.

$$\psi = u_{nw} - u_w = -\frac{4\gamma_{nw}}{D}\cos\alpha_{nw} \tag{2}$$

In Eq. (2), *D* represents the pore diameter; *u*, *γ* and *α* indicate the fluid pressure, surface tension between fluids and contact angle of fluids. The subscripts *nw* and *w* are associated with non-wetting and wetting fluids. When there are two fluids in contact with solid surface, one fluid acts as a wetting fluid and the other acts as a non-wetting fluids. Non-wetting fluid does not spread on a solid surface, while wetting fluid does. Figure 2 shows the concept on how wetting and non-wetting fluids in contact on a solid surface. In MIP test, mercury acts as non-wetting fluid and air acts as wetting fluid. The contact angle between mercury and air is generally taken about 130° and the surface tension of mercury is about 485 N/mm.

3. MATERIALS AND METHOD

Materials

Four different soils have been used in this study, which are K-7 sand, Kaolin clay, Zeolite and Commercial Diatomite. They have different type of particle distributions and pore space characteristics. Figure 3 shows the particle-size distributions of all materials. K-7 sand and Zeolite are classified as coarse-grain soils, but they have different type of pore space. Unlike K-7 sand, Zeolite has bigger size and it does not only has interaggregate pore space but it also has intraaggregate pore space. Kaolin clay and Commercial Diatomite are classified as fine-grain soil based on the particle size. Similar with K-7, Kaolin clay is only has interaggregate pore space, while Commercial Diatomite has both interaggregate pore space and intraaggregate pore space. Regarding of the type of pore space, K-7 sand and Kaolin clay are classified as single-porosity materials, while Zeolite and Commercial Diatomite are classified as dual-porosity materials. Scanning Electron Microscopic (SEM) test can be used to indicate the existence of intraaggregate pore space. Figure 4 presents the result of SEM for all materials. The SEM tests were aimed to show the image of particle clearly on a certain enlargement. Figure 4a shows that particle of K-7 sand contains smooth surface and rough surface, but there is no indication of intraaggregate pore. Figure 4b and 4d shows clearly that particle of Zeolite and Commercial Diatomite has intraaggregate pore space. The Kaolin clay has very small size platy shape particle as shown in Figure 4c.

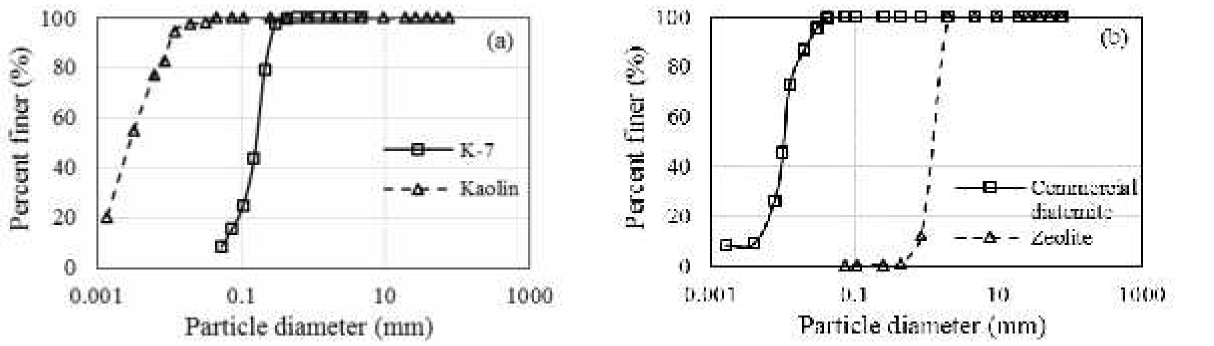

Figure 3. Particle-size distribution of: a) single-porosity soils, and b) dual-porosity soils

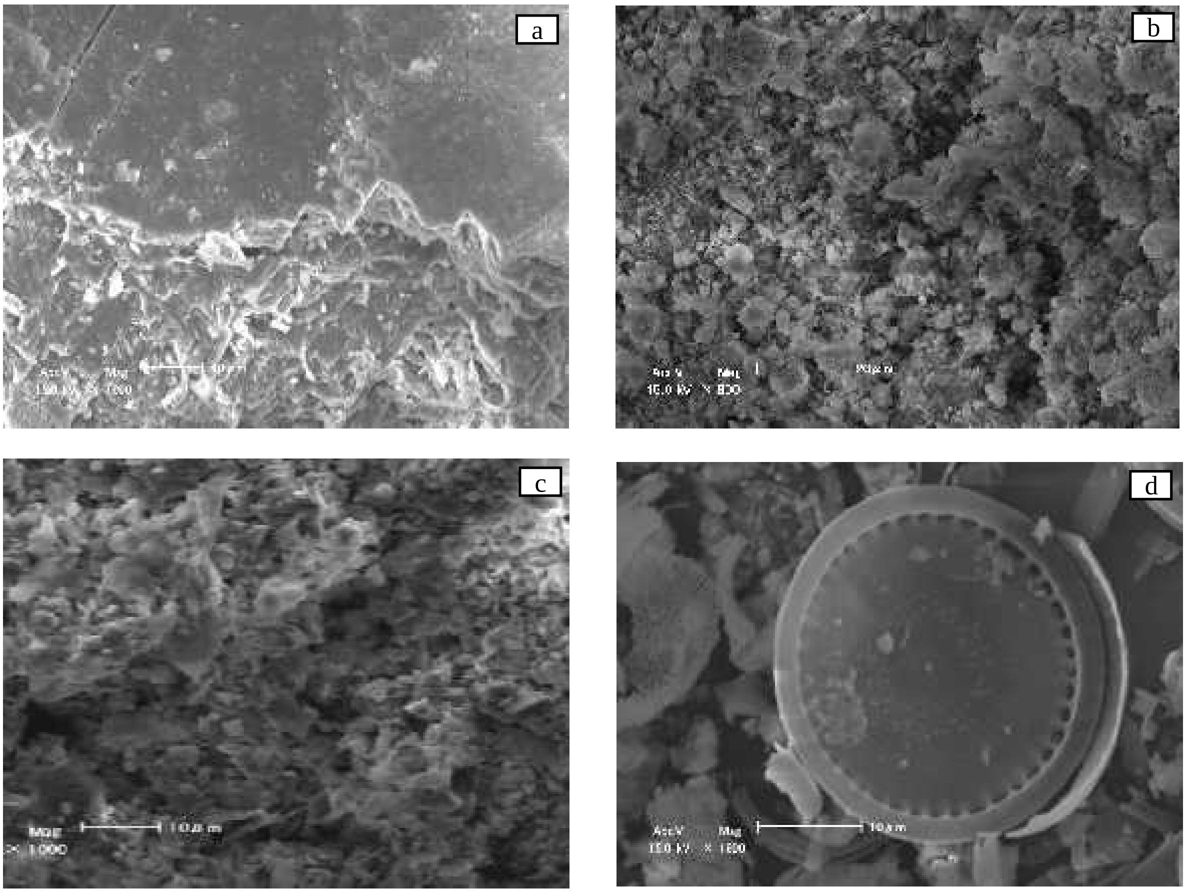

Figure 4. Scanning electron microscopic for a) K-7 sand, b) Zeolite, c) Kaolin clay, and d) Commercial Diatomite

Centrifuge test

In this study, a Centrifuge test apparatus which able to rotate specimen between 100 rpm up to 10000 rpm was used. That rotation can generate suction about 0.21 kPa up to 2105 kPa. Four cylinder specimens of no more than 3 grams different in weight are needed to perform this test. The specimen height is 5 cm and the diameter is 5.1 cm. Each soils was compacted to the mold and to be saturated prior to the test. During saturation process, the specimens were submerged into water and negative pore water pressure was applied to accelerate the saturation process of the specimens. Series of tests were conducted, started by rotating specimen with low angular velocity. Depending on the particle size of the specimens, the required duration of rotation is different for each specimen. Coarse-grain specimen requires about 2-4 hours to reach equilibrium. Equilibrium state means that there are no water excluded from specimen during rotation. Longer equilibrium time is required for fine-grained soils. It may take about 24 hours to reach equilibrium state when it is desired to apply high matric suction. After finishing rotation, the weight of each specimen was measured to calculate the amount of water retained inside of the specimens. Water content of each specimen was measured at the end of the test. Water content of specimen at each series of tests can be obtained by conducting back calculation. Data obtained from these series of tests are then plotted into semi-logarithmic scale to draw SWRC.

Mercury intrusion porosimetry (MIP) test

AutoPore IV apparatus was used to measure the porosity of soils. Dry specimen from the end of the Centrifuge tests were used in this tests. This condition is selected because at the end of Centrifuge test soils has smaller volume which is similar to compacted soils. This will reduce volume change during the MIP test. Small amount of soils were trimmed from each specimens and then placed in chamber for dehydrating. The sample was dehydrated by using freeze-drying technique for about 24 hours. Soil samples were then put into penetrometer stem and processed for MIP test. Pore size diameter and the associated volume of mercury that intruded into the soil pore are the raw data obtained from MIP test. The pore size diameter can be used to calculate matric suction by using Eq. (2) by

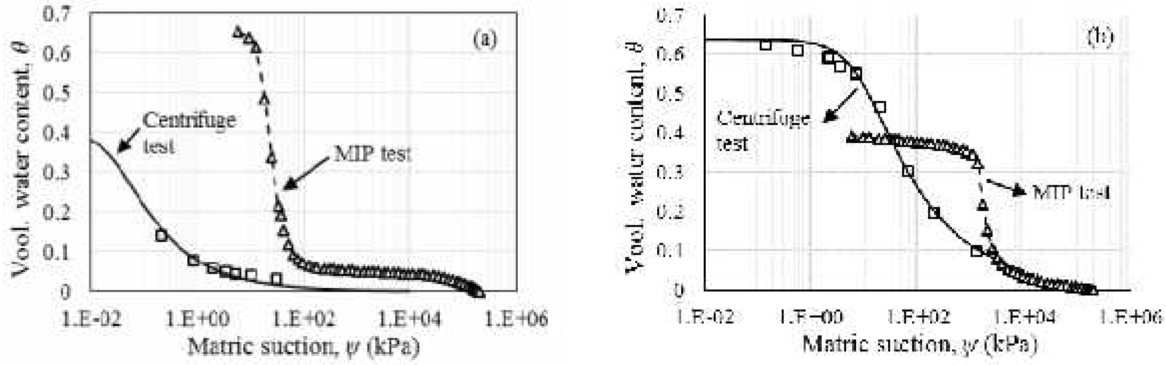

Figure 5. SWRC of single porosity soils based on centrifuge test and MIP test: a) K-7 sand, and b) Kaolin clay

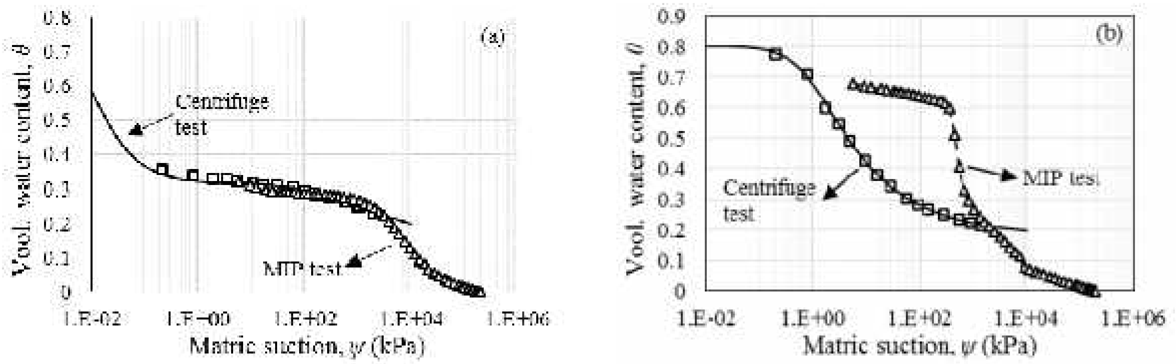

Figure 6. SWRC of dual-porosity soils based on Centrifuge and MIP test: a) Commercial Diatomite, and b) Zeolite

taking water as non-wetting fluid and air as wetting fluid. The contact angle between water and air on a solid surface is 0° and the surface tension is of water is 72.75 N/mm. In MIP test, mercury acts as non-wetting fluid which is similar to air in SWR test which uses air and water as fluids. Thus, the volume of mercury which is intruded to the soil pore is equal to the volume of air in SWR test. Volume of water are then can be callculated by reducing the total volume of pore with the volume of air. SWRC can be drawn based on this calculation.

4. RESULTS AND DISCUSSIONS

SWRCs from Centrifuge tests and MIP tests for all specimens are presented in Figure 5 and Figure 6. Volume reduction were indicated from all specimens during Centrifuge tests. Fine-grain soil specimens (i.e. Kaolin clay and Commercial Diatomite) experience the most significant volume change. The saturated volumetric water content informs the total volume of pore that exist in the soil specimens (see Figure 1). From Figure 5b and 6b, the saturated volumetric water content from MIP tests is maller than those of Centrifuge tests.

The matric suction resulted from MIP tests are higher than those from Centrifuge tests for the same value of volumetric water content as shown in Figure 5b and 6b. It is true, because the specimen used in MIP tests were taken from dry specimen at the end of the Centrifuge tests. Volume reduction in specimen results in smaller pore size diameter of soils, thus based on Eq. (2), soils will have higher matric suction. The above explanation become the main factor that SWRC from Centrifuge tests do not coherent with those from MIP tests. By consdering the volume change of soil spcimens, the results of both tests might be similar. This requires furhter calculation considering the volume change to MIP tests results. Simms and Yanful (2001) proposed the estimation method for volume shrinkage in clay soils during SWR tests.

K-7 sand and Zeolite consist of coarse-grain soil particle. It exhibited less volume reduction than Kaolin clay and Commercial Diatomite. As shown in Figure 5a, SWRC from Centrifuge test and MIP test are far different. It is because the shape of dry sand soil in MIP test is very difficult to maintain. When it is trimmed from dry Centrifuge specimen, it breaks easily. Thus, for sand soils, it is difficult to obtain SWRC from MIP tests. The best coherency of SWRC between Centrifuge test and MIP test occured in Zeolite specimen as shown in Figure 6a. The result of

SWRC from MIP test is more likely to represent the intraaggregate pore space because it shows high matric suction that can be correlated with small pore diameter based on Eq. (2). Zeolite particle is bigger than K-7 sand, thus it is difficult to measure the interaggregate pore space. This becomes the limitation of MIP test which cannot be used to measure large pore diameter.

The SWRC for single-porosity soils (Figure 5a and 5b) show unimodal curve. Figure 6a (for Zeolite) shows bimodal curve which indicates the interaggregate pore space (from Centrifuge tests) and intraaggregate pore space (from MIP tests). Unlike Zeolite, dual-porosity features can not be indicated within the SWRC of Commercial Diatomite (Figure 6b). This is because the particle size of Commercial Diatomite are very small. The distance between each particle which represents the interaggregate pore space diameter is nearly the same as the diameter of intraaggregate pore space. Thus, SWRC does not show bimodal curve.

5. CONCLUSION

SWRC were determined by conducting Centrifuge tests and MIP tests. Both techniques do not directly measure the volumetric water content and the associated matric suction. The advantage of using these methods is that they offer a significantly shorter duration of tests compared with conventional techniques such as in pressure plate apparatus and tempe pressure cell. Centrifuge and MIP tests also cover broad range of matric suction.

Based on the test results, the following conclusions can be drawn:

- Dual-porosity soils do not always presents bimodal shape SWRC. Unimodal or bimodal shape SWRC depends on the size of soil particles. Larger particle size of dual-porosity soils are likely to have bimodal shape SWRC, but for fine-grain dual-porosity soils may have only unimodal shape SWRC.
- Volume change significantly influences the coherency between SWRC from Centrifuge tests and MIP tests. Soils that exhibit less volume change tends to have similar SWRC from Centrifuge tests and MIP tests.

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