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MEASUREMENTS OF THE COEFFICIENT OF PERMEABILITY OF AN UNSATURATED SOIL

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ABSTRACT: The permeability function for an unsaturated silty sand was experimentally measured using a specially designed triaxial permeameter. Twelve specimens were consolidated either isotropically or one-dimensionally, followed by the measurements of the coefficient of permeability at specified matric suction values. The total volume changes during the tests for the isotropically consolidated specimens were continuously monitored. The specimens were consolidated to various void ratios. The measurements of the coefficients of permeability at different void ratios during a drying process showed a bi-linear relationship between the coefficient of permeability and matric suction on a log-log scale.

1. INTRODUCTION

The coefficient of permeability of unsaturated soils is of increasing concern for analyses of flow in saturated/unsaturated soil for applications in the geotechnical and geo-environmental areas. As such, a proper evaluation of the coefficient of permeability can make the saturated/unsaturated flow analysis more accurate. In general, there are two ways to determine the coefficient of permeability of an unsaturated soil. The coefficient of permeability of an unsaturated soil may be predicted using one of several empirical estimation procedures available in the literature. However, the accuracy for such a prediction sometimes is not satisfactory. Each of the estimation procedures has been tested on limited amount of data. Therefore, there are limitations when applying each procedure. The coefficient of permeability can also be experimentally measured. Despite their high cost and time-consuming nature, experimental measurements can provide good data for the verification of the coefficient of permeability. For both theoretical and experimental determinations, the soil under consideration is commonly assumed to be of constant-volume.

This appears to be a common assumption in the soil science area. In the geotechnical field, however, soil is known to behave as a deformable porous medium. The total volume of a soil may change due to changes in the stress state variables (i.e., the net normal stress (σ - u_a), and the matric suction, (u_a - u_w), where, σ = confining pressure, u_a = pore-air pressure, and u_w = pore-water pressure). Available experimental methods have also been developed based on the assumption that the soil specimen remains at constant-volume. As such, the deformation in the soil specimen is usually neglected. There is, however, some data in the geotechnical literature which takes into account deformation induced by changes in the net normal stress. However, it appears that none of the available method considers the influence of deformation induced by changes in matric suction. In order to properly deal with soils as a deformable porous medium, a better measurement method is required, in which the coefficient of permeability of a deformable, unsaturated soil can be measured and the change in total volume of the soil specimen can also be monitored.

In this paper, a specially designed triaxial permeameter system for deformable, unsaturated soils is introduced. The testing material and testing procedures are then described. The test results are presented and discussed. The performance of the permeameter system is also discussed.

2. DEVELOPMENT OF THE TRIAXIAL PERMEAMETER SYSTEM

Different versions of permeameters have been developed for the direct measurement of the coefficient of permeability of an unsaturated soil (Christensen, 1943; Corey, 1957; Klute, 1965; Mitchell et al., 1965; Barden and Pavlakis, 1971). The common disadvantage for all designs is that the total volume change in the soil sample cannot be monitored during these permeability measurements (Huang, 1994).

For the measurement of the coefficient of permeability of a deformable, unsaturated soil, a more elaborate design is required to ensure that permeameter is capable of (i) controlling the stress state variables in the specimen, and (ii) monitoring the total volume change of the specimen during permeability measurements. According to these two fundamental requirements, a new triaxial permeameter system was constructed. The general assembly of the triaxial permeameter cell is shown in Fig. 1. The cell consists of a steel cylindrical cover, an aluminum base plate and an aluminum loading cap. It was modified from an apparatus which was initially designed to study the volume change characteristics of unsaturated soils (Ho, 1988). The cylindrical cover remained the same as the original design. The base plate was modified while the loading cap was redesigned. A control board for the permeability test was also developed as shown in Fig. 2. The triaxial permeameter cell, together with the control board, become the triaxial permeameter system. As shown in Figs. 1 and 2, the pore-air pressure in the specimen is controlled by regulator A and applied to the top of the specimen through the pore-air pressure line. The confining pressure is adjusted by regulator B and connected to the permeameter cell using the cell pressure line.

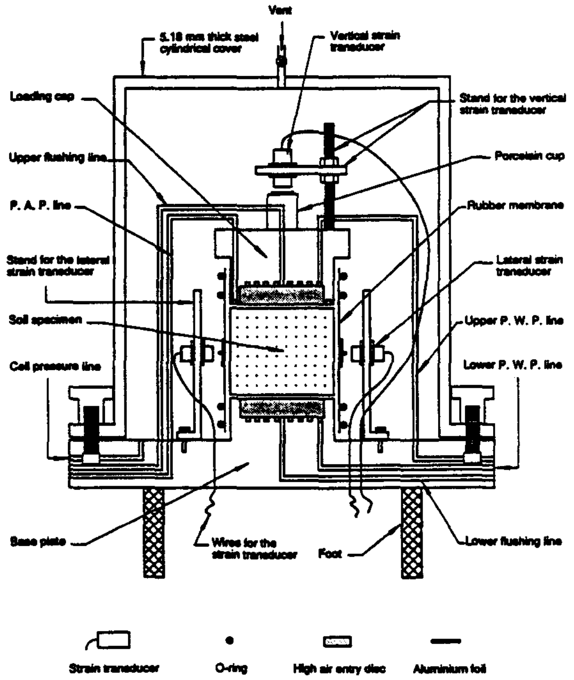


Figure 1: General assembly for the triaxial permeameter cell (Huang, 1994)

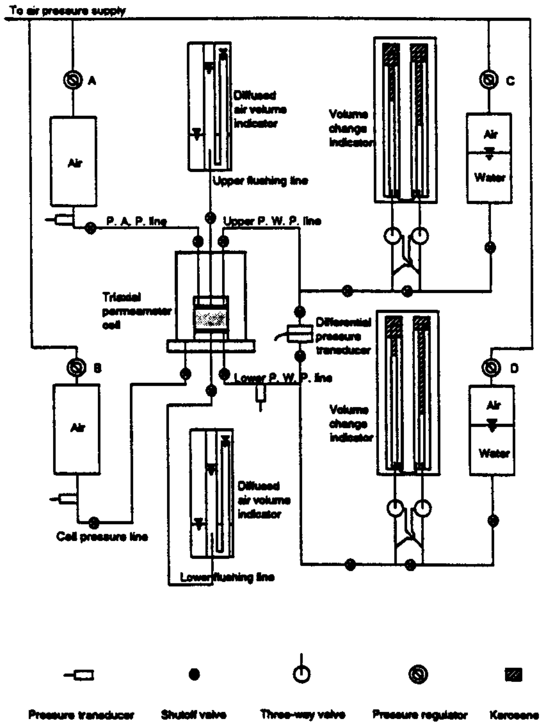


Figure 2: Schematic for the control board (Huang, 1994)

The upper pore-water pressure is balanced by regulator C and joined to the top of the specimen through the upper pore-water pressure line. Similarly, the lower pore-water pressure is maintained by regulator D and linked to the bottom of the specimen with the lower pore-water pressure line. There must be a difference between the upper and lower pore-water pressures in order to induce a flow through the specimen. This pressure difference is monitored using a high precision differential pressure transducer sold by Servo Systems Corporation, Montville, N.J.

The cell pressure, the pore-air pressure and the lower pore-water pressure are monitored using pressure transducers. The upper pore-water pressure is determined by the lower pore-water pressure and the differential pressure. Two conventional twin-burette volume change indicators were installed in the upper and lower pore-water pressure lines to measure the inflow and outflow water volumes. The resolution of the volume change indicators is 0.02 cm^3. Non-contacting strain indicators manufactured by the Kaman Sciences Corporation at Colorado, Springs, Colorado were used to monitor the total volume change of the specimen. The total volume change of the sample is calculated from the displacements of the lateral and vertical strain indicators shown in Fig. 1. The diffused air from the top and bottom high air entry disks was regularly flushed through the upper and lower flushing lines, respectively. The volumes of the diffused air were measured using two diffused air volume indicators (Fredlund, 1975).

In general, the above design allows the stress state variables in the specimen to be controlled and the total volume change of the specimen to be monitored during a permeability test. The calibration results indicated that the saturated coefficients of permeability of the top and bottom high air entry disks were from 2.04×10^{-8} to 2.47×10^{-8} m/s and the permeameter can be used to measure the coefficient of permeability down to 5×10^{-11} m/s.

3. MATERIAL AND METHODS

A silty sand from a Saskatchewan Department of Highway pit, Canada was selected as the soil for testing. This soil contained 52.5% sand, 37.5% silt and 10% clay with w_L = 22.2%, w_P = 16.6% and G_s = 2.68.

The saturated coefficient of permeability for the soil was determined using the triaxial permeameter system. The soil was initially in a slurried state. After assemblage into the triaxial cell, the specimen was consolidated under six different confining pressures (i.e., 10, 25, 50, 100, 200 and 400 kPa, respectively) to six void ratios. The saturated coefficient of permeability of the specimen was measured after consolidation at each confining pressure. As a result, the relationship between the saturated coefficient of permeability and the void ratio of the silty sand was established.

In order to investigate the coefficient of permeability of an unsaturated soil as a function of both matric suction and void ratio, a group of flexible wall permeability tests (i.e., FWPT1 to FWPT6) were conducted. In these tests, the initially slurried specimens were assembled and covered with a rubber membrane. The specimens were then consolidated to various void ratios under five different confining pressures (i.e., 10, 25, 50, 100 and 200 kPa, respectively). For each particular consolidation pressure, the coefficient of permeability was measured at matric suctions of 0, 10, 20, 30, 40, 50, 60, 75 and 90 kPa, respectively. The net normal stress was kept at a constant value for each test. The total volume change of the specimen was monitored using the non-contacting strain indicators described above. When the specimens were still at saturated condition, the total volume change was also determined from inflow and outflow water volumes. The coefficient of permeability of a specimen for a specific stress state (i.e., a particular combination of the net normal stress and matric suction) was measured only after the specimen came to equilibrium under this stress state. The first test in this group (i.e., FWPT1) was terminated at a matric suction of 40 kPa due to leakage from the bottom high air entry disk. A duplicate test (i.e., FWPT2) was performed at the same net normal stress after the replacement of the disk. This group of tests provided a set of coefficient of permeability data for different matric suctions at various void ratios.

Based on the experience with the flexible wall permeability tests, a group of rigid wall permeability tests (i.e., RWPT1 to RWPT6) were performed using a stainless steel sample ring inside the rubber membrane. The total volume change of the specimen induced by increasing matric suction was not monitored in this group of tests due to negligible volume change. The initially slurried specimens were consolidated one-dimensionally under six different vertical pressures (i.e., 12.5, 25, 50, 100, 200 and 400 kPa, respectively). For each particular vertical pressure, the coefficient of permeability was measured at matric suctions of 1, 10 or 20, 40 and 80 kPa, respectively.

4. TEST RESULTS AND DISCUSSIONS

Four sets of test results were obtained from the laboratory program described above. The results are presented and discussed as follows.

Coefficient of Permeability Function for Saturated Soil

The relationship between the saturated coefficients of permeability and the void ratio for the saturated specimens is presented in Fig. 3. Three types of test results are plotted together in Fig. 3. The first set of results was obtained from a single saturated specimen as described above. The second set of results was provided by six flexible wall permeability tests. The third set of results was determined by six rigid wall permeability tests. These data indicate that the higher the void ratio, the greater the saturated coefficient of permeability. In addition, these results indicated that an approximately linear relationship on a void ratio versus log k_s scale. This relationship was first described by Lambe and Whitman (1969). Using the linear regression technique, it was shown that the slope of the best-fit line was 7.363 and the correlation coefficient was 0.8782.

Coefficient of Permeability Function for Unsaturated Soil

Two groups of permeability tests were conducted on unsaturated specimens, namely, flexible and rigid wall permeability tests. The test data obtained from the flexible wall permeability tests are presented in Fig. 4. The test data determined from the rigid wall permeability tests are shown in Fig. 5. In both cases, the coefficient of permeability versus matric suction at different void ratios follows a bi-linear relationship on a log-log scale. This relationship was suggested by Brooks and Corey (1964). For a particular void ratio, the coefficient of permeability is almost the same as the saturated coefficient of permeability when the matric suction is less than the air entry value. The coefficients of permeability decrease considerably as the matric suction is increased. These test results are better described by a general coefficient of permeability function recommended by Huang (1994), in which the coefficient of permeability

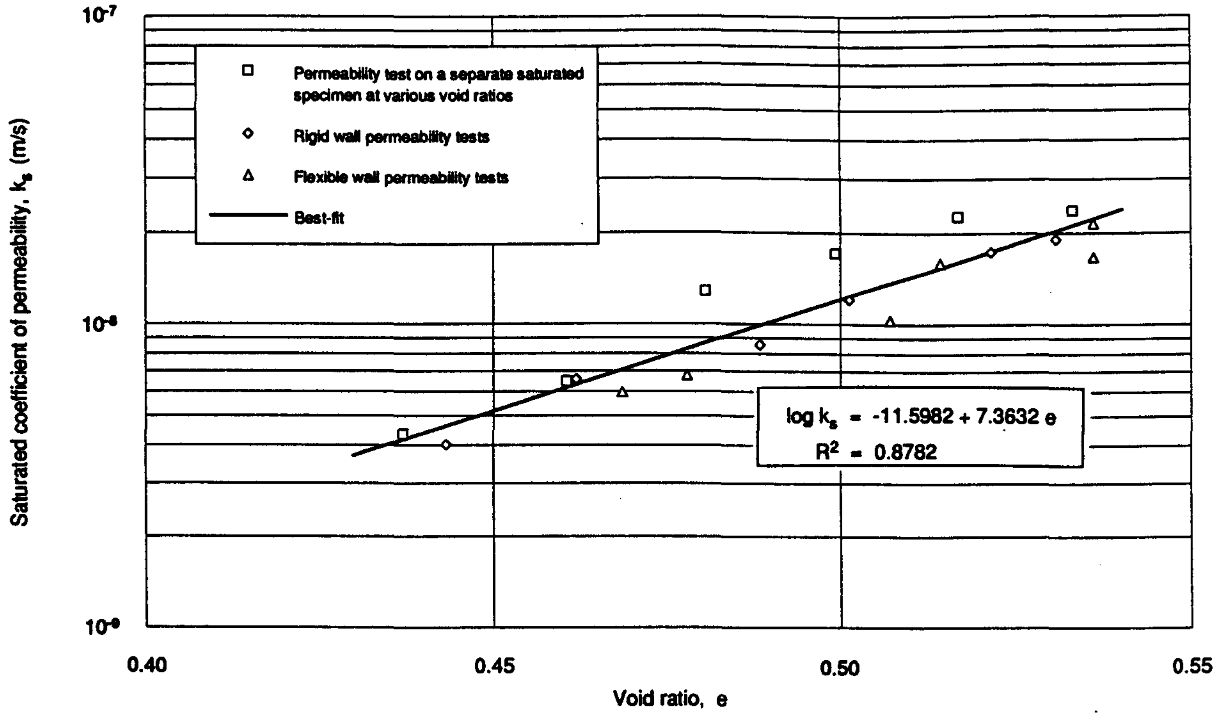
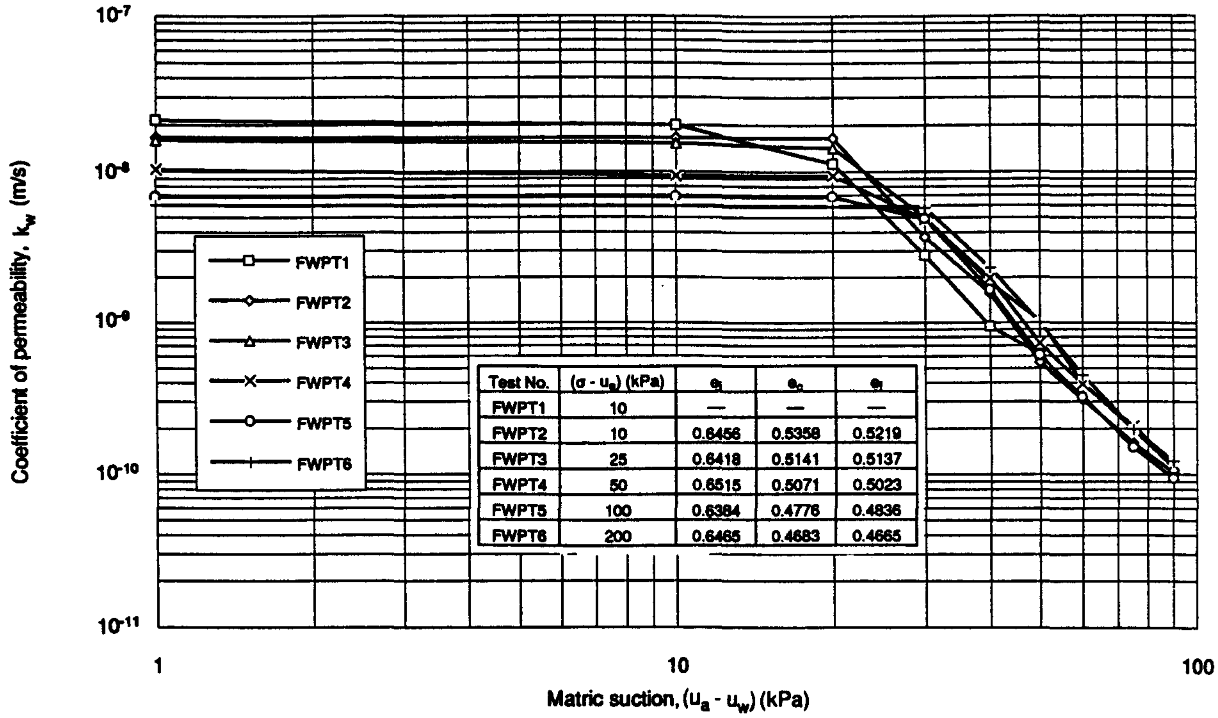
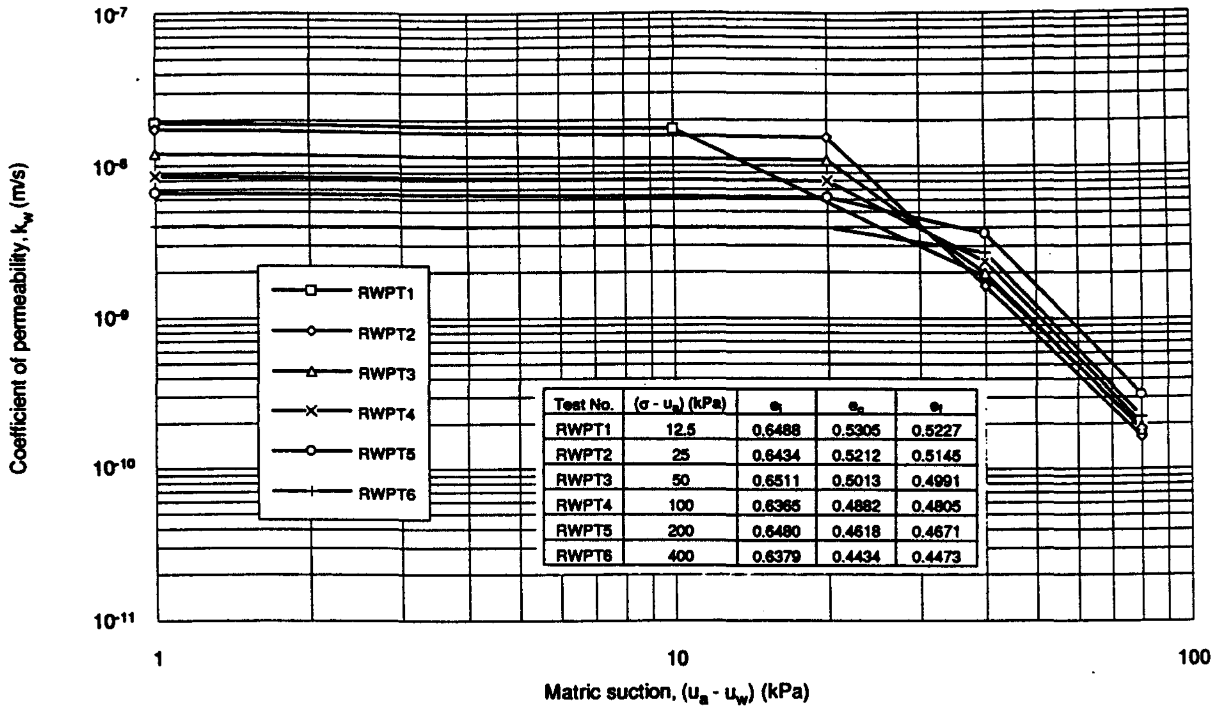


Figure 3: Saturated coefficient of permeability versus void ratio relationship for the soil tested



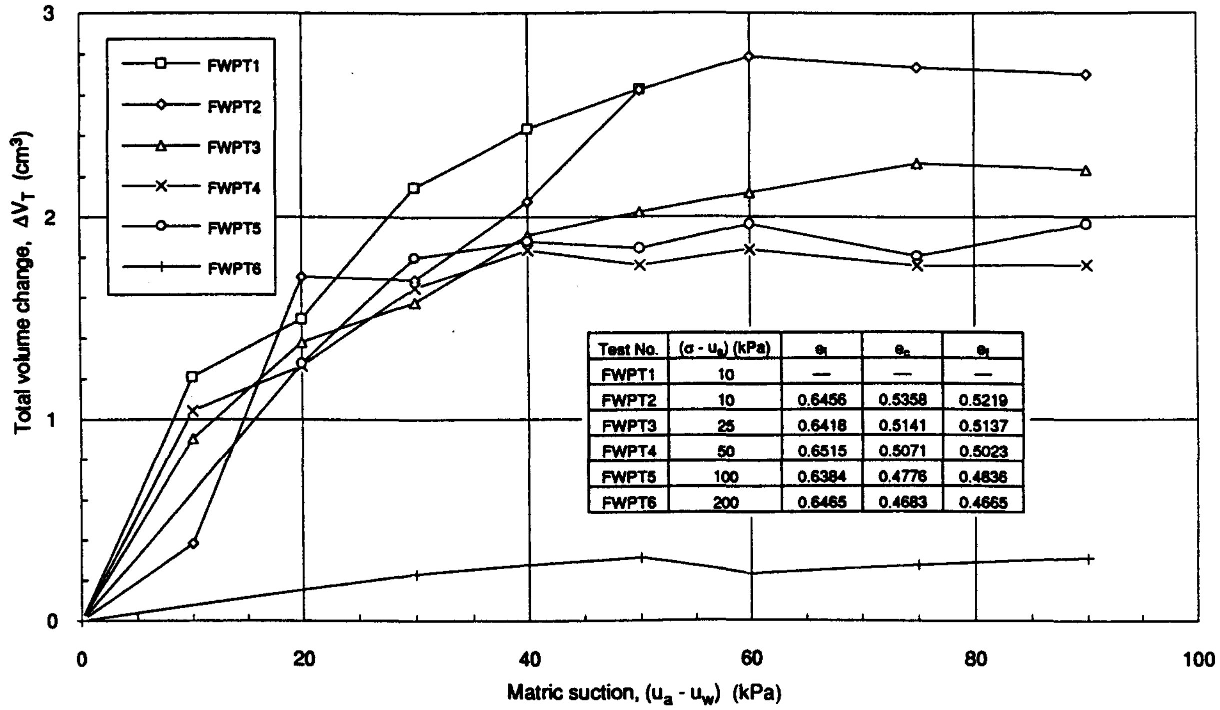
Test No.	$(\sigma - u_a)$ (kPa)	e_i	e_c	e_f
FWPT1	10	—	—	—
FWPT2	10	0.6456	0.5358	0.5219
FWPT3	25	0.6418	0.5141	0.5137
FWPT4	50	0.6515	0.5071	0.5023
FWPT5	100	0.6384	0.4776	0.4836
FWPT6	200	0.6465	0.4683	0.4665

Figure 4: Coefficient of permeability versus matric suction curves for the flexible wall permeability tests (FWPT)



Test No.	$(\sigma - u_a)$ (kPa)	e_i	e_o	e_f
RWPT1	12.5	0.6488	0.5305	0.5227
RWPT2	25	0.6434	0.5212	0.5145
RWPT3	50	0.6511	0.5013	0.4991
RWPT4	100	0.6365	0.4882	0.4805
RWPT5	200	0.6480	0.4618	0.4671
RWPT6	400	0.6379	0.4434	0.4473

Figure 5: Coefficient of permeability versus matric suction curves for the rigid wall permeability tests (RWPT)



Test No.	$(\sigma - u_a)$ (kPa)	e_i	e_o	e_f
FWPT1	10	—	—	—
FWPT2	10	0.6456	0.5358	0.5219
FWPT3	25	0.6418	0.5141	0.5137
FWPT4	50	0.6515	0.5071	0.5023
FWPT5	100	0.6384	0.4776	0.4836
FWPT6	200	0.6465	0.4683	0.4665

Figure 6: Total volume change versus matric suction curves for the flexible wall permeability tests (FWPT)

of a deformable, unsaturated soil was described as a function of matric suction and void ratio.

Total Volume Change Monitoring Results

The total volume change of the specimens in the flexible wall permeability test was monitored using non-contacting strain indicators. Total volume change results are presented in Fig. 6. The test results indicate that the total volume change induced by increase in matric suction depends on the initial void ratio. The smaller the initial void ratio, the lower the total volume change. In addition, most of the total volume change for a specimen has occurred when the matric suction approaches the 50 kPa level. In general, the total volume change for the consolidated specimens is fairly small and negligible.

5. SUMMARY

The developed triaxial permeameter system can be used to measure the coefficient of permeability for a deformable, unsaturated soils down to 5×10^{-11} m/s. The total volume change of the specimen can also be monitored using this system. The logarithm of the saturated coefficient of permeability versus void ratio relationship appears to be linear for the soil tested. The coefficient of permeability versus matric suction relationship appears to be bi-linear on a log-log scale for the soil tested at a particular void ratio. The coefficient of permeability decreases rapidly with matric suction when the matric suction is higher than the air entry value. It is close to the saturated coefficient of permeability when the matric suction is less than the air entry value. The total volume change for the soil tested after consolidation is fairly small and negligible.

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