Temperature Effect on Water Retention and Swelling Pressure of Clay Soils

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Clay-water interaction in soil systems where solute effects are negligible is measured by the matric potential. The two forces contributing to the matric potential are the swelling and capillary forces. Theoretical expectation and available experimental evidence indicate that temperature changes influence the two components differently. While an exact separation of forces cannot be made because they may not necessarily be completely independent, an assessment of the specific contribution of each can be attempted through controlled experiments.

Measurements were made at 10, 25, and 45 C of soil suction on plaster of paris samples with different void-size distribution, and of soil suction and swelling pressure on kaolinite-glass bead mixtures. Soil suction was measured on the adsorption cycle. The clay-glass bead samples were precompressed to 10 bar and were then either allowed to swell (rebound) under decreasing load, or were transferred to a pressure plate apparatus and allowed to take up water under decreasing air pressure.

The results show that in the swelling pressure test, where complete saturation exists, increased temperatures resulted in slightly increased water contents for the same swelling pressure. This is consistent with qualitative predictions based on the theory of swelling due to interaction of diffuse ion-layers. For soil suction measurements, where unsaturation occurs, increased temperatures resulted in decreased water contents for the same soil water potential. This would result from decreased values of surface tension with the temperature increases. This is demonstrated more clearly with the plaster of paris samples where the capillary force is the only component of matric potential.

These measurements of temperature effects are more useful because both swelling and water uptake are measured on identical samples. The various proportions of glass beads in the clay-glass bead mixtures—from pure glass beads to pure clay systems—provide a series of results from which the temperature effect is evaluated. The purpose is to provide information on the contribution of the components of the matric potential in water retention and swelling as affected by temperature.

THE ENERGY with which water is held in soils is referred to as the total soil water potential. Where solute effects are negligible and assuming that gravitational and gas pressure effects are insignificant, the matric potential becomes the sole component of the total potential. This situation is usually true for laboratory experimental studies. The matric potential is the component that depends upon the soil grains, i. e., the matrix of the soil (6).

The two main forces contributing to the matric potential at higher water contents are swelling and capillary forces. The former are important in clay soils while the latter are dominant in coarse-grained soils. Although it may be possible to separate the components in thermodynamic terms for theoretical considerations, it has not been possible to do so experimentally because of the interdependent behavior of the separate components. However, with the aid of controlled experiments, an assessment of the magnitude of the two forces can be made.

Several studies on the effect of temperature in the range from 5 to 50 C on water retention have been reported in the literature. The general conclusion is (a) that the effect is small and sometimes not measurable, and (b) that the amount of water retained at a given value of matric potential decreases as temperature increases (e. g., 2). These results have usually been explained as due to the decrease in surface tension, because water was considered to be held in soils primarily by surface tension forces at air-water interfaces, i. e., capillary forces. Wilkinson and Klute (4) showed that the decrease in surface tension accounted for the measured results for large sand grains, but the decrease was not large enough to explain the temperature effect in silt-size grains.

The large influence of temperature on water retention occasionally measured is thought to be due to temperature effects on the measuring instrument. The most precise measurements of matric potential are now being made with special psychrometers. Converting these measurements of vapor pressure to water potential, Klute and Richards (1) found that water content of a clay soil at constant potential did not change with temperature, but the water content of a sodium montmorillonite increased with increase in temperature. Studies of the temperature effect on swelling pressures of high-swelling sodium montmorillonite have also shown that increased temperatures resulted in increased swelling pressures for the same volume (5).

This is the temperature effect predicted from the diffuse ion-layer theory of swelling of clays (6). While this theoretical calculation of swelling pressure is based on certain assumptions that are not generally admissible for soils, and experimental confirmation of theory is limited to high-swelling soils, it is not unreasonable to expect the swelling component of the matric potential to behave in the same manner, albeit on a lesser scale. Thus, one would predict for the swelling component of matric potential that increased temperature will result in increased water content at a constant value of the matric potential.

Changes in temperature also influence the properties of adsorbed water. This is most important at lower water contents, and will not be considered here.

This paper reports measured temperature effects for water retention and swelling pressure for different clays and porous media, chosen to give both swelling and/or capillary components of matric potential. This study is part of a larger study on forces of water retention in different soils.

EXPERIMENTATION

Test samples used in this study of temperature effects on matric potential were plaster of paris blocks made with different void ratios, clay, and clay-glass bead mixtures. The clay used was a kaolin containing a small amount of mica and marketed under the name English Clay by Domtar Limited, Montreal. The glass beads used in the kaolin-glass bead mixtures were No. 14 glass beads, supplied by Potters Bros. Inc., New Jersey, with over 95 percent between 0.06 and 0.15 mm in diameter.

The plaster of paris blocks were made by mixing different proportions of plaster of paris and water to produce blocks with three different bulk densities: 0.93, 0.70 and 0.55 gm/cc. The proportions of clay to glass beads used in the different mixtures were 100 percent clay (by weight), 80, 60, 40, and 20 percent clay. The samples were wetted to saturation with water at a water potential of -1 mb. The clay and the clay-glass bead mixtures were then consolidated mechanically in the swell apparatus under a pressure of 10 bar at one of the three test temperatures, 10, 25, or 45 C. This process is similar to the consolidation process used in soil mechanics. The samples were thus always fully saturated. For the swelling pressure test, the samples were allowed to rebound

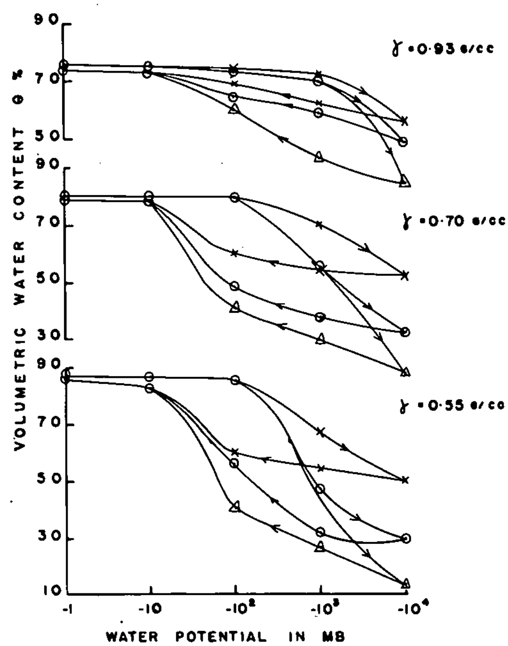

Figure 1. Temperature effect on water retention in plaster of paris (MB = millibars, γ = density).

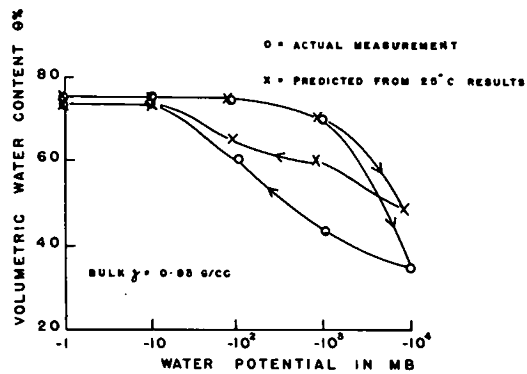

Figure 2. Predicted and measured water retention curves for plaster of paris at 45 C (MB = millibars, γ = density).

under controlled mechanical loads applied as air pressure to a flexible rubber membrane. Water content computations were made from measured values of water uptake, after drying the sample to measure the final water content.

For the water retention tests on the clay and clay-glass bead mixtures, the samples were removed from the swell chambers following equilibrium at 10 bar at one of the three test temperatures and introduced into the pressure plate apparatus at that temperature, where an air pressure of 10 bar was immediately applied directly to the sample until a new equilibrium was established. Further water expulsion occurred, possibly due to unsaturation which could occur when air pressure was applied directly to the sample. The air pressure was then lowered stepwise by a factor of 10, and the water taken up at each step measured.

The plaster of paris samples were saturated, then placed in the pressure plate apparatus at one of the three test temperatures and the equilibrium water contents measured at different air pressures on drying and rewetting.

The test results reported for the clay-glass bead mixtures are the average of two tests conducted simultaneously. Three replicates were averaged for the plaster of paris samples. The measured value agreed within 2 to 3 percent water.

DISCUSSION OF RESULTS

The three sets of results to be discussed are (a) temperature effect on water retention in plaster of paris, (b) temperature effect on swelling pressure of clay and clay-glass bead mixtures, and (c) temperature effect on water retention in clay and clay-glass bead mixtures.

The plaster of paris samples have fixed void-size distributions. The capillary force is the only means whereby water is held in the system. As would be predicted from the effect of temperature on surface tension, increasing temperatures decrease the water retention at constant potential where the sample is unsaturated (Fig. 1). The magnitude of the effect increases with decreasing bulk density. Bearing in mind that the water potential is a negative quantity, it is seen that the water potential at the point of unsaturation increases with decreasing bulk density due to increase in average void diameter. Increasing temperature increases the potential at unsaturation. These two effects, which are predicted from changes in surface tension forces, appear to result in the measured effect of bulk density.

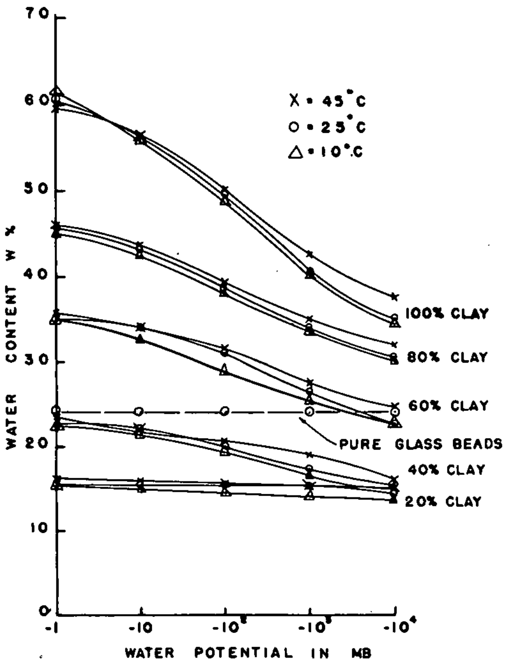

Figure 3. Temperature effect on swelling of clay and clay-glass bead mixtures (MB = millibars).

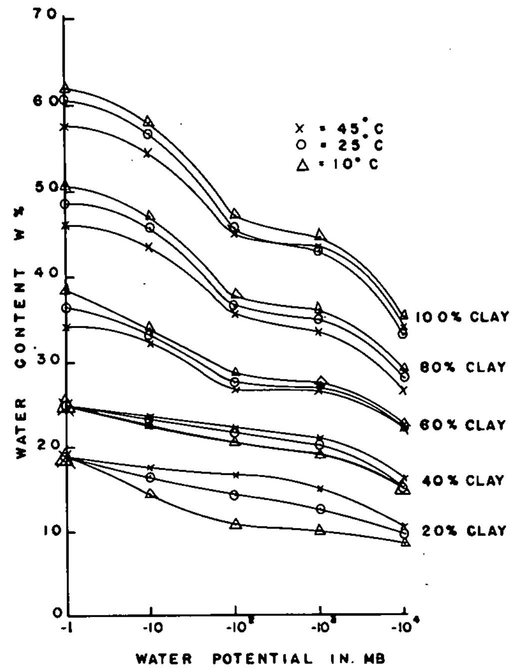

Figure 4. Temperature effect on water retention for clay and clay-glass bead mixtures (MB = millibars).

It is then interesting to determine whether the predictions from capillary theory explain the measured differences quantitatively. Calculations can be made from the equation for height of rise of water in a capillary, with surface tension and density of water having different values depending upon temperature. In Figure 2, the expected values at 45 C as calculated from measured values at 25 C are compared with measured values at 45 C.

While the effects of temperature are qualitatively as predicted, the decrease of surface tension with increasing temperature does not account for all of the measured decrease in water retention. This result is the same as found by Wilkinson and Klute (4). The calculation probably does not make an adequate correction, because it does not apply exactly to the geometry of the interconnecting voids of different sizes in the porous medium.

The measured swelling volumes for completely water-saturated samples swelling from a pressure of 10 bar are shown in Figure 3. The samples remain completely water-saturated, i.e., pores are completely filled with water, while swelling against a mechanical constraint in decreased pressure steps. Increased temperatures result in increased swelling pressures for the same water content. The effect of temperature is already established during compression where higher temperature results in higher water content at -10^4 mb potential. The amount of swelling is essentially independent of temperature with a trend at higher potential for decreasing swelling with increasing temperature. This results because more of the swelling occurs at lower potentials (3), and the temperature effect is not likely to be fully reversible.

The individual differences in pressure due to temperature changes are not large, and are about the same magnitude as the reproducibility of the measurement. However, the trends are consistent. This result is consistent with the predicted and measured influence of temperature on swelling of high-swelling montmorillonite clays. While the difuse ion-layer model for swelling cannot be applied quantitatively to the mixtures, the evidence is that the swelling component of matric potential has the op-

posite temperature coefficient to the capillary component. Temperature effects calculated from diffuse ion-layer theory show water content increases of 2 to 3 percent per 20 C—the same order of magnitude as values measured.

It has been shown from Figures 1 and 3 that opposing results occur due to temperature changes if the separate components of matric potential are considered. These results are qualitatively confirmed by the simplified theories applied to swelling and capillary retention of water. Thus measurements of water retention, where both components are known to exist, can be difficult to evaluate. In Figure 4, water retention curves for the wetting cycle are shown for samples equilibrated initially at a suction of 10 bar at the desired test temperature. Except for the 100 percent kaolinite sample, where the results for the 45 and 25 C tests appear in the reverse order, a consistent picture is presented. For clay concentrations of 60 percent and over, increased temperatures show decreased values of water retention. In the region of 40 percent clay concentration and lower, the reverse effect is seen.

The effect of the temperature changes on the two components is assumed to produce the overall change in water retention value. Thus, at proportions of clay higher than about 50 percent, the capillary component seems to dominate. Swelling within clusters or aggregates is not large enough to alter the trend produced in the large voids by the decrease in surface tension (3). At clay contents less than about 50 percent, the effect of temperature on the swelling component dominates. The clay particles tend to orient around the glass beads. One would also expect a denser packing of the beads. Swelling seems to be the dominant force in water retention.

While the effects of temperature can be predicted qualitatively with certain assumptions about fabric of the sample, it is obvious from the foregoing discussion that a number of additional factors must be evaluated before temperature effects on water retention in soils can be more completely understood. This is part of a continuing study on water retention in soils.

CONCLUSIONS

The two main components of the matric potential have been investigated in experiments designed to test their change with changes in temperature. As predicted from simplified theory, increased temperatures cause increased swelling pressures and decreased capillary water retention values in experiments where only one of the components is active. However, where the two components exist together, the two opposing trends cause different effects under temperature changes. In clay-glass bead mixtures, this may be traced to aggregate size. Where aggregate sizes are large, the swelling pressure mechanism dominates. Thus, where clay content is small, swelling of oriented clay between aggregates occurs as a dominant mechanism in water retention. On the other hand, capillary effects are dominant in the high-clay system where clay particles are irregularly aligned.

ACKNOWLEDGMENTS

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