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ON TOTAL, MATRIC AND OSMOTIC SUCTION

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Most of the basic research associated with the role played by the pore fluid in a soil was initiated by soil physicists and agronomists during the late 1800's and was later transferred to engineering. Probably the first group to recognize its importance in civil engineering was Croney et al at the Road Research Laboratory in London, England (1948, 1950). They borrowed their terminology from soil science and observed the effect of soil moisture deficiency on soil behavior. Later research workers, (Croney, Coleman and Black, 1958; Bishop, 1959; Aitchison, 1960; Jennings, 1960), attempted to incorporate the soil suction term into an effective stress equation that could be used to describe the volume change and shear strength behavior of a soil.

The review panel for the soil mechanics symposium, "Moisture Equilibria and Moisture Changes in Soils" (Aitchison, 1965), adopted the subdivision of soil suction and the definitions quoted by the International Society of Soil Science.[1]

The definitions state that total suction is equal to the sum of the matric and osmotic suction and may be determined by the measurement of the vapor pressure in equilibrium with the soil water. The fact that the vapor pressure is controlled by the dissolved salts in the pore fluid and the hydrostatic tension of the pore water lends credence to this subdivision of total suction (Edlefsen and Anderson, 1943).

Although numerous methods are available for the measurement of each component of suction, few documented cases are available in which independent measurements of matric and osmotic suction have been performed and their sum compared with the measurement of total suction on the same sample. Richards and Ogata (1961) found that their measurements of total suction and the sum of the matric and osmotic suction were not the same. It should be noted that their samples were prepared as a slurry; a small amount of extract was removed for the osmotic suction measurement and then the samples were brought to equilibrium under relatively high matric suction values (pressure membrane technique). Their analysis of the data assumes that the concentration of the salts in the pore fluid (and, therefore, the osmotic suction) remains the same as the pore fluid is being squeezed out of the sample.

Oster et al. (1969) devised a technique which allowed the independent measurement of matric suction and osmotic suction. They compared the difference of the measured osmotic suction (psychrometric measurement on pore fluid) with the osmotic suction predicted by electrical conductivity measurement on the salt solution used to saturate the samples. The latter values were smaller than those determined by the psychrometer. Their work indicates the importance of the procedure used when attempting to predict osmotic suction.

This paper presents data on the independent measurements of matric, osmotic, and total suction where dry density and water content are used as the basis for comparison of all soil suction components. The osmotic suction was computed from electrical conductivity measurements on the saturation extract as well as an extract of

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[1] Matric suction is the negative gauge pressure relative to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water.

The osmotic suction is the negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable (i.e., permeable to water molecules only) membrane with a pool containing a solution identical in composition with the soil water.

The total suction is the negative gauge pressure relative to the external gas pressure on the soil water to which a pool of pore water must be subjected in order to be in equilibrium through a semipermeable membrane with the soil water. Total suction is thus equal to the sum of matric or soil water suction and osmotic suction.

the pore fluid at the actual water content under consideration (squeezing method).

The matric and total suctions were measured only at the "as prepared" water contents and dry densities. No attempt was made to vary suction and measure changes in volume or water content since this involves the area of constitutive relationships. The purpose of this research was to verify the existing state variables under static conditions.

The research literature contains some information on the variation of matric suction with density and water content; however, the results are somewhat conflicting. Croney et al. (1958) showed that for an incompressible material such as sand or chalk, the matric suction was affected by dry density. He also stated that a compressible, compacted clay is not affected by changes in dry density. In 1960, Croney and Coleman showed a unique relationship between the suction of a "continuously disturbed" clay and water content. In other words, the density did not affect the suction measurements. However, natural undisturbed samples had a suction-water content relationship dependent upon density. Box and Taylor (1961) used a null-point tensiometer and showed that at constant water contents, higher densities resulted in a decrease in matric suction. However, the variations appear to be small from an engineering standpoint. For example, the suction decreased 1 lb/in^2 (70.3 g/cm^2) for an increase in dry density of 30 lb/ft^3 (0.48 g/cm^3). Their testing was performed in the low suction range. Olson and Langfelder (1965) presented considerable data on the effect of changing dry density and method of compaction of the soil. They tested five soil types and measured matric suctions (null-technique) up to 280 lb/in^2 (19.7 kg/cm^2). On all soil types, it can be concluded that the variation of matric suction with dry density appears to be of a secondary interest.

APPARATUS AND TECHNIQUE

Matric Suction

The apparatus used in this investigation to measure the matric suction was a Modified Anteus Consolidometer (fig. 1) developed at the University of Saskatchewan (Pufahl, 1970). The chamber of the consolidometer was filled with air at a pressure regulated by the back pressure valve (axis translation technique). Any tendency for movement of water through the stone was detected by a pressure transducer (null-point tech-

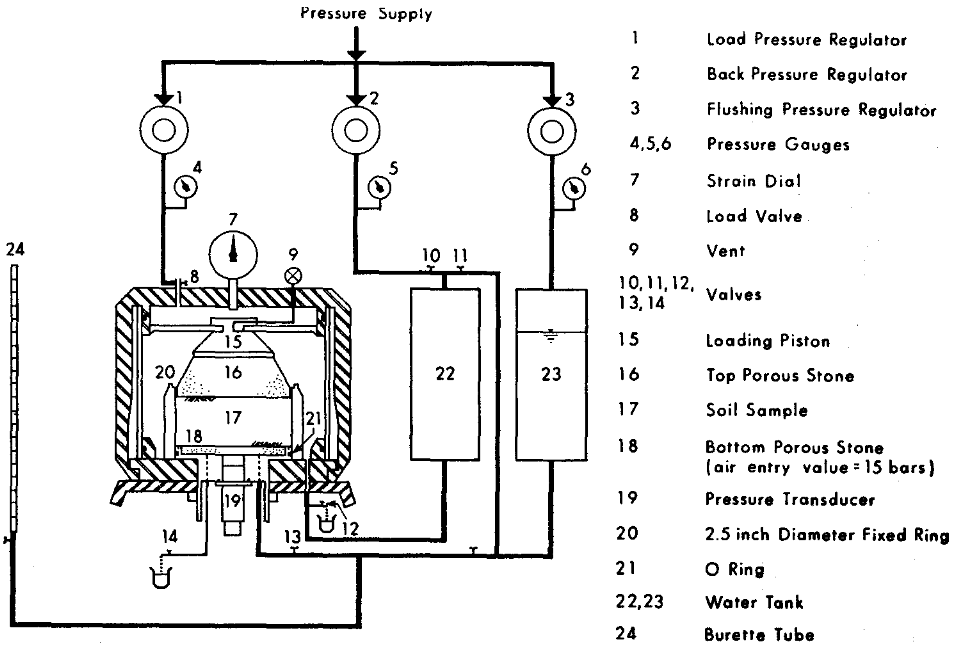

FIG. 1. Modified Anteus Consolidometer (after Pufahl, 1970).

nique). The air-entry value of the ceramic disc was 15 bars.

This technique should not measure the osmotic suction since the dissolved salts in the pore fluid are able to pass through the porous disc. Mitchell (1960) and Pufahl (1970) have shown that this type of porous disc does not act like a semi-permeable membrane.

Osmotic Suction

The osmotic suction can be determined from the electrical conductivity of an extract of the pore fluid. The saturation extract technique (USDA Agricultural Handbook No. 60, 1950) generally used in soil science involves wetting the soil to a slurried paste and measuring the electrical conductivity of a portion of the pore fluid.

The osmotic suction determined by the saturation extract technique corresponds to the water content of the slurried soil at the time of extraction. However, there is no theoretical procedure for back-calculating to obtain the osmotic suction at lower water contents. The most reasonable procedure for back-calculating would be to assume an inverse linear relationship between cation concentration and volume of water in the soil. In other words, the electrical conductivity is assumed to be inversely proportional to the water content during the wetting of a soil (i.e., linear dilution).

Alternatively, the pore fluid in the soil at a particular water content can be retrieved using a squeezer or pressure plate apparatus. A heavy-walled cylinder and piston squeezer employing pressures up to 5,000 psi (351.5 kg/cm^2) was used in this investigation. The squeezer is essentially the same in design as Manheim's (1966) but is considerably larger. The pore fluid was then analyzed in the same manner as in the saturation extract technique.

Total Suction

The total suction was measured with a psychrometer. The theory and operational technique upon which the psychrometer is based has been well documented by Spanner (1951); Dalton and Rawlins (1967); and Richards (1969). Basically, the psychrometer measures the relative humidity inside a closed chamber containing the soil sample. The total suction of the soil is computed from the relative humidity measurement (Edlefsen and Anderson, 1943).

The most difficult aspect in using the psychrometer is related to the temperature control (fig. 2). In order to measure total suction to an accuracy of 0.1 atmosphere the constant temperature bath must be maintained to within ±0.001 degree centigrade. The thermoregulator used in this study responded to a fluctuation in temperature of ±0.001 degree centigrade and it is estimated that the soil temperature was maintained within the same degree of accuracy due to the buffering effect of the glass beaker.

The thermocouple probe and the sample container are shown in fig. 3. The sample containers are considerably larger than those reported elsewhere in the literature. The only effect of the large containers appeared to be in the length of time required for the vapor pressure to equalize. Figure 4 is a plot of the galvanometer deflection versus time after the calibrating solution in the

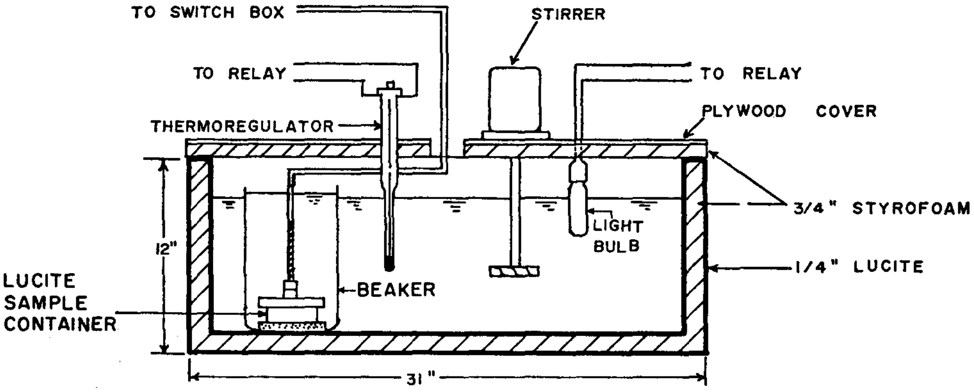

FIG. 2. Schematic Diagram of Constant Temperature Bath.

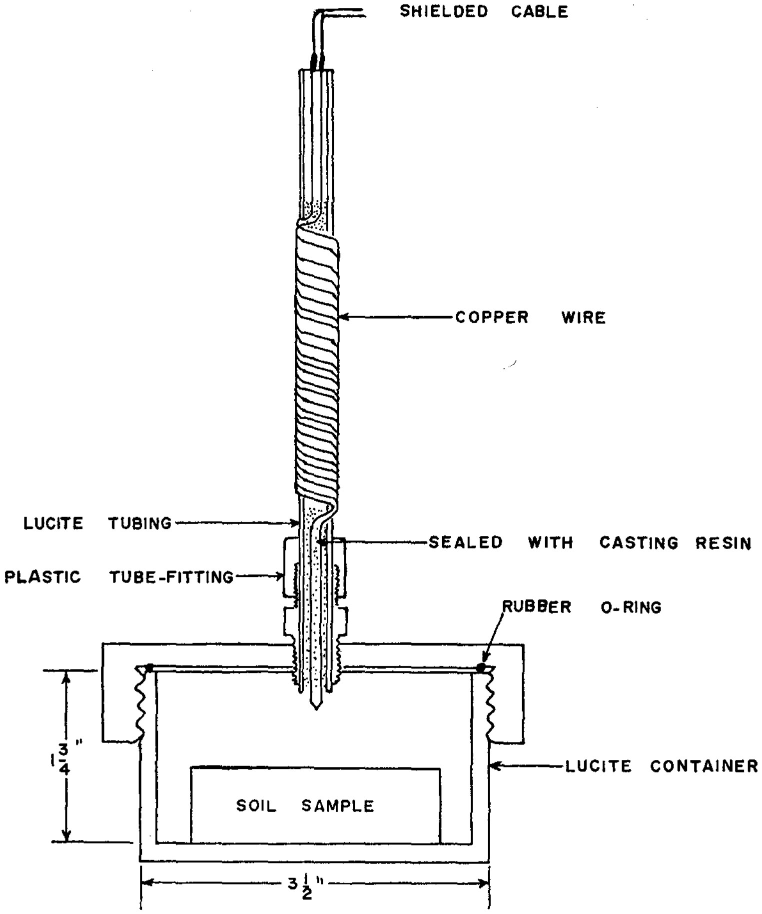

FIG. 3. Schematic Diagram of Sample Container and Thermocouple Psychrometer.

containers was placed in the bath. From the graph, it can be seen that there was little change after approximately 24 hours. However, it was found that in order to obtain consistent results, the containers had to be left in the bath until the slow decrease after 24 hours had ceased. As a result, the samples and calibrating solutions were left in the bath for approximately three days.

The bath was operated at 25° C and the thermocouple probes were calibrated using solutions of potassium chloride.

Materials Tested and Sample Preparation

Two types of soil were used in this project, a low and a high plasticity clay. The low plasticity, sandy clay is typical of the glacial till found in central and southern Saskatchewan, Canada. The high plasticity clay is from a highly swelling, lacustrine deposit found beneath the city of Regina, Saskatchewan (commonly referred to as Regina clay). Classification test results, together with the mineralogical composition and the cations in the pore water are presented in table 1.

The till was screened through a number 10 sieve, oven-dried and then mixed with the required amount of distilled water for a desired water content. The Regina clay samples were initially air-dried, crushed and passed through a number 10 sieve. The prepared soil was stored in a plastic container for at least 24 hours after which the samples were formed by static compaction. The samples were compressed in the compaction mold for at least 24 hours, then removed from the mold, wrapped in plastic wrap and waxed. They were cured for a minimum of seven days prior to testing.

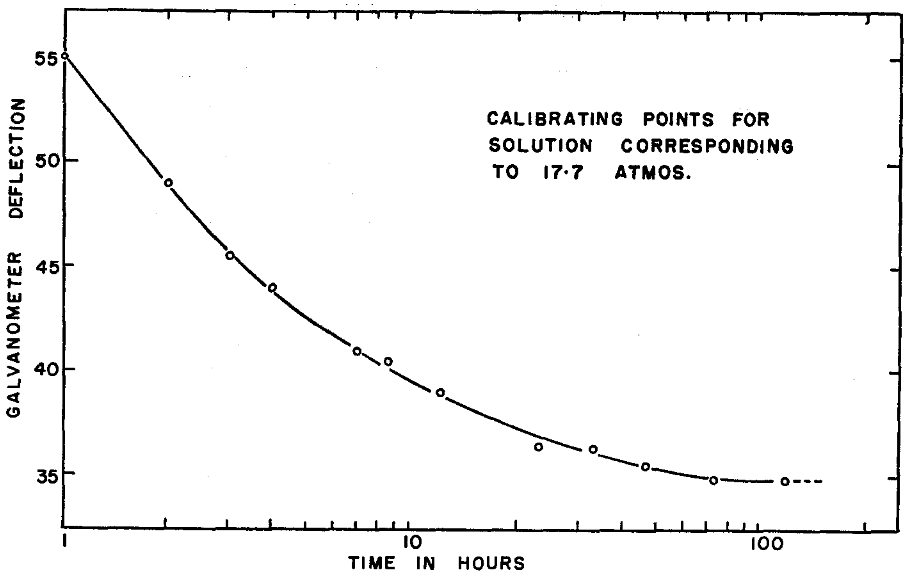

Fig. 4. Galvanometer Deflection Versus Time After Solution was Placed in the Bath.

TABLE 1

Classification Tests

	Till	Regina Clay
Specific Gravity	2.74	2.83
Atterberg Limit		
Liquid Limit (%)	33.9	78.4
Plastic Limit (%)	17.0	30.6
Plasticity Index	16.9	47.8
Grain Size Distribution[a]		
Per cent Sand	31.8	5.6
Per cent Silt	38.5	27.2
Per cent Clay	29.7	67.2
Standard Compaction		
Maximum Dry Density (lb./ft.^{3})	122.9	91.8
(g./cm.^{3})	(1.97)	(1.47)
Optimum Water Content (%)	11.8	27.8
Modified AASHO		
Maximum Dry Density (lb./ft.^{3})	112.5	—
(g./cm.^{3})	(1.80)	—
Optimum Water Content	15.6	—
Mineralogical Composition (of minus 2 micron fraction)[b]		
Montmorillonite (%)	14	20
Illite (%)	50	42
Kaolinite (%)	14	14
Mixed (12 Å) Mineral Layer	22	24
Cations in Pore Water (Saturation Extract) (Milliequivalents/100 grams dry soil)		
Sodium	1.03	1.05
Calcium	3.17	3.16
Magnesium	4.84	1.66
Potassium	0.11	0.33

[a] MIT Grain Size Scale.

[b] X-Ray Diffraction.

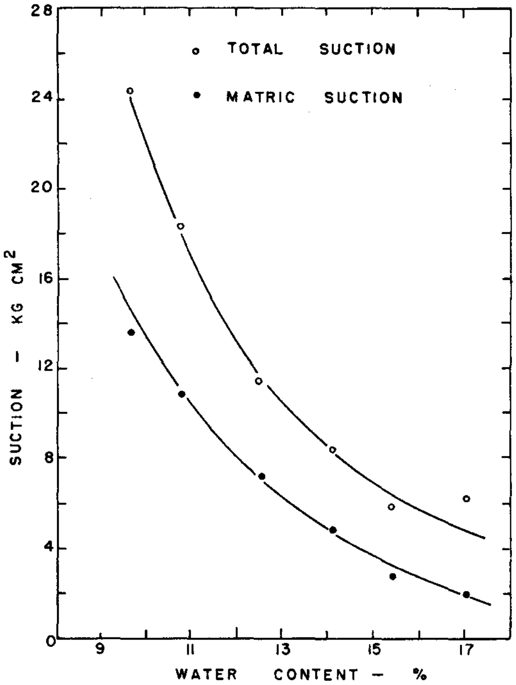

FIG. 5. Comparison of Total and Matric Suction for the Till.

EXPERIMENTAL RESULTS

Comparison of Total and Matric Suction

Figure 5 shows the results of the total and matric suction measurements on the till at various water contents and a dry density of 110.1 lb./ft.^{3} (1.76 g/cm^3). Similar results for the Regina clay at a dry density of 88.5 lb/ft^3 (1.42 g/cm^3) are shown in fig. 6. Although some scatter is evident, the trends are clear. The matric and total suction curves show similar shapes. The difference between the two curves (the osmotic suction) decreases with increasing water content as anticipated.

The Osmotic Suction

The results of the electrical conductivity measurements on the saturation extract and the pore fluid from the squeezer are shown in figs. 7 and 8. Also shown are the computed osmotic suction values, assuming a linear dilution up to the water content of the saturation extract. These results are compared with the difference between the measured total and matric suction.

The osmotic suctions obtained for the Regina clay by the squeezer technique show an excellent correlation with the difference between the total and matric suction measurements. A good correlation was also obtained for the till at the higher water contents. The osmotic suction obtained from the saturation extracts is lower than the actual osmotic suction at lower water contents. This is as anticipated, since the concentration of salts in the pore water increases with decreasing water content. The computed osmotic suctions, assuming a linear dilution up to the saturation extract water content, give values that are much higher than those obtained by the squeezing technique. For the two soils tested, the difference is substantial (in the order of 100 per cent). It appears that a linear dilution of the pore fluid does not occur upon wetting. However, to assume a more realistic, non-linear dilution theory would require more data than is obtained during the saturation extract test. From these results, it is obvious that the squeezing technique is a superior procedure.

The difference between the total and matric suctions on the till (fig. 7) deviate somewhat from the "squeezing technique" values at lower water contents. Several factors may be involved, but it is most probable that the matric suction measurements are low since the measurements are approaching the air-entry value of the porous disc. However, the dispersion in data is relatively small, and the results would appear to reinforce the validity of the subdivision of soil suction.

Relationship Between Dry Density, Water Content and Suction

The suction versus water content curves at various dry densities are shown in fig. 9 and 10. It does not appear that the suction (matric or total) is significantly affected by a change in dry density. For the sake of interest, some loose soil was placed in the psychrometer container and tested. The results showed close agreement with those obtained on the compacted soil (see fig. 9).

The results are similar to those obtained by Olson and Langfelder (1965) and further verify that a variation in dry density has little effect on the matric suction of remolded, compacted soils. The results obtained in this investigation also substantiate this for the total suction measurements. Croney and Coleman (1960) also emphasized the existence of a unique water content versus suction relationship for remolded soils.

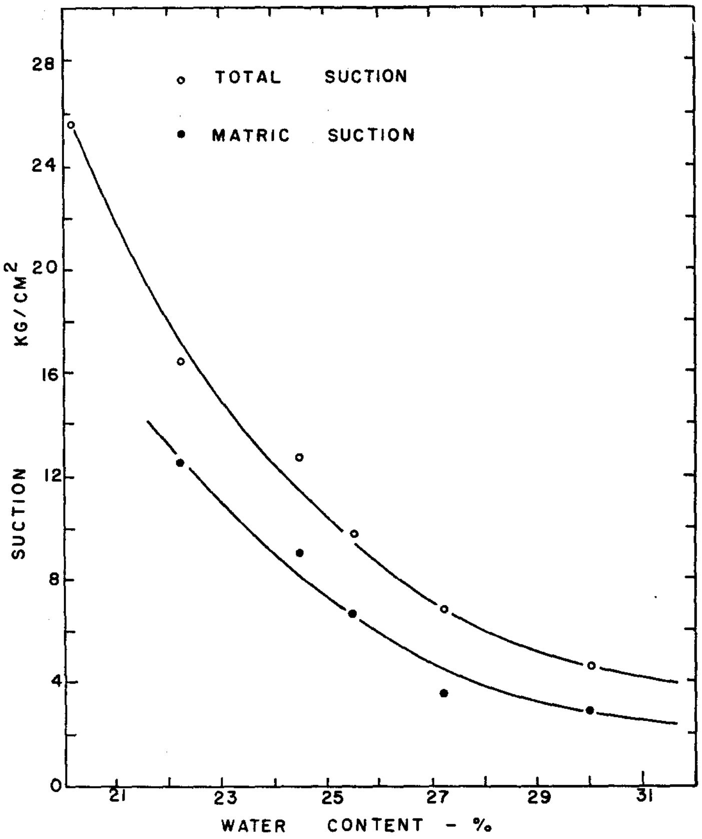

Fig. 6. Comparison of Total and Matric Suction for the Regina Clay.

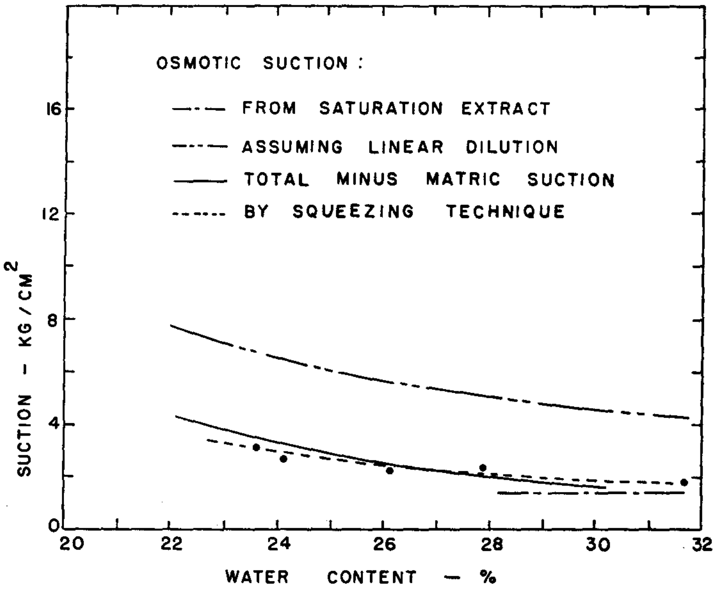

Fig. 7. Comparison of Osmotic Suctions for the Till.

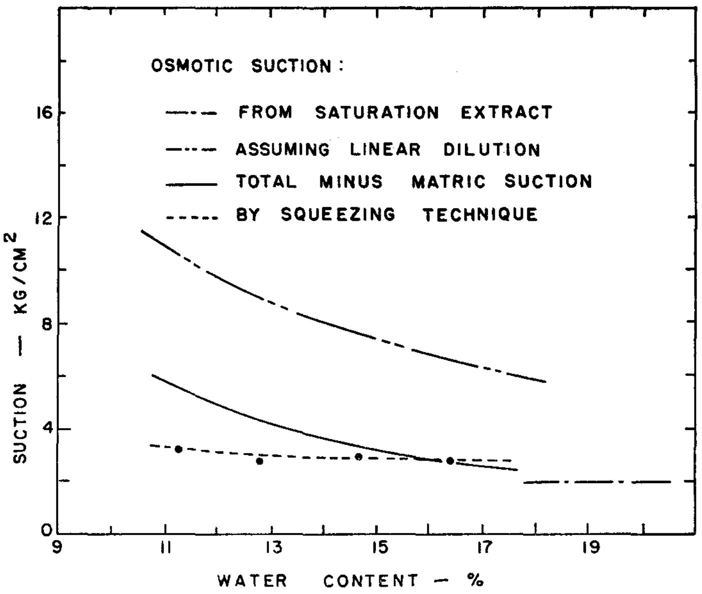

Fig. 8. Comparison of Osmotic Suctions for the Regina Clay.

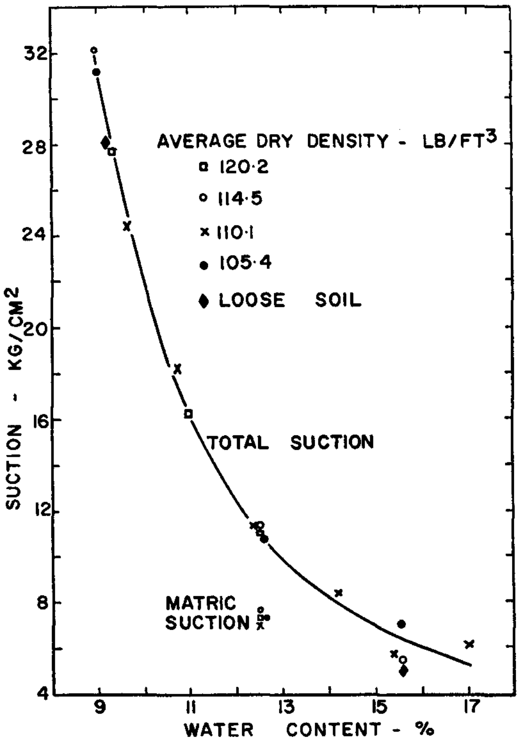

Fig. 9. Suction at Various Densities for the Till.

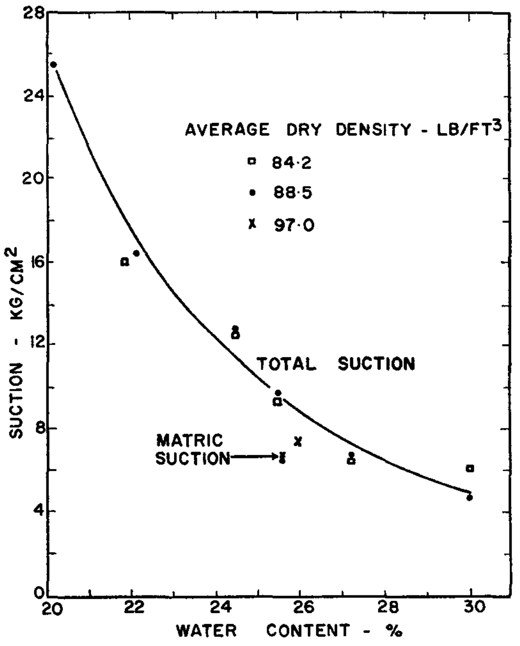

Fig. 10. Suction at Various Densities for the Regina Clay.

Although this unique relationship has repeatedly occurred, its explanation is not presently clear.

Conclusions

The conclusions which can be made on the basis of the soils tested and procedures used are as follows:

a) The values of osmotic suction determined on a saturation extract differ significantly from values obtained by using pore water obtained by squeezing. Applying a linear dilution factor to the saturation extract values also produces values that are substantially different from those obtained by the squeezer technique. The values obtained on the squeezed pore fluid were in much closer agreement with the difference between matric and total suction than were the values obtained using the saturation extract technique. The squeezer technique appears to be a satisfactory way of obtaining pore fluid for the determination of the osmotic suction.

b) The sum of independent measurements of matric and osmotic suction is equal to the measured total suction. Therefore, the generally accepted subdivision of total suction is experimentally verified.

c) For remolded, compacted soils, the matric and total suctions are dependent on the molding water content but essentially independent of the dry density.

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