Apparatus for Measuring Suction Under External Loads

G. KASSIFF and Z. GLOBINSKY
Respectively, Senior Lecturer and former Research Student, Faculty of
Civil Engineering, Israel Institute of Technology

An apparatus which measures negative pore pressures during drying and wetting processes under external loads is described, and test results on a heavy clay and a sand are presented. The present apparatus continuously measures suctions under external loads (negative pore pressures) in a single operation and determines moisture contents without removing the soil sample from the suction plate, thus avoiding interference in the contact between the soil and the plate. For the range of measurable suction the apparatus produced a compressibility factor, α, equal to unity for the heavy clay and equal to approximately zero for the sand, which agrees with the British Road Research Laboratory (RRL) work.

●THE ENGINEER RESPONSIBLE for the design of pavement foundations is primarily concerned with the soil above the water table, in which the pore pressures are negative. These pressures are functions of the moisture regime in the soil and of the applied loads. Prediction of changes in the moisture content distribution occurring when the soil is covered and loaded is of great interest in highway and airfield construction.

During the last decade, the British Road Research Laboratory (RRL) made a major contribution to this field (1, 2, 3, 5) by developing theories, instrumentation, and techniques, coupled with field experiments, for the evaluation of moisture changes occurring in the subgrade under various types of cover. From these changes other soil characteristics, such as strength and volume change, were predicted. This work was summarized by Croney and Coleman (3) and discussed by Penner (4).

It is well established now that the surface forces by which water is retained in the soil structure cause pressure reduction (below atmospheric) known as the soil moisture suction, or tension. This term has been reserved by the RRL for pressure reduction in a small sample of the soil, measured when the soil is entirely free from externally applied stresses. A relatively simple apparatus is used for the detection and measurement of soil suction, in which the suction of the soil moisture is balanced by a suction applied to the system.

In the ground, however, the soil is subjected to stress by the surrounding soil as well as by external loads. Since the stress may be effective in changing the stress-free suction of the moisture in a soil element, the pressure of the water in the soil pores, generally known as the pore water pressure, can be regarded as the algebraic sum of two components, i. e., the suction and the effect on the suction of the applied stress, as follows (1, 2, 3, 5):

$$u = s + \alpha p \tag{1}$$

in which

u = pore pressure when sample is loaded (negative),
s = suction pressure with no loading (negative),

p = applied pressure (positive), and

α = change of negative pore pressure at constant moisture content, termed compressibility factor.

The compressibility factor, α, can be measured directly by a series of loading tests on a sample of known suction. The technique used by RRL (3) consists of inclosing the sample in a thin membrane and subjecting it to increments of all-round pressures. The effect of each increment of external pressure on the pore pressure is measured by adjusting the suction applied to the system to give a static condition of the measuring meniscus in a flow tube connected to the soil sample.

The value of α may vary between unity and zero, depending on the degree of saturation and type of soil. Heavy clays remain saturated down to a moisture content corresponding to the shrinkage limit, and, therefore, α is equal to unity for these soils. Partly saturated sands exhibit a value of α close to zero. Other typical values (2) ranged from $\alpha = 0.15$ for sandy clays to $\alpha = 0.5$ for silty clays.

The RRL method of determining the negative pore pressure, u, has the main disadvantage of carrying out the measurements by two different apparati using two different samples, one for the suction and the other for α. Also, the compressibility factor, α, is measured by applying a uniform all-round pressure, whereas the soil element in nature is subjected to different pressures in the vertical and horizontal directions. It would, therefore, be desirable to develop an apparatus which would continuously measure the negative pore pressure under drying conditions in a single operation and subject the soil sample to different stresses in the vertical and horizontal directions.

This paper reports progress of work on development of a tensiometer for determination of moisture-suction under load (negative pore pressure) function, which conforms with the requirements specified previously. The range of measureable suction
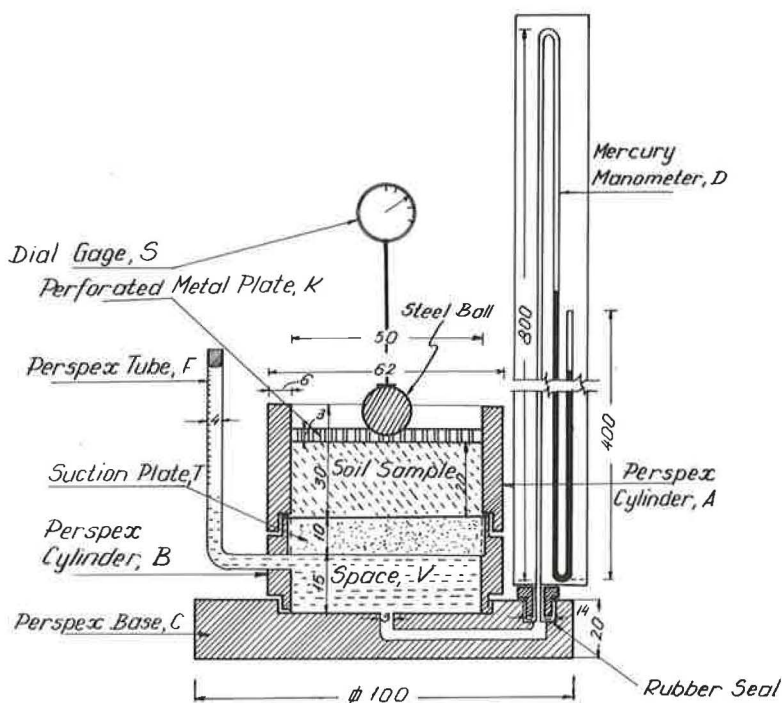
Figure 1. Detailed section of tensiometer.

at this stage, however, is limited to $\frac{3}{4}$ atmos. Continuation of the work to increase the range of measureable suctions, as well as the number of soils tested, is underway (6).

DESCRIPTION OF APPARATUS

The apparatus consists of a tensiometer made of a suction plate and a manometer mounted on a loading frame.

Figures 1 and 2 show a detailed drawing and a closeup photo of the tensiometer. The latter consists of a Perspex cylinder, 50-mm I. D., made of two parts, A and B, screwed to a Perspex base, C. At the top of part B a suction plate, T, is fitted, below which the space, V, was filled with deaired distilled water. The soil sample, 30 mm high, is placed on top of the suction plate. The sample is covered with a light metal plate, K, and a steel ball to allow for uniform distribution of the external load on the sample. The plate, K, is perforated for the purpose of wetting as well as drying to the air of the sample. A dial gage, S, is mounted on the ball to measure movement of the soil on swelling and shrinkage. The suction plate, T, is connected through the space, V, to a graduated stand-tube, F, for the purpose of measuring accumulation of air entrapped during the saturation process. A mercury manometer, D, is connected through the base to the suction plate, T.

The tensiometer is placed on a loading frame, which allows for the application of load to the soil sample through a lever system. Figure 3 shows the loading setup.

TEST PROCEDURE

After saturating the suction plate by applying vacuum through the base C, the soil sample is compacted by a static pressure into the Perspex cylinder A. The two parts of the cylinder, A and B, are then fitted tightly to each other to secure close contact between the soil sample and the suction plate. The apparatus is placed on the loading frame and the desired pressure applied on the soil sample. Under this pressure the sample is allowed to saturate by being exposed to water filling the top part of cylinder A. The vertical swelling is measured during saturation by the dial gage until com-
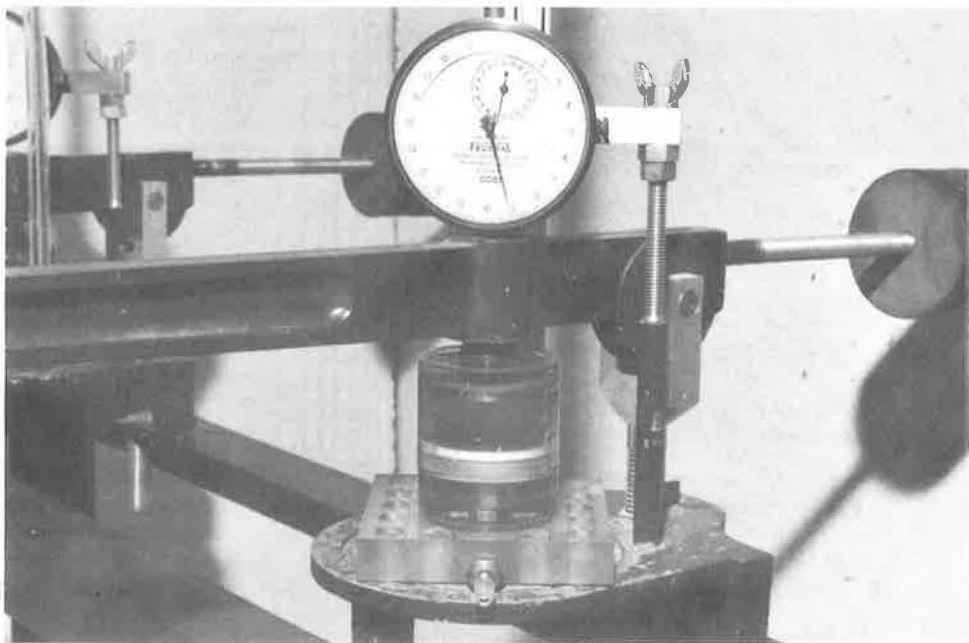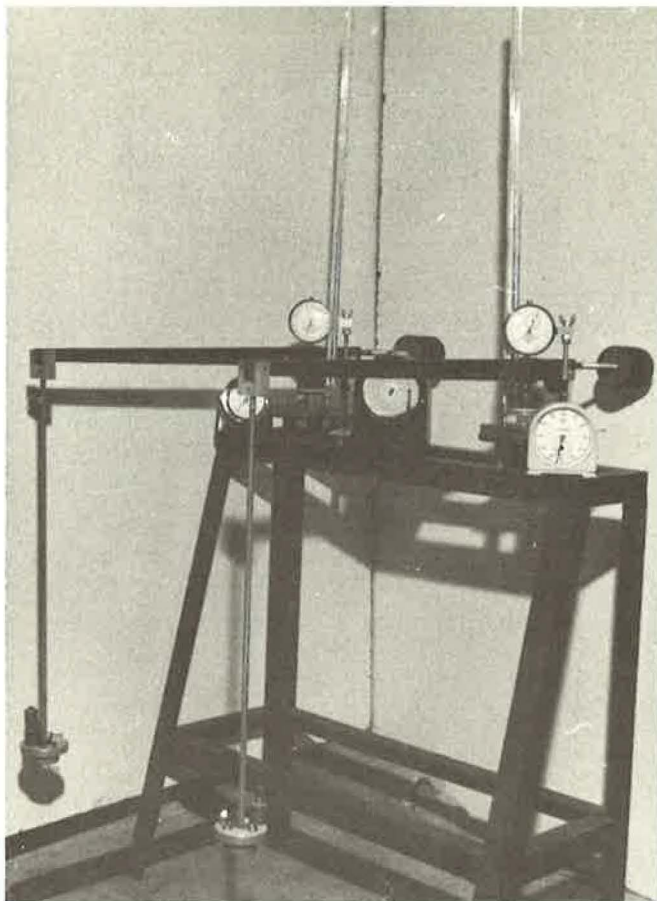

Figure 2. Closeup of tensiometer.

Figure 3. Loading setup of tensiometer for application of external loads.

plete saturation is achieved and no movement is registered, which takes about 7 days. Free water left on top of the sample is then removed and the apparatus is weighed by a precision balance. With the dry weight of the sample and the weight of the apparatus filled with water known, the moisture content at saturation may be determined. The reading on the manometer taken at this stage corresponds to zero suction.

The soil sample is then allowed to dry to the atmosphere. At various stages of the drying process, readings are taken on the manometer to determine the suction and on the dial gage which indicates skrinkage by its downward movement. The corresponding weights of the apparatus at these stages indicate the loss of water, which is used to determine moisture content. Before each weighing, the sample is prevented from drying for 2 to 3 hr to insure moisture equilibrium within the soil.

When the maximum suction measurable by the apparatus is attained ($\frac{3}{4}$ atmos), the sample is gradually wetted and the hysteresis in the moisture-suction function is established.

Two corrections should be applied to the weight of the apparatus to allow for the following changes during the process of drying: (a) a correction for the change in the weight of the water within the capillary tube of the manometer due to changes in suction; and (b) a correction for a change in weight of the water within the stand-tube, F, due to accumulation of air, usually occurring at suctions above $\frac{3}{4}$ atmos. The weight of the suction plate is assumed constant throughout the test.

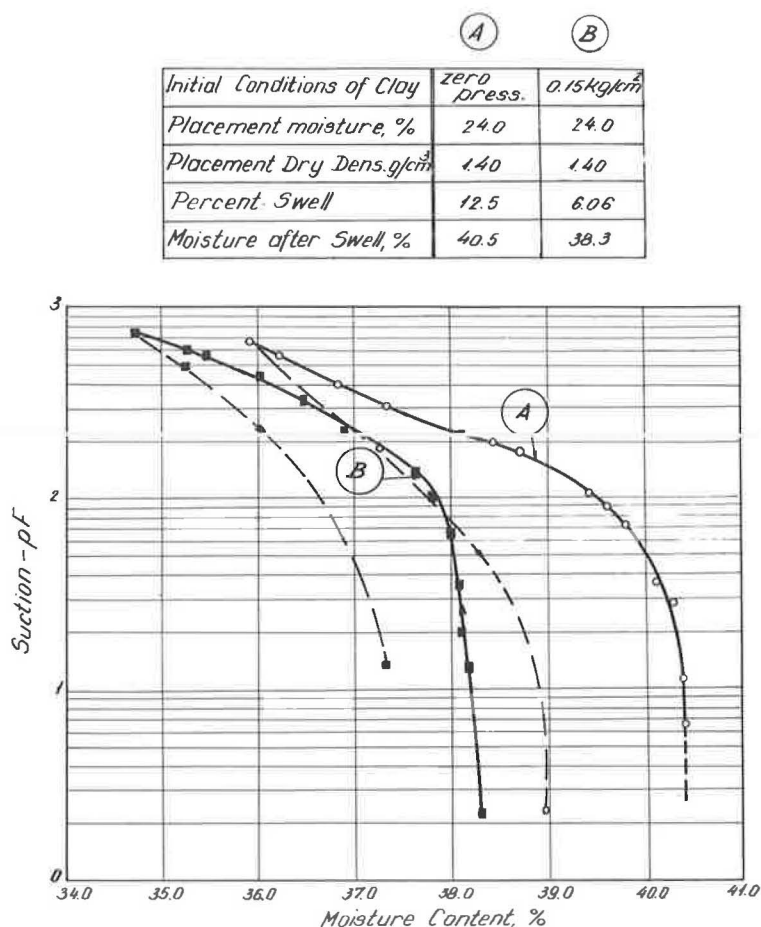|	Ⓐ	Ⓑ
Initial Conditions of Clay	zero press.	0.15kg/cm²
Placement moisture, %	24.0	24.0
Placement Dry Dens. g/cm³	1.40	1.40
Percent Swell	12.5	6.06
Moisture after Swell, %	40.5	38.3

Figure 4. Moisture-suction functions for externally loaded and unloaded heavy clay.

The test is carried out in a constant temperature room to avoid effects of temperature changes on the measurements.

RESULTS

Two soils were tested by the apparatus, and their moisture-suction functions up to ¾ atmos were determined. The first soil was a heavy clay, with a liquid limit of 75, a plasticity index of 55, and a shrinkage limit of 9.5. The second soil was a uniform fine sand with a 50 percent size equal to 0.15 mm. Both soils were tested for suction under zero external pressure, as well as under an external pressure of 0.15 kg/sq cm.

The test results are shown in Figure 4 for the clay and in Figure 5 for the sand. The difference in suction for the clay (Fig. 4) between the unloaded sample and the loaded one is approximately 0.15 kg/ sq cm, which corresponds to the external pressure on the loaded sample. This means that the compressibility factor, α, for this soil is approximately unity, as the clay remained saturated within the range of moistures under which the suction was measured. The corresponding curves for the sand, however, are almost identical (Fig. 5), which means that α is approximately zero, as would be expected from a purely granular soil.
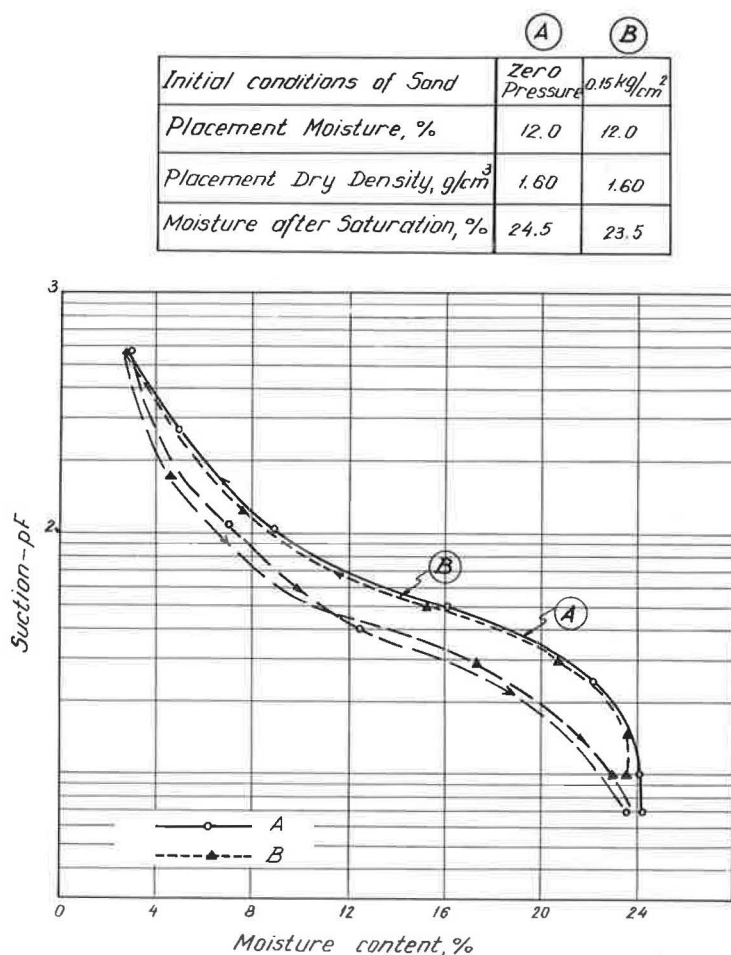
Initial conditions of Sand	Zero Pressure	0.15 kg/cm²
Placement Moisture, %	12.0	12.0
Placement Dry Density, g/cm³	1.60	1.60
Moisture after Saturation, %	24.5	23.5

Figure 5. Moisture-suction functions for externally loaded and unloaded sand.

CONCLUSIONS

An apparatus which measures negative pore pressures during drying and wetting processes under external loads has been described and test results on a heavy clay and a sand presented. As compared with the British methods, the present apparatus has the advantage of continuously measuring suctions under external loads (negative pore pressures) in a single operation. It has also the advantage of determining moisture contents without removing the soil sample from the suction plate, thus avoiding interference in the contact between the soil and the plate. The test results show that for the range of measureable suction the apparatus produced a compressibility factor, α, equal to unity for the heavy clay and to approximately zero for the sand, which agrees fully with the RRL work.

The apparatus has, however, the limitation that the range of measureable suctions is up to ¾ atmos. Another limitation of the work presented is the small number of soils tested to date. Continuation of this work in respect to both limitations is underway and will be reported in the future.

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