Movement and Distribution of Water in Soil in Relation to Highway Design and Performance

D. CRONEY, J. D. COLEMAN, and W. P. M. BLACK, Road Research Laboratory, Department of Scientific and Industrial Research, United Kingdom

Introductory Remarks by the Chairman

In 1907, Buckingham published his pioneering work on the capillary potential. Ever since, agronomists and engineers have tried to develop this concept into a practically useful methodology. With respect to highway engineering, Mr. Croney and his associates at the Road Research Laboratory have made the most outstanding contribution in this development. The present paper is a lucid exposition of this concept and what they have done with it.

The essence of science is abstraction and generalization; the essence of engineering is to use abstractions and generalizations as guides to treatment of actual systems possessing specific geometrical and material properties. This means that before becoming useful engineering tools, abstract concepts must be reinvested with real properties and must be modified according to the actually obtaining conditions, if the latter differ from those that had to be assumed in the formulation of the theoretical concept. Some of the basic assumptions on which the capillary potential concept is based, such as equilibrium conditions and reversibility, are seldom fulfilled in actual road soil structures. There exists an urgent need for more information concerning the extent to which such actual deviations from the theoretical assumptions determine the behavior of real systems. The work reported by Deryaguin and Melnikova and by Hallaire in this symposium touches on a number of problems that must be solved before we can be sure that we know the real limits within which we can safely employ this valuable and attractive concept of the capillary potential. This acknowledged need does not diminish, however, our great respect for the fine work and achievement of Mr. Croney and his associates.

● 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. In this respect he may be regarded as having more in common with the agriculturalist than with his colleagues dealing with the soil mechanics of deeper foundations. At the Road Research Laboratory in Great Britain the importance of the energy concept of soil moisture, developed by agricultural research workers, has for long been recognised and over the past 12 years its application to subgrade moisture problems has been systematically developed.

In the saturated zone beneath the water table the fundamental importance of the soil moisture suction or tension in determining moisture flow is not immediately apparent. It is only in the last few years that the growing interest in the strength characteristics of unsaturated soils has focused general attention on the influence of soil suction both in relation to soil moisture migration and shear strength. It is felt therefore that this may be an appropriate time to summarise some of the work in this field carried out by the Road Research Laboratory since the World War II.

THE THERMODYNAMIC APPROACH TO SOIL MOISTURE MOVEMENT

Moisture content on a weight basis provides the simplest method of evaluating the water in soil. At the same time the inadequacy of moisture content as a criterion when the mechanical and physical properties of the soil/moisture system are being considered, has become apparent. To establish moisture equilibrium, water may flow from a granular soil of low moisture content into an adjacent clay soil of initially much higher moisture content. Even in a mass of uniform soil, moisture migration may take place from areas of low moisture content to areas of higher moisture content, depending on the previous moisture history of the soil. Moisture content does not therefore provide the gradient responsible for liquid flow. Similarly the work necessary to extract or displace moisture in soil is not fundamentally related to the moisture content on a weight basis. It seems reasonable to suppose that the stresses required to shear or compact the soil are more likely to be related to the stress condition of the water than to the weight of the water.

It was considerations of this type that led agricultural research workers, commencing with Buckingham (1) as long ago as 1907 and followed by Thomas (2) and Schofield (3), to develop the energy approach to soil moisture problems. This early work has led to a general thermodynamic approach which enables equilibria following all reversible changes of pressure, volume and temperature in the soil/water/air system to be expressed mathematically (4). Although not quantitatively applicable to irreversible processes such as compaction and shear, energy concepts, as is shown later in this paper, provide a powerful adjunct to the standard soil mechanics approach to such processes.

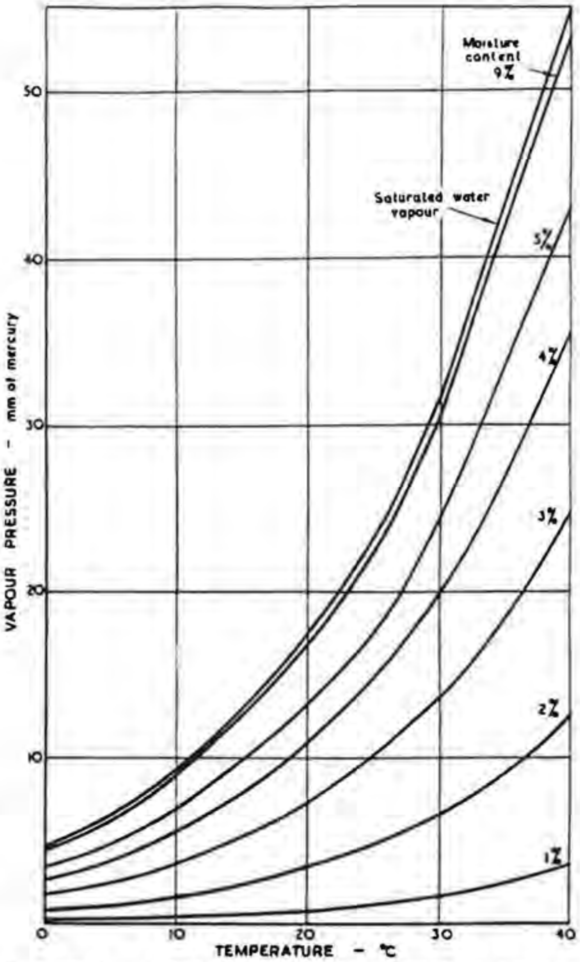


Figure 1. Variation of soil vapour pressure with temperature.

In a soil mass, the potential gradient causing water to flow from one point to another may be one of hydrostatic pressure, of vapour pressure or of both in combination. Under uniform temperature conditions, the variation of vapour pressure with moisture content is small for soils at the moisture contents likely to be found in practice, as is shown in Figure 1. It is only in very dry soil that vapour-pressure gradients are likely to be appreciable, assuming uniform temperature conditions. On the other hand the large variation of vapour pressure with temperature does give rise to considerable gradients of vapour pressure when temperature differences exist. In considering uniform temperature conditions, however, the contribution of vapour flow to soil moisture migration can be neglected.

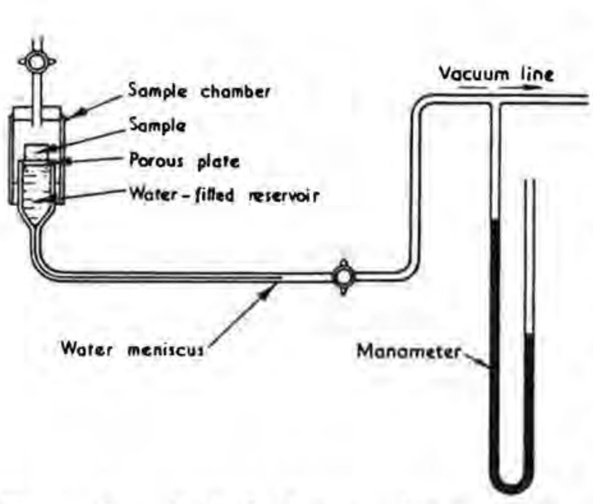


Figure 2. Method of measuring soil suction.

The surface forces by which water is retained in the soil structure are responsible for the pressure reduction (below atmospheric pressure) known as the soil suction or tension. In Great Britain this term has been reserved for the pressure reduction in a small sample of the soil measured when the sample is entirely free from externally applied stresses. Figure 2 shows a simple apparatus 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. On the pF scale of measuring soil suction, the pF value of the soil moisture is equivalent to the common logarithm of the suction expressed in centimeters of water. The letter F represents the free energy of the soil when not subjected to external stress (3).

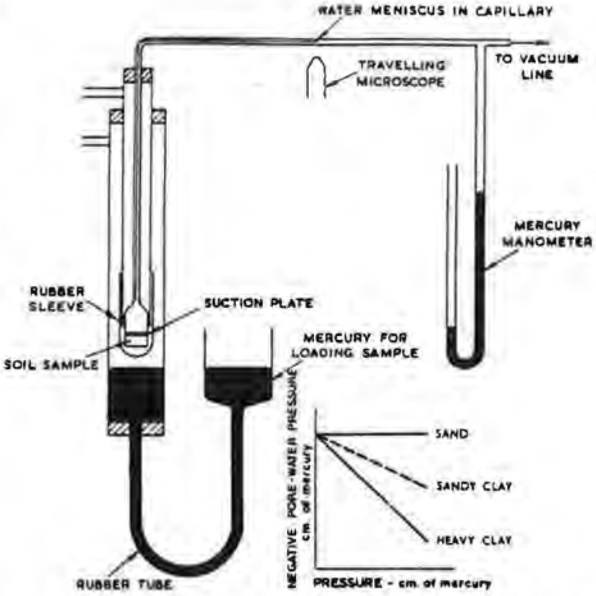


Figure 3. Determination of compressibility factor for soil by measuring the change in pore water pressure caused by an applied load.

In the ground, each small element of soil is subjected to stress by the surrounding soil and hence indirectly by externally applied loads. Since this stress may be effective in changing the stress-free suction of the moisture in the 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, viz., the suction and the effect on the suction of applied stress. The effect of external stress on pore water pressure can be measured by the apparatus shown in Figure 3. The suction of a small unloaded sample is first measured by an apparatus inverted but otherwise exactly similar to that shown in Figure 2. The sample, enclosed in a thin rubber membrane, is then subjected to increments of all-round pressure by introducing mercury into the concentric external tube. The effect of each increment of external pressure is measured by adjusting the suction applied to the system to give a static condition of the meniscus in the flow-tube.

If u is the pressure of the pore water when the sample is loaded (the pore-water pressure), s is the suction in the sample when the soil is free from external loading and P is the applied pressure, the relationship between these quantities can be expressed by the equation

$$u = s + \alpha P \qquad (1)$$

where α is the fraction of the applied pressure P which is effective in changing the pressure of the soil water. The limits of α are therefore 0 and 1.

If the change of pore-water pressure with applied pressure, determined by the apparatus shown in Figure 3, is plotted in the manner shown inset on that figure, the intercept on the vertical axis corresponds to the suction s and the slope of the pore-water pressure/applied pressure relationship gives the value of α, to which the term "compressibility factor" has been applied. For moderate applied pressures the relationship between pore pressure and applied pressure is found to be approximately linear except when the suction is numerically small in relation to the applied pressure, which is likely to be the case when the soil is close to saturation. Figure 4 shows measurements of the compressibility factor carried out on a sand, a heavy clay and an intermediate soil. For the unsaturated sand the value is close to zero, although a value approaching unity would be obtained for the same soil in the saturated condition. For the heavy clay the value is substantially 1 and for the silty clay 0. 3.

Since the value of suction for a soil increases as the soil becomes drier any local change in moisture content will cause a redistribution of water in the soil. Similarly the application of a local pressure to a soil mass may set up hydrostatic pressure gradients tending to cause a redistribution of moisture. In either case, Eq. 1 can be used to calculate the magnitude of the redistribution, as is shown later in this paper. In making such calculations the possibility of irreversible changes in the suction of the soil due to changes in the soil structure, that is, the particle arrangement, must be taken into account.

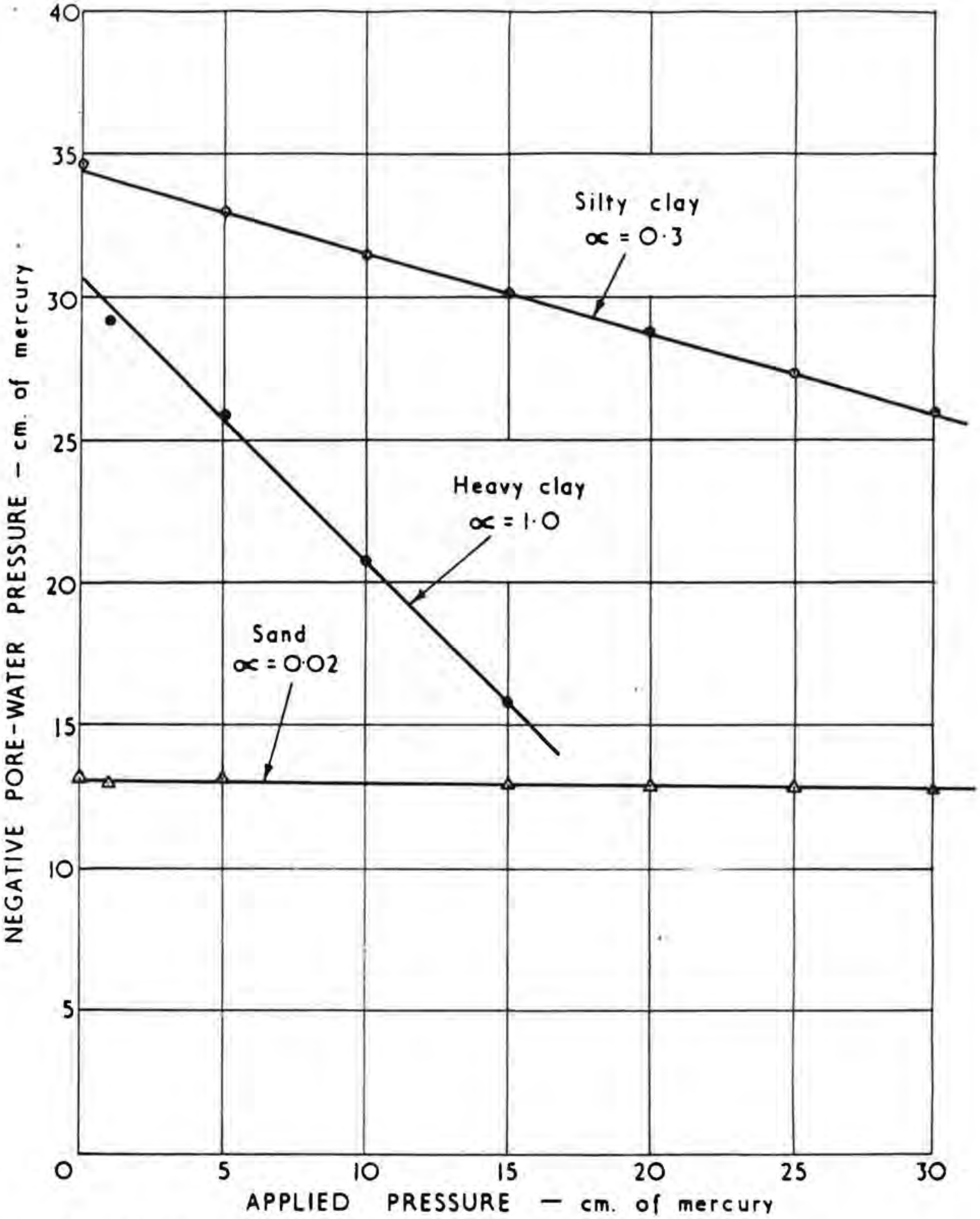


Figure 4. Relationship between pore-water pressure and applied pressure for various soils.

The migration of water in soil is accompanied by some change of volume. This may be reversible or irreversible again depending on whether any permanent structural modification has occurred due to the moisture movement. The subsoil within a few feet of the earth's surface will by virtue of its relatively exposed condition tend to behave reversibly for any normal seasonal climatic fluctuations.

Volume changes resulting from applied pressure can be measured unidirectionally

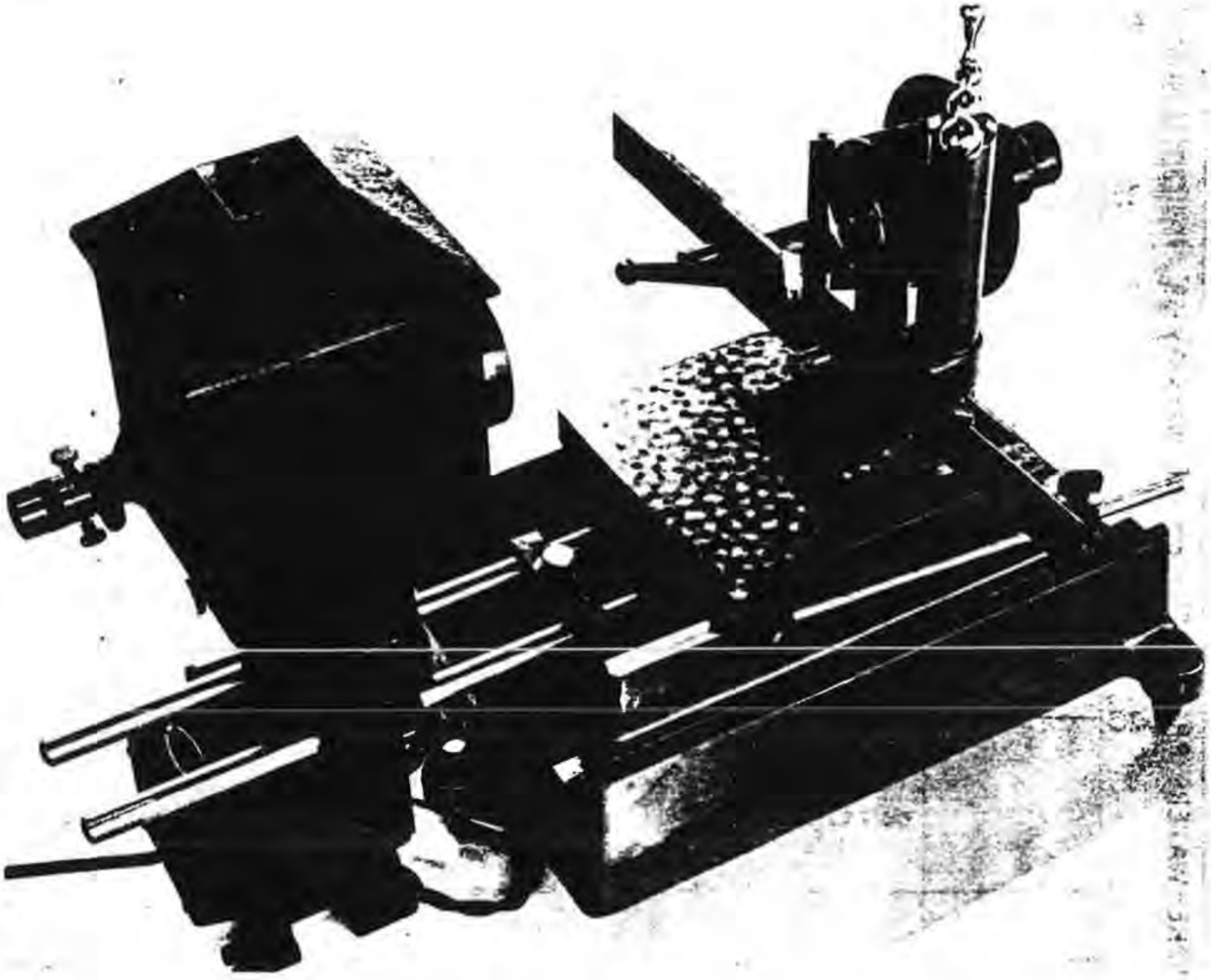
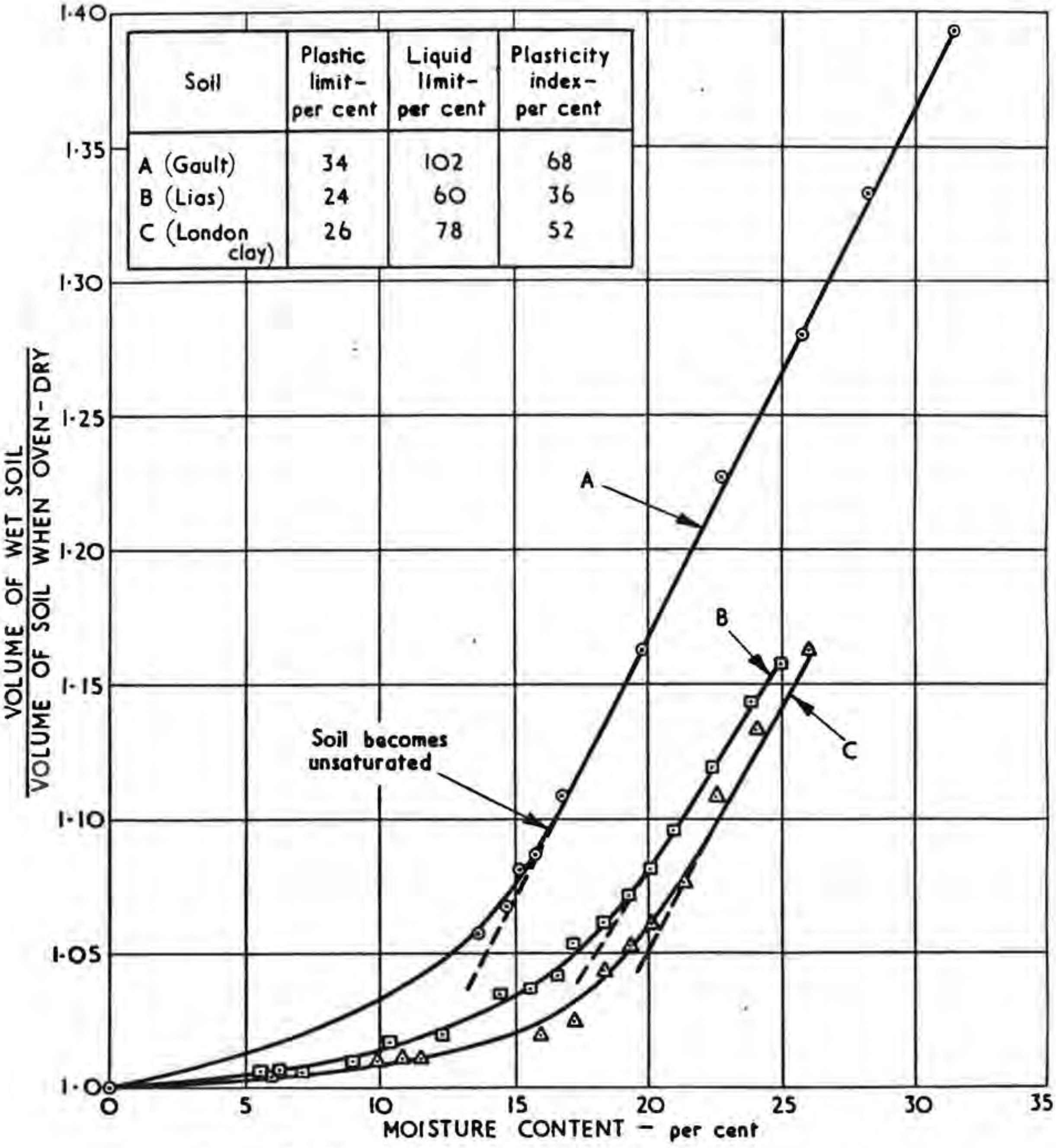


Figure 5. Optical projector used to measure the shrinkage of soil.

by the oedometer apparatus or three-dimensionally by a triaxial cell. The mercury displacement method has been used for studying the shrinkage and swelling of soils with change in moisture content. In recent years, however, an optical projection method developed at the Road Research Laboratory has been found to be more convenient and capable of greater accuracy. An engineering profile projector (as used for screw threads) is used. A cylindrical sample of the soil up to 2 cm in height and in diameter is placed in the focal plane of the projector, Figure 5, and an image is obtained at a magnification of about 50 times. Diameter and height measurements are made in three planes and the volume of the sample is computed. To overcome the difficulty of focusing the flat ends of the sample, the latter is placed in a rotating stage between upper and lower sets of knife-edges, each set consisting of three knife-edges mutually at 120 deg. The height measurements are made between the projected images of the knife-edges. In studying soil shrinkage, the sample after the initial measurement of weight and volume is allowed to dry in air for a few minutes, after which it is sealed in an enclosure to allow the moisture to equilibriate within the soil, before the next set of measurements is made. This process is repeated, the final stages of drying being carried out in the oven. Using this method the shrinkage curve can be studied in detail, particularly the critical region for heavy clays where the shrinkage curve begins to deviate from the saturation line. Typical curves obtained by this method are shown in Figure 6.

Temperature gradients in soil give rise to vapour pressure differences, the magnitude of which can be deduced from curves of the type shown in Figure 1. In soils with continuous air voids a rapid transfer of moisture by a process of evaporation and condensation would be possible. Any equilibrium set up by a steady temperature gradient would be a dynamic one. The moisture transferred in one direction in the vapour phase would equal the liquid transfer in the other direction arising from the hydrostatic gradient created by vapour flow. The transfer of moisture by temperature gradients has been studied fairly extensively (5, 6, 7). Some results obtained many years ago at the Road Research Laboratory (6) are shown in Figure 7. The tests were conducted on sealed cylinders of soil 11 cm long compacted at various initial moisture contents, to the same dry density, that is, to various air contents. The ends of the samples were maintained at temperatures of 22 and 42 C and the moisture distributions were obtained by slicing the specimens after preliminary tests had shown that moisture equilibrium had been attained.

Although these results confirm that the movements of moisture are greatest in the least saturated soils, that is, those in which transfer in the vapour phase is likely to be greatest and transfer in the liquid phase least, the fact that some transfer occurred



Soil	Plastic limit–per cent	Liquid limit–per cent	Plasticity index–per cent
A (Gault)	34	102	68
B (Lias)	24	60	36
C (London clay)	26	78	52

Figure 6. Shrinkage curves for three heavy clay soils.

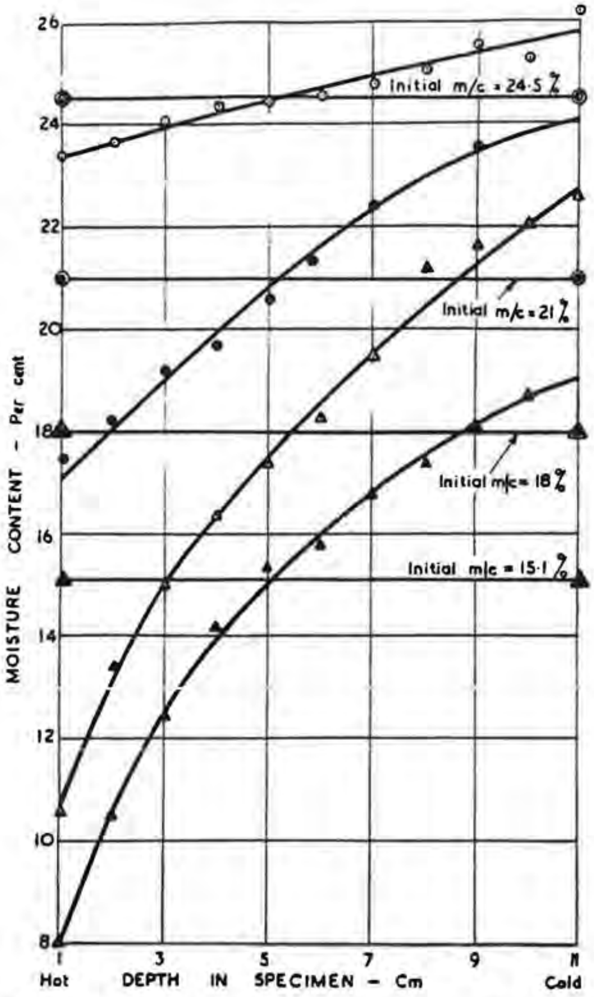


Figure 7. Effect of moisture content on equilibrium moisture gradient in clay specimens at a dry density of 97 pcf.

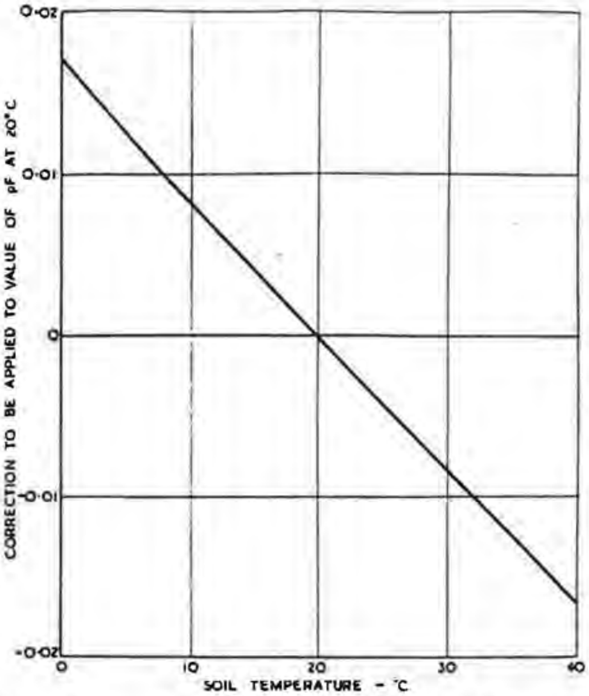


Figure 8. Correction to be applied to pF of soil at 20 C to obtain pF at other temperatures.

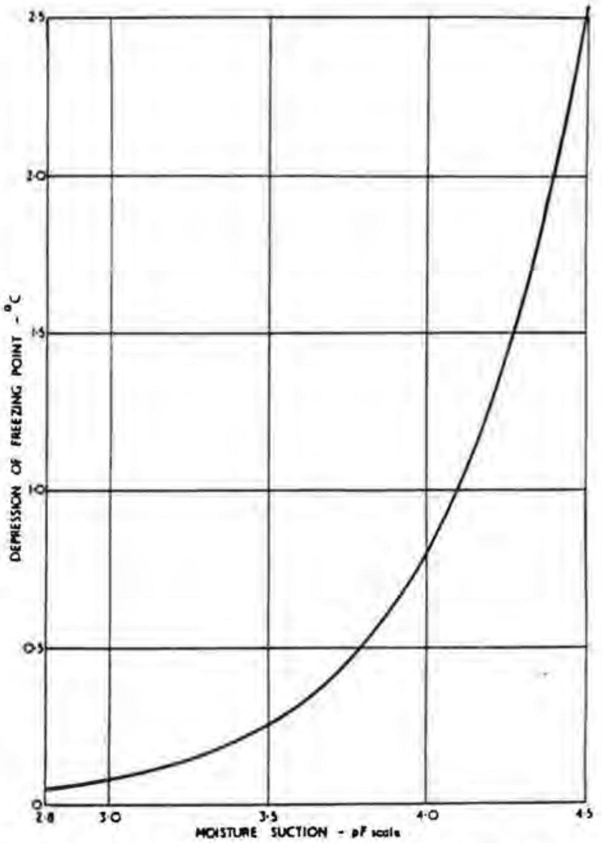


Figure 9. The relationship between suction and freezing point depression of moisture in porous materials.

in the soil when the air content was less than 5 percent of the total volume, suggests that some other mechanism may be present. Theoretically the effect of temperature on soil suction can be shown to be small (8). Figure 8 shows that raising the temperature of a soil from 20 to 40 C would reduce the suction by about 0.015 units on the pF scale. Thus, although a small hydrostatic gradient would be created tending to move water from the hot end of the samples, referred to in Figure 7, to the cold end, the gradient would hardly be sufficient to cause any appreciable change in moisture content. Work recently reported from France may throw more light on the mechanism of moisture transfer resulting from temperature differences (9).

It has been established in some actual subgrades that wetting has occurred subsequent to construction, even in quite arid climates. This moisture transfer could be due to liquid movements, or vapour movements. Theoretical studies (10), in which the transfer of heat and moisture in the soil are regarded as a coupled system, have suggested that for temperate climates there is unlikely to be any net upward movement of water caused by vapour transfer, the moisture merely rising and falling with season. (Any linear analysis describing the subgrade moisture movements caused by a moderate annual variation of pavement temperature is likely to lead to the same result.) For more extreme climates, however, the analysis describing the coupled heat and moisture flow becomes non-linear, and a net upward flow of moisture is predicted. Studies of an airfield pavement abroad (11) have shown quite large subgrade moisture changes with season, which may be associated with vapour movement.

TABLE 1

METHODS OF DETERMINING THE RELATIONSHIP BETWEEN SOIL SUCTION AND MOISTURE CONTENT

Method	pF Range
Suction plate or pressure plate	0 - 3
Pressure membrane	0 - 6.2
Centrifuge	3 - 4.5
Freezing point	3 - 4
Vacuum desiccator and sorption balance	5 - 7
Calibrated electrical absorption gauges	3 - 7

The forces by which water is retained in soil lower the freezing point. The thermodynamic relationship between soil temperatures below the freezing point of free water and the suction of the unfrozen soil moisture was first deduced by Schofield (3). This relationship, Figure 9, enables the suction distribution associated with any given temperature distribution within the frozen zone to be calculated. The suction curve then permits the amount of water frozen initially by this temperature distribution to be found. The extent to which water will move into the frozen zone to cause the phenomenon known as frost-heave, depends on the suction of the surrounding unfrozen soil, as

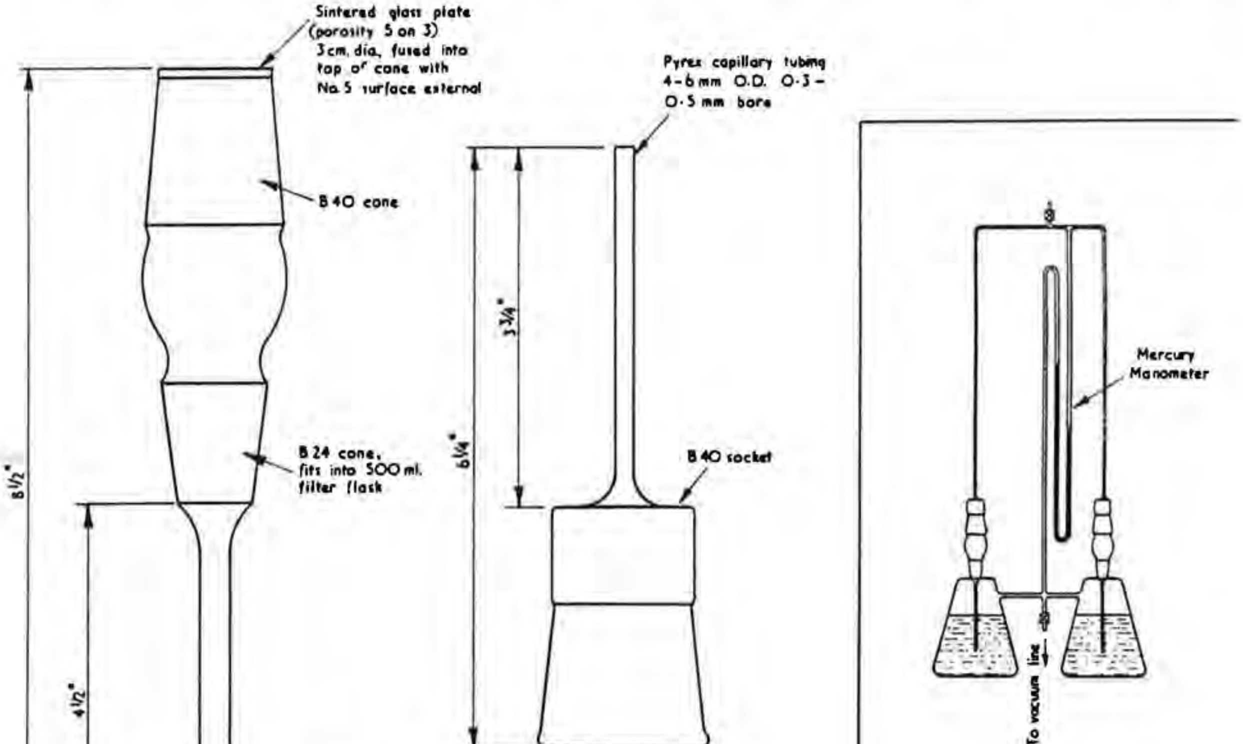


Figure 10. Suction plate apparatus.

well as on that of the frozen soil, and on the permeability to liquid flow of the soil at the high suctions present during freezing. The problem again is one of coupled heat and moisture transfer. The comparative rarity of severe frosts in Great Britain has not encouraged further research on the relation of soil suction and frost heave, but work is in progress in the United States (12).

THE RELATIONSHIP BETWEEN SOIL SUCTION AND MOISTURE CONTENT

Measurement of Soil Suction/Moisture Content Relationship

The thermodynamic approach to soil moisture movement can be used to evaluate moisture migration in terms of moisture content on a weight basis if the appropriate relationships between suction and moisture content are known.

There are a number of ways of determining these relationships. These are listed in Table 1 together with the range of suctions which each covers. Most of the methods can also be used in research for bringing soil samples to a predetermined suction condition.

Since the methods have been described fully elsewhere (13) it is not intended to discuss them in detail here. Mention may be made, however, of very recent developments in connection with the suction plate, pressure membrane and sorption balance techniques.

The form of suction plate equipment in use at the Road Research Laboratory is shown in Figure 10. De-mountable chemical glassware is used, the No. 5 sintered-glass porous-plate being fuzed into the narrow end of a No. B. 40 cone. This is fuzed at its other end into the wider end of a No. B. 24 cone to the narrow end of which is also fuzed a glass tube of about 5 mm internal diameter. The No. B. 24 cone fits into a female joint at the mouth of a standard filter flask, the length of the glass tube on the filter unit being adjusted so that it reaches almost to the bottom of the flask when the apparatus is set up. The filter unit is filled with air-free water and the flask itself contains air-free water above the level of the tube connected to the filter unit. A reduced pressure of between a few centimetres and one atmosphere can be applied to the sintered plate by evacuating the space in the filter flask, the minimum being determined by the difference in level between the plate and the water in the flask. A glass cap is fitted over the No. B. 40 joint carrying the sintered plate, and this is connected by a tube to what would otherwise be the open end of the manometer recording the pressure in the filter flask. This minimises fluctuations of pressure in the apparatus due to variations of atmospheric pressure and temperature. The suction/moisture content relationship is explored by allowing samples to reach moisture equilibrium successively with plates operating at a range of suctions. The equilibrium wet weight for each suction is measured and the moisture contents on a dry-weight basis are calculated from the dry weight determined at the conclusion of the tests.

In the pressure membrane apparatus, originally devised by Richards (14) and Woodruff (15), the sample is placed in contact with a cellulose membrane, which is itself in contact with water at atmospheric pressure. The air pressure surrounding the sample is increased to produce a pressure differential between the water in the soil and the water in the membrane. Moisture leaves the sample until the suction of the soil is numerically equal to the applied pressure. The suction/moisture content relationship can then be examined by carrying out tests at increasing suctions. For research purposes, the range of this method, previously regarded as pF 0 - pF 5.0, (16) has been extended at the Road Research Laboratory to suctions as high as pF 6.2, the latter value involving air pressures of 1500 atmospheres. The apparatus is shown photographically in Figure 11 and the constructional details can be seen from Figure 12. In carrying out a test, the sample is placed symmetrically on the membrane which is supported, in the manner shown, on a smooth sintered alloy-steel plate, which is itself in contact with water at atmospheric pressure. The cylinder is then bolted in position and the apparatus is mounted in the hydraulic loading press with the piston so arranged that the Bridgman seal is above the side inlet port. Compressed air at a pressure of about 1500 psi is then introduced into the cylinder through the port. When the piston is pushed down by the hydraulic press, the compressed air supply is automatically isolated from the pressure cylinder as the piston passes the port. Thereafter any further downward movement of the piston intensifies the working pressure of the machine. No difficulty has been experienced in obtaining and maintaining pressures of the order 1500 to 2000 atmospheres. The actual operating pressure is deduced from the pressure gauge of the hydraulic press and the measured piston friction.

A new sorption balance, which has been developed at the Road Research Laboratory for studying the suction/moisture content relationships for comparatively dry soils, is shown in Figure 13. The sample of soil is allowed to reach moisture equilibrium with a known humidity and the equivalent suction is computed from the thermodynamic relationship between suction and humidity (4). The Joly spring balance enables continuous weighing to be made during the progress of equilibriation and a series of tests at different humidities can be conducted without the need to remove the soil from the apparatus. The detailed shape of the suction/moisture content relationship at low humidities gives a valuable indication of the mechanism of adsorption in soils containing different clay minerals, for example, where montmorillonite is present the suction curve oscillates slightly with moisture content. From such tests, surface areas per unit mass of clay fraction have been deduced for natural clay soils using

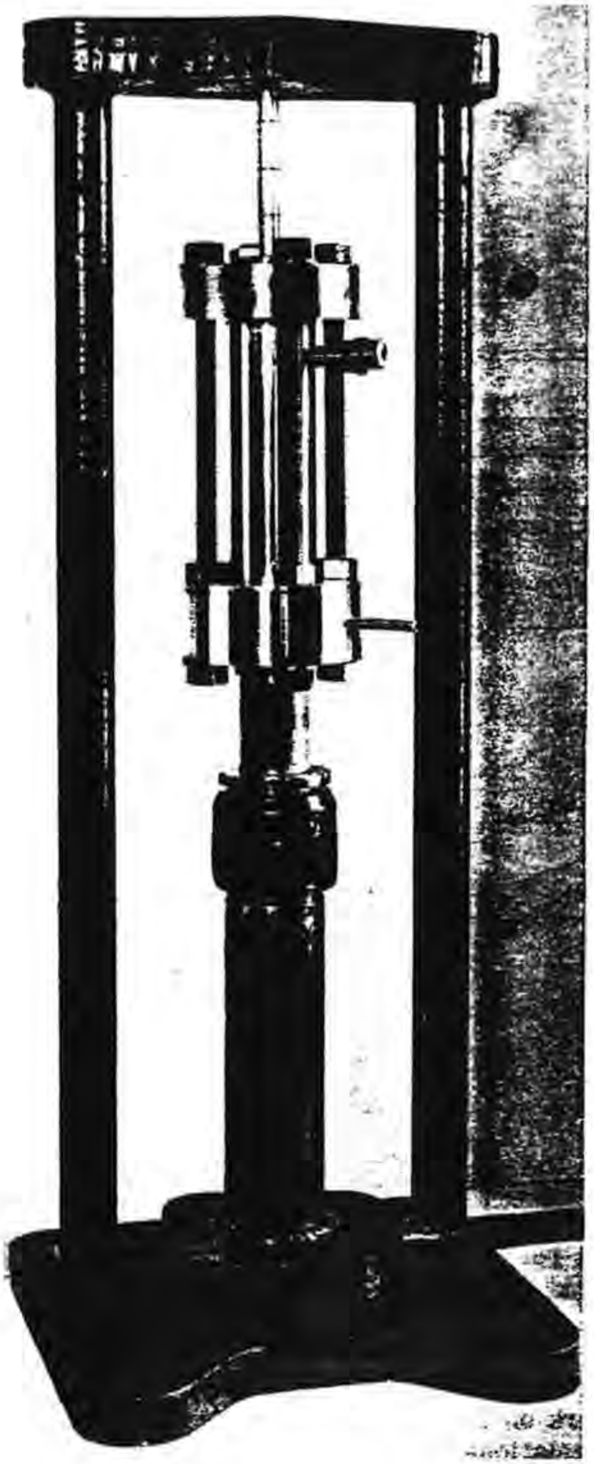


Figure 11. Pressure membrane apparatus for use up to pF 6.2 (1500 atmospheres).

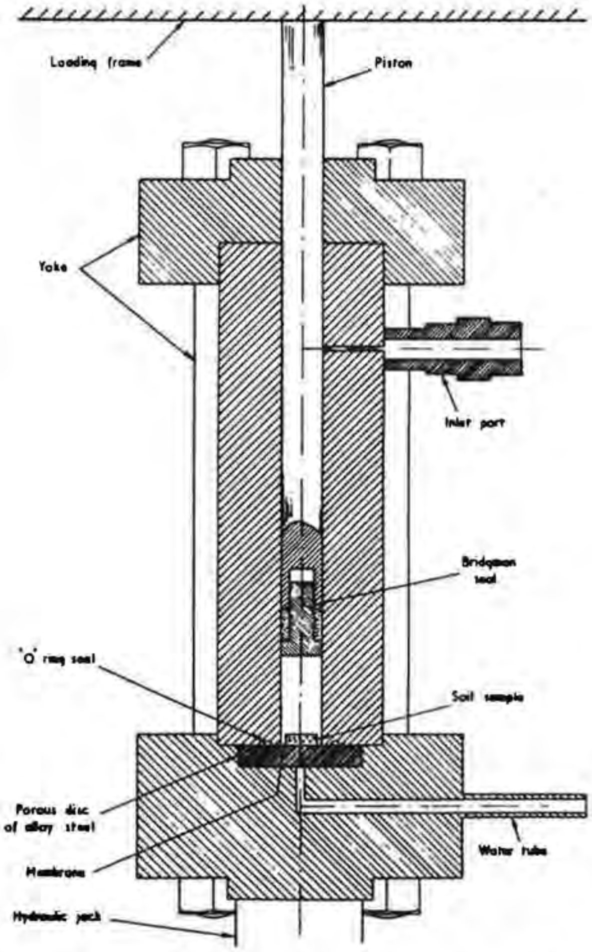


Figure 12. Membrane apparatus for high pressure.

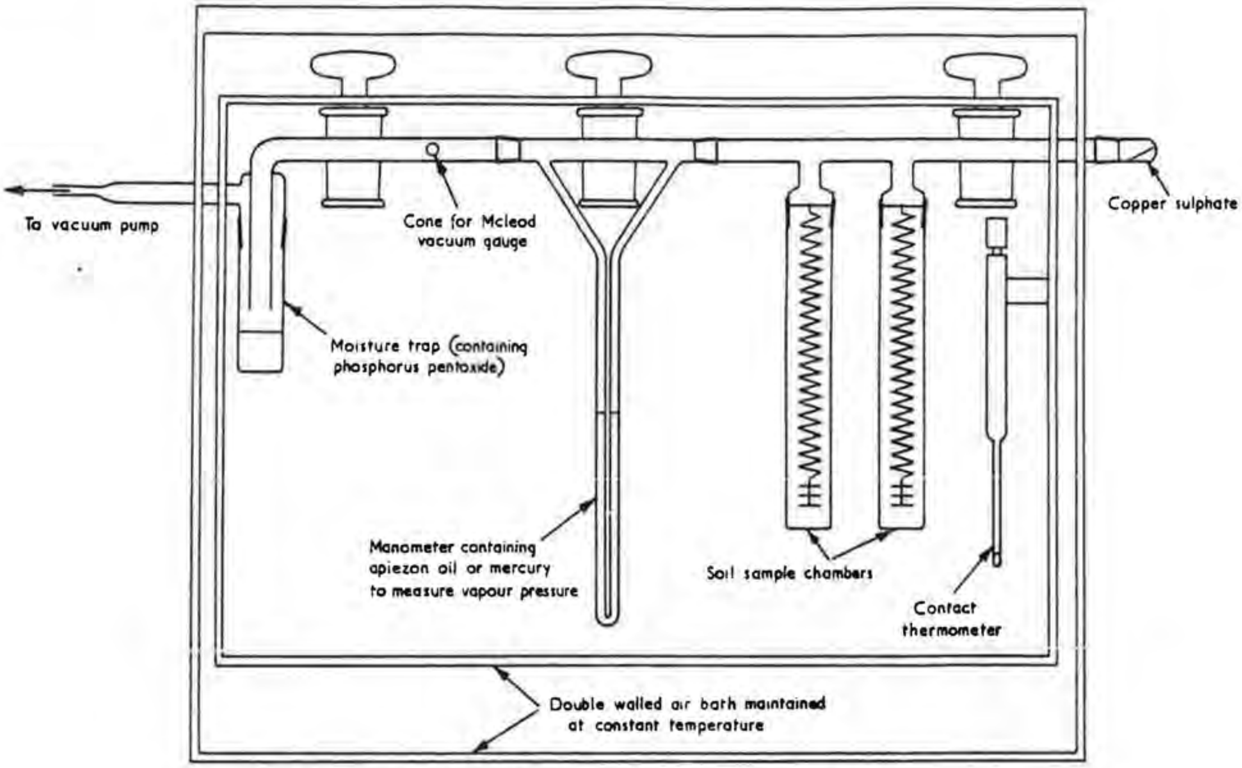


Figure 13. Diagram of sorption balance.

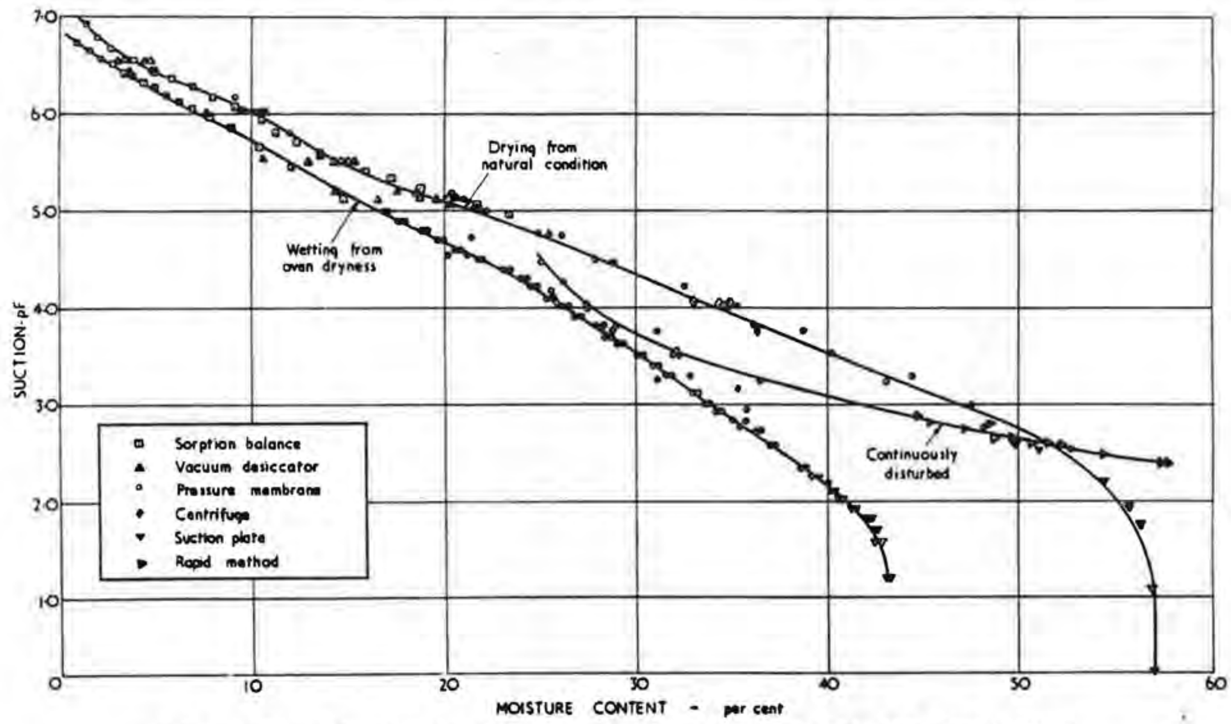


Figure 14. Suction/moisture content relationships for Gault clay.

plots of the B. E. T. type, and the surface areas compared with published data for pure clays. The results of X-ray analyses and nitrogen adsorption experiments at 195 C confirm that this may provide a useful approximate method for assessing the clay mineral constituents of natural soils. Further work on these lines is in progress.

Figure 14 shows suction/moisture content relationships determined on a heavy clay soil in the undisturbed condition (a) drying from zero initial suction and (b) wetting from oven-dryness. Use was made of all the methods listed in Table 1 (other than the freezing point and electrical methods, which are not readily applicable to undisturbed soils) and the figure shows the substantial equivalence of the various methods where their ranges overlap.

Relationship Between Suction and Moisture Content. The nature of this relationship depends on the characteristics of the soil. It is convenient to consider three categories (a) incompressible soils and materials of rigid structure, (b) compressible soils which may remain saturated at high suctions, any change of moisture content being accompanied by a change in volume, for example, heavy clays, and (c) intermediate soils such as sandy clays.

Characteristic suction curves for two incompressible materials, in this case two grades of chalk (soft limestone), are shown in Figure 15. There is considerable hysteresis between the wetting and drying curves; this arising from the fact that pores may empty at a suction different from that at which they fill. The vertical part of the drying curves indicates that considerable suctions can be applied to the pore water without change of moisture content, the effect being only a change in the radii of the water menisci in the surface pores. When the air-entry suction of those pores is reached drainage

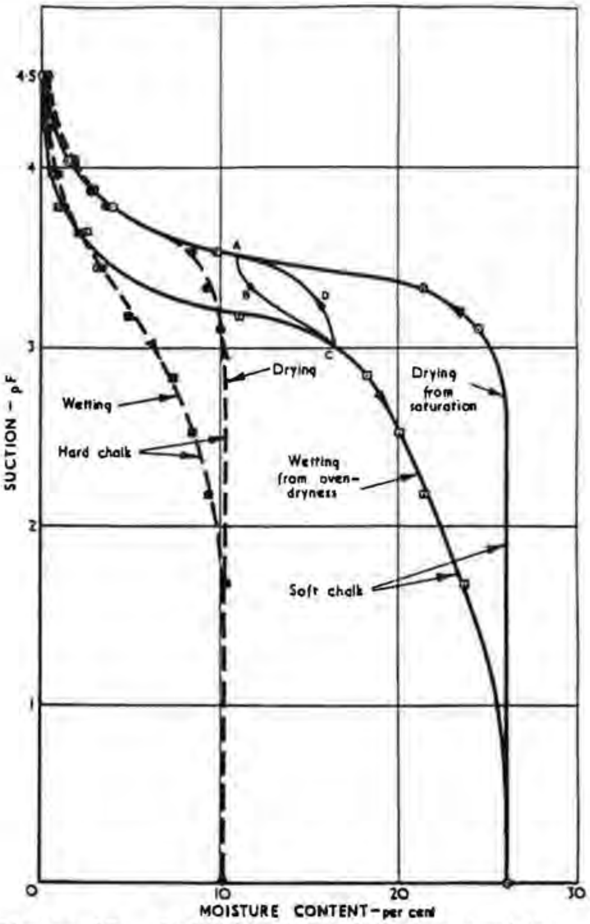


Figure 15. Relationships between suction and moisture content for samples of hard and soft chalk.

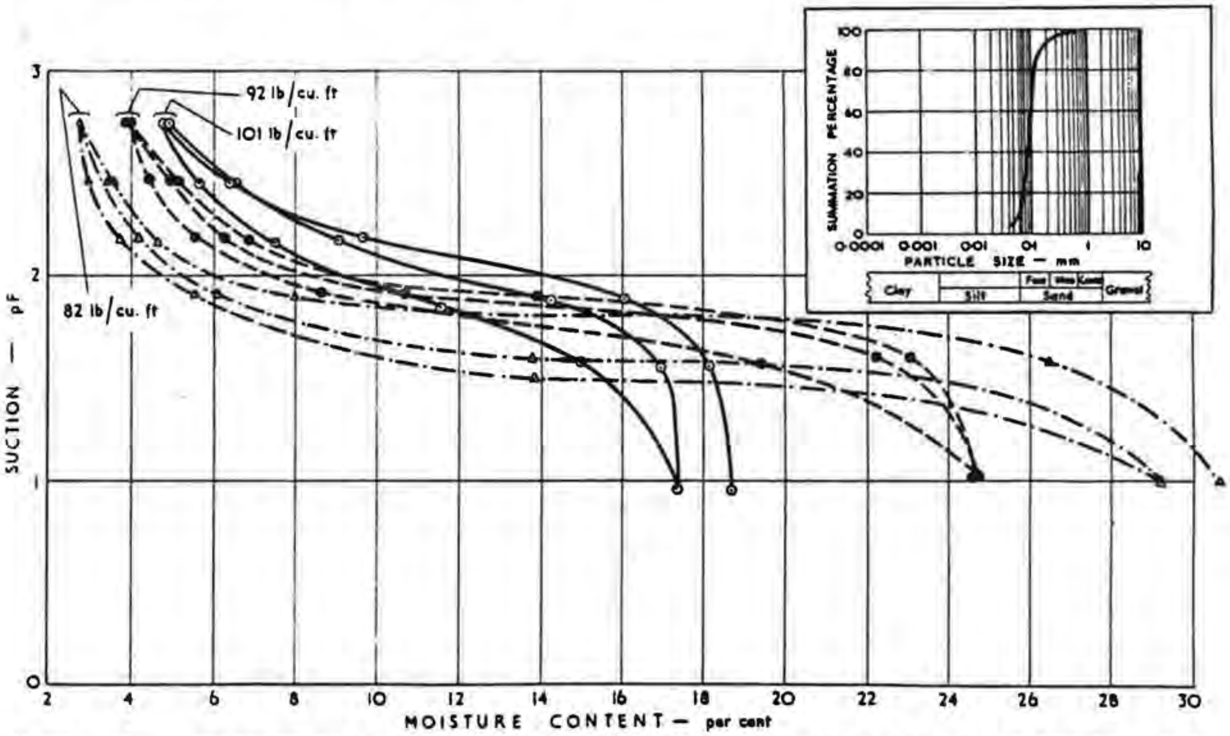


Figure 16. Relationship between suction and moisture content at various dry densities for a fine sand.

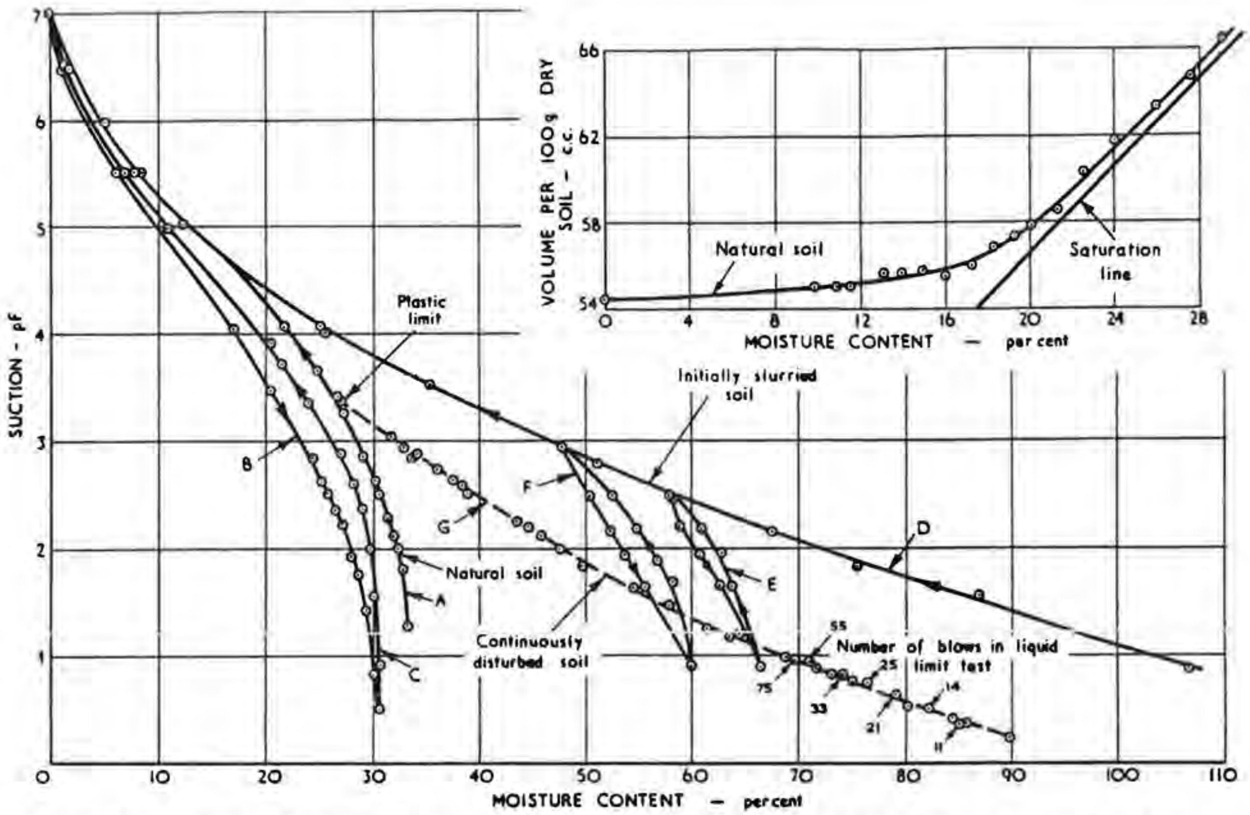


Figure 17. Suction/moisture content and shrinkage relationships for a heavy clay soil.

commences and is indicated by the change of slope of the suction curve. At high suctions the water may be discontinuous and concentrated at the points of intergranular contact. The difference between the two sets of curves in Figure 15 indicates different densities and hence different saturation moisture contents in the two materials. Much can be learned about the pore structure of rigid materials from the detailed analysis of tests of this type, and such tests may have further application, for example, to the pore size of acoustic absorbing materials.

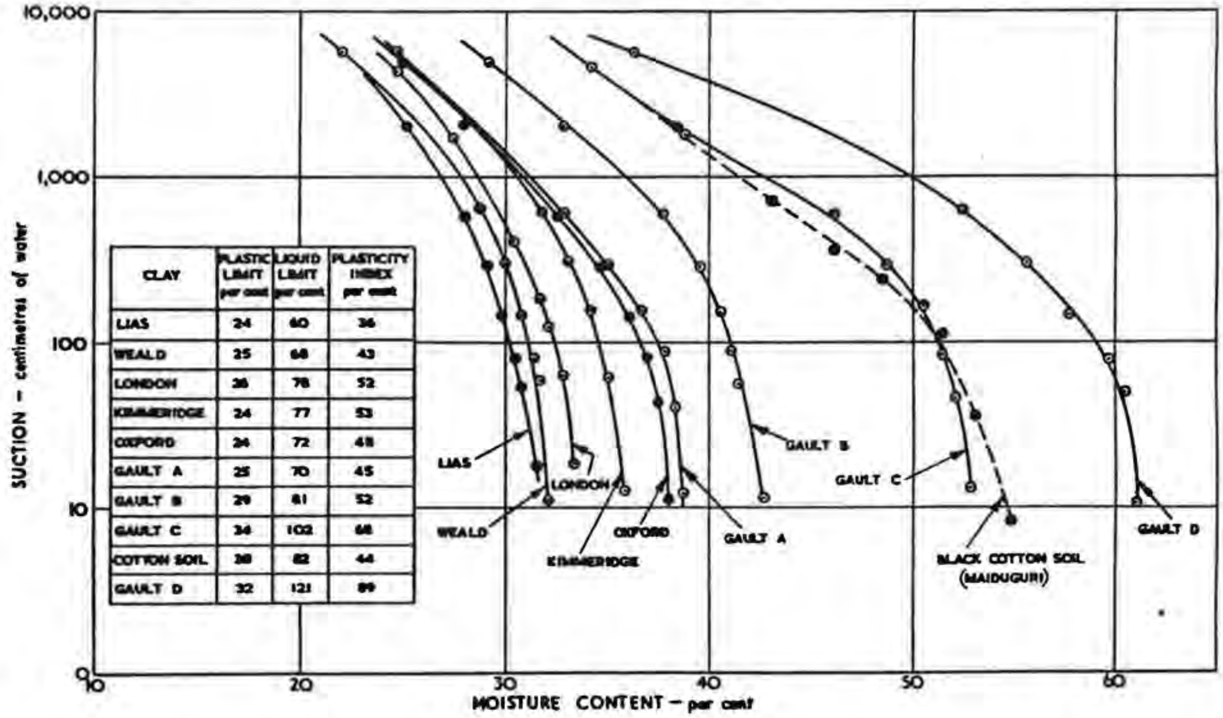
When the material is incompressible (in that fluctuations of moisture content are not accompanied by density changes) but when it can nevertheless be compacted to various degrees, as with sands and gravels, the relationship between suction and moisture content can be expressed by a family of curves of the type shown in Figure 16. These curves cross because at low suctions the pore space available determines the moisture content, whereas at higher suctions the smaller pores associated with the higher densities remain full when the larger pores associated with low densities have drained.

The nature of the relationship for compressible heavy clay soils is shown in Figure 17. Curve A represents the drying condition for an undisturbed sample taken from the ground and initially wetted to a very low suction. Curve B refers to the same soil wetting from oven-dryness, and curve C is the second drying curve. The shrinkage curve corresponding to the initial drying condition (curve A) is shown inset and indicates that air does not enter the soil structure until the suction is in excess of pF 4. Curve D refers to the same soil drying from an initially slurried condition. The curve is identical with the drying curve of the natural soil (curve A) at suctions above pF 4.5, suggesting that the development of such high suctions produces a structural condition similar to that present in the natural ground. The intermediate suction loops E and F show the effect on the suction relationship of slurrying at lower moisture contents than that used in preparing the soil for the tests used to obtain curve D.

A most important and surprising fact which has emerged from tests such as these is that if the soil is sheared at constant moisture content (through an angle of about 60 deg) the suction changes to the value given by the dotted curve G, which is unique for any particular soil. Thus, irrespective of whether the suction/moisture content value was initially represented by a point on curve A, B, C, D, E or F, on shearing the value would be found to be that given by curve G at the moisture content at which shear occurred. It follows from Figure 17 that for most natural conditions over-consolidated clays would increase in suction on shearing and normally consolidated clays would tend to decrease in suction on shearing. During shear tests such as are normally carried out in the triaxial apparatus, the suction component of the pore pressure will change in the shear plane or planes in this manner and the average pore pressure in the sample as a whole must also change to some extent in the same way. This may be either in the positive or negative direction depending on the initial condition of the soil. This could account for such changes of pore pressure reported during triaxial testing (17).

Curve G is not a suction curve in the same sense as the other curves shown on Figure 17. If a change of moisture content occurred in the soil after shearing the corresponding suction relationship would not follow curve G, but would rise above or fall below it depending on whether the soil was drying or wetting, and only by a repetition of the shearing process could the suction condition be brought back to curve G. The suction/moisture content condition of the soil during all tests involving shearing will be represented by a point on a curve of type G; thus all points obtained during a liquid limit test have been found to fall on that line as also does the plastic limit point, Figure 17. Tests on several heavy clays have indicated a value of about pF 3.4 for the plastic limit. One worker has attampted to obtain suction values for the liquid limit from drying curves carried out on slurried soils (18). Such a technique would give erroneously high values of suction.

Figure 18 shows the suction curves for samples taken from the principal clay deposits of the South of England. These curves were obtained on "undisturbed" samples and for the sake of clarity the drying condition only is considered. The heaviest clays shown, which are from the Gault stratum, contain a considerable amount of montmorillonite and in this respect have much in common with some of the black cotton soils of Africa and India. For comparison, tests on a sample of cotton soil from Nigeria are included in Figure 18 and the close similarity between the suction properties of this sample and those of the Gault clay samples is apparent. Although the Gault pre-



CLAY	PLASTIC LIMIT per cent	LIQUID LIMIT per cent	PLASTICITY INDEX per cent
LIAS	24	60	36
WEALD	25	68	43
LONDON	26	78	52
KIMMERIDGE	24	77	53
OXFORD	24	72	48
GAULT A	25	70	45
GAULT B	29	81	52
GAULT C	34	102	68
COTTON SOIL	38	82	44
GAULT D	32	121	89

Figure 18. Relationship between suction and moisture content for undisturbed heavy clay soils.

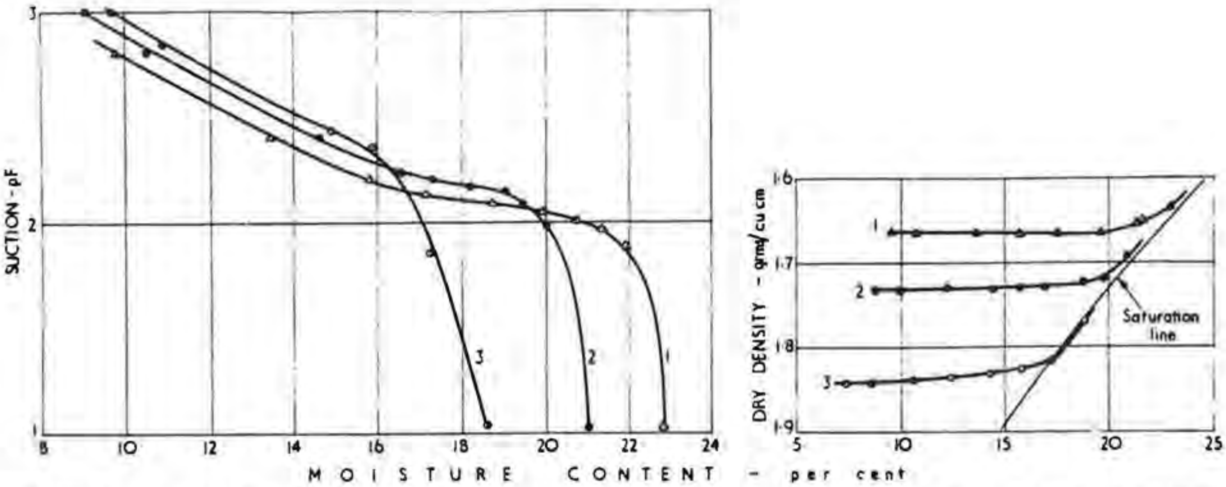


Figure 19. Relationship between suction and moisture content of a silty soil at three densities. Inset are the corresponding shrinkage curves.

sents considerable constructional problems in Great Britain, these problems are secondary in comparison with those that can arise with cotton soils in their more extreme climatic environment.

The suction curves for intermediate soils partake of the characteristics of both the incompressible and compressible soils. The curves for undisturbed natural samples of such soils lie between those of the sands and the heavy clays to form a continuous spectrum, the vertical characteristics of the sands at low suctions becoming less and less pronounced as one passes through the sandy and silty clays towards the heavier soils. When heavy clays in the natural moisture condition are remoulded and compacted to different degrees the compacted material consists of aggregates of saturated or nearly saturated clay with comparatively large air voids. Although it is the magnitude of these air voids which determines the difference in dry density between the samples, their presence has little effect on the suction/moisture content relationship as a whole. In sandy and silty clays, however, where saturated aggregates of this type are not present, compaction modifies the particle arrangement and the density of remoulding has an effect on the suction/moisture content relationship. Although by carrying out a series of tests on sandy or silty clay soils at different initial densities a family of curves is obtained, these curves are not strictly comparable with those for an incompressible soil since the curves do not represent iso-density conditions because of the natural swelling and shrinkage of the soil. By carrying out swelling/shrinkage tests simultaneously with the suction determinations, a family of suction curves corresponding to constant density conditions can be prepared. These curves show the same cross-over characteristic as the curves for incompressible soils. A detailed study of the suction/moisture content/density relationships of this kind is likely to be of fundamental importance in studies which are in progress into the interrelationship between suction, shear strength and compaction. Figure 19 shows typical suction/moisture content curves for a silty soil in three states of compaction. The corresponding swelling and shrinkage curves are shown inset. Again for clarity drying curves only are shown.

MOISTURE MIGRATION BENEATH ROADS AND STRUCTURES

In the natural soil the pore-water pressure is determined by the rainfall, evaporation, transpiration from vegetation and the soil permeability. These factors may give rise to a water table whose depth can be determined from a borehole. Under an infinite impermeable surfacing and under uniform temperature conditions the level of the water table alone determines the ultimate distribution of pore-water pressure. In practice if the water table is sufficiently near the surface for the water films to be continuous throughout the profile a linear distribution of pore-water pressure with respect to the water table is reached, that is, x ft above the water table the pore pressure is negative by x ft of water, and x ft below the water table it is positive by the same amount. Figure 20 shows an example of such a linear distribution measured beneath the concrete floor of a building some 50 ft square. The water table was at a depth of about 9 ft and the equilibrium distribution of pore-water pressure consistent with this depth of water table is shown by a chain-dotted line in Figure 20.

From any known distribution of pore-water pressure with depth the corresponding variation of suction with depth can be deduced using Eq. 1. In conjunction with the appropriate relationships between moisture content and suction, the suction distribution can be converted to a distribution of moisture content.

Beneath an infinite impervious surfacing, the vertical pressure P on any horizontal plane will be the pressure exerted by the wet soil above the plane together with any surface loads. The value of the compressibility factor α can be determined by the apparatus already described. (In the solution of particular practical problems the value of α should strictly speaking be determined by the application of the system of principal stresses to which the soil is subjected in situ and not necessarily by an all-round pressure. However, the small gain in accuracy is hardly likely to compensate for the increased complication of the test.)

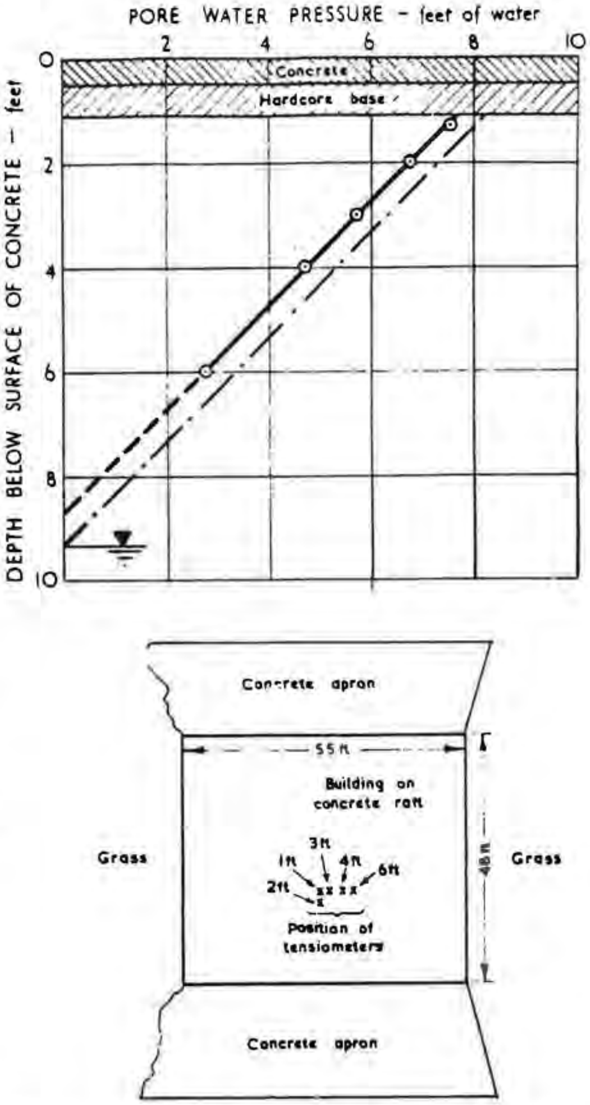


Figure 20. Pore water pressures measured at different depths beneath a building foundation.

During the last eight years observations of pore-water pressure and moisture content have been in progress at several sites in Great Britain representing a range of soil conditions. Measurements have been made under grass cover, under bare soil and under impervious road pavements laid at various times of the year. The earlier stages of these experiments have been reported elsewhere (19). Figure 21 (a) shows the variation of pore-water pressure at various depths under grass cover (Area A) at Site 1 for the period 1951-56. The soil profile at this site consisted of sandy and silty clay strata overlying gravel at a depth of 6-7 ft. The rainfall and water table data over the same period are given at the bottom of Figure 21. Measurements of pore-water pressure made under bare soil (Area C) at the same site are reproduced in Figure 21 (b) and they show the part played by vegetation in removing water from the soil. The manner in which impervious pavements (Area B, E and G) stabilize the moisture conditions in the soil beneath can be seen from Figure 22, which again refers to the same soil profile. In this instance an accurate linear distribution of pore-water pressure with respect to the water table had not yet been realised, partly because of the finite area of the pavements (30 ft square) and partly because of the presence of the coarse gravel layer above the water table. This layer was relatively impermeable to capillary moisture flow and retarded vertical migration of moisture. The influence of these factors on the pore-water pressure distribution was satisfactorily explained using the principle of flow nets. The associated measurements of unsaturated permeability, both vertical and horizontal, were made using an apparatus developed from that de-

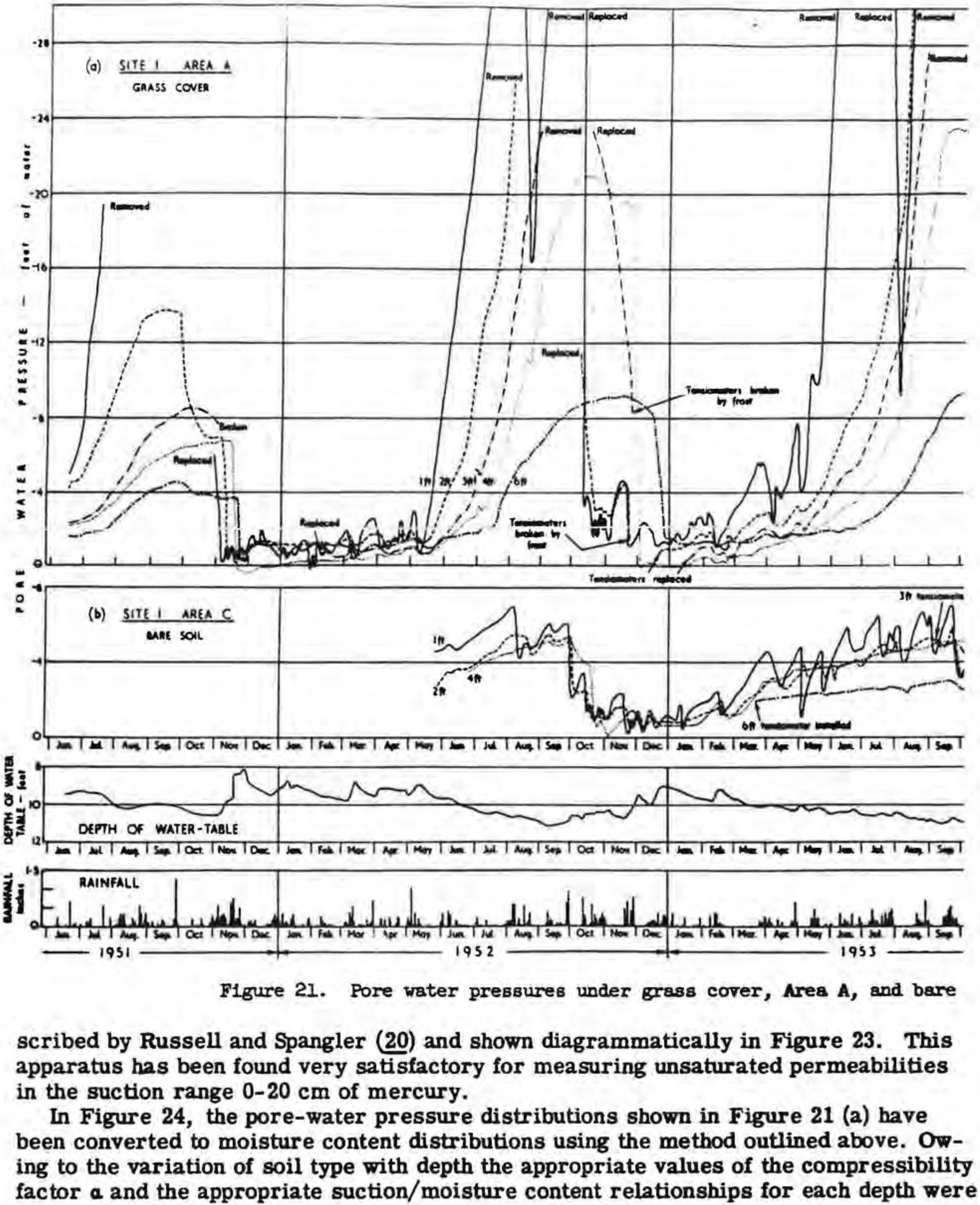
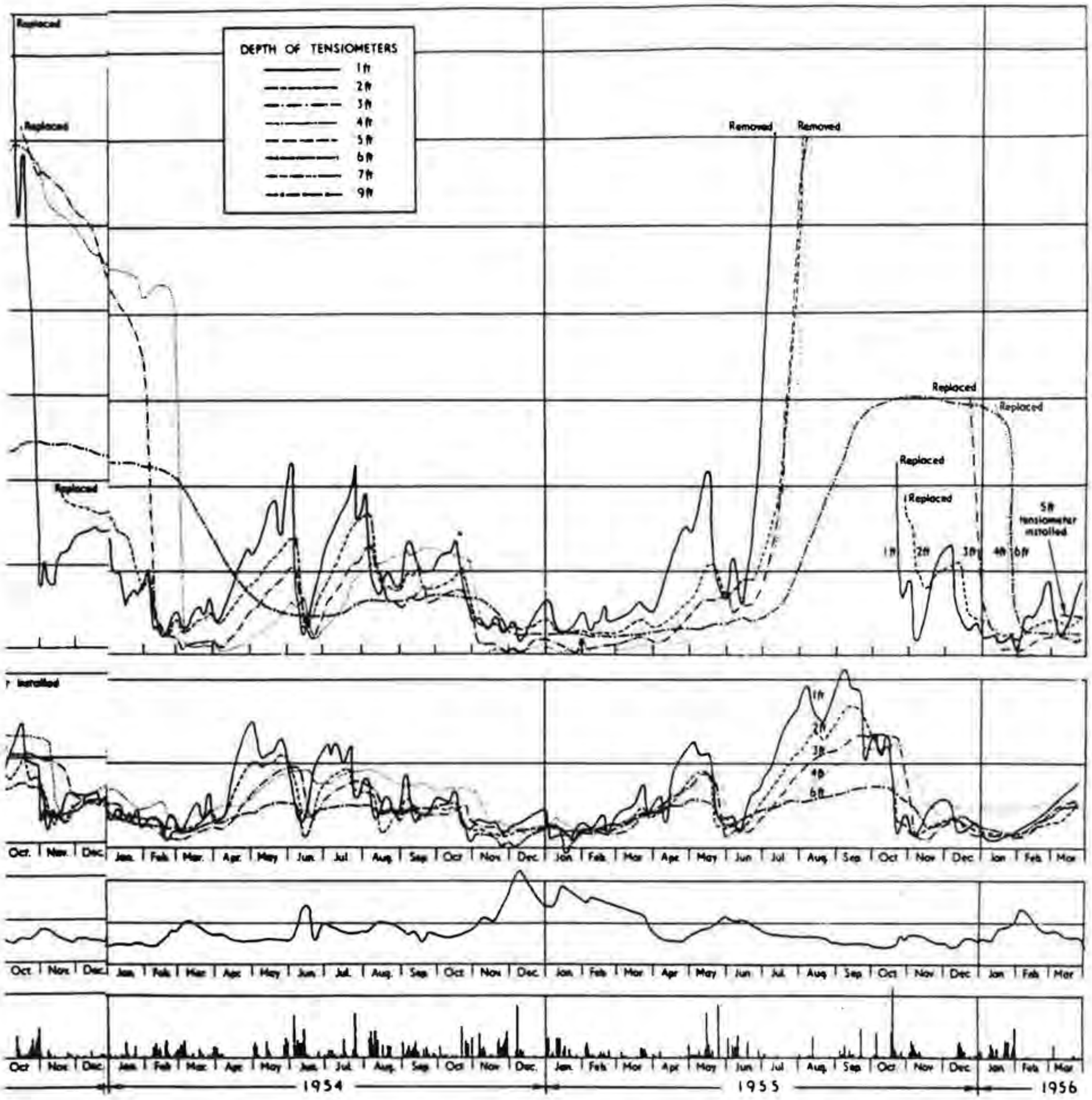


Figure 21. Pore water pressures under grass cover, Area A, and bare

scribed by Russell and Spangler (20) and shown diagrammatically in Figure 23. This apparatus has been found very satisfactory for measuring unsaturated permeabilities in the suction range 0-20 cm of mercury.

In Figure 24, the pore-water pressure distributions shown in Figure 21 (a) have been converted to moisture content distributions using the method outlined above. Owing to the variation of soil type with depth the appropriate values of the compressibility factor α and the appropriate suction/moisture content relationships for each depth were measured and used in making the conversion. Moisture content distributions estimated in this way have been compared with measurements made by boring and sampling at specific times. The comparison shows close agreement (see Fig. 25, which is typical) and confirms that the suction approach can be used with confidence for estimating the ultimate moisture distribution beneath pavements in Great Britain. In these field investigations, the pore-water pressure measurements were made with large numbers of all-glass tensiometers of the type shown in Figure 26 and which were developed for the work. They were found to be reliable and required little attention over a period of years. Research was carried out to investigate the reliability of electrical absorption



soil, Area C, together with water table and rainfall data at Site 1.

gauges for measuring pore pressures, but the results showed that they would be too insensitive at the low values of negative pore-water pressure generally found under pavements in Great Britain (21).

The combination of suction and shrinkage data provides a valuable analytical method for estimating the settlement or heave of structures resulting from moisture migration, due for example to the covering by foundations of previously exposed soil or to the lowering or raising of the ground-water level. Such computations, made in connection with the site referred to in Figures 21-25, showed that the soil when covered in the driest summer condition by an impervious surfacing would heave at the surface by about 0.2 in. as a result of the subsequent attainment of an equilibrium pore-water pressure condition. For a heavy clay soil the corresponding heave would have been about 2 in.

VOLUME AND MOISTURE CONTENT OF UNSATURATED SOILS

In the foregoing treatment the suction and shrinkage relationships have been con-

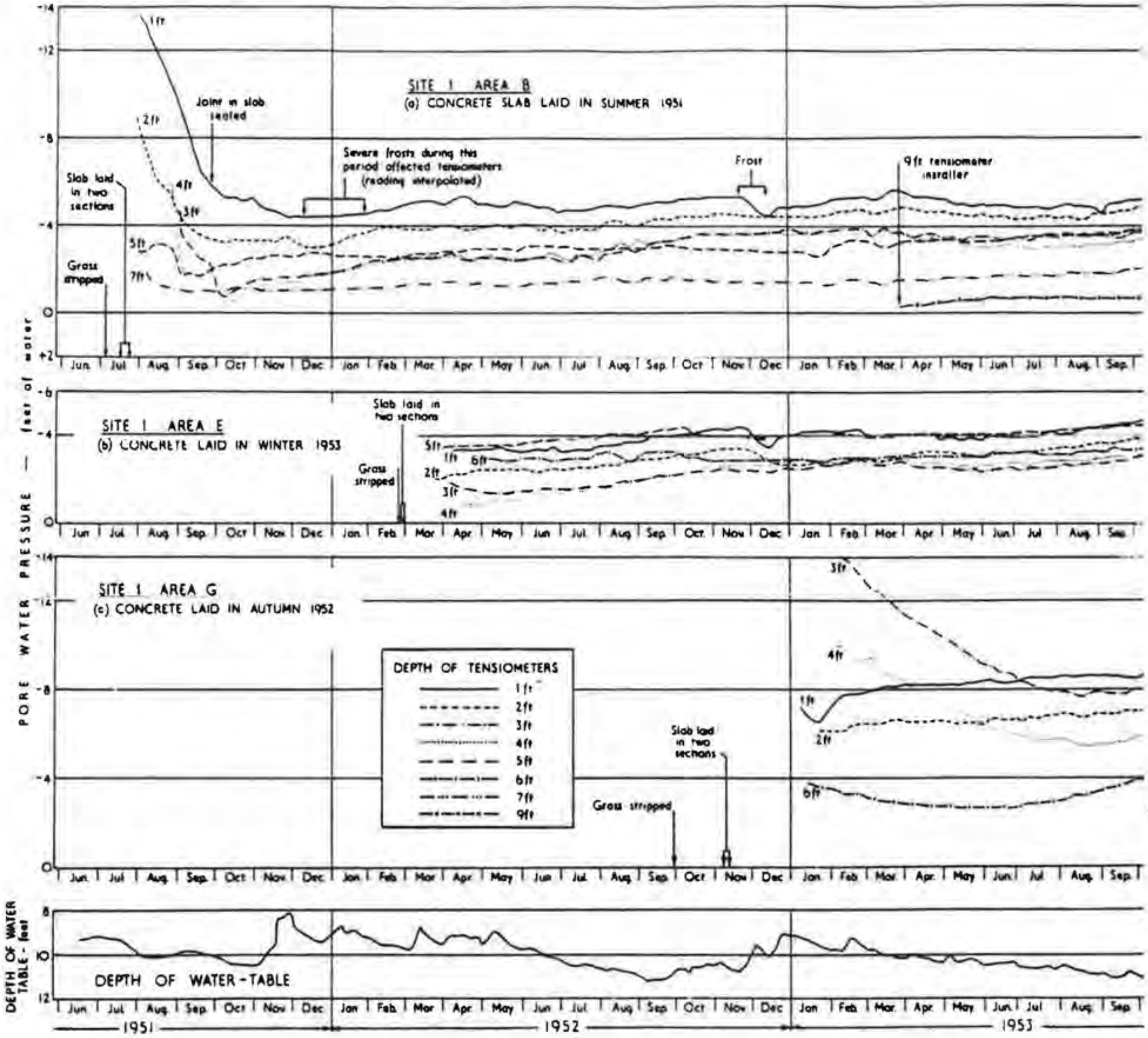


Figure 22. Pore water pressures under centre of 30-ft square concrete

sidered independently although there is clearly a measure of interdependence in so far as reversible changes of suction and volume are concerned.

If the volume of a fixed mass (of dry soil) is V_s and the volume of contained water is V_M, then any small change of the applied pressure p and the pore-water pressure u will do work equal to $p \cdot dV_s$ and $u \cdot dV_M$. The sum of these is the change dF in the free energy of the system, that is

$$dF = u \cdot dV_M - p dV_s \tag{2}$$

From Eq. 2 it may be deduced that,

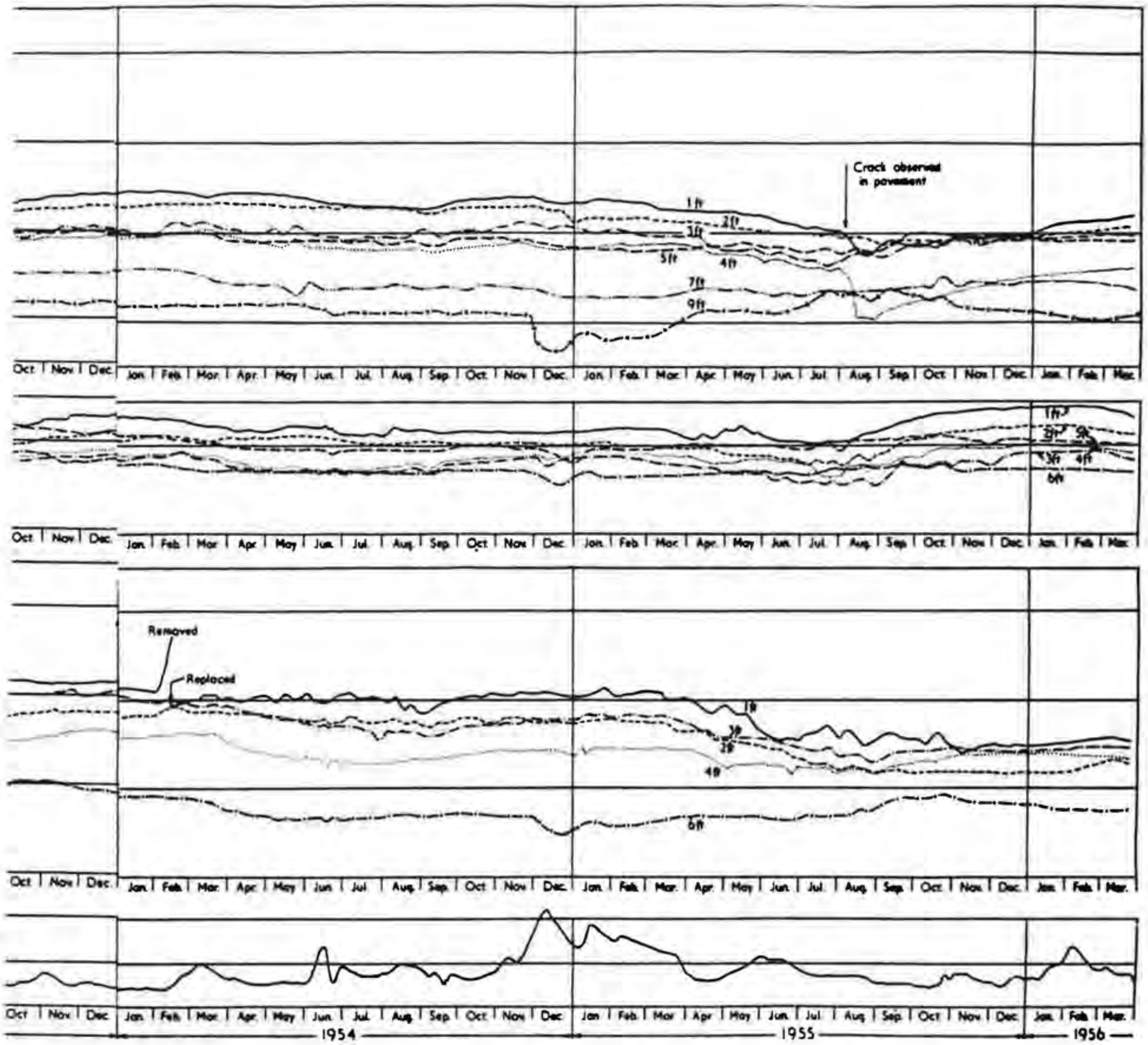
$$\left(\frac{\partial F}{\partial V_M}\right)_p = u - \left(\frac{\partial V_s}{\partial V_M}\right)_p \cdot p \tag{3}$$

and

$$\left(\frac{\partial F}{\partial V_s}\right)_u = u \left(\frac{\partial V_M}{\partial V_s}\right)_u - p \tag{4}$$

It may further be shown theoretically that

$$\left(\frac{\partial V_s}{\partial V_M}\right)_p = \left(\frac{\partial u}{\partial p}\right)_{V_M} = \alpha \tag{5}$$



slabs laid at different seasons together with water table levels—Site 1.

where α is also as defined as in Eq. 1 (the equivalence of the shrinkage and direct loading method of determining α is illustrated in Figure 27), also

$$\left(\frac{\partial V_M}{\partial V_S}\right)_u = \left(\frac{\partial p}{\partial u}\right)_{V_S} = \beta \tag{6}$$

If α and β approximate to constants for small variations of soil conditions Eqs. 3 and 4 can be written in the form,

$$s = u - \alpha p \tag{7}$$

and

$$\sigma = p - \beta u \tag{8}$$

These equations can be used to find (1) that pore pressure s (the suction) which combined with zero applied pressure produces the same moisture content in the soil as p and u combined and (2) that pressure σ which combined with zero pore-water pressure produces the same volume in the soil as p and u combined. For saturated soils, from Eqs. 5 and 6, $\alpha = \beta = 1$ and Eqs. 7 and 8 reduce to the normal expression for effective pressure used in soil mechanics, viz., $\sigma = p - u$. It is generally assumed that the effective pressure defined in this latter manner determines both the volume and shear

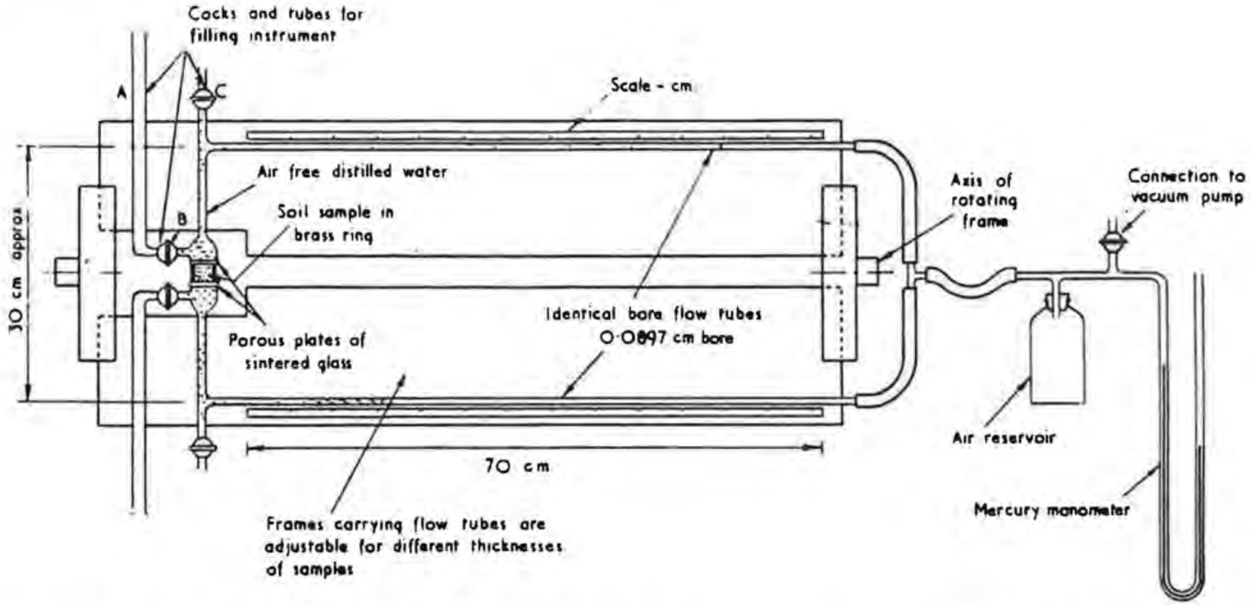


Figure 23. Diagram of apparatus for measuring the coefficient of permeability of soils at low suctions.

strength of saturated soils. It is apparent that for unsaturated soils the volume will be determined more nearly by σ as defined in Eq. 8.

SHEAR STRENGTH OF UNSATURATED SOILS

It is probable that the shear strength of unsaturated soils will be determined by an

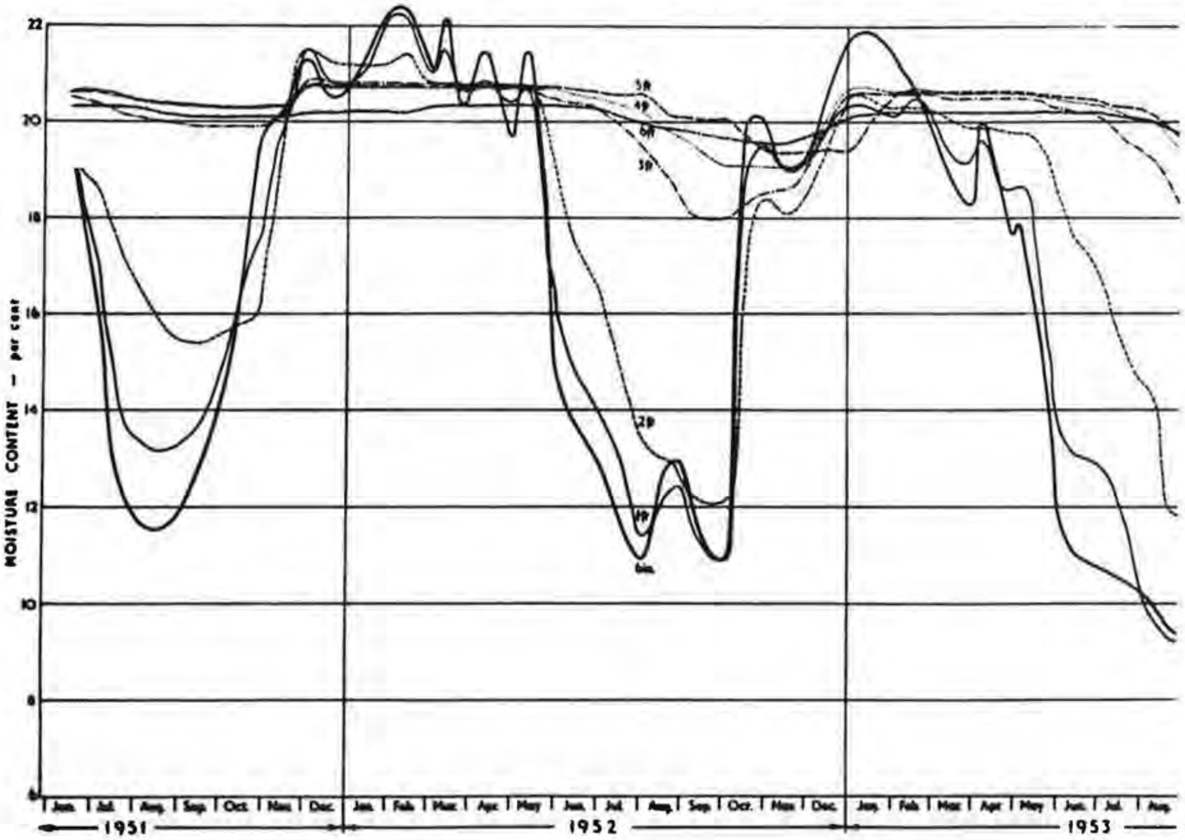


Figure 24. Moisture contents at various depths under grass cover, Area A. Curves deduced

expression similar to that for determining the volume, that is

$$\sigma' = p - \beta' \cdot u \tag{9}$$

where p is the total normal pressure on the shear plane and u is the pore-water pressure on the shear plane.

The pore pressure u will in general be below atmospheric pressure and in principle can be measured by some suitable energy method. In practice it may be inferred from a knowledge of the suction/moisture content relationship for the soil and from the known effect of applied pressure on pore-water pressure.

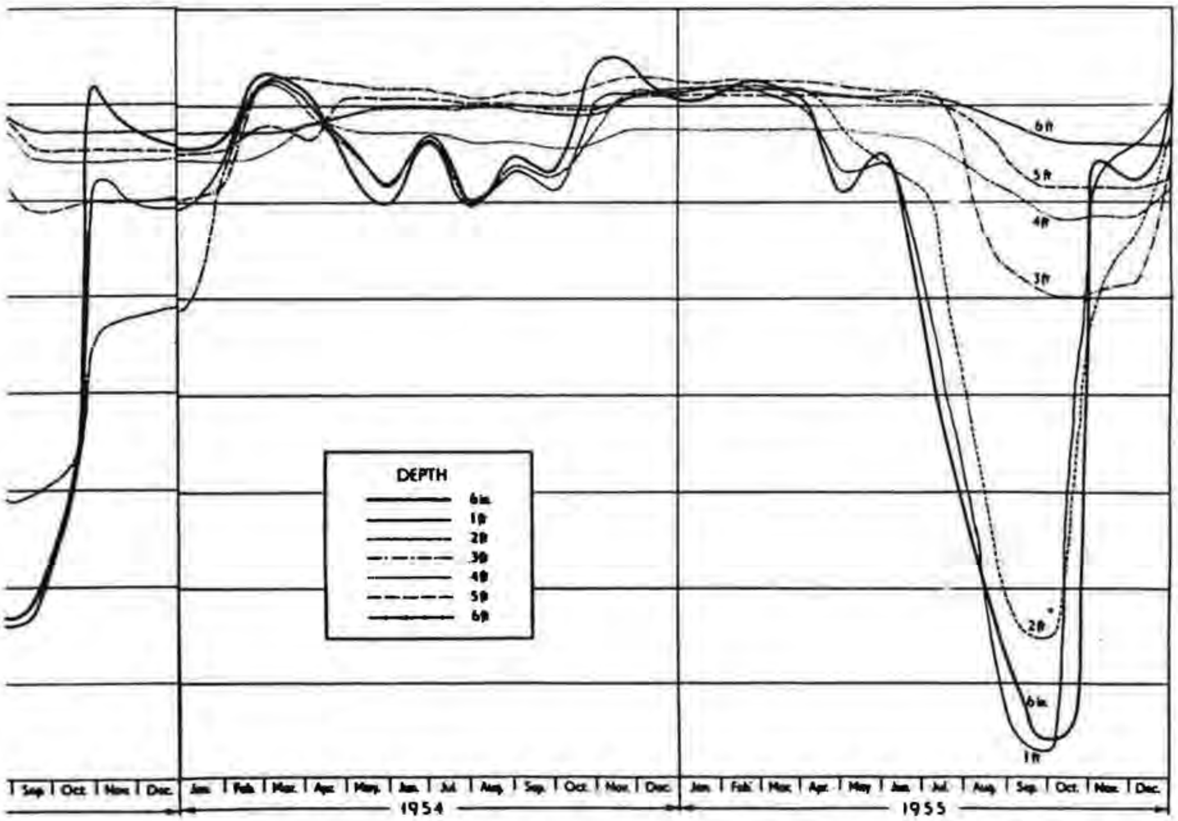
The extent to which the coefficients β and β' are equivalent can only be determined by experiment, since the shearing process in soil is almost completely irreversible, and is not at present susceptible to a thermodynamic treatment.

The coefficient β' appears to be holding or bonding factor, and is a measure of the number of bonds of water under tension effective in contributing to the shear strength of the soil. Considering the variation of the shear strength of soil with moisture content, as the soil dries the suction increases and the strength of the bonds per unit area of water contact also increases. On the other hand, the number of bonds and the area of each individual bond both decrease as the soil becomes more unsaturated. In this way the product β's may reach a maximum as the soil dries, giving also a maximum of shear strength. At such a maximum,

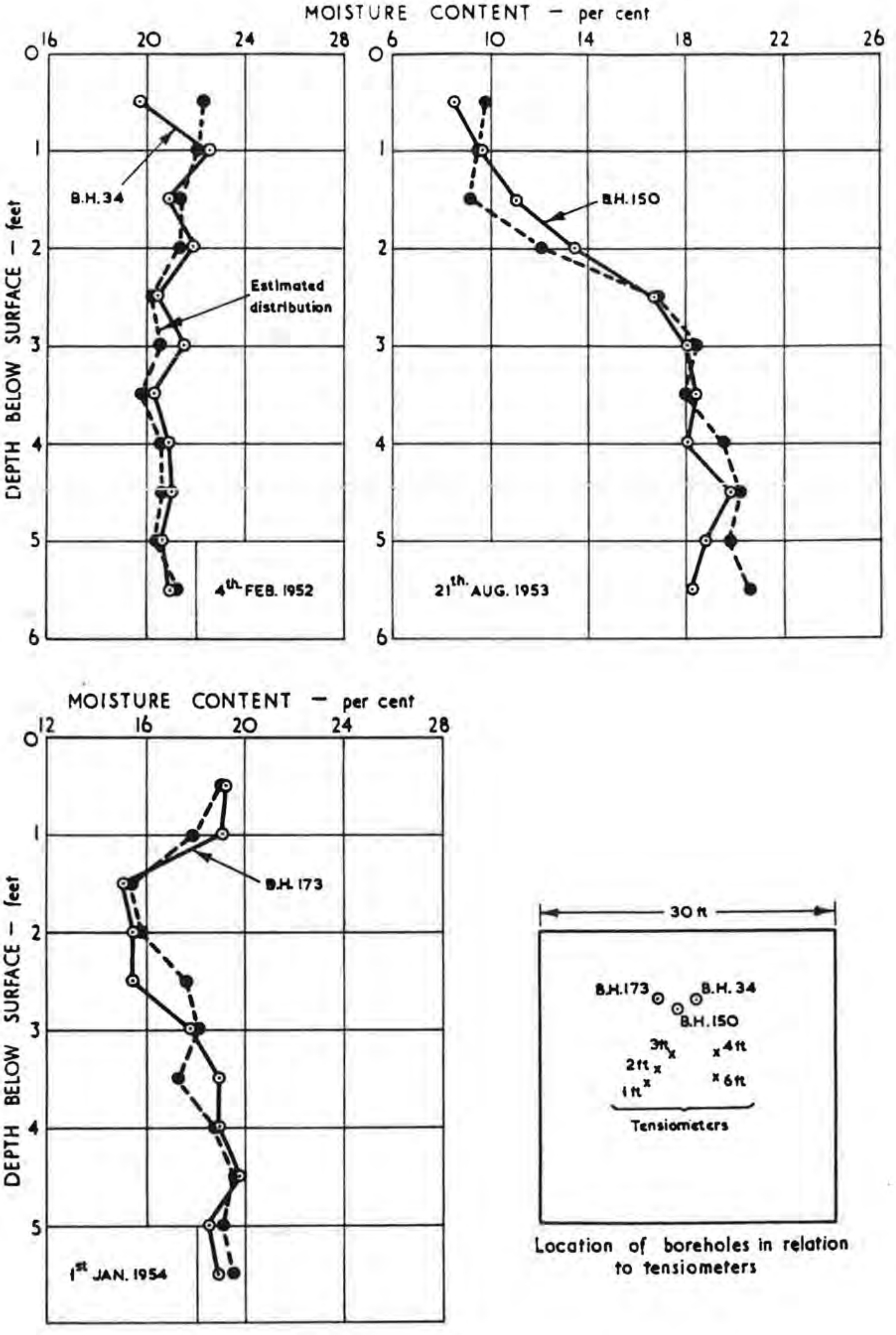
$$\beta' \cdot ds + s \cdot d\beta' = 0 \tag{10}$$

The maximum strength will occur at suctions less than one atmosphere for coarse sands, β' being zero for such soils when oven-dry. For silts the maximum will occur at higher suctions than for sands and for clays at very high suctions.

Some experimental evidence of the relationship between shear strength and suction has been obtained from laboratory vane tests carried out on completely remoulded samples, Figure 28 (22). The suctions were determined before shearing and when the



from measurements of pore water pressure and from suction/moisture content data — Site 1.



Location of boreholes in relation to tensiometers

Figure 25. Comparison of estimated and measured moisture distributions at different times under grass cover—Area A.

suction condition of each soil was represented by a point on the "unique line" of that soil (see discussion on Fig. 17). The lighter soils in Figure 28 may have some frictional strength imposed by the stress distribution set up by the vane used in the tests.

CALIFORNIA BEARING RATIO (C. B. R.) AND SUCTION

Studies which have been made of the California bearing ratio of soils at various moisture contents and dry densities also suggest a close relationship between suction and the bearing ratio of the soil. Figure 29 shows a family of curves relating California bearing ratio on a log scale with moisture content for various constant dry densities. The similarity between the shape and characteristics of these curves and those relating suction (also on a log scale), moisture content and dry density, Figure 16, will be apparent. The results suggest a linear relationship of the type,

$$\text{C.B.R.} = C_1 + C_2 \cdot s \qquad (11)$$

where C_1 and C_2 are constants and s is the soil suction.

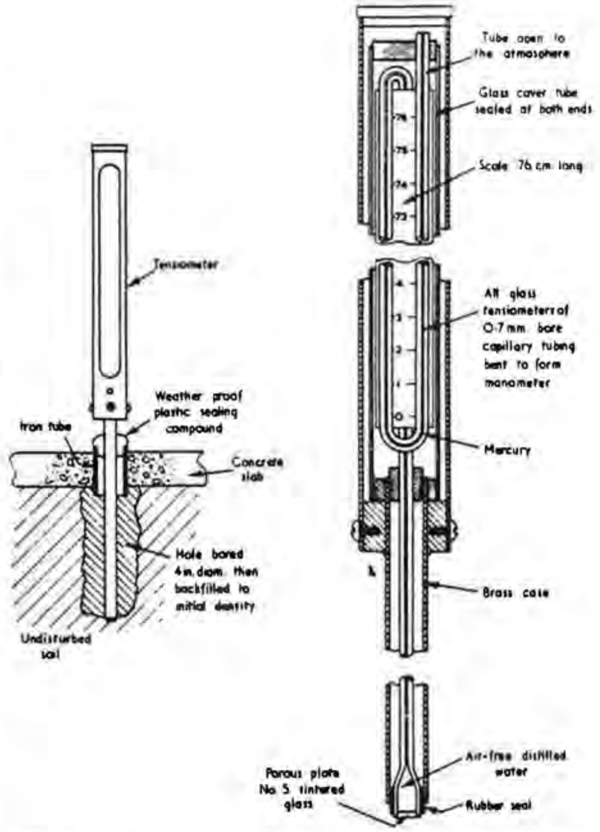


Figure 26. Details of construction of tensiometers and method of installation.

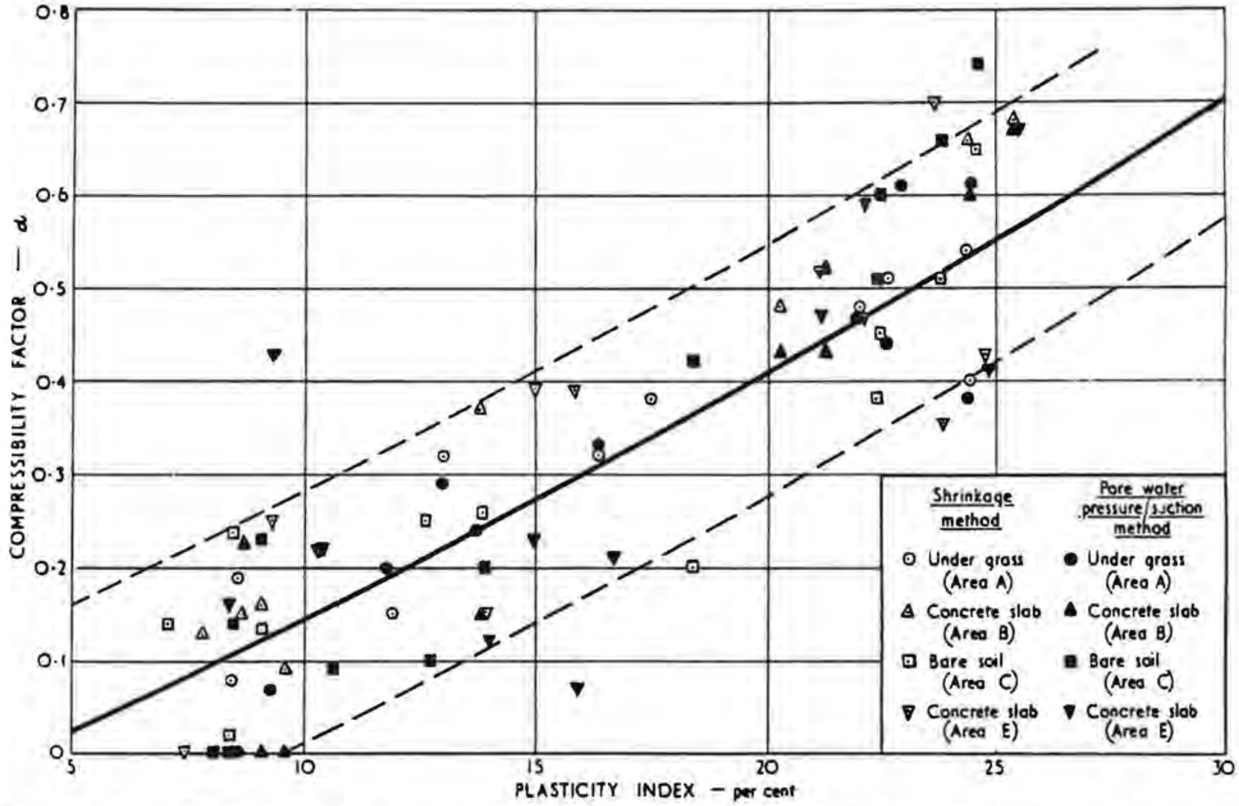


Figure 27. Variation of compressibility factor α with plasticity index of soil using two methods of determination.

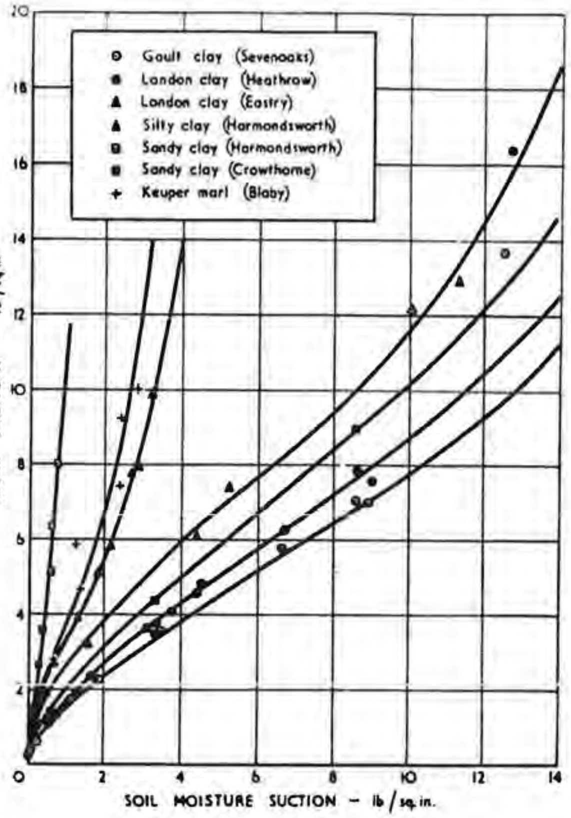


Figure 28. Relationship between shear strength and soil moisture suction for continuously disturbed soil.

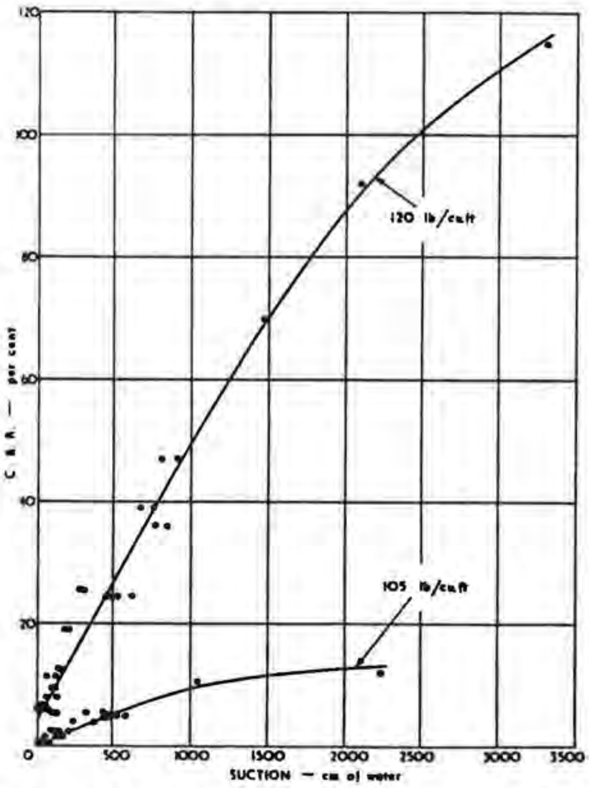


Figure 30. Variation of C.B.R. with suction of a silty sand at densities of 105 and 120 pcf.

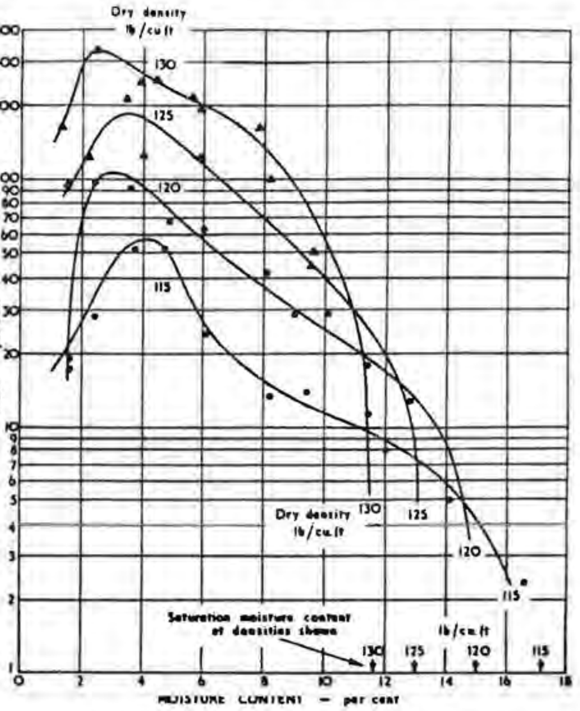


Figure 29. Variation of C.B.R. with moisture content for a sand at different densities.

In the C. B. R. test a bearing capacity failure may occur in some cases. Restraint due to the pot, and incomplete mobilisation of the full bearing capacity at 0. 1-in. deflection will in other cases make a bearing capacity analysis inapplicable to the test. The relationship between the bearing capacity of soil, the apparent angle of internal friction, ϕ, and the apparent cohesion, c, is, however, of the form

$$\text{Bearing capacity} = f_1(\phi) + c \cdot f_2(\phi) \quad (12)$$

This type of relationship applies to both a strip or circular footing. If the apparent cohesion be proportional to the product β's, then Eq. 12 becomes,

$$\text{Bearing capacity} = f_1(\phi) + \beta' s \, f_3(\phi)$$

and is of the same form as the experimental Eq. 11.

The approximate linearity of the variation of C. B. R. values with suction at suctions below one atmosphere, for an unsaturated silty sand (LL 24, PL 22) is shown in Figure 30.

At the Road Research Laboratory it has for some years been the practice in designing flexible road pavements to estimate first the equilibrium moisture content of the subgrade using the method outlined in this paper. The C. B. R. test has then been carried out at that moisture content and at a density likely to be achieved in the field. Now that means of checking the pore-water pressure are available it would appear more logical to bring the sample to the appropriate pore-water pressure rather than moisture content, since reference to Figure 29 shows that a small error in moisture content may lead to a very serious error in the C. B. R. value when the moisture content approaches saturation. Another factor which is at present under investigation in relation to the C. B. R. test is the effect which pore-water pressure, density, and stress gradients, present in the sample immediately after compaction, may have on the C. B. R. value. Such gradients arise from the effects of wall friction in the mould.

CONCLUSION

The paper summarises the research in progress at the Road Research Laboratory in Great Britain on the application of soil thermodynamics to the design of road foundations.

It is hoped that it will be of interest to those concerned with the more fundamental aspects of "moisture conduction phenomena" as well as to those whose concern it is to solve as expeditiously as possible the problems that arise in connection with highway engineering.

ACKNOWLEDGMENT

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