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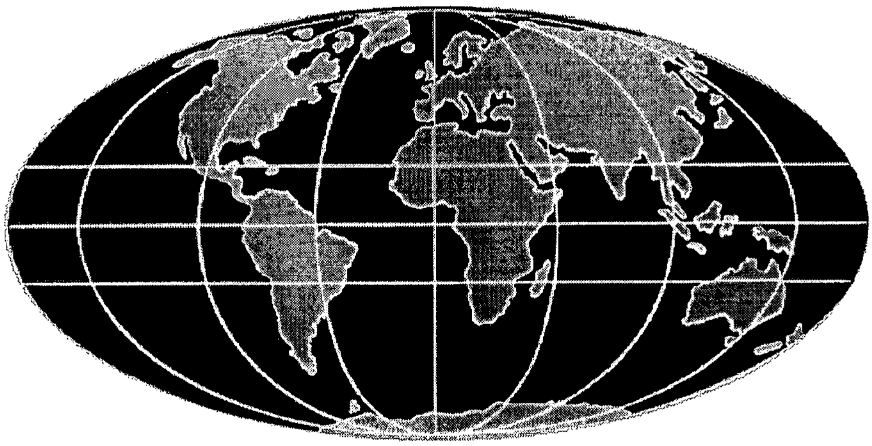

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Field measurement of soil suction

Mesure in situ de la succion du sol

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ABSTRACT: This paper describes a field probe for determination of the *in situ* suction which is based on the filter paper technique of total suction measurement. The main components of the probe and the installation procedure are described. The values of total suction determined using the probe are dependent on the ground temperature conditions and the length of time that the filter paper sensor is exposed to the soil. The results of a calibration experiment which takes into account the effect of temperature and equilibration time on the filter paper moisture content for the configuration of the probe are given. An example of the field results from Kenya are shown, where the probe was used on an experimental road constructed on expansive soils.

RESUME : Cet article décrit une sonde de mesure conçue pour déterminer la succion *in situ*, basée sur la technique du papier filtre pour la mesure de la succion totale. Les principaux composants de la sonde et la procédure de mise en place sont présentés. Les valeurs de la succion totale déterminées à l'aide de la sonde sont dépendantes de la température du sol et de la durée d'exposition du papier filtre dans le sol. Les résultats d'un essai de calibration qui prend en compte les effets de la température et le temps d'équilibrage de la teneur en eau du papier filtre pour la configuration de la sonde sont donnés. Un exemple d'essais *in situ* est présenté, où la sonde a été utilisée pour la construction expérimentale d'une route sur sols gonflants au Kenya.

1. INTRODUCTION

Gardner (1937) was the first to introduce calibrated filter paper as an indirect means of measuring the suction in soils. The air dry filter paper is placed in contact or close to the soil and the pore fluid (liquid or vapour) is allowed to transfer to the filter paper. The flow continues until the suction in the water in the filter paper and in the soil reach equilibrium. The water content of the filter paper is then related to the suction through a suitable calibration. The filter paper can be used in two modes depending on whether the matrix or total suction is to be measured. Where the filter paper is placed in contact with the soil the matrix suction is measured, since the soil water and the water transferred to the filter paper are identical and there will be no osmotic effects. Where the filter paper is close to but out of contact with the soil water, the water transferred to the filter paper will effectively be distilled water and the measured suction will be the total suction. Whatman No.42 filter paper has been shown to be a suitable absorbent sensor though other grades and types of filter paper are commonly used. Hamblin (1981) demonstrated that there was no significant difference between batches of filter paper produced at different times and it was concluded that Whatman No.42 filter paper could be used routinely without re-calibrating for each new batch. The problem of hysteresis of the filter paper is avoided by using the filter paper on the wetting cycle only (Chandler and Gutierrez 1986). Drying the papers at 105-110°C can alter the absorption properties of the filter paper irreversibly and the papers must therefore be used once only and then discarded.

2. TRL's SOIL SUCTION PROBE

TRL have developed a soil suction probe for monitoring the suction in subgrade soils and embankment fills on experimental roads in the tropics. The probe is a further refinement of the apparatus described by Crilly et al (1991). The probe is simple to operate, robust and reliable in use and overcomes many of the limitations of *in situ* suction equipment such as tensiometers and gypsum blocks. The probe, which is illustrated in Figure 1, is fabricated from commercially available sizes of PVC piping which fit around a small glass phial with a polythene closure. The sensor comprises ten strips of Whatman No.42 filter paper which are sealed within a retrievable sensing chamber.

The outer access assembly is driven into the ground using a technique based on the dynamic cone penetrometer (DCP). When the driving cone is displaced from the perforated sleeve, a section of soil is exposed where the sensor is located. The filter paper sensor is held in position by a retrievable inner assembly which seals into the outer assembly. With the inner assembly in the sensing position the filter paper is exposed close to the soil and the suction measured therefore corresponds to the total suction. The space within which the filter paper is contained is isolated from the atmosphere above the surface by the outer and inner assemblies as shown in Figure 2. Within this closed system the relative humidity will reach an equilibrium with the soil water. The time for this equilibrium to be achieved will be dependent on the total suction which exists in the soil water and the moisture content of the filter paper. The moisture content of the initially dry

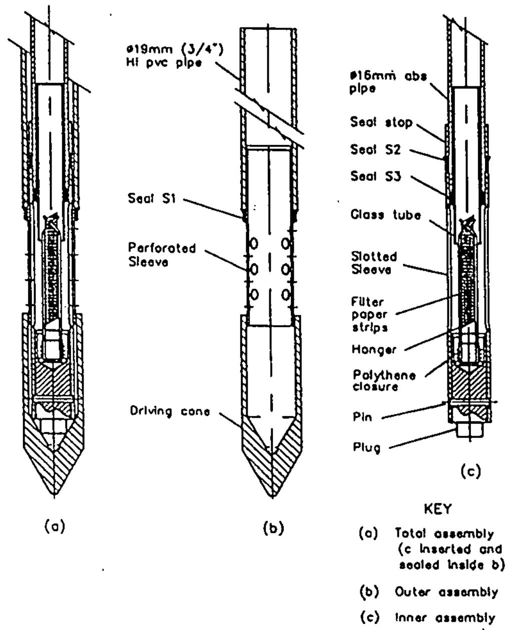

Figure 1 Sketch showing the main components of the TRL suction probe.

filter paper increases until it reaches a state of equilibrium with the relative humidity in the measuring chamber.

3. CALIBRATION

A number of calibration curves for Whatman No.42 filter papers have been published in the literature. The calibration equations of Chandler & Gutierrez (1986) for suctions in the range 80kPa to 6000kPa (equation 1) and Chandler et al (1992) for suctions below 80kPa (equation 2) which are:

$$Log_{10}P_k = 4.84 - 0.0622W_p \qquad (1)$$

$$Log_{10}P_K = 6.05 - 2.48Log_{10}W_p \qquad (2)$$

P_k = soil suction (kPa)
w_p = moisture content of the filter paper (%)

Unpublished work by TRL has shown that these calibration equations are not appropriate for the suction probe. It is generally accepted that these equations can apply for determinations of both matrix and total suction determinations. However, with the exception

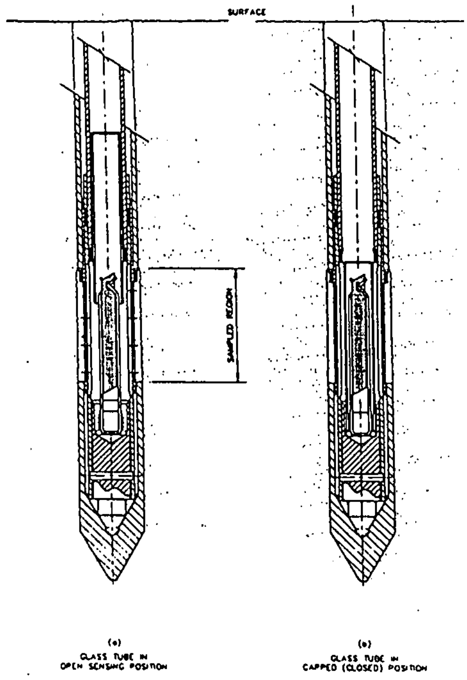

Figure 2 Filter paper sensor in opened sensing position (a) and closed position (b) ready for retrieval.

of the high suction range (above 3MPa) the calibration has been derived using contact measurements, and moisture transfer to the filter paper is therefore predominantly in the liquid phase. Further work has also shown that for total suction measurement the moisture content of the filter paper, and hence the suction derived using the equations 1 and 2, will depend on the soil-air temperature and the time that the filter paper is exposed to the soil.

A new calibration was carried out for the filter paper which could take into account the effect of temperature and equilibration time on the filter paper moisture content as well as the probe configuration. The partial vapour pressure (and hence relative humidity) developed above solutions of sodium chloride was used to calibrate the filter paper sensor used in the soil suction probe.

3.1 Theory

The thermodynamic relation between the free energy (total suction) of the soil moisture and the relative humidity of the soil air is given in equation 3.

$$P_k = -\frac{RT}{gm} Log_e H \qquad (3)$$

P_k = total suction (or in cms of water)
R = ideal gas constant, 82.058 cm^3 atms K^{-1} $mole^{-1}$
T = absolute temperature, °K.
g = acceleration due to gravity, 981cm/sec.^{2}
m = molecular weight of water, 18.02 g/mol.
H = relative humidity.

The application of equation 3 to the filter paper method uses the assumption that the moisture content of the filter paper comes into equilibrium with the relative humidity of the soil air.

Data were acquired from the Institute of Chemical Engineers relating the partial vapour pressure to the concentration of sodium chloride solutions for a range of temperatures. The partial vapour pressure was converted to relative humidity by dividing the partial vapour pressure by the vapour pressure of a solution of pure water at the same temperature. The relative humidity was then expressed as a suction (in kPa) using equation 3 for the range of concentrations of the sodium chloride solutions and temperatures.

An expression was then sought whereby the suction could be calculated for any concentration of sodium chloride solution (M) and for any temperature (T in °C) between 0 and 50°C. A least squares regression technique was used to derive an equation for suction in terms of the molarity of sodium chloride and temperature. The form of the equation was:

$$P_k = 3444M + 339M^2 + 141M^3 + 31.7M.T \qquad (4)$$

M = molarity of the sodium chloride solution
T = temperature, °C

3.2 Calibration experiment

A range of relative humidity was generated using solutions of sodium chloride at

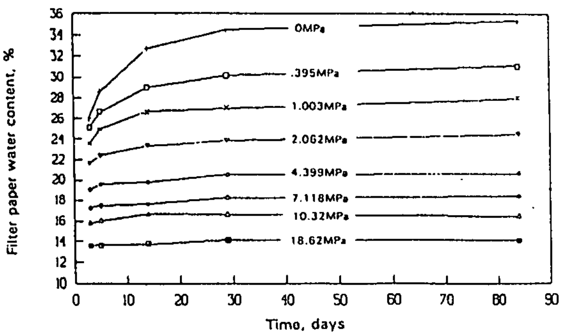

Figure 3 Filter paper water content versus time for 15°C.

molarities of 0, 0.1, 0.25, 0.5, 1.0, 1.5, 2.0 and 3.0. Wide mouthed jars of $125 cm^3$ capacity were used which gave a surface area of solution corresponding to the surface area of soil exposed to the filter paper sensor in the soil suction probe. For correctly installed suction probes this volume is about $55 cm^3$ and the surface area of soil exposed is around $25 cm^2$. The diameter of the jar was 5.5cm which gave a surface area of approximately $24 cm^2$. Each jar was filled with $70 cm^3$ of solution, leaving an air volume of $55 cm^3$ for equilibration. The Whatman No.42 filter paper strips rested on two clips attached to the roof of the jar. After sealing, the jars were put inside a temperature controlled cabinet which was itself placed within a large temperature controlled room. The cabinet maintained the desired temperature to ± 0.1°C and the room was controlled to ± 1°C. The jars were then left for the desired equilibration period. The temperatures selected for the calibration were 5, 15 and 30°C and the equilibration periods were 3, 5, 14, 28, 56 and 82 days. At each temperature, molarity and equilibration period, between five and seven jars were tested.

After equilibration the jars were retrieved from the cabinet, the seal broken, and the filter papers removed and placed inside small sealable test tubes. This operation took place inside the large temperature controlled room to avoid problems with condensation. Transfer and sealing of the test tubes took about 5 to 7 seconds and moisture loss from the filter paper was very low. The moisture content of the filter paper was then determined using a scientific balance weighing accurately to 0.0005g. Molarity checks were carried out on solutions from three jars at each molarity, temperature and time period.

3.3 Experimental results

An example of the experimental data at 15°C is plotted in Figure 3 and shows the mean filter paper water contents at the set equilibration periods for the range of suctions used. Similar plots were obtained at 5 and 30°C.

Using all of the data generated from the experiment a calibration equation was derived which includes the filter paper water content, the equilibration period and the temperature as variables. The total suction, P_k, is calculated using:

$$P_k = 10^{5.82 - \frac{T^{0.4}}{15} - 0.096Wp} - \frac{2.2\times10^6}{t^{\frac{lnT - 0.41}{3}} \times Wp^{2+\frac{t}{82}}} + \frac{500}{t}\times(\sqrt{T} - 3.87) - T^{1.5} \qquad (5)$$

w_p = filter paper water content, %
t = equilibration period in days
T = temperature (°C)

The range of this calibration is 20MPa to 380kPa and it has been determined for temperatures between 5 and 30°C and for equilibration times of 3 to 82 days. Use of the calibration outside these limits may lead to errors.

Figure 4 shows the 82 day data with minimum, mean and maximum measured water contents, and calibration lines for 5,15 and 30°C calculated from equation 5. Figure 5 shows the data and calibration lines for 3, 14 and 82 days for 15°C.

The relationship in equation 5 can be used to determine the suction from the filter paper water content of the sensor used in the soil suction probe when the equilibration time and soil-air temperature (°C) are known. The scatter in the experimental data, for this work was around $\pm 10\%$, whilst previously published calibrations, e.g. Chandler and

Gutierrez (1986) quote around ±25 per cent.

It is important to note that this calibration, which includes the period of exposure of the paper to the suction source, is specific to the system in which the testing was done. This system was designed to have similar characteristics to the field probe and does not replace the Chandler and Gutierrez (1986) calibration. The calibrations differ in that most of the data used for the Chandler and Gutierrez (1986) calibration was obtained from contact type measurements while the probe calibration is specifically for non-contact measurements. This calibration equation is therefore specific to the TRL suction probe and has not been tested in other configurations of measurement system.

4. *IN SITU* SUCTION MEASUREMENT

An experimental section of road has been constructed by TRL in an arid area of north eastern Kenya to evaluate the potential for construction of earthworks at moisture contents dry of their optimum. The road crosses a large tract of expansive clay soil where alternative road building materials are difficult to locate. The expansive clay was utilised for fill and subgrade and was compacted at its natural moisture content of around 16 per cent. The densities achieved met the specification required for the design strength. The road pavement, which was designed to carry 0.5 million equivalent standard axles over 15 years, consists of a triple surface dressing above 175mm sub-base and 125mm of permeable crushed stone base. The cross-fall on the running surface is 2.5% and 4% on the 1 metre sealed shoulder. The side-slopes were constructed at 1:4.

Immediately after construction the suction probe was installed across the road and at various depths within the embankment structure. The probe array was positioned so that the modes of suction change could be discriminated i.e. the influence of rainfall run-off and evaporation close to the shoulder could be distinguished from other wetting or drying mechanisms such as changes in ground water level. Aluminium access tubes were also

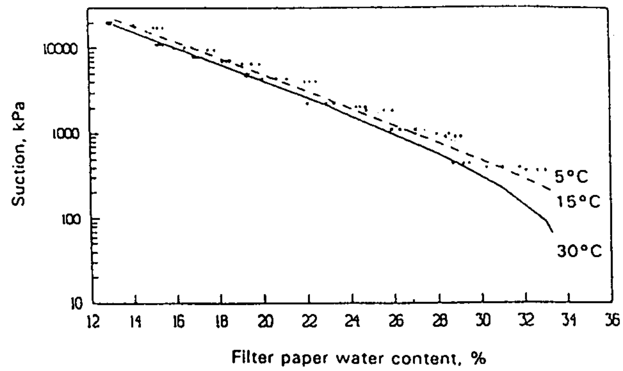

Figure 4 Comparison of the measured data and equation 5 for 5, 15 and 30°C at 82 days.

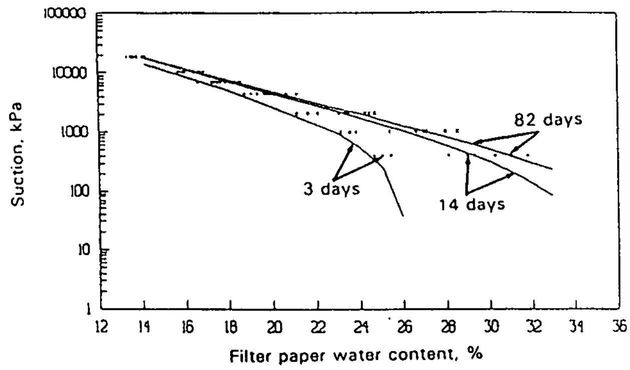

Figure 5 Comparison of the measured data and equation 5 for 15°C and 82 days.

installed 1 metre away from the suction probes to enable nuclear gauge measurements of sub-soil moisture to be taken.

The initial set of data taken shortly after construction showed initial moisture contents of around 12-16% with corresponding total suctions of 10-12MPa. The data collected seven months after construction is shown in Figure 6 and has been contoured. It can be seen from the figure that little change in suction or moisture has occurred close to the centre-line or at a depth below about 600mm from the road surface. However, a wetting front can be seen extending into the body of the embankment and along the subgrade to a depth of about 600mm from the surface. It is apparent that water is penetrating the subgrade at the edge of the sealed shoulder and that under the influence of the relatively high soil suctions it is capable of further ingress into the

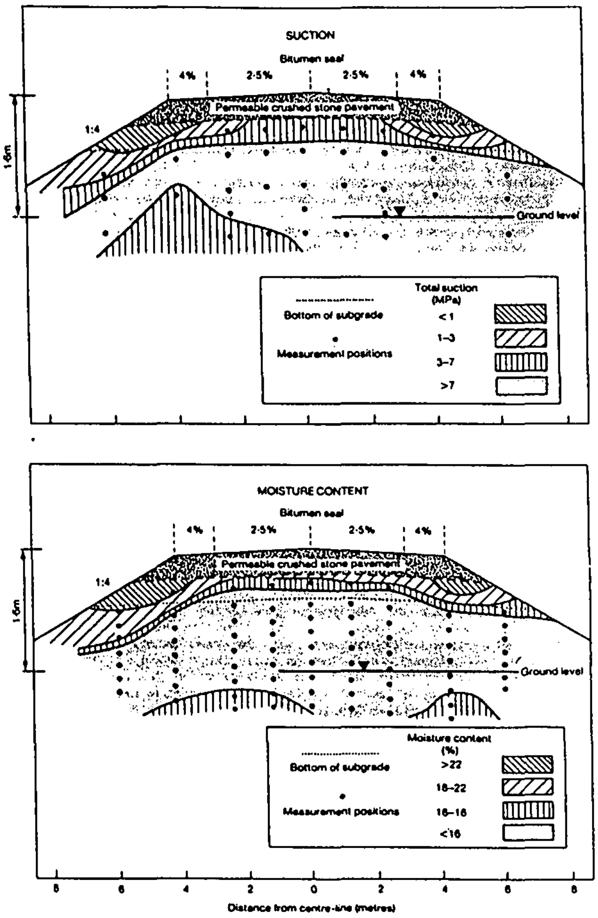

Figure 6 Total suction and moisture content seven months after construction.

body of the embankment. There is therefore a potential for both a soil volume change on wetting and a corresponding loss of strength early in life of the road. The suction probe is now used to study the transient and equilibrium moisture-suction conditions existing beneath road pavements.

The probe has also seen application in Australia for a ground subsidence investigation, in Brazil for an evaluation of sub-soil moisture response to deforestation and in the UK for a research study on the seasonal moisture condition of borrow materials for earthworks.

5. CONCLUSIONS

A probe has been developed for the *in situ* measurement of total suction. The probe, which uses a filter paper sensor, is simple to fabricate, economical and mechanically easy to install and operate. These features make it an ideal tool for monitoring soil suction conditions over long periods in particularly remote areas.

An extensive and thorough calibration has been undertaken for Whatman No.42 filter paper, as used with the TRL suction probe. Temperature and equilibration period have been introduced into the calibration for the first time. The use of this calibration equation with data obtained using the TRL suction probe provides a relatively simple means of determining *in situ* suction. The scatter in the experimental data for this work is much less than that in previously published calibrations. However, the calibration equation is specific to the TRL suction probe and has not yet been tested in other configurations of measurement system.

Though it was developed for monitoring suction in clay subgrades and embankment fills in arid areas the probe is now being used on a number of widely different soils engineering projects around the world.

6. REFERENCES

Chandler R.J. and Gutierrez C.I. (1986). The filter paper method of suction measurement. *Geotechnique, 36, p265-268.*

Chandler R.J., Crilly M.S. and Montgomery-Smith G. (1992). A low-cost method of assessing desiccation for low rise buildings. *Proc.Instn.Civ.Engng., 92, May, p82-89.*

Crilly M.S., Schreiner H.D. and Gourley C.S. (1991). A simple field suction measurement probe. *Proc. 10th African Regional Conference Soil Mechanics and Foundation Engineering, Lesoto, p291-298.*

Gardner R. (1937). A method of measuring the capillary tension of soil moisture over a wide moisture range. *Soil.Sci., 43, No.4, p277-283.*

Hamblin A.P. (1981). Filter paper method for routine measurement of field water potential. *J.Hydrology, 53, 355-360.*

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