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Prediction of subgrade moisture conditions for purposes of pavement design

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ABSTRACT: The purpose of this paper is to summarize the procedures for determining moisture conditions in subgrade soils and make recommendations regarding the practical applications to pavement design. By using data from different moisture studies some moisture models were tested to demonstrate their capability of predicting ultimate moisture contents.

1 INTRODUCTION

The effect of water in road earthworks, foundations and pavements may be a cause of premature pavement failure.

In fact the mechanical behavior of subgrade soils is affected by the presence of water and the development of capillarity potential above the water table.

In some pavement designs methods it is assumed that the materials will not be in any worse condition than if they were soaked in water for four days-hence the well known soaked CBR value. Field observations have shown that this assumption is somewhat conservative for most well drained roads.

Nowadays the use of mechanistic design needs the resilient and plastic properties of the subgrade soil and these have to be obtained for the moisture conditions expected during the construction and subsequent to the completion of roadwork during the life of road structure.

These two stages of design are important because the moisture conditions of soil during the earthworks may be different than the ultimate conditions that will be reached when an impervious road structure is constructed. For instance, taking Figure 1 showing gradients of moisture within the soil profiles determined during summer and winter we can conclude that the mechanical properties for design should be determined from soil tested with water content considered as following:

- if the pavement is to be constructed during the winter, the soil should be tested at whatever is the moisture content (w_w). This value must be used to study a platform which may not rut excessively under construction and ensure that the asphalt mixture can be adequately compacted. This water content may also be considered for designing the first period of road life until the moisture content can decrease to its equilibrium value (w_{ew});
- if the road is to be built during the summer, the value (w_s) can be used during the road construction but the road structure must be design for the ultimately moisture content value - w_{es} (equilibrium value).

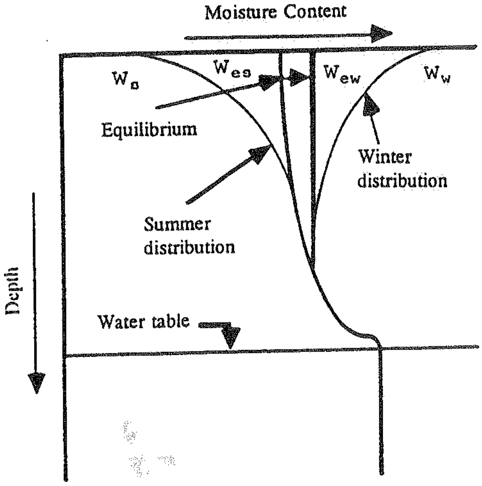

Fig.1 Seasonal variations in the moisture content of fine subgrade soil

It is therefore essential for the road design to simulate the field moisture conditions for the subgrade soils that exist during construction and in service under the pavement.

2 EXPERIMENTAL OBSERVATIONS OF MOISTURE CONDITIONS IN SUBGRADE SOILS - EMPIRICAL RULES

One of the first experimental work was done by Kersten (1944) who investigated the field moisture of the upper 150 mm of the subgrade on flexible pavements. This work is summarized as follows:

- the subgrade soils of numerous projects in 6 states in which a high average percent of saturation occurred were in most instances either clay or silty clay;
- the degrees of saturation average was 73%, ranging between 60 up 81%. In general the high values concerned the clays and the lower for the sandy silts;
- subgrade moisture expressed as percentage of the plasticity limit for a large variety of soils in 6 states average 77%; averages for individual states varied from 64 to 82%. Approximately 17% of the determinations disclosed moisture contents in excess of the plasticity limit, which was the case of clays and rarely sandy silts. The loessical silty soils tended to attain moisture close to their plasticity limit;
- the optimum moisture contents of the soils were exceeded by the field moisture in about 1/3 of the determinations reported. This was most commonly the case with clays.

Another important experimental research was undertaken by OCDE and the results presented in the OCDE (1973) report.

These results are summarized in Table 1.

Janssen and Dempsey (1980) reported, from field studies realized in different states of USA, that a significant number of subgrade soils were above the optimum water content. The number of such cases increased directly with increasing clay content.

Emery (1984) based in moisture studies carried out in different Provinces in Southern Africa, which integrate 1608 samples covering a wide range of climates, site conditions and material properties, concluded that the best predictors of subgrade, sub-base and base moisture are the optimum moisture content, liquid limit and linear shrinkage and Thornthwaite's moisture index. However, for pavement design, he proposed a prediction model based in the ratio between equilibrium moisture content (EMC) and optimum moisture content at modified Proctor ratio (OMC), incorporating a statistical factor of safety to ensure there is only a small probability that the design moisture content will be exceeded. This water content is defined by Haut (1981) as the characteristic moisture content. Analyzing the results presented by Emery, it was found that ratio EMC/OMC, integrating a probability of 90 or 95 % is not significantly different for intermediate climate regions between arid and humid climates. So, a simplified prediction of design moisture content (EMC_c) may be obtained by using the ratios

Table 1. Water contents in the subgrade soils (OCDE 1973).

Organization	Moisture conditions	Comments
"Centre de Recherches Routières"	$S_r = w/w_{sat} = 80\%$	Plastic soils in different pavements sections. $S_r = 95\%$ with a water level 2 m from the platform surface.
"Laboratoire Central des Ponts et Chaussées"	$0{,}8\ w_p \leq w \leq 1{,}2\ w_p$	Scatter obtained from measurements done 30, 80 and 150 cm beneath the platform of 20 pavement sections in 8 different areas. The average value is about the plasticity limit. The greater values of water content were obtained in spring and the lowest in summer, which were near the optimum water content of Modified Proctor.
Minnesota States Highway Department	$w = 1{,}16\ w_p - 7{,}4$	Clayey silt soils with plastic limits between 15% and 30%. Samples taken 15 cm beneath the platform. For a depth of 45 cm the water content increase 2 to 3%. Water content measured in Spring is 0,8% greater than the water content in summer.
Transport and soil mechanics laboratory of Madrid	$0{,}8\ w_p < w < 1{,}11\ w_p$ $0{,}38\ w_L < w < 0{,}49\ w_L$ $0{,}33(\% \leq 75\ \mu m) < w < 0{,}60\ (\% \leq 75\ \mu m)$	
U.S. Navy	$w = w_p + 2\%$	Clayey and silty soils under 70 airfields of U.S. Navy, with a water table level deeper than 60 cm from the surface of platform.
University of Minnesota	$0{,}8\ w_p < w < 1{,}2\ w_p$ $70\% < Sr < 90\%$	Clayey and silty soils in moisture areas of 7 US states with different climatic conditions. The water contents were measured 30 cm beneath the platform of airfield pavements.
Water Experiment Station	$Sr = 90\%$	Plastic soils in different airfield pavements with 85% or more of material passing the 75 μm sieive.

Table 2. Ratios of characteristic moisture content to optimum content of modified Proctor (EMC_c/OMC).

Climate area	Thornthwaite (Im)	EMC_c/OMC	
		Probability 90%	Probability 95%
Arid	-50 to -30	1.15	1.27
Intermediate	-40 to +100	1.34	1.46
Humid	+20 to +100	1.49	1.61

presented in Table 2.

These results were obtained from pavements with both cracked and uncracked surfacing, and with different drainage conditions and consequently they are slightly conservative. Care should also be taken that a shallow water table is not present, since these predictions do not apply.

Emery (1984) also stated that the coefficient of variation of moisture contents associated with the seasonal variations is 5%.

Branco and Gomes Correia (1990) investigated the field moisture content of a large variety of soils (Figure 2) under portuguese pavements (600 mm from the edge of pavement structure) in the Lisbon and Setubal areas and concluded:

- the subgrade moisture content in 90% of the observations were below the plasticity limit (Figure 3) and rarely were above the upper boundary reported in the OCDE (1973) study;
- the best relationship of observed moisture content is with the optimum water content of modified Proctor (Figure 4). The values lower than the optimum were generally observed for the non-plastic soils (A-1, A-3 and some A-2-4).

If the relationship for intermediate climate region presented in Table 2 is used and a probability of 95 % is assumed, the characteristic moisture content for the subgrade soils will be 1.46 times the optimum water content, which is a reasonable prediction.

From the results presented before, we may conclude that none of the available results could be applied successfully to local conditions without modifications because of their lack of accuracy. However it seems that the best predictor of soil moisture is the optimum water content and the ratios presented in Table 2 may be used as a first approach.

3 SEMI - EMPIRICAL METHODS OF ULTIMATE MOISTURE CONTENT ESTIMATION

3.1 Shallow water table

Chu et al. (1977) cited by Elfino (1986), analised the results of investigations on the variation of subgrade moisture, which were conducted in the United States and abroad, and showed that, after a certain period of time following construction, subgrade soils below impervious pavements remain at fairly stable moisture conditions, except for a zone close to the pavement edge. Under idealized conditions, the variation in subgrade moisture depends mostly on the relative elevation of groundwater table if it is within a certain depth below the pavement. Russan (1965) stated that, for highway and airport pavements, this depth would be

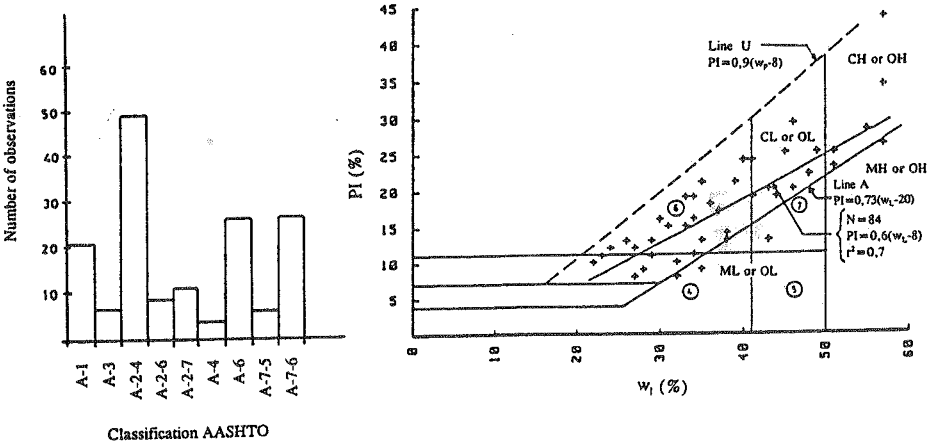

Fig.2 Variety of soils in field moisture investigations by Branco & Gomes Correia (1990)

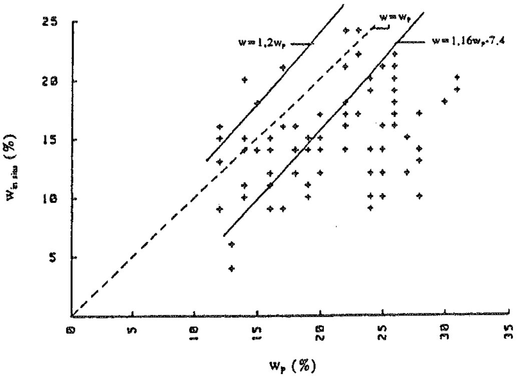

Fig.3 Relationship between moisture content and plasticity limits (Branco & Gomes Correia 1990)

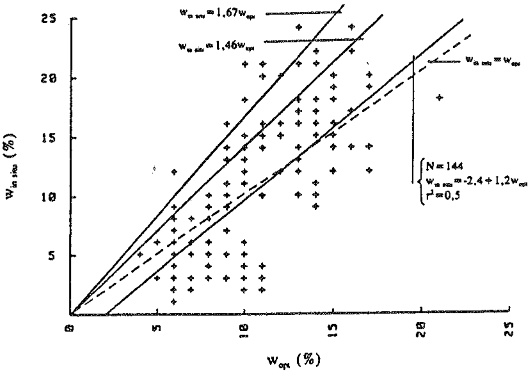

Fig.4 Relationship between moisture content and optimum moisture content of modified Proctor (Branco & Gomes Correia 1990)

approximately: 6 m in clays; 3 m in sandy clays on silts; 0,9 m in sands.

In these situations the moisture content of subgrade soils may then be estimated on the basis of the depth of the water below the pavement, together with soil suction data, provided that a moisture equilibrium condition has been reached in the subgrade (Croney 1952).

This require laboratory suction tests on samples taken from the formation level using a suction corresponding to the most adverse antecipated water table conditions.

The relationship between suction, overburden pressures, and water table positions has been fully dealt with elsewhere. It has been shown that suction can be calculated using the equation.

$$s = \gamma_w z - \alpha \sigma \qquad (1)$$

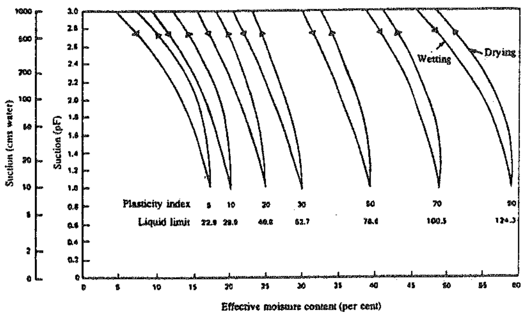

Fig.5 Relationship between suction and effective moisture content for various soils (Black and Lister 1978)

where s = the soil moisture suction, or pore water pressure at zero overburden pressure and air pressure at atmospheric pressure; γ_w = unit weight of water; z = depth of water table below the surface; σ = overburden pressure; and α = portion of the overburden pressure which is effective in changing the pore water pressure. This cofficient may be estimated by the following equations (Verbrugge 1972):

$$\alpha = 0 \ (PI < 5\%) \qquad (2)$$

$$\alpha = 1 \ (PI > 40\%) \qquad (3)$$

$$\alpha = 0.027 \, PI - 0.2 \ (5\% \leq PI \leq 40\%) \qquad (4)$$

Except in the case of sand soil, suction at equilibrium is therefore controlled both by depth of the water table and by surcharge imposed by the pavement.

Moisture content changes in subgrade can then be established from the relations between soil suction and moisture content. For this purpose Black and Lister (1978) present a series of average suction effective moisture content curves for a great variety of soils, with plasticity index varying between 5 and 90% (Figure 5). These soils must satisfy a line on the Casagrande Plasticity chart typical of cohesive soils with an equation:

$$PI = 0.838 \, w_L - 14.2 \qquad (5)$$

For the soils that do not satisfy this equation the effective water content must be estimated from the following equation:

$$w_e = w_a + (PI + 14.2)/0.838 - w_L \qquad (6)$$

where w_e = effective moisture content; and w_a = actual moisture content.

As a consequence of hysteresis in the suction/moisture content relation (Figure 5), it can be seen that once the soil has became very wet it will follow a drying curve which ensures that the soil will always remain wetter at equilibrium than on the same soil which has never allowed to become so wet (Black and Lister 1978).

For practical purposes it is usually accepted that the amount of hysteresis lies between 2 and 3% of water content for all soils. This amount is for low plasticity soils very important in the change of the consistency index and in consequence in the mechanical properties of these soils when subjected to different amounts of wetting during road construction.

If facilities for conducting suction tests are not available, a estimate of the "equilibrium" moisture content can be obtained from measurements taken at a point below the zone of seasonal fluctuation, but at least 0,3 m above the water table. In cohesive soils in Britain, particularly those supporting dense vegetation, the moisture content at a depth of 1,00 - 1,25 m will normally provide a good estimate of the ultimate moisture contents (O'Flaherty 1988).

If the cohesive soil is to be used as an compacted material, the disturbance to the soil structure is likely to cause the "equilibrium" moisture content to be increased above the normal ultimate value for the undisturbed soil. This will be taken in account for a heavy clay increasing by about 2% the water content measured at the depth indicated previously. For compacted lighter silty and sandy clays a corresponding addition of 1% should be made. For sandy soils, which do not normally support a dense cover grass the "equilibrium" water content may be obtained from the water content measured at a depth of 0,3 to 0,6 m.

Uppal and Singh (1972) investigate the relationship between the moisture content and water table level for different types of soils under pavements in Australia. They conclude that in a sandy type of soil with a plasticity index ranging from 0 to 4, the moisture content in the worst waterlogged area can go up to about 14%, whereas for a highly plastic soil, the moisture content under the pavement can rise up to 19% when the water table is high.

Using the data collected from Uppal and Singh (1972), a comparison with the results presented by Black and Lister (1978) was done and presented in Figure 6. In this analysis the values of water content were converted in effective water content by equation 6 and by simplification it was assumed that the therm $\alpha\ \sigma$ is zero in equation 1.

The analysis of Figure 6 shows that the curves proposed by Black and Lister (1978) conducted to an acceptable prediction of the in situ data obtained by Uppal and Singh (1972).

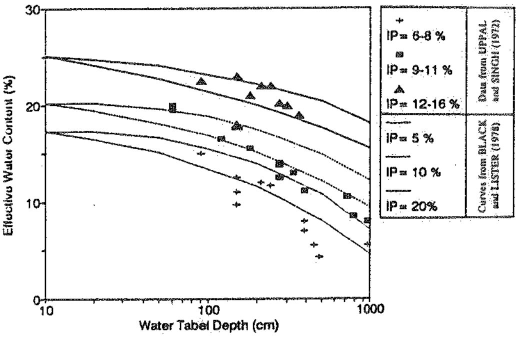

Fig.6 Assessment of Black and Lister (1978) moisture model to predict moisture content of subgrades of varying soils using data of Uppal and Singh (1972

3.2 Deep water table level or no existing

When the water table is deeper than the values presented earlier for the different types of soils, the moisture conditions were controlled by the balance between rainfall and evapotranspiration. In these conditions we can also consider the following situations (Russan and Coleman 1961):

- sites where the rainfall during at least two months of year exceed the evapotranspiration;
- in theses sites usually the rainfall is greater than 250 mm per annum; sites when the rainfall is lower than 250 mm per annum.

For sites with rainfall greater than 250 mm per annum the equilibrium moisture content may be estimated from the average Thornthwaite moisture index by means of Figure 7 and the suction curve of the soil.

For practical purposes, and within a given climatic environment, the ratio of ultimate

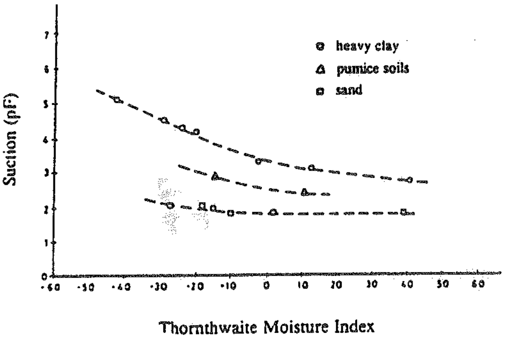

Fig.7 Relationship between thornthwaite moisture index and suction for different types of soils (Russan & Coleman 1961)

moisture content to plasticity limit or optimum moisture content tends to be constant, as demonstrated before. This ratio can be determined from data obtained by sampling the soil beneath existing roads over five years old. However it must be kept in mind that the design moisture content may integrate the drainage conditions. If there are not covered areas near the construction of the new road this ratio may be established by sampling the soil under the zone of surface change of moisture.

The sites with rainfall less than 250 mm per annum are typical of arid climate zones. In this instance, except immediately after rain, the soil suction is controlled by the atmospheric humidity and the ultimate moisture content differs little from the uncovered soil at the same depth.

4 CONCLUSIONS

The design moisture content or the design suction taken for pavement design must be that corresponding to the most adverse conditions likely to arise during construction and during the project lifetime of the pavement. The water content during construction is very important because it may take many years to reach the ultimate conditions. As a result, a special attention during the earthworks is necessary to prevent infiltration of water.

The fact that the design water content during construction may be different from that during the pavement in service justifies the need of a two stage pavement design.

For deep water table, parameters such as Thornthwaite moisture index, plasticity limit or optimum moisture content, influence the ultimate water content. With these parameters some moisture models may be use to predict the design water content. These models may be adjusted according to site conditions, by sampling the soil under the zone of surface moisture change and taking into account the drainage and boundary conditions.

For shallow water table conditions, the ultimate moisture content is very dependent on the depth of groundwater and the suction curve of the material. A prediction approach is presented for these conditions. As the depth of water table is a prominent parameter influencing moisture it is indispensable to have a good drainage system working properly during the life of the road.

The use of new materials in road construction require that the results summarized in this paper be updated with the new developments.

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