Predictability of Certain Properties of Soil-Water Mixtures

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Results of consistency tests performed on cement pastes, cement mortars, and concretes show that the relationship between the change in consistency and the change in water content can be approached by a certain power function within practical limits. A similar approach for soil-water mixtures was recommended earlier by the Waterways Experiment Station as a "rapid" or "one-point" method for the simplification of the liquid limit test procedure. In this paper a simple physical interpretation of this approach by power function, called "assumption of independence," is presented. Also, three other approaches concerning the relationship between the consistency and water content of soil-water mixtures are analyzed mathematically, as follows: (a) assumption of a logarithmic relationship; (b) assumption of a point of convergence; and (c) assumption of a hyperbolic relationship.

The equations expressing the assumptions can be derived from each other; thus, the four methods are essentially four different mathematical descriptions of the same phenomenon concerning the soil consistency as a function of water content. Data are presented from the technical literature which indicate that the assumption of independence might also be used as a simple approach to soil properties other than the consistency.

•RESULTS of consistency tests on cement pastes, cement mortars, and concretes show that the relationship between the change in consistency and the change in water content can be approached by certain power functions within practical limits. A similar approach was previously recommended for soil-water mixtures. A simple physical interpretation of the approach by power function, called "assumption of independence," is presented. Three other assumptions concerning the relationship between the consistency and water content of soil-water mixes, are analyzed mathematically. A well-known utilization of any of these assumptions is to simplify the determination of the liquid limit, or more precisely, to predict the liquid limit of soils by so-called "one-point" or "rapid" methods. The approximation by power function, however, could be also used advantageously for soil properties other than consistency.

The consistency of a soil-water mixture will be characterized numerically in the usual way, i. e., by the number of drops of the cup of a standard mechanical liquid limit device at which the two halves of a soil cake will flow together for a distance of ½ in. along the bottom of the groove separating the two halves, when the test is performed according to the "Tentative Method of Test for Liquid Limit of Soils," ASTM Designation: D423-61T. The numerical characteristic of the consistency is called "consistency measure" in this paper.

ANALYSIS OF ASSUMPTIONS

The Relationship of a Power Function

The earliest assumption for the change in consistency, where change is due solely to the change in water content, is the assumption of the relationship of a power function.

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This was first proposed by the U. S. Waterways Experiment Station (1) for the prediction of liquid limit of soil-water mixtures. The pertinent power function can be written as

$$w = aN^b \tag{1}$$

in which

w = water content of the soil-water mixture, percent by weight;
N = number of drops of the cup of the standard device, i. e., the consistency measure;
a = factor which is a function of the soil type; and
b = factor which is constant for every soil but depends on the method of measuring consistency. (For the standard method for soils, the following value of "b" is recommended by ASTM D423-61T: $b = -0.12$.) It is characteristic of the rate of change in consistency.

The meaning of Eq. 1 can also be expressed as follows: The amount of (relative) change in consistency which is due solely to the (relative) change in water content is independent of the type and original consistency of the material.

This statement is called the "assumption of independence." Obviously, the assumption of independence is valid only to the extent that the assumptions expressed by Eq. 1 are valid.

To illustrate the assumption of independence, assume that a certain soil sample of 100 g and $w = 77$ g water requires $N_1 = 20$ drops of the cup to close the groove. Also, assume that a reduction of 2 g water (2.6 percent of the original water content) will increase the number of needed drops to $N_2 = 25$. If the assumption of independence is valid, then this 2.6 percent reduction of water content will result in the increase of the required drops from 20 to 25 for every soil.

In this example the relative value of the water reduction, and the relative value of the change of consistency were as follows:

$$\Delta w = 100\,(77 - 75)/77 = 2.6 \text{ percent decrease}$$

and

$$\Delta N = 100\,(25 - 20)/20 = 25 \text{ percent increase.}$$

The accuracy of the approximation by a power function, particularly its practical applicability to predict the liquid limit, has been checked by several investigators: the liquid limits of various soils were determined by the customary three-point method and predicted by the one-point method which is an approximation by a power function; then the results of the two methods were compared for significant differences. The analyses of the test results showed that the overwhelming majority of these differences were small within certain limits of validity (1 - 5) even though these differences also contained the experimental errors of the three-point method (6). Opinions differ slightly concerning the exact value of "b" power, the limits of validity, and the extent of accuracy of the approximation; nevertheless, it seems established that the application of a power function for the relationship between consistency and water content is, within certain limits, acceptable. However, any modification in the test method of measuring consistency can cause a significant change in the value of the power "b" (7).

The use of the approximation by power function on concrete consistency was explored in previous papers (7, 8) without knowledge of the proposition of the U. S. Waterways Experiment Station. In these papers the identity of the assumption of independence and Eq. 1 is mathematically shown.

Another simple proof is based on the fact that the values calculated from Eq. 1 with various "a" factors will give a family of parallel straight lines (so-called "flow curves") when plotted in a log-log system of coordinates (Fig. 1).

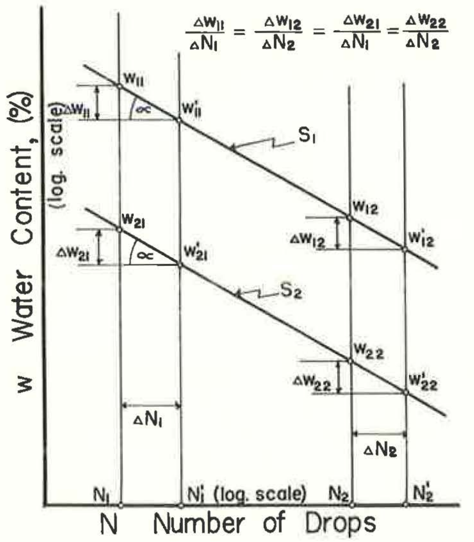

Figure 1. Consistency and water content relationship using a power function.

Proof:

1. That the relative change of consistency is independent of the N_i original consistency, follows from the fact that the flow curve gives a straight line in the log-log system; because if the following designation is used

$$\Delta w_{ij} = \log (w_{ij}/w'_{ij}) \tag{2}$$

and

$$\Delta N_i = \log (N_i/N'_i) \tag{3}$$

then the S_1 straight line of Figure 1 fulfills the equation as follows:

$$\Delta w_{11}/\Delta N_1 = \Delta w_{12}/\Delta N_2 \tag{4}$$

regardless of the value of N_i.

2. From the parallelism of any two S_1 and S_2 flow curves it follows that the relative change of consistency is independent of the type of the soil because (from Fig. 1):

$$\Delta w_{11}/\Delta N_1 = \Delta w_{21}/\Delta N_1 \tag{5}$$

regardless of the value of w_{i1} which value is indicative of the type of soil.

Various Forms for the Approximation by Power Function

Various forms can be derived from Eq. 1 for the approximation by a power function, i. e., for the assumption of independence. One such form is:

$$N_2 = N_1 (w_2/w_1)^n \tag{6}$$

in which

N_1 = consistency measure for the initial consistency;
N_2 = consistency measure for the changed (predicted) consistency;
w_1 and w_2 = water contents for the consistency measures of N_1 and N_2, respectively; and
$n = 1/b$ = test method constant.

Another form is as follows:

$$N_2 = N_1 (0.01\, w_{rel})^n \tag{7}$$

where $w_{rel} = 100\, w_2/w_1$ = relative water content in percent.

A further form is

$$N_{rel} = 100\, (0.01\, w_{rel})^n \tag{8}$$

where $N_{rel} = 100\, N_2/N_1$ = relative consistency measure in percent

And finally (10):

$$Y = 100\left[(1 + 0.01X)^n - 1\right] \tag{9}$$

where $X = 100(w_2 - w_1)/w_1$ = relative change in water content, percent, and $Y = 100(N_2 - N_1)/N_1$ = relative change in consistency measure which is due to the change of X in water content, percent.

Eqs. 6-9 provide further possibilities to visualize the extent of agreement between the experimental results and their approximation by a power function. For instance, the better the flow curves of various soils approach a family of straight lines in a log-log system, the better the approximation of Eq. 6. This principle has been used in soil mechanics to check graphically the accuracy of the approximation by a power function. The same principle is illustrated on consistencies of cement pastes in Figure 2 where results of Vicat penetration test (ASTM C187-58) are presented as a function of water content. The results were obtained by various investigators on a variety of portland cements (9, 11, 12). It can be seen that the Vicat penetrations form a family of parallel straight lines in fairly close agreement within the limits of 6 mm and 30 mm. Penetrations smaller than 6 mm or larger than 30 mm showed more considerable discrepancies from the parallelism, which gave a basis for the determination of the limits of validity for this approximation. The postulate for the parallelism of flow curves can also be used for the construction of a nomographic chart that makes easier the practical application of Eq. 6. Such nomographic charts for cement, mortar and concrete have been previously presented (13).

Results obtained on cement pastes indicate two other points: (a) if some kind of penetration test were used for the determination of liquid limits of soils (14) rather than the present standard liquid limit device, then a "one-point" method based on the assumption of independence could probably be developed for this new test also; (b) there is a good chance that a "one-point" method can be developed for the standard Vicat penetration test on cement pastes.

Eq. 7 provides another possibility for checking. If the water content related to the consistency of N_1 is w_{rel} = 100 percent, then the N_2 values calculated from Eq. 7 will form a single straight line in a log-log system, regardless of the original w_1 moisture content. Consequently, the approximation by a power function is accurate only to the

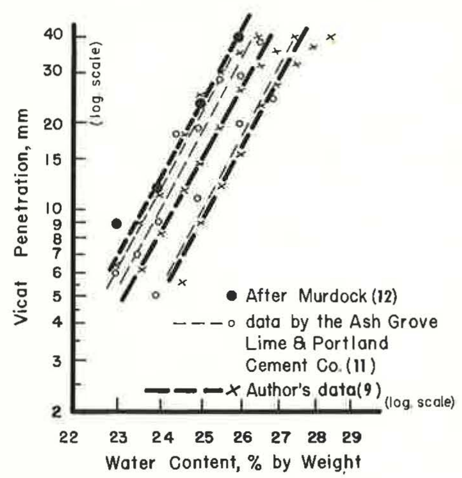

Figure 2. Vicat penetration as a function of water content for various portland cements.

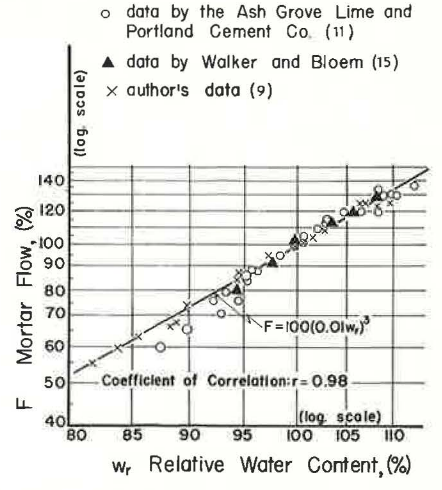

Figure 3. Flow of cement mortar as a function of relative water content for various portland cements (water content related to 100% flow is 100%).

extent that the experimental results approximate this straight line. Thus, from such a chart the value of the "n" power, the extent of approximation, and the limits of validity for the adequate approximation can be easily determined. This principle is illustrated in Figure 3 on consistencies of cement mortars where results of standard flow tests (ASTM C230-61T) are presented as a function of relative water content. The results were obtained by various investigators on a variety of cement mortars (9, 11, 15). Within the flow limits of 55 percent and 130 percent, the flow results form a straight line with a good approximation. This is also shown by the significantly high value of the coefficient of correlation. The discrepancies of flow values smaller than 55 percent or larger than 130 percent were considerable higher. Thus, Eq. 7 provides a comfortable visual method for checking the accuracy of the approximation by power function. In addition, the value of "n" power and the limits of validity for the adequate approximation can be determined easily from such a chart.

Eqs. 8 and 9 again reveal the identity of the approximation by power function and the assumption of independence. They show directly that a fixed relative change takes place in the consistency as a consequence of a given relative change in the water content, and this fixed change is independent of the original moisture content and original consistency. If, for instance, a Δw_1 percent reduction in water content makes a change in the N_1 consistency measure (for example, the number of blows changes from 15 to 16 which is an increase of $6\frac{2}{3}$ percent) then, according to the approximation by a power function or assumption of independence, the same Δw_1 percent reduction in water content will cause a $6\frac{2}{3}$ percent increase in the consistency measure when $N_1 = 30$. In other words, in the latter case the consistency measure will change from 30 to 32. The application of this principle is particularly useful for concrete consistency, and for several other soil properties.

Figures 2 and 3, as well as previous papers (8, 9), show that the presented approximation by power function, and at the same time the applicability of the assumption of independence, far exceeds the standard mechanical liquid limit device.

Assumption of a Logarithmic Relationship

A logarithmic form was recommended for the rapid determination, or more precisely, for the prediction of liquid limit by Cooper and Johnson (6), and later by Fang (7). The flow curve of this assumed logarithmic relationship gives a straight line in a w (linear) and N (log) semilogarithmic system of coordinates (Fig. 4). Also, Fang assumed that the slope of a flow curve in Figure 4, which he called "flow index" and designated by I_f, is a linear function of w_{i1} water content which belongs to any fixed N_1 consistency. (If $N_1 = 25$, then $w_{i1} = LL$ = Liquid Limit). The mathematical expression of this relationship is

$$w = w_{i1} + I_f \log N_1 - I_f \log N = A - I_f \log N \tag{10}$$

and

$$I_f = Bw_{i1} + C \tag{11}$$

where A is independent of N but is a function of the type of soil; and B and C are constants for every soil and consistency.

With a certain restriction, Eqs. 10 and 11 can be derived from Eq. 1. In other words, Eq. 1 and Eqs. 10 and 11 are saying essentially the same thing concerning the soil consistency as a function of water content—only the form of expression is different.

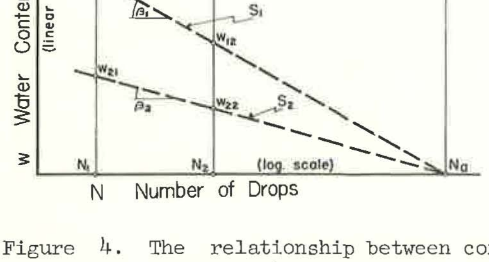

Figure 4. The relationship between consistency and water content approached by a logarithmic function.

Proof:

It can be seen from Figure 1 that for

any two fixed N_1 and N_2 values of consistency the following is valid:

$$w_{11}/w_{12} = w_{21}/w_{22} = \text{const.} \tag{12}$$

without respect to the type of soil, because N_1/N_2 = constant. On the other hand, if points w_{11} and w_{12} of the flow curve S_1 (Fig. 1) are represented in the semilogarithmic system of Figure 4, then the flow index, i. e., the slope of the straight line which passes through the points w_{11} and w_{12}, can be expressed, as follows:

$$\text{tg}\ \beta = I_f = \frac{w_{11} - w_{12}}{\log N_2/N_1} = w_{11} \frac{1 - w_{12}/w_{11}}{\log N_2/N_1} \tag{13}$$

In Eq. 13, however, the factor of the w_{11} term is a constant because, from Eq. 12, w_{11}/w_{12} is a constant; therefore,

$$I_f = Bw_{11} \tag{14}$$

It can be seen that Eq. 14 is a particular form of Eq. 11 when C = 0. Consequently, if and when C = 0, then Eq. 1 and Eqs. 10 and 11 are not independent of each other.

Although the assumption of a power function and the logarithmic assumption are "essentially" the same, the identity is not complete even when C = 0. A flow curve of a power function which gives a straight line in the log-log system of coordinates will resolve into a curve in the semilogarithmic system. The substitution of a straight line for this curve is tolerable because the logarithmic form represents the first approximation of the power function formula. The approximation is obtained by omitting the terms of second and higher degree from Taylor's series of the power function.

Proof:

$$w = aN^b = a \exp(b \ln N) = a(1 + b \ln N + R) \cong A(1 + c \log N) \tag{15}$$

where R is the remainder term of the Taylor's series; and c and A are constants. The other symbols correspond to those of Eq. 1. If the c term is written

$$c = -I_f/A \tag{16}$$

then Eq. 15 will give Eq. 10 what was to be proven.

Figure 5 shows that the agreement between the P flow curve of a power function and the L logarithmic flow curve is good within fairly wide limits, i. e., the R remainder term is small. The same agreement is also shown numerically in a paper by Joslin and Davis (18).

Assumption of a Point of Convergence

Olmstead and Johnston (19) showed that the flow curves of various soils converge toward a point in a semilogarithmic system of coordinates which point was near the zero moisture-content axis. By arbitrarily moving this N_a point of convergence to the zero axis for the sake of simplicity, the flow curves formed a family of straight lines having the following equation (Fig. 4):

$$w = w_{i1} \frac{\log N_a}{\log N_a/N_1} = \frac{w_{i1} \log N}{\log N_a/N_1} = D - E \log N \tag{17}$$

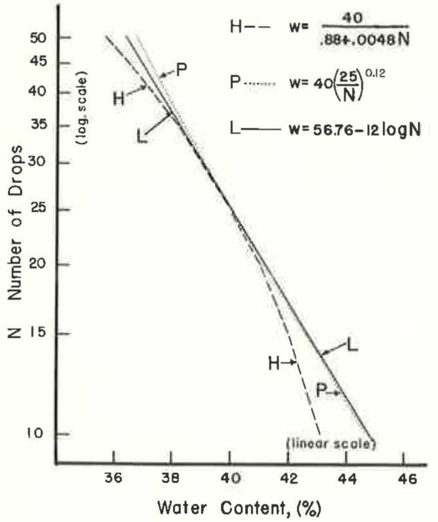

Figure 5. Comparison of three formulas for the relation of water content vs consistency.

where the values of D and E are determined by the position of the point of convergence, and the type of soil.

From Figure 4, however, the factor of the log N term in Eq. 17 is nothing else but the slope of the flow curve; therefore,

$$E = I_f = \frac{w_{il}}{\log N_a/N_1} = F w_{il} \qquad (18)$$

Thus, Eq. 17 is identical to Eq. 10, i. e., D = A; and Eq. 18 is identical to Eq. 11, i. e., F = B, if C = 0. This means that the arbitrary moving of the point of convergence to the zero moisture-content axis is equivalent to making arbitrarily C = 0 in Eq. 11; that is, in the case of a fixed N_a point, the slope of a flow curve in Figure 4 changes proportionally to the value of w_{il}.

Consequently, the assumption of a point of convergence expresses again essentially the same thing as the approximation by power function or the logarithmic relationship, only the form is different.

The identity of these assumptions makes it possible to convert from one to the other. For instance, with the knowledge of the I_f flow index and LL liquid limit, the location of the N_a point of convergence on the N-axis can be calculated by Eq. 18.

$$\log N_a = 1/F + \log 25 = LL/I_f + 1.4 \qquad (19)$$

Eq. 19 provides another possibility to check experimentally the validity of the assumption of a logarithmic relationship, or the assumption of a point of convergence.

Assumption of a Hyperbolic Relationship

The relationship between the soil consistency and water content can also be approached by a hyperbolic formula. After Mohan and Goel (20), by using the designation of Figure 4, this formula can be written

$$w = w_{il}/(d + eN) \qquad (20)$$

or

$$w = 1/(f + gN) \qquad (21)$$

where the values of d and e are the same for every soil; and the values of f and g depend on the type of the soil. If, for instance, w_{il} = LL, then d = 0.88 and e = 0.0048 (20).

The assumption of a hyperbolic relationship is related again to the previously discussed assumptions, because Eq. 20 was obtained from Eq. 1 by an expansion into binomial series and omitting the terms of second and higher degrees. Mohan and Goel found that this hyperbolic approximation is acceptable when the number of blows is within 20 and 30. The agreement between the hyperbolic approximation (curve H) and two other approximation (curves F and L) is shown within wider limits in Figure 5.

FURTHER APPLICATIONS

The approximation by power function has an important interpretation—the assumption of independence which is always applicable whenever the approximation by power function is applicable. The significant point is that the exploitation of the assumption of independence can simplify to a great extent the prediction of certain soil properties. Thus, it is interesting to examine whether the approximation by power function is applicable for properties of soil-water mixtures other than consistency, and if so, to show the simplifying influence of the assumption of independence on the prediction. For this purpose results of four test series, taken from the technical literature, are analyzed. This presentation is confined to test series which were readily available; no thorough study of the literature was undertaken.

Penetration Resistance

It appeared logical to try to apply the approximation by power function for the relationship of soil strength versus moisture content because this can be considered as an extension of the consistency test for soil-water mixtures that are too dry for the standard liquid limit device.

Figure 6 shows the so-called Ohio typical moisture content-penetration curves in a log-log system. The original set of Ohio typical curves was based on the results by Woods and Litehiser. The set of curves presented is that part of the Ohio typical curves shown in a study by Johnson and Sallberg (21, Fig. 101) which is within the limits of 50- and 1,000-psi penetration resistance. The curves form a family of parallel straight lines with a fairly good approximation; i.e., the approximation by power function is fairly good. The discrepancy is the largest in the first curve, but it is not serious. For instance, where the experimental value is about 110 psi, the value from the power function is 100 psi. Consequently, it seems possible to develop a "one-point" or "rapid" method for the prediction of penetration resistance as a function of the moisture content only. For instance, by using the form of Eq. 7 and choosing the water content as 100 percent relative water content which is related to the penetration resistance of 500 psi, the following formula can be applied for the prediction of the presented penetration resistance of Ohio soils:

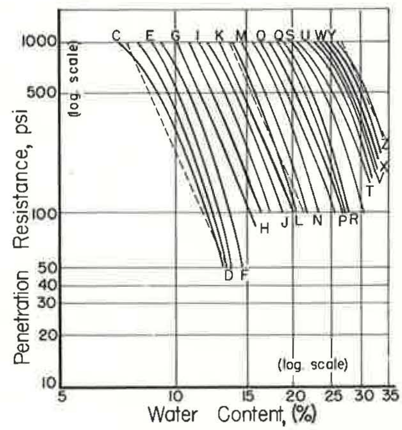

Figure 6. Ohio typical moisture content-penetration resistance curves (21).

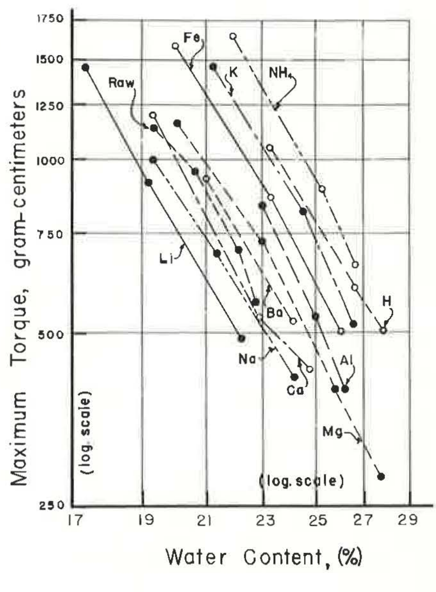

Figure 7. Effects of various cations on the shearing strength of a clay (22).

$$P = 500\,(0.01\,w_{rel})^{-5} \qquad (22)$$

in which

P = penetration resistance, psi; and
w_{rel} = relative water content, percent.

Also, by applying the assumption of independence, this whole set of typical curves can be substituted, in a sense, by the following rule of thumb: a fixed relative change takes place in the penetration resistance as a consequence of a given relative change in the water content, and this fixed change is independent of the soil type, original moisture content, and original penetration resistance. This simple rule is expressed mathematically by Eq. 8 or 9. For example, a 20 percent relative increase in moisture content (e. g., from 15 to 18 percent) will reduce the penetration resistance to about one-third of the original value for the presented Ohio soils, regardless of the original strength, and original moisture content.

The approximation by power function is a simple method. In addition, the application of the assumption of independence produces very simple, practical rules that not only visualize the conclusions of the test series but, through the elimination of the irrevelant variables, contribute to the better understanding of the mechanism of the phenomenon.

Shearing Strength of Clay

In Figure 7 the shearing strength of a clay is plotted in a log-log system as a function of water content and type of absorbed cation. The data, originally obtained by Sullivan, were taken from Tschebotarioff (22, Figs. 7-29). The test results form a family of parallel straight lines with a good approximation, i. e., the approximation by power function is good. In this case, the various cations influence the shearing strength of the clay differently; nevertheless, as the rule of thumb based on the assumption of independence states, the same relative increase in the water content causes the same relative decrease in the shearing strength for every cation, every original moisture content, and original shearing strength. For example, a 5 percent relative increase in the water content will reduce the presented values of the shearing strength by about 20 percent regardless of the other variables involved.

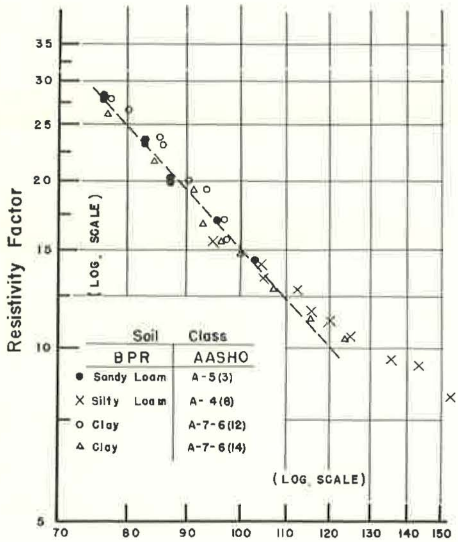

Figure 8. Electrical resistivity factor as a function of relative moisture content for four soils (23).

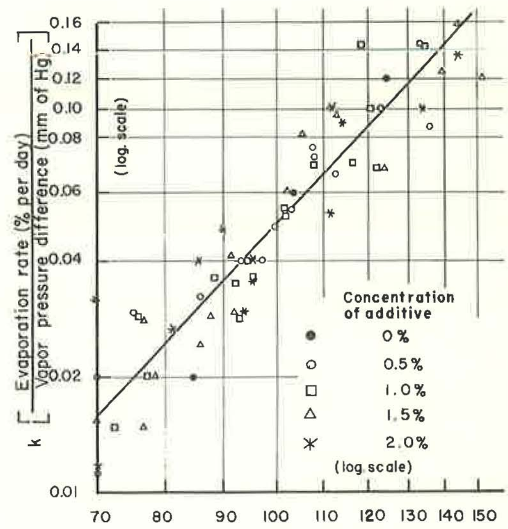

Figure 9. Index of moisture retention effectiveness for various additives as a function of relative moisture content (24).

Electrical Resistivity

Figure 8 shows the electrical resistivity factors of four soils mixed with brines of two concentrations as a function of relative moisture content. The data were taken from Sheeler et al. (23, Fig. 17). The resistivity factor is defined as "the ratio of the resistance of the soil-brine sample to the resistance of the brine." Figure 8 shows that the resistivity factors, within the limits of 75 and 120 percent relative moisture content, form a straight line with good approximation. Thus, within these limits, there exists a well fitting approximation by power function. Furthermore, a fixed relative change takes place in the resistivity factor as a consequence of a given relative change in the moisture content, original resistivity factor, and the concentration of brine.

Moisture Retention

Figure 9 shows the "k" index of moisture retention of various soil mixtures as a function of relative moisture content. The data were taken from Gow et al. (24, Figs. 9-14). The purpose of the test series was to investigate the effects of the treatments with calcium chloride, sodium chlorides, lignosulfonates, and molasses in various concentrations on the evaporation rate of soil-aggregate mixtures. Inasmuch as the test results again form a straight line with good approximation within the limits of 70 and 140 percent of relative moisture content, both the approximation of a power function and the approximation of the assumption of independence are good for the data presented. Thus, the conclusion of this test series can be summarized very simply; for example: the relative change in the evaporation rate, due solely to a given relative change in the moisture content, is practically the same for all six additives and is also independent of the original moisture content and the concentration of the used solution.

CONCLUSIONS

1. The four methods express essentially the same statement concerning the soil consistency as a function of water content; only the form of expression is different. Thus, it is understandable that the values calculated by the various formulas show good agreement within practical limits (Fig. 5).
2. From a practical point of view, it is difficult to give preference to any of these methods. It might well be that the form of the logarithmic approximation recommended by Fang has wider limits of validity because Eq. 11 contains two experimental constants, whereas the corresponding equations of the other methods contain only one. This is, however, at the expense of simplicity.
3. The approximation by power function is advantageous in principle because of its significant physical interpretation, the so-called assumption of independence.
4. When the results of a test series on a soil-water mixture, plotted in a log-log system, provide a family of parallel straight lines as a function of water content, or a single straight line as a function of relative water content, several of the tested variables are irrevelant in a sense. Such variables may be the original moisture content, original consistency, and type of soil. Therefore, the tested relationship can be expressed in a form where the number of variables is reduced. Consequently, the application of the assumption of independence produces simple practical rules that not only visualize the conclusions of the test series but, through the elimination of the irrevelant variables, contribute to better understanding of the mechanism of the phenomenon.
5. Figures 6 through 9 seem to indicate that the approximation by power function and the assumption of independence might be used for the prediction of various properties of soil-water mixtures with an accuracy that is satisfactory for many practical purposes. Therefore, it would be worthwhile to undertake more thorough investigation to see to which soil properties this assumption is applicable, what the degree of the expected accuracy is, and what the limits of validity are.

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