Soil Moisture Conditions and their Effects on the Engineering Properties of Compacted Soils

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Abstract

As the properties of compacted soil conditioned for a construction work may change after the construction is completed, it is essential for a reliable design for the construction to investigate not only the strength of the compacted soil directly after compaction but also the future strength of it. In either case the strength of the soil is affected mainly by the moisture content and the dry density. For this purpose the authors studied in this paper several subjects concerning (a) qualitative moisture scales to estimate future moisture condition, (b) the effect of moisture content and dry density on the strength of compacted soil, and (c) future moisture content and future dry density of compacted soil.

1. Introduction

Compacted soils may change their properties depending upon their circumstances in which they are placed after compaction, and change of moisture content may be an important factor changing their properties. For example, when a pavement is placed on a compacted subgrade soil and evaporation from the surface of the subgrade is ceased, moisture content in the subgrade soil increases until it reaches the equilibrium by receiving its supply from the water-table. In this case, therefore, to rationally design a pavement whose thickness depends on the bearing capacity of the subgrade, designers must pay attention not only to the strength of the subgrade directly after compaction but also to the future strength which the subgrade may have under the pavement. Thus it is essential for a reliable design of a construction work using the compacted soil to investigate the future strength as well as the present strength of the compacted soil. In either case the strength of the compacted soil is affected mainly by moisture content and dry density. The authors in this paper have studied the following subjects concerning this problem: (I) To estimate the future moisture condition, the qualitave moisture scales, such as the *pF* scale, and the soil moisture suction, which are discussed in chapter 2, 3, and 4. (II) The effects of moisture content and dry density on the strength of compacted soils, which are studied experimentally in the part (a) of chapter 5 and in chapter 6. (III) Moisture contents and dry densities of compacted soils are measured after the soils have been balanced under each *pF* condition and each overburden condition, and they are discussed in the part (b) of chapter 5.

2. Scales to indicate Soil Moisture Conditions

Scales to indicate the soil moisture conditions can be classified roughly into two groups, namely, one group is quantitative and the other is qualitative. The quantitative scale of the moisture content (or the water content) is most widly used in civil engineering. The qualitative scales can further be divided into two groups, one group is hydraulic such as the soil moisture suction and the other is thermodynamical such as the *pF* scale.

(a) The Moisture Content

The moisture content of a soil mass w is defined as the ratio (usually expressed in percentage) of the weight of water to the weight of oven-dried soil grains in the mass as in the equation

$$w = \frac{W_1 - W_2}{W_2}, \qquad (1)$$

in which W_1=weight of a moist soil mass,

W_2=oven-dry weight of the same soil mass.

Although the moisture content is a simple index showing the condition of a soil, it is a good indication of the shear strength of a saturated clay or clay-like soil as shown later. On the other hand, the qualitative scale is important for studying the movement or the equilibrium of soil moisture.

(b) The Soil Moisture Suction

When soil moisture is in an equilibrium state above the water-table, it generally has a negative pressure and this negative pressure can be used to express soil moisture condition. Sometimes the term "suction" is accepted as synonymous with this negative pressure. But the "suction" defined by D. Croney and J. D. Coleman1) is a little more complex. According to their explanation, "if the pressure of the water in the pores of a small sample of soil, removed (without disturbance or change of moisture content) from above the water-table, is measured when the sample is free from external stress, a value less than atmospheric pressure is obtained. The difference between the pressure of the water in the small unloaded sample and atmospheric pressure is defined as the moisture suction or more briefly, as the suction of the soil." This "suction" which can be measured by a suction plate technique in laboratory is related to the pore water pressure which can be observed in situ, as follows:

$$\alpha p - s = u \qquad (2)$$

where α = the fraction of the normal pressure which is effective in changing the suction,
p = the total normal pressure caused by overburden load including any surface loading,
s = the moisture suction of the soil,
u = the pore water pressure which can be measured by tensiometer or any other convenient method in situ.

A method to estimate moisture distribution in the soil layer under the pavement using the moisture suction of the soil has been shown by D. Croney and J. D. Coleman.1)

(c) The *pF* Scale

We can use the Gibbs' free energy of soil moisture which is a thermodynamical function as a qualitative scale of soil moisture. The *pF* scale introduced by R. K. Schofield2) is based on the Gibbs' free energy of soil moisture. Using this scale, the energy condition of soil moisture can be expressed consistently over the whole range extending from the free water condition to the oven-dry condition regardless of holding mechanism of soil moisture.

When R. K. Schofield proposed the *pF* scale in 1935, he explained it as follows: "The *pF* is the logarithm of Buckingham's potential. By analogy with Sørensen's acidity scale the symbol '*p*' indicates its logarithmic character, while the symbol '*F*' is intended to remind us that by defining *pF* as the logarithm of the height in centimetres of the water column needed to give the suction in question, we are really using the logarithm of a free energy difference measured on a gravity scale. By basing our scale on free energy rather than pressure, we are not troubled in our calculations by the influence of pressure on the density of water. We can also transfer the scale to any liquid, defining its *pF* as the logarithm of the height of a column of that liquid." Buckingham's potential in this quotation can be taken to mean the capillary potential3a) which was suggested by Gardner and his co-workers4) to be defined as the work required to move a unit mass of water from a point where the potential is zero to the point in question.

To understand the *pF* scale of this nature, it appears to be more benefitial to consider about the thermodynamical condition of soil moisture in the Ideally Balanced Soil Layer which is introduced by the authors for the convenience of thermodynamical treatment of soil moisture as shown in the next chapter.

3. Thermodynamical Consideration of the Soil Moisture in the Ideally Balanced Soil Layer

(a) The Ideally Balanced Soil Layer

For the convenience of thermodynamical treatment of soil moisture, the Ideally Balanced Soil Layer is introduced as a semi-infinite soil layer in which soil moisture everywhere is in the state of thermodynamical equilibrium. Namely, as shown in Fig. 1, it is covered with an infinitely wide impervious pavement on its surface so as to prevent movement of moisture through the surface, and the temperature within it is kept uniform and constant, and the water-table in it is kept at a constant level. Thus, the soil moisture in it is perfectly and constantly balanced thermodynamically because there is no factor disturbing its equilibrium state.

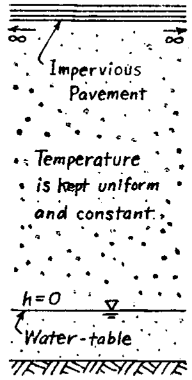


Fig. 1. Ideally Balanced Soil Layer.

Using the concept of the Ideally Balanced Soil Layer, we can find that "the height in centimetres of the water column needed to give the suction in question" (Schofield) corresponds to the elevation head in the Ideally Balanced Soil Layer. In this way, we can define the *pF* as the common logarithm of the elevation head (measured in centimeters from the water-table) where the energy condition of the soil moisture in question should hold in the Ideally Balanced Soil Layer. The thermodynamical meaning of the *pF* will be shown fully in the following.

(b) Thermodynamical Treatment of Soil Moisture in the Ideally Balanced Soil Layer.

The total potential Φ of a unit mass of soil moisture is defined by the equation:

$$\Phi = \bar{G}+\phi \tag{3}$$

Where $\bar{G}$ = the chemical potential of the soil moisture,

ϕ = the positional potential per unit mass of the soil moisture in a force field or force fields.

If more than one force field are present, ϕ may be resolved into its components as follows:

$$\phi = \phi_a+\phi_b+\phi_c+ \cdots +\phi_z = \sum_{q=a}^{z} \phi_q \tag{4}$$

in which the subscripts, $a, b, \cdots z$, represent different force fields. An alternative expression therefore is:

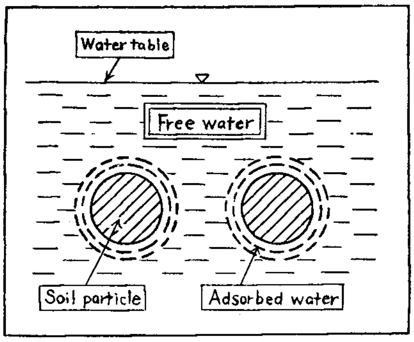
$$\Phi = \bar{G}+ \sum_{q=a}^{z} \phi_q . \tag{5}$$

From the knowledge of thermodynamics, the total potential of a unit mass of soil moisture at any point must be uniform in the Ideally Balanced Soil Layer because the soil moisture in this Layer is absolutely balanced. Therefore, in this case,

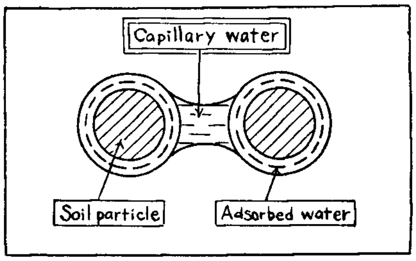
$$\Phi = \text{const.} \qquad (6)$$

regardless of location or phase of soil moisture.

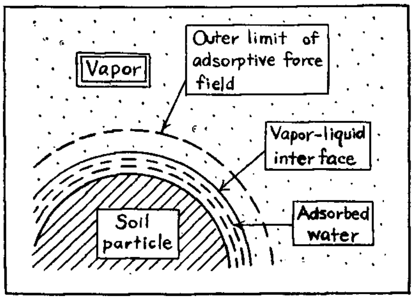
Irrespective of the phase of soil moisture, it is convenient for us to pay attention to the soil moisture existing outside the adsorptive force field of soil particles so long as the whole soil moisture of the soil mass is in the state of thermodynamical equilibrium. The soil moisture, which is in liquid phase and free from adsorptive force of soil particles, exists as free water when it is below the water-table as shown in Fig. 2 (a) or as capillary water when it is over the water-table as shown in Fig. 2 (b).



(a) Free Water



(b) Capillary Water



(c) Vapor which is free from adsorptive force

Fig. 2. Soil Moisture existing outside the Adsorptive Force Field of Soil Particles.

When the soil moisture exists neither as free water nor as capillary water, we must pay our attention to the aqueous vapor (as shown in Fig. 2 (c)) which exists outside the adsorptive force field and balances thermodynamically with the adsorbed water of soil particles. In order to investigate the thermodyanmical condition of the soil moisture, therefore, it suffices to study only the soil moisture in the gravitational field. The problem becomes simpler when the soil moisture is assumed to be of the pure water containing no solute. In this case, $\bar{G}$ in equation (5) becomes a chemical potential of the pure water, which is the Gibbs' free evergy of a unit mass of pure water. Therefore, we can obtain the equation:

$$\Phi = G + hg = \text{const.} \quad \text{(in the Ideally Balanced Soil Layer)} \qquad (7)$$

where G = the Gibbs' free energy of a unit mass of the soil moisture existing at the height h from the water-table in the Ideally Balanced Soil Layer,

g = gravitational acceleration.

The value of Gibbs' free energy of the soil moisture at the water-table ($h=0$) is G_0 which is a constant so long as the atmospheric pressure and temperature is kept constant in the Ideally Balanced Soil Layer. Consequently, the constant in the above equation can be replaced with G_0. And, we get

$$G = G_0 - hg \tag{8}$$

or

$$h = \frac{1}{g}(G_0 - G) . \tag{9}$$

These equations show that the difference of the Gibbs' free energy measured on a gravity scale between the moisture contained in the soil mass existing at a height h (cm.) from the water-table and that of the water-table is h (gr. cm.), and it corresponds to the elevation head measured from the water-table in the Ideally Balanced Soil Layer.

Schofield's words, "We are really using the logarithm of a free energy difference measured on a gravity scale", mean that the pF is the logarithm of the elevation head in the Ideally Ballanced Soil Layer. Then, the pF can be formulated as:

$$pF = \log_{10} h = \log_{10}\left[\frac{1}{g}(G_0 - G)\right]. \tag{10}$$

(c) Capillary Water in the Ideally Balanced Soil Layer

Capillary water changes its Gibbs' free energy only by the change of its own pressure in the Ideally Balanced Soil Layer in which the temperature is kept uniform and constant.

Therefore,

$$dG_w = V_w dp_w \tag{11}$$

where dG_w = the differentiation of the Gibbs' free energy of a unit mass of the capillary water,

V_w = the specific volume of the water,

dp_w = the differentiation of pressure of the water.

Although V_w changes with the change of pressure of the water, the change in V_w is negligible in the case of capillary water. As V_w can be treated as a constant V_{w0}, equation (11) is integrated as follows;

$$G_w - G_{w0} = V_{w0}(P_w - P_{w0}) \tag{12}$$

where G_{w0} = the Gibbs' free energy of a unit mass of liquid water at the water-table,

P_{w0} = the pressure at the water-table which is equal to atmospheric pressure.

From equations (9) and (12), we obtain,

$$h = \frac{1}{g} V_{w0}(P_{w0} - P_w) . \tag{13}$$

Equation (13) represents the relationship between the height of the existing point of the soil moisture and the pressure of the soil moisture in the case of capillary water in the Ideally Balanced Soil Layer. This is the principle of the suction plate method and the tensiometer method which are used to measure the *pF* or energy condition of soil moisture by measuring its negative pressure.

(d) Aqueous Vapor in the Ideally Balanced Soil Layer

The Gibbs' free energy of aqueous vapor is influenced only by its own vapor pressure in the Ideally Balanced Soil Layer, where the temperature is kept uniform and constant.

Therefore, we obtain

$$G_a - G_{a0} = \int_{P_s}^{P_a} V_a \, dp_a \tag{14}$$

where G_a = the Gibbs' free energy of aqueous vapor free from adsorptive force and which exists at any height,

G_{a0} = the Gibbs' free energy of aqueous vapor which is in contact with the water-table,

P_a = the vapor pressure corresponding to G_a,

P_s = the saturated vapor pressure which is in contact with a free water surface and is a function of temperature only,

V_a = specific volume of aqueous vapor.

If we assume the aqueous vapor as an ideal gas, its specific volume V_a can be expressed as a function of the vapor pressure P_a as follows,

$$V_a = \frac{RT}{M} \cdot \frac{1}{P_a} , \tag{15}$$

where R = universal gas constant,

M = molecular weight of water in vapor phase,

T = absolute temperature.

Therefore, we obtain

$$G_a - G_{a0} = \frac{RT}{M} \ln \frac{P_a}{P_s} . \tag{16}$$

From equation (16), we can express equation (9) as follows,

$$h = \frac{RT}{gM} \ln \frac{P_s}{P_a} . \tag{17}$$

Equation (17) represents the relation between the height h, where the aqueous vapor in question is existing in the Ideally Balanced Soil Layer, and the aqueous vapor pressure P_a. Using the relative humidity H defined as

$$H = \frac{P_a}{P_s} \times 100\ (\%), \tag{18}$$

we obtain

$$h = \frac{RT}{gM} \ln \frac{100}{H}. \tag{19}$$

This equation shows the relation between humidity and height in the Ideally Balanced Soil Layer. Equation (19) is the same with the formula shown by R. K. Schofield for calculating the height of liquid column to give equivalent suction in centimeter. This is the principle of the vacuum desiccator method for measuring the *pF*.

4. The Relationship between *pF* and Moisture Content and *pF* Conditions treated in Soil Engineering

Fig. 3 shows a relation between the *pF* and moisture content of a natural alluvial clay sample obtained by several measuring methods[5], i.e. the suction plate method for the lower part of the *pF*, the centrifugal method and consolidation method for the medium part of the *pF*, and the vacuum desiccator method for the higher part of the *pF*. Generally the *pF* of the soil moisture increases as the moisture content is decreased, but the relation between the moisture content and the *pF* is not unique but has a hysteresis between the wetting and drying processes. The sample is drier at a given *pF*, when the *pF* is approached in the wetting process than when it is approached in the drying process. Soil structure, particle-size distribution, clay content, dry density of soil mass, mineralogical property of soil particle, kind of adsorbed cation and character of held water all affect the relationship between the *pF* and the moisture content of a soil. Fig. 4 shows the *pF*-moisture content curves for five different types of soils[6]. These curves show the fact that each type of these soils will reach its equilibrium state at each different moisture content even if an equal *pF* condition is given. Fig. 5 shows the *pF*-moisture content curves for the two specimens prepared of same sand but having different dry densities. Fig. 6 is made from data[7] of consolidation tests and Fig. 7 drawn from data[3b] of hygroscopicity,

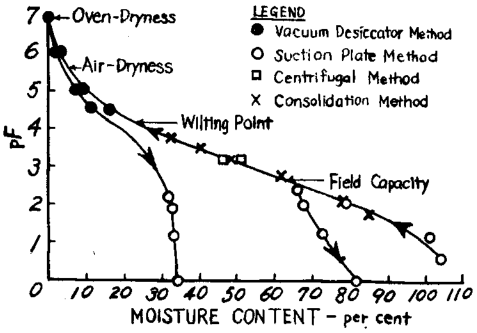
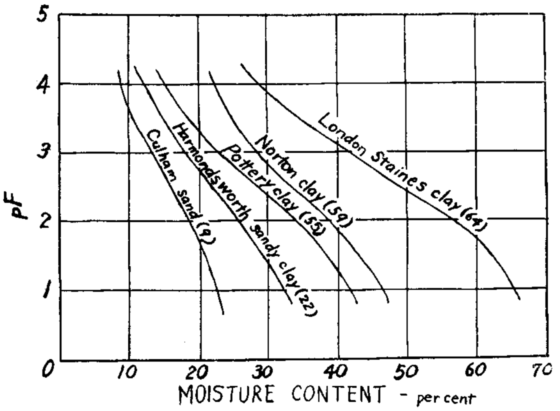


Fig. 3. Relationship between *pF* and Moisture Content for a Natural Heavy Clay.



Note: Figures beside Soil Titles are Clay Contents.

Fig. 4. Comparison of the *pF*-Moisture Content Curves of drying Process for five Soils (Croney and others[6]).

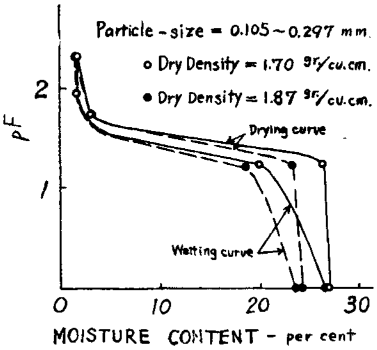


Fig. 5. Comparison of the *pF*-Moisture Content Curves for two Toyoura Standard Sand Specimens having different Dry Densities.

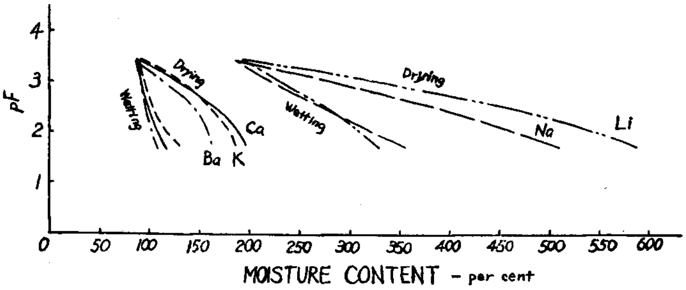


Fig. 6. The Effect of Exchangeable Cations on the *pF*-Moisture Content Curves of Bentonite (Montmorilonite) (Jimenez Salas and Serratosa[7]).

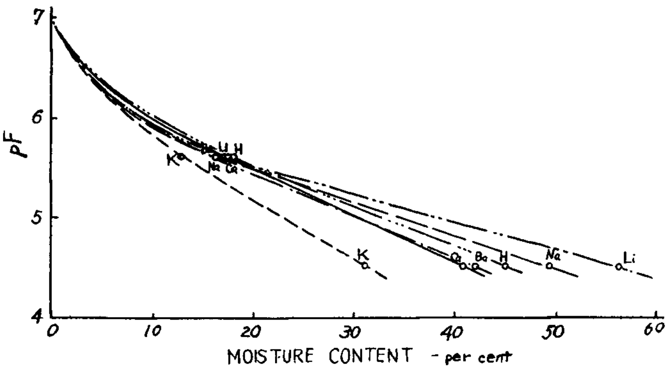


Fig. 7. The Effect of Exchangeable Cations on the *pF*-Moisture Content Curve of Putnam Clay (Beidelite)(3b).

and both figures show the effect of exchangeable cations on the *pF*-moisture content relations in clays.

The driest condition of the soil which we treat in soil engineering is the oven-dry condition in which the moisture content is defined to be zero. This condition corresponds to about *pF* 7. It was calculated by Schofield[2] as 6.91, 6.93 and 6.95 for 100°C, 105°C and 110°C of oven temperature assuming the relative humidity in the air of the oven to be 1 per cent. But the authors' calculation[8] gives the average *pF* of oven-dryness in Kyoto, Japan, as 6.89, 6.91 and 6.93 for 100°C, 105°C and 110°C of oven temperature assuming that the aqueous vapor pressure in the oven is in balance with the aqueous vapor pressure of atmosphere calculated from the data of the temperature and relative humidity of Kyoto, Japan. Next, applying equation (19), the *pF* of the air dry condition is calculated to be about *pF* 5.6 from the Japanese statistical values of relative humidity and temperature. The other well known conditions of *pF* are *pF* 4.2 of the wilting poing below which the plants are unable to draw water and *pF* 2.7 of the field capacity which is defined as "the amount of water held in the soil after excess gravitational water has drained away." Further, when the water table is one meter below the soil surface paved by impermeable surface, this soil surface is likely to have the soil moisture of *pF* 2.0, and when the water table is ten centimeters below it, it is likely to have the soil moisture of *pF* 1.0.

5. Engineering Characteristics of Compacted Soils

(a) Strength Characteristics of Compacted Soils directly after Compaction

In many instances a desired bearing capacity of the soil can be obtained by compaction. The attainment of high degree of strength is usually associated with a high degree of compaction. But this association is not entirely correct. In 1953 C. R. Foster[9] pointed out these exceptional phenomena using experimental data in laboratory and field.

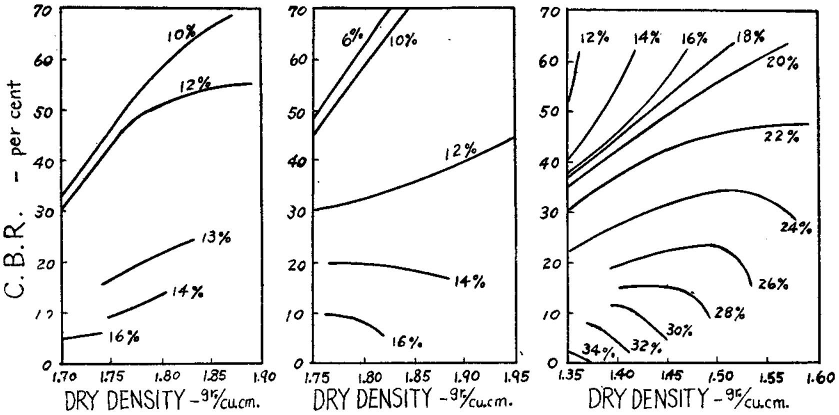
To observe these phenomena, the C.B.R. tests were performed with sand, sandy loam and clay samples denoted in Table 1. And as the results of these tests,

Table 1. Properties of Soils used in Experiments for Chapter 5.

Soil Type	Particle-size Distribution			Atterberg Limits			JIS Compaction	
	Sand 2.0~ 0.05mm.	Silt 0.05~ 0.005mm.	Clay <0.005mm.	LL	PL	PI	M.D.D. gr./cu. cm.	O.M.C. %
Sand	82	13	5	—	—	—	1.85	13.8
Sandy Loam	66	19	15	29	—	—	1.87	13.5
Silty Clay Loam	26	52	22	42	26	16	1.70	18.0
Clay	22	40	38	51	28	23	1.52	23.0

Note: M.D.D.=Maximum Dry Density, O.M.C.=Optimum Moisture Content.

the relationships among the compaction energy, moisture content, dry density and C.B.R. were presented as shown in Figs. 8, 9 and 10. Figs. 8 (a), (b) and (c) represent the relationships between C.B.R. and dry density using the moisture content as a parameter for each sample mentioned above. These curves having higher moisture content than 16% (in Fig. 8 (a)), 14% (in Fig. 8 (b)) and 24% (in Fig. 8 (c)) respectively, indicate that the sand, inspite of increasing its density, does not increase in C.B.R.; and the sandy loam and clay decrease in C.B.R. inspite of increase in their density. In the case of clay used for Fig. 8 (c), it is obvious that the specimen, having lower moisture content and higher dry density, have a lower C.B.R. than the C.B.R. of the specimen having higher moisture content and lower dry density under the condition of higher moisture content than 28% as shown in Fig. 8 (c). These phenomena are caused, it seems, by the occurrence of excess pore water pressure and the remolding effect of compaction.



(a) Sand (b) Sandy Loam (C) Clay

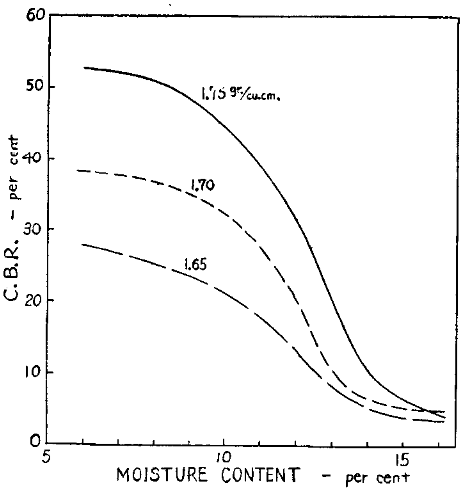
Note: Figure beside Curve is Molding Moisture Content (Moisture Content directly after Compaction).

Fig. 8. Relationships between C.B.R. and Dry Density for equal Moisture Contents from Laboratory Tests.

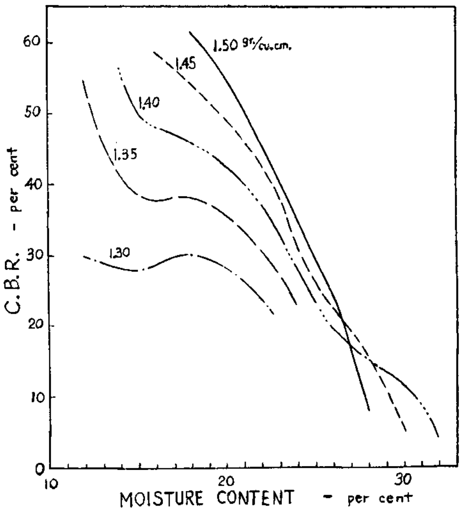
Recently, also in practical works, such phenomena have become to be noticed as the term of over-compaction. It is necessary to compact the soil economically so as not to dissipate compaction energy which may cause over-compaction in the construction work.

The relationships of C.B.R. versus moisture content for equal dry densities are shown in Figs. 9 (a), (b) and (c) for each sample mentioned above. In Fig. 9 the curves cross each other in the region of relatively high moisture content as a result of over-compaction. Generally, the specimen having the same dry density becomes smaller in C.B.R. with increase in moisture content.

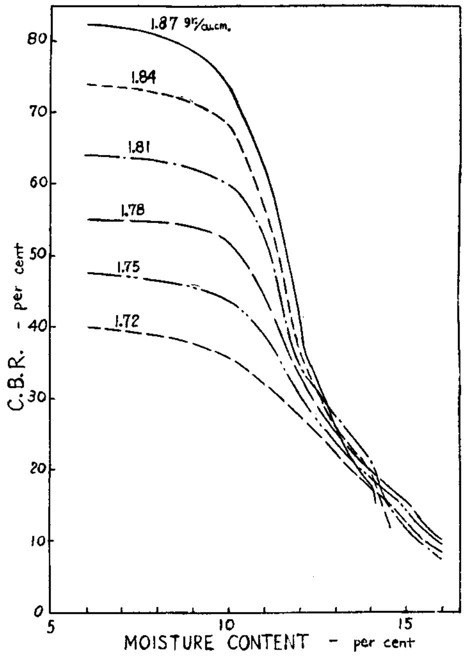
Next, the relationships of C.B.R. versus moisture content for equal compaction energies are shown in Figs. 10 (a), (b) and (c) together with the corresponding compaction curves which show the relationships of dry density versus moisture content for equal compaction energies. These figures show that the moisture content corresponding to the maximum C.B.R. is smaller than the optimum moisture content. In the case of unconfined compressive strength, the same phenomena have been shown[10]. These phenomena can be explained as follows. As shown in Figs. 8 (a), (b) and (c), C.B.R. of the compacted soil with a certain moisture content increases with increase in dry density within the range excluding over-compaction. Thus, under the condition



(a) Sand



(c) Clay



(b) Sandy Loam

Note:
Figue beside Curve is Dry Density.

Fig. 9. Relationships between C.B.R. and Moisture Content for equal Dry Density from Laboratory Tests.

of lower moisture content than the optimum moisture content, the compacted soil increases in its C.B.R. with increase in its dry density. But, as shown in Figs. 9 (a), (b) and (c), C.B.R. of the soil having equal dry density decreases with increase in moisture content. When a soil is compacted with a certain energy, its dry density increases with increase in moisture content until it reaches the maximum dry desity as shown in Figs. 10 (a-1), (b-1) and (c-1). Therefore in this case, C.B.R. is affected by both of these elements. As the increase in dry density increases C.B.R. and the increase in moisture content decreases it, the peak of the C.B.R.-moisture content curve comes on the lower side of the optimum moisture content. Namely, the water, which helps the soil to have the maximum dry density, lessens the strength of the soil by the decrease of attractive force caused by suction rather than strengthen it by the increase of dry density. These phenomena depend partly on the fact that the water confined in the compacted soil having the maximum dry density has smaller suction than that of the compacted soil with less moisture content as shown Fig. 14 (a). In Fig. 14 (a), specimen III, having the maximum dry density directly after compaction as mentioned later, has less suction than the suction of the same specimen placed under

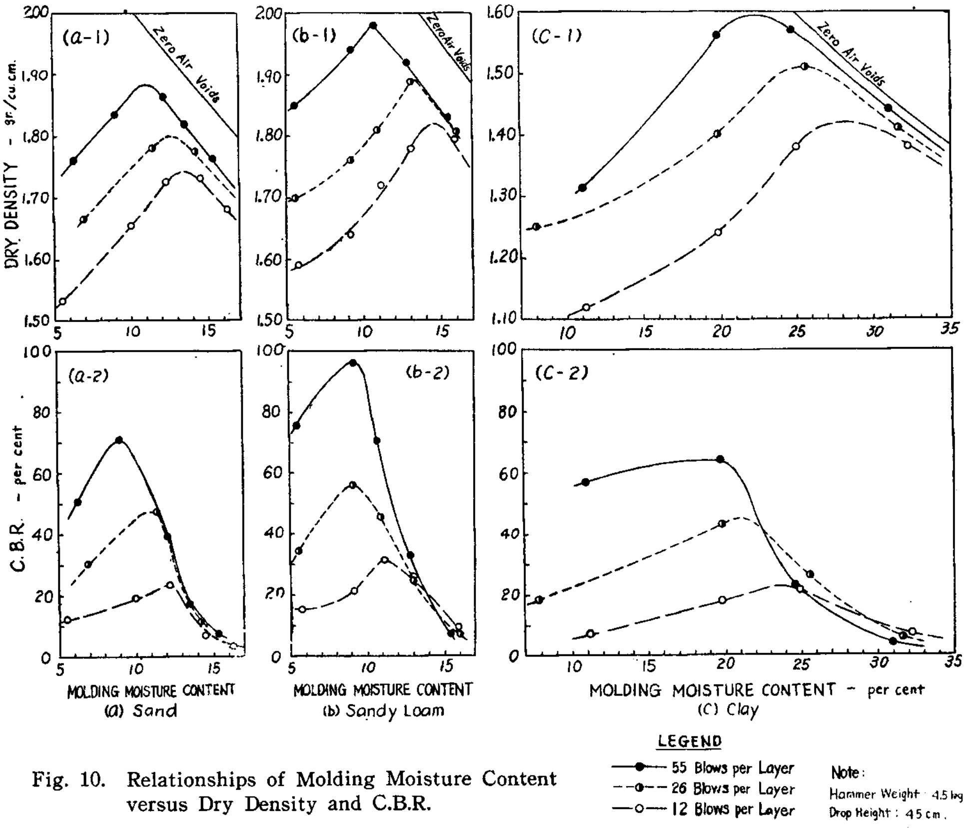


Fig. 10. Relationships of Molding Moisture Content versus Dry Density and C.B.R.

pF 2.0 ; on the other hand specimen II, having lower moisture content than the optimum one directly after compaction, has higher suction than that of this specimen which is placed under *pF* 2.0. Further, the above phenomena seem to depend partly on the excess pore water pressure which is apt to occur under the test load of C.B.R. The ratios of moisture content of the maximum C.B.R. to the optimum moisture content are from 0.69 to 0.89 for the experiments shown in Figs. 10 (a), (b) and (c) as tabulated in Table 2. In order to obtain the maximum C.B.R. for a given soil, therefore, the soil should be compacted with the moisture content 10∼30% less than the optimum moisture content for a given compaction energy. The phenomena mentioned above concerns only with the compacted soils directly after compaction. However, in general the properties of compacted soils change in future with change of the soil moisture conditions. The authors researched experimentally how the engineering properties of compacted soils change in future with changes of the *pF* condition of soil moisture as described in the next part.

Table 2. Ratios of Moisture Content for the Maximum C.B.R. to the Optimum Moistue Content.

Soil Type	Blows per Layer	Optimum Moisture Content (A)	Moisture Content for Max. C.B.R. (B)	$\frac{(B)}{(A)}$
Sand	55	11.0	9.0	0.82
	26	12.5	11.0	0.88
	12	13.5	12.0	0.89
Sandy Loam	55	10.7	9.0	0.84
	26	13.3	9.1	0.69
	12	14.5	11.1	0.77
Clay	55	22.5	19.0	0.84
	26	25.5	21.0	0.82
	12	28.0	23.5	0.84

Note: The Soil is compacted into the C.B.R. Mold in five equal Layers to give a total compacted Depth of 12.5 cm. by the 4.5 kg. Rammer dropped through 45 cm.

(b) Influence of Change in Moisture Energy Condition on Engineering Properties of Compacted Soils

In order to study how the dry density and moisture content of a compacted soil would change with a change in the *pF* of its moisture, four samples, whose properties are shown in Table 1, were used in these experiments. The specimens were compacted in the special molds attached to the apparatus as shown in Fig. 11. These compactions were performed with four different moisture contents, one of which was taken as the optimum moisture content of the soil. For the convenience of explanation these specimens are called here the specimen I, II, III and IV from the dry side according to their moisture content, and the specimen III is the one which is compacted with the optimum moisture content. Then these compacted specimens kept in the special molds were given the conditions of $pF\,0.5$, $pF\,1.5$, $pF\,2.0$, $pF\,4.5$, $pF\,5.5$ and $pF\,6.5$ by using the suction plate method or the vacuum desiccator method. After these treatments, the changed dry densities and moisture contents of the specimens were measured.

Figs. 12 (a), (b), (c) and (d) show the changed dry densities and moisture contents

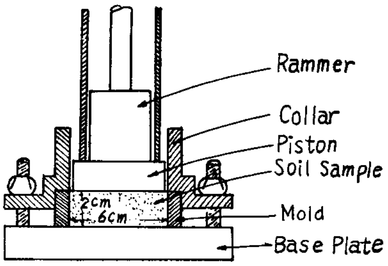
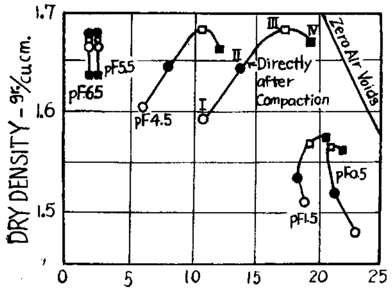
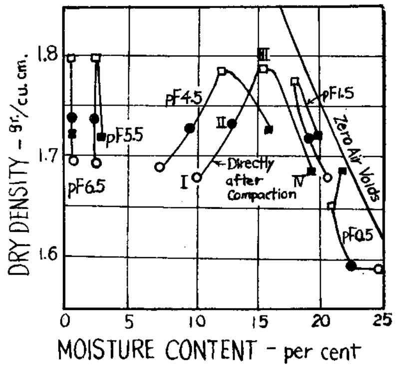


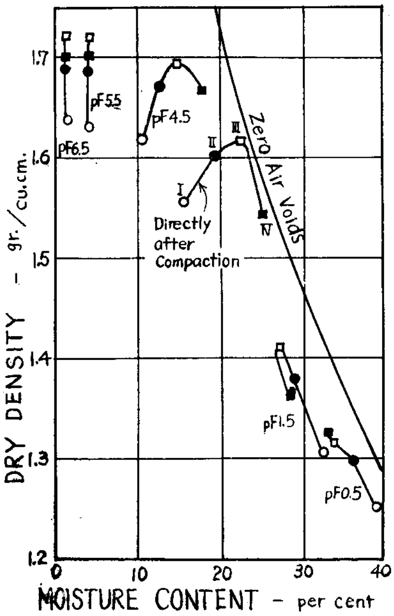
Fig. 11. Compaction Apparatus for pF Tests.



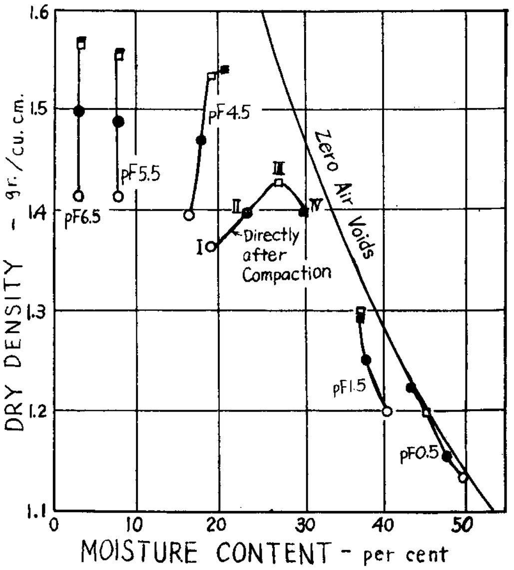
(a) Sand



(b) Sandy Loam



(c) Silty Clay Loam



(d) Clay

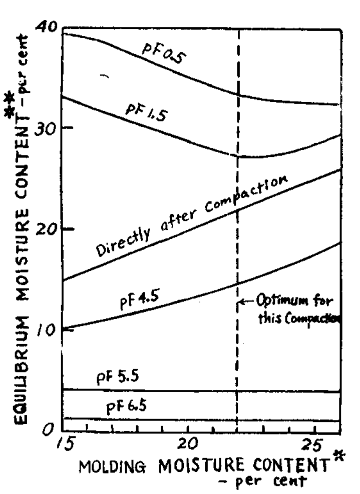
Fig. 12. Relationships between Dry Density and Moisture Content of Compacted Soils without Surcharge Weights after the Compacted Soils were allowed to become drier or wetter by regulating the pF of Soil Moisture.

under various *pF* conditions, without any surcharge weights, for specimens of sand, sandy loam, silty clay loam and clay. The designated position on each *pF* condition curve corresponds to the same designated position on the curve "directly after compaction" from which the *pF* condition changes. As the *pF* of the soil increases, the soil decreases in its moisture content and volume, and increases in its dry density and strength.

At *pF* 1.5, the specimens III, which were compacted with their optimum moisture contents, had the highest dry densities and the lowest moisture contents as compared with the specimens I, II and IV except in the case of sand, and the specimens IV of sand and clay were nearly equal to the specimens III in dry density.

At *pF* 0.5, the specimens IV showed better order in dry density then the specimens III, except in the case of sand. As for clay and silty clay loam, the order of moisture content at *pF* 0.5 became completely reverse as compared with the order directly after compaction, but in the case of sand and sandy loam, the specimens III had the lowest moisture contents.

The typical curves showing the relation between the moisture content, with which the soil sample was compacted, and the equilibrium moisture content, which was reached at each *pF* condition, are shown in Fig. 13.



Note:

* The moisture content with which the soil was compacted.

** The moisture content which the soil reached under a given *pF*.

Fig. 13. Molding Moisture Content*–Equilibrium Moisture Content** Curves of Silty Clay Loam without Surcharge Weights.

As the ordinary subgrade soils of highways are covered by pavements, experiments on change of dry density and moisture content of the compacted soil should be performed under the appropriate surcharge weights. In the following experiments, therefore, the specimens were loaded with pressure of 30 gr./sq. cm. which is equivalent to approximately 15 cm. of flexible pavement, and in order to investigate how the soils would weaken themselves they were placed under several *pF* conditions lower than those at which the specimens were compacted. As shown in Figs. 14 (a), (b), (c) and (d), the results of these experiments generally have a tendency that the moisture content increases and the dry density decreases as the value of *pF* decreases.

In these experiments, the specimens III still have the highest dry density and the lowest moisture content as compared with the specimens I, II and IV under *pF* 2.0, *pF* 1.5, *pF* 0.5 and even under the submerged condition. But in the case of the silty

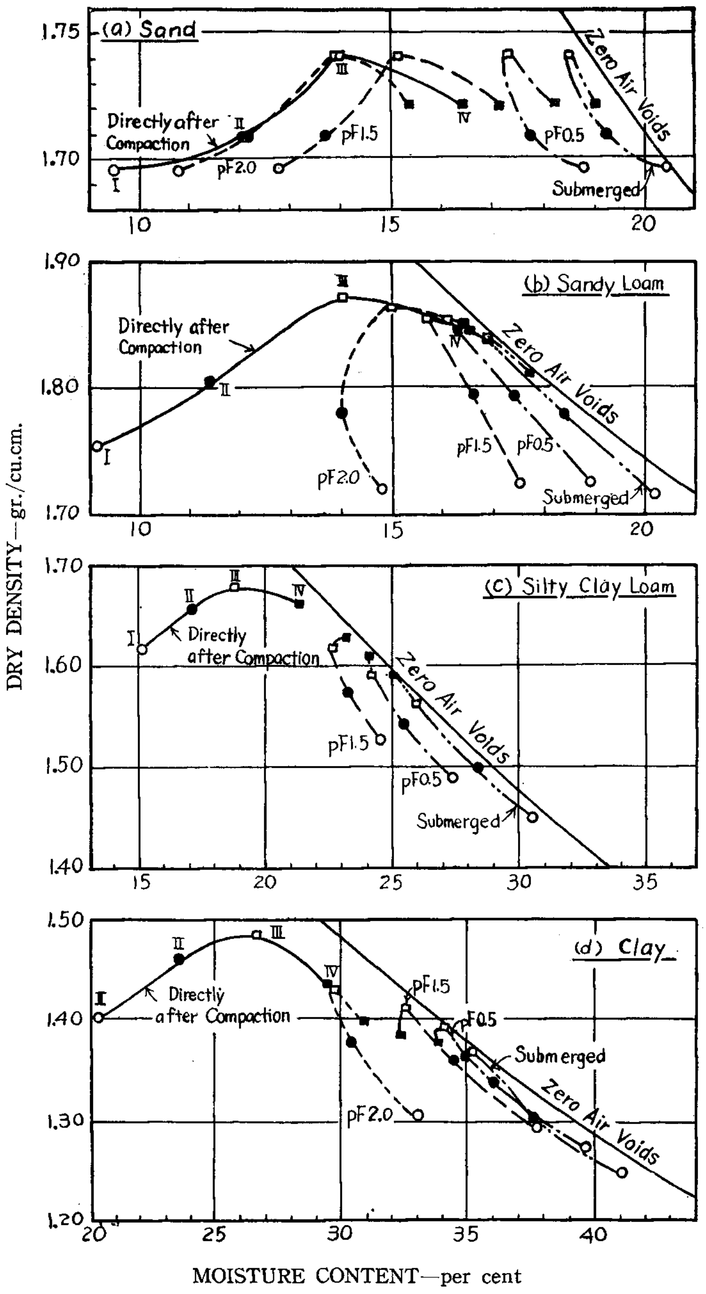
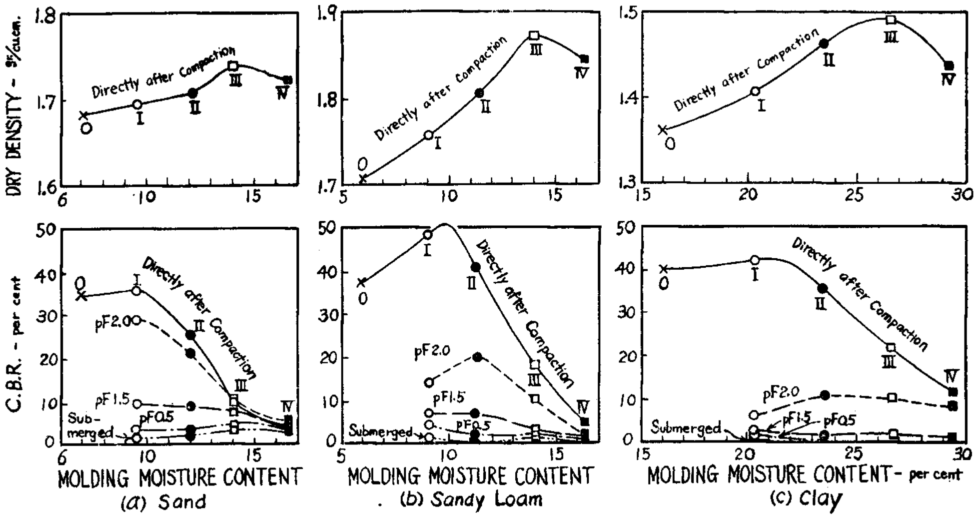


Fig. 14. Relationships between Dry Density and Moisture Content of Compacted Soils with Overburden Pressure of 30 gr./sq. cm. when allowed to become wetter by regulating the *pF* of Soil Moisture.

clay loam, the specimen IV has a tendency to have the highest dry density, and in the case of the clay the specimen IV has a tendency to have the lowest moisture content. In these experiments, the relation between the moisture content, with which soil was compacted and the equilibrium moisture content, to which the moisture content of the soil was reached under *pF* 1.5 or *pF* 0.5, became similar to those shown in Fig. 13. The changed dry densities and moisture contents shown in Fig. 14 are converted into the corresponding C.B.R. values using the fact that C.B.R. depends on dry density and moisture content as shown in Figs. 8 or 9 and then those C.B.R. values are represented as a function of molding moisture content using a *pF* value as a parameter as shown in Fig. 15. To show clearly the peaks of the C.B.R.-molding moisture content curves directly after compaction, the specimens 0 denoted in Fig. 15, whose molding moisture contents were less than the specimens I, were supplemented. The upper figures of Fig. 15 are the compaction curves, which show the relations between the dry density directly after compaction and molding moisture content. The order of C.B.R. measured directly after compaction was still kept unchanged when the specimens were placed under *pF* 2.0 or *pF* 1.5, but the C.B.R. of these four specimens approached each other at *pF* 1.5. In the case of clay, although the strength of the specimens directly after compaction showed that of "fair to excellent subgrade or good sub-base", the strength of the specimens decreased under the condition of *pF* 1.5 to that of "very poor subgrade". But in the case of sand its C.B.R. did not decrease as much as in the case of clay.



(a) Sand (b) Sandy Loam (c) Clay

Fig. 15. Compaction Curves and the C.B.R.-Molding Moisture Content Relations of Compacted Soils surcharged by 30 gr./sq. cm. under Various *pF* Conditions.

6. Shearing Resistances of Loose Compacted Soils

(a) Influence of Moisture Content on Cohesion and Angle of Internal Friction of Loosely Compacted Soil

In order to investingate how cohesion and angle of internal friction change with moisture content, air-dried, powdered clay loam, whose properties were shown in Table 3, was mixed with several moisture contents, and put very loosely in a shear box and then compacted statically only by the normal stress which was kept on the shearing surface during the shearing test. The sample was sheared when it completed its compression in the shear box. The range of moisture content tested was so restricted as the water in the specimen would not seep out from the specimen during the test. A pair of values of cohesion and angle of internal friction corresponding to each moisture content were obtained by the tests with the specimens having the same moisture content and under at least three different normal stresses.

Table 3. Properties of Soils used in Experiments for Part (a) of Chapter 6.

Soil Type	Particle-size Distribution			Atterberg Limits		
	Sand 2.0～0.05mm.	Silt 0.05～0.005mm.	Clay <0.005mm.	LL	PL	PI
Clay Loam	48	26	26	43	24	19

From these tests, Figs. 16 and 17 were obtained. As shown in Fig. 16, cohesion increases with increase in the moisture content at first, but there is a peak at about 23% of moisture content and after the peak it decreases with increase in the moisture content. This phenomenon seems to be explained as follows: At first the number of capillary moisture film at contacting points of the soil particles increases as the moisture content increases and, consequently, cohesion increases. And the maximum cohesion is obtained at the moisture content at which moisture films are formed at all contacting points of the soil particles. Beyond this limit, however, cohesion

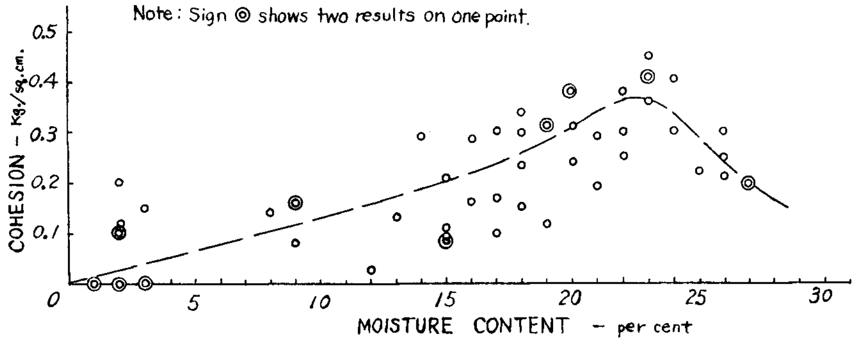


Fig. 16. Relationship of Cohesion versus Moisture Content for Clay Loam.

decreases as the thickness of the moisture film increases.

As for the angle of internal friction, at a low moisture content it is hardly influenced by the moisture content, but from a certain moisture content (which is about 15% in Fig. 17) it decreases rapidly with increase of the moisture content and approaches to zero. This phenomenon seems to be explained as follows: Beyond a certain moisture content, soil moisture acts as a lubricant among the soil particles, and near the saturating point an excess pore water pressure is likely to occures and the effective intergranular stress decreases accordingly.

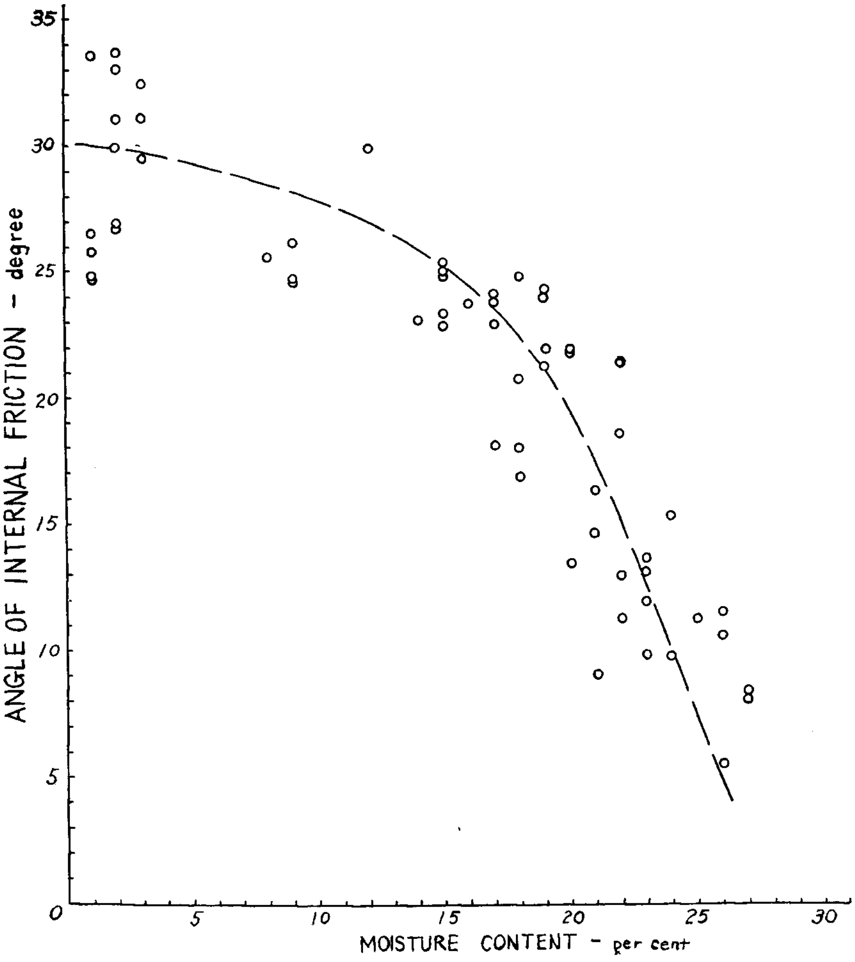


Fig. 17. Relationship of Angle of Internal Friction versus Moisture Content for Clay Loam.

As a reference for this kind of experiments, some results obtained by S. Matsuo[11] are shown in Figs. 18 and 19.

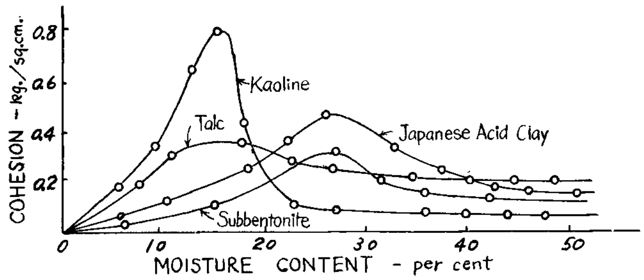


Fig. 18. Relationships of Cohesion versus Moisture Content for Typical Pulverized Samples (S. Matsuo11)).

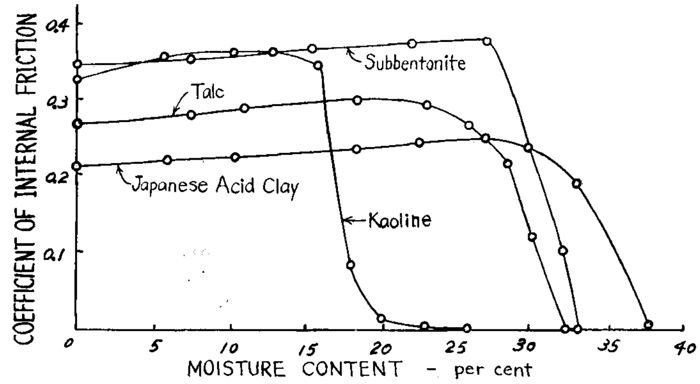


Fig. 19. Relationships of Coefficient of Internal Friction versus Moisture Content for Typical Pulverized Samples (S. Matsuo11)).

(b) Influence of Moisture Content on Vane Shear Strength, Soil Moisture Suction and Effective Pressure of Remolded, Saturated Clays

As mentioned in the part (a) of this chapter, shearing resistance depends only on cohesion in the range of comparatively high moisture content where angle of internal friction is nearly equal to zero. To research experimentally the relation between the shearing strength and moisture content in this range, the vane shear tests were performed on five soil samples listed in Table 4. The samples were kneaded with

Table 4. Properties of Soils used in Experiments for Part (b) of Chapter 6.

Soil Type	Particle-size Distribution			Atterberg Limits		
	Sand 2.0~0.05mm.	Silt 0.05~0.005mm.	Clay <0.005 mm.	LL	PL	PI
Sandy Clay	55	13	32	31	17	14
Clay Loam	27	49	24	50	24	26
Silty Clay Loam	26	52	22	46	28	18
Nara Clay	18	38	44	58	24	34
Osaka Clay	22	40	38	53	29	24

various moisture contents and then compacted in the molds until the air bubbles contained in the samples in the molds were entirely removed by tapping the molds. After that treatment the samples in the molds were sheared by a vane tester. The results are shown in Figs. 20 (a), (b), (c), (d) and (e), which show that the linear relation is held between the vane shear strength and moisture content on the both-logarithmic papers.

Next, the relation between the soil moisture suction and moisture content obtained by the suction plate method and centrifugal method with these samples are plotted on the same papers as shown in Fig. 20. These newly plotted curves show that these relationships are also almost linear and parallel to the vane shear strength-moisture content curves on the papers.

Moreover, the relationships between effective pressure and moisture content obtained by the standard consolidation tests on these samples are plotted on the same papers. These curves also become almost straight lines and parallel to the former two curves on the paper.

If the soil used is perfectly compressible clay whose α in equation (2) is considered as unity, the effective pressure-moisture content curve must fall on the soil moisture suction-moisture content curve according to equation (2). But in these cases, these two groups of curves are apart. These differences seem to be caused by the fact that these soils used here are not perfectly compressible, that is $\alpha \neq 1$, and there is unavoidable friction on the inside wall of container ring in the procedure of consolidation test.

In 1944, P. C. Rutledge showed the strength characteristics of homogeneous saturated clay as follows;[12]

1. The maximum principal stress difference $(\sigma_1-\sigma_3)$, called the compressive strength of the clay, depends only on the water content at maximum stress, provided the test specimens have not been preconsolidated under pressures greater than the test maximum stress and then allowed to rebound to equilibrium under lower pressures. With this one limitation, it is independent of pore water pressure and of the test method that produces the final water content.
2. A plot of water content at end of test vs. logarithm of principal stress difference is a curve that begins at the unconfined compressive strength and the natural water content and runs roughly parallel to the semi-logarithmic pressure-water content curve obtained from a standard consolidation test on the same clay.

The both-logarithmic representation of the effective pressure-water content curve and the strength-water content curve is somewhat unusual, however, this presentation seems to be also applicable for the Rutledge's experimental results as shown in

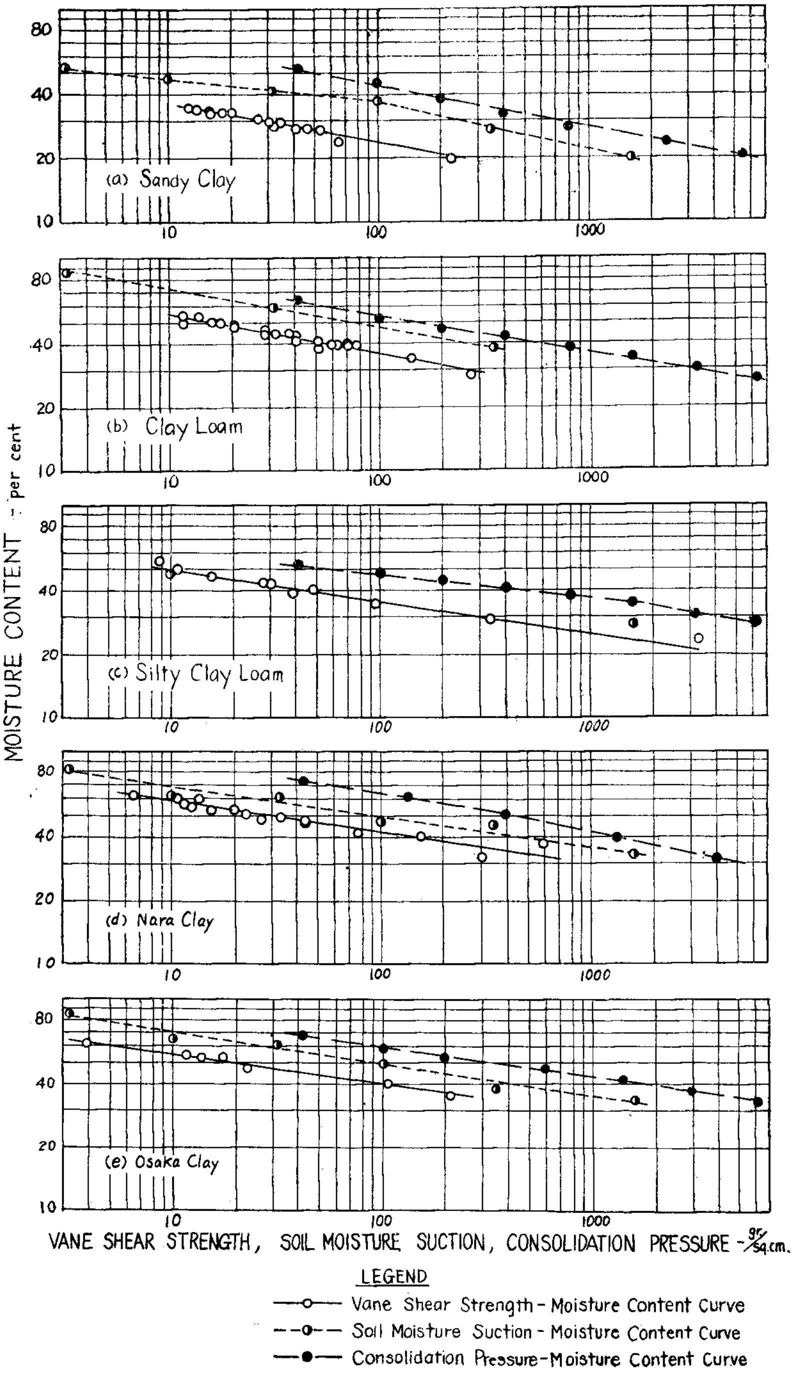


Fig. 20. Relationships of Vane Shear Strength, Soil Moisture Suction and Consolidation Pressure versus Moisture Content.

Fig. 21 which is replotted on a both-logarithmic paper from his results.[13)]

7. Conclusions

Results of the authors' considerations and researches in this paper are summarized as follows:

1. As the properties of compacted soil used in a construction may change after the construction is completed, it is necessary to estimate the critical strength which the soil may have after it balances in its environment. Therefore, it is essential for a reliable design for construction using compacted soil to investigate not only the strength of the soil directly after compaction but also the future strength of the soil.

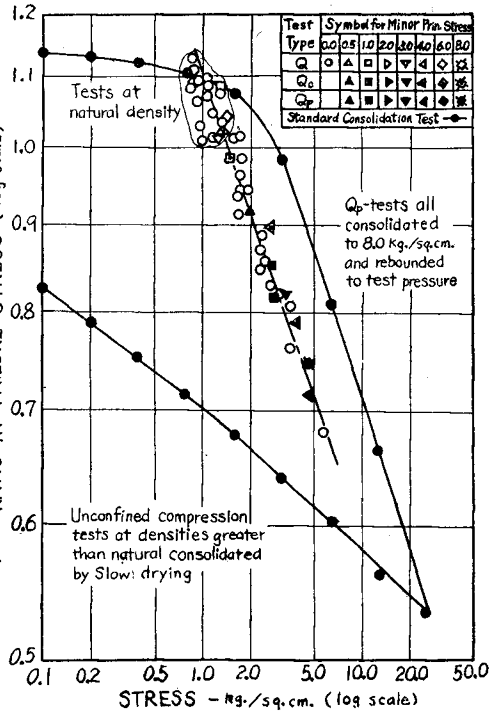


Fig. 21. Stress versus Void Ratio for a Minnesota Clay (From Rutledge's data[13)]).

2. There are three useful scales to express soil moisture condition; namely, the moisture content defined in JIS A 1203, the soil moisture suction defined by D. Croney and J. D. Coleman[1)], and the *pF* scale introduced by R. K. Schofield[2)].

To understand the *pF* scale, the concept of the Ideally Balanced Soil Layer was introduced and soil moisture conditions were considered thermodynamically in this Layer.

3. Relations between the *pF* and moisture content were observed and influences of various elements such as clay content, dry density, exchangeable cation on these relations were demonstrated with the data of the authors and also of other researchers.

4. The *pF* values of air-dryness and oven-dryness were calculated to be pF 5.6 and *pF* 6.9 from the statistical data of temperature and relative humidity in Kyoto, Japan.

5. When the clay-like soil is compacted with a relatively high moisture content, there is a boundary in dry density beyond which C.B.R. decreases with increase in dry density. Further in the case of clay, it is noticeable that the sample having lower moisture content and higher dry density has lower C.B.R. than the C.B.R. of the sample having higher moisture content and lower dry density in the condition of rather high moisture content. These phenomena seem to be caused by the occurrence

of an excess pore water pressure and a remolding effect of compaction.

6. The moisture contents for the maximum C.B.R. directly after compaction are generally smaller than the optimum moisture content and the ratios of the former to the latter are from 0.69 to 0.89 in the authors' experiments.

7. Generally, the compacted soils increase their moisture content and decrease their dry density according to the decrease of the *pF* of their soil moisture after compaction. When there was no surcharge weight on the specimens, the specimens compacted with their optimum moisture contents swelled about 8 per cent of their initial volume for sand and sandy loam, and about 20 percent for clay and silty clay loam when they were placed in the environment of *pF* 0.5. But when an overburden pressure of 30 gr./sq. cm. was loaded on the specimens, sand and sandy loam did not show any visible change, but clay and silty clay loam swelled about 6 percent. The compacted soils loaded with an overburden pressure of 30 gr./sq. cm. decreased their strength considerably at *pF* 1.5 especially in the case of clay.

8. In the shearing tests with soils which were compacted statically by the normal stress kept constantly on the shearing surface during the test, the following aspects became clear. As for the cohesion, it increased at first with increase in moisture content, but beyond some moisture content it decreased with increase in moisture content. On the other hand, the angle of internal friction was hardly influenced by moisture content when the content was low, but from some moisture content it decreased rapidly with increase of moisture content and approached to zero.

9. The relationship between shearing strength of the remolded saturated soil and moisture content was presented experimentally as a straight line on the both-logarithmic paper. The same relationships were also obtained between the soil moistuse suction and moisture content and between the effective pressure and moisture content. And these three curves are roughly parallel to each other on the both-longarithmic paper. This relationship held well against the data13) for natural saturated clay reported by P. C. Rutledge.

The authors wish to express their hearty thanks to their collaborators, Messrs. K. Ueda, T. Tobe and K. Otsuka, the former undergraduate students.

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