

estimating CBR were obtained by using five parameters. It should be remembered that the data used for the models come from all the different geological series. Better models may result in the future when more complete data sets are available for separate geological formations, but results obtained should not be extrapolated beyond the range of test conditions of this study.

This partial analysis indicates that, when the data are divided into groups based on geological origin, the one-to-one correlation can be increased over that of all the data lumped together.

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## Using Indicative Properties to Predict the Density-Moisture Relationship of Soils

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The need for predictions of density-moisture relationships by means of the index properties of a soil is obvious because an engineer first becomes acquainted with a soil by determining these properties. Preliminary engineering reports normally use information from soil classification surveys to obtain findings relevant to earthwork, slope design, and structural pavement design. It is, therefore, natural to analyze the accumulated density test results taken from various sites in order to obtain correlations between the index properties and the engineering properties of the soil. This paper presents a method for predicting the optimum line—the curve that connects the peaks of the density-moisture curves obtained at different levels of compaction effort. The first stage in the prediction process is to make a qualitative and quantitative acquaintance with the soil compaction mechanism governing the characteristics of the typical density-moisture curve. The next step is to predict maximum densities and optimum moisture contents for given levels of compaction effort (standard and modified AASHTO). Graphs and regression equations based on the plastic and liquid limits of the soil and using the suction criterion are presented. The predicted maximum density and optimum moisture content are also related to the critical voids percentage. The method does not substitute the execution of the tests themselves but enables one to obtain reliable preliminary information.

The density-moisture relationship of soils is a well-known criterion for the compaction design of subgrades and embankments of flexible pavements. Such compaction design

can be expressed in terms of (a) compaction moisture content, (b) recommended compaction degree, and (c) type of compaction effort.

The need for predictions of density-moisture relationships by means of the index properties is obvious, because one's first acquaintance with soils is made by determining these properties. Stated differently, one of the objectives of soil classification surveys is to produce general information about the expected engineering properties. Preliminary engineering reports usually use this information to determine earthwork, slope design, and structural pavement design.

The usefulness of predicting density-moisture relationships is expressed mainly in the preliminary design phase and feasibility studies of highways and airports when major information is needed for the evaluation of the earthwork and design parameters in terms of degree of natural density, maximum density, required molding water content, etc. It is also very important in cases where soil types are variable along the alignment. In this case

a reliable field control requires valid correlative relationships between parameters that are easy to determine and moisture-density relationships. The correlation presented in this paper can serve as a guideline to similar correlations in other highway or airport projects. It is, therefore, natural that many researchers are still continuing to analyze the accumulated density test results taken from various sites in order to obtain correlations between the soil's index properties and the engineering properties.

As an example, several investigators (1, 2, 3, 4, 5, 6) have related the laboratory maximum density and optimum moisture content to the various index properties of the material. Others (6, 7, 8, 9, 10, 11), however, have related the laboratory California bearing ratio (CBR) values to similar index properties.

This paper continues the search for and refinement of the correlations expressed in the above works and seeks similar relationships between the index properties and the compaction properties of the soil. Special emphasis is given to the optimum line, namely to the maximum density of the compacted soil and its appropriate optimum moisture content at any compaction effort, while the essence of the correlations obtained is defined qualitatively.

#### DENSITY-MOISTURE CURVE

The density-moisture curve can be determined in the laboratory by using one of the standard dynamic compaction methods. The characteristics of the curve are a function of soil type, but generally it can be observed that, at a constant level of compaction effort, density increases with increasing moisture content up to a maximum density value, which is accompanied by the optimum moisture content. The increase in moisture above the optimum value will cause the density to decrease (see Figure 1). The explanation of this phenomenon by Lambe (12) is based on the attraction and repulsion forces between particles, the magnitudes of which are influenced by the moisture content. In other words, moisture usually governs the extent of resistance to the relative displacement of soil particles under compaction. In addition to the existence of friction forces between particles, this resistance is caused by the resultant electric attraction and repulsion forces.

The presence of a low moisture content (point A in Figure 1) creates an equivalent attraction force that pre-

vents the relative displacement of soil particles. In this condition, the density is low, or the voids content is high. The increase in moisture above this content increases the repulsion forces and thus decreases the equivalent attraction forces. By this action, particles can slip one above the other to form a denser packing. The effect of increasing moisture, which is often called lubrication action, softens the soil and improves its workability. This actually leads to higher densities or to lower voids content. The increase in density accompanied by the decrease in voids continues until optimum moisture content and maximum density are reached (point B in Figure 1).

Above this optimum content the percentage of voids reaches an almost constant value, which will be called here the "critical voids percentage". (In this paper critical voids percentage refers to air voids percentage and is defined as the ratio, expressed as a percentage, of the volume of air voids of a given soil mass to the total volume of the soil mass, when the soil mass has been compacted at optimum moisture content for the given compaction effort.) In this condition the power of the compaction effort decreases because of the development of pore pressures, which increase with the increasing degree of saturation of the sample.

In other words, water content that is higher than the optimum does not permit a decrease in the entrapped inter-particle air voids, even if the particles are arranged in an efficient state for compaction. The outcome is that the addition of water causes the particles to dilate, which allows more water to enter the gaps. As a result of this phenomenon of the separation of particles, the volume occupied by air and water increases and the dry density of the soil decreases.

The increase of compaction effort increases the maximum density and decreases the optimum moisture content (point C in Figure 1). The increase in density is natural since higher compaction effort was invested. The optimum moisture content decreases because less water is needed to obtain the critical voids percentage at the higher density. This can be shown in the following equation, which expresses the weight-volume relationship in the soil sample in terms of the percentage of its moisture content ( $\omega$ ):

$$\omega = [(100 - G_v)/\gamma_d] - 100/G_s \quad (1)$$

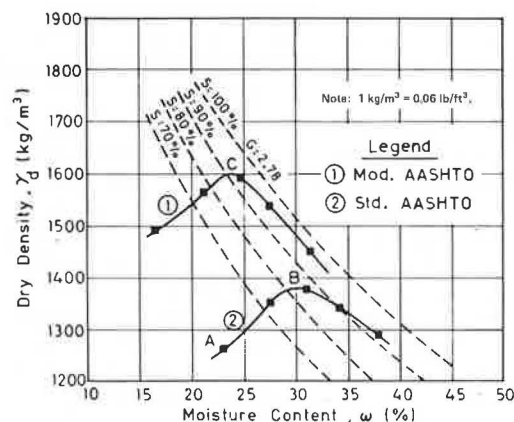
where

- $G_v$  = percentage air voids,
- $\gamma_d$  = dry density in grams per cubic centimeter, and
- $G_s$  = specific gravity of the solids.

Actually, it is not necessary for the critical voids percentage to be independent of the level of compaction effort, as will be proved later in this paper. The change in dry density, however, is more significant than the possible change in air voids. Therefore, even if the critical voids percentage decreases as compaction effort increases, the dry density still increases by such an extent as to be sufficient to decrease the optimum moisture content (see also Equation 1).

A preliminary estimate of maximum density at modified AASHTO compaction effort can be made using Table 1. In this paper, modified AASHTO compaction effort will refer to the procedure of the U.S. Army Corps of Engineers, namely 15-cm (6-in) mold, 4.5-kg (10-lb) rammer, 46-cm (18-in) drop, five layers, and 56 blows/

Figure 1. Density-moisture relationship of fat clay for two levels of compaction effort.



layer. Accordingly, standard AASHTO compaction effort will refer here to the same procedure, but with 12 blows/layer, which has the same compaction effort as in AASHTO T99. Therefore, for the purpose of this paper the difference between the two methods is negligible.

It is clear that maximum density depends on various factors, such as the specific gravity of the solids, the geometry of the particles, size distribution, and the plasticity of the fines; therefore, there is a wide range of

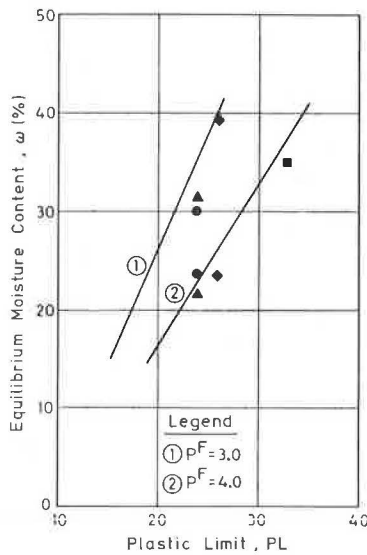
**Table 1. Range of maximum density at 100 percent modified AASHTO for different soils.**

Factor	AASHTO Classification						
	A-1	A-2	A-3	A-4	A-5	A-6	A-7
Maximum density range, kg/m <sup>3</sup>	1900 to 2300	1800 to 2100	1400 to 1800	1700 to 2000	1400 to 1700	1600 to 2000	1400 to 1900
	2.7	- <sup>a</sup>	2.65	2.65	2.70	2.75	2.80

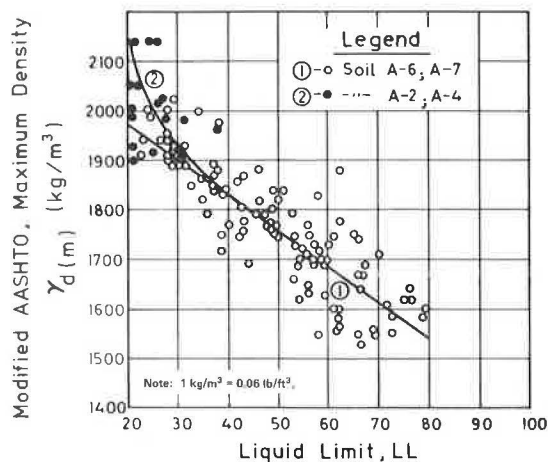
Note: 1 kg/m<sup>3</sup> = 0.06 lb/ft<sup>3</sup>.

<sup>a</sup>Varies according to the groups A-4, A-5, etc; for example, for an A-2-4 soil G<sub>s</sub> = 2.65 and for an A-2-7 soil G<sub>s</sub> = 2.80.

**Figure 2. Relationship between plastic limit (PL) and equilibrium moisture content (ω) for constant values of suction.**



**Figure 3. Relationship between liquid limit (LL) and modified AASHTO maximum density [γ<sub>d(m)</sub>].**



densities for a given classified soil (as shown in Table 1). The next section presents relationships that narrow density ranges.

**PREDICTION OF MAXIMUM DENSITY VALUE**

The value of the maximum density at a given compaction effort depends on soil type. If one assumes that this value depends qualitatively on the suction potential of the soil, it is clear that the higher the suction potential the lower the resistance of the soil to gaining density. (The difference between the energy of water in the soil and the energy of free water, when the temperature, elevation, and atmospheric pressure are the same, is called "suction potential".) It is well known that suction potential increases with an increase in the plastic limit of the material. Figure 2 (13) shows the relationship between plastic limit and equilibrium moisture content for constant values of suction. It can be seen here that, for a material with PL = 20, the value of the suction in this moisture content ranges between P<sup>F</sup> = 3.0 and P<sup>F</sup> = 4.0. On the other hand, for a material with PL = 30, the suction value is higher than P<sup>F</sup> = 4.0.

It is therefore natural to look for a correlation between the liquid limit of the soil and its maximum density. For example, this correlation according to Ramiah, Viswanath, and Krishnamurthy (5) is

$$\gamma_{d(s)} = 2125 - 10 LL \tag{2}$$

where γ<sub>d(s)</sub> is the maximum dry density in kilograms per cubic meter using standard AASHTO compaction effort, and LL is the liquid limit.

Another correlation, but for maximum density according to modified AASHTO, is given in Figure 3. This correlation is suitable for A-2, A-4, A-6, and A-7 soils with index properties as described in Figure 4. Actually, this correlation fits well for cohesive soils. For granular materials, the density is usually higher and is a function of the gradation of particles. The prediction of such density can be made by using the values in Table 1.

A property similar to that of decreasing density with increasing liquid limit is that of an increasing optimum moisture content with increasing soil plasticity. When the soil is highly plastic, its particles have a higher specific surface; therefore the lubrication action needs more water. According to Ramiah, Viswanath, and Krishnamurthy (5), the following relationship exists:

$$\omega_{(s)} = 1/3 (LL + 15) \tag{3}$$

where ω<sub>(s)</sub> is the standard AASHTO optimum moisture content expressed as a percentage, and LL is the liquid limit.

Another correlation, but this time with plastic limit, is given in Figure 5. This correlation is suitable for the materials described in Figure 4 and is also valid for the modified AASHTO moisture content, ω<sub>(m)</sub>. For granular materials, Figure 6 represents the cumulative distribution of optimum moisture contents, which for most granular soils ranges from 7.0 to 9.0 for standard AASHTO, and from 5.0 to 7.0 for modified AASHTO.

In addition to the prediction discussed so far, it is of interest to predict the relationship between density and compaction effort. The ratio between standard AASHTO maximum density, γ<sub>d(s)</sub>, and modified AASHTO maxi-

imum density,  $\gamma_{d(m)}$ , can serve as an index to this relationship. Figure 7 describes this ratio as a function of the modified AASHTO maximum density. Contrary to other findings (14) (see also Figure 8), the relationship presented here is a function of soil type. In any case, the ratio  $\gamma_{d(s)}/\gamma_{d(m)}$  increases with the increase in soil density or with the decrease in the plasticity of the material. In both cohesive and granular soils, higher density indicates lower

resistance to densification. This explains the increase in density ratios with the increase in density for any type of soil. It is clear that the density ratio obtained for granular materials is higher than that for cohesive soils. For example, A-1 and A-3 materials can reach, in standard AASHTO compaction effort, 97 percent of the modified AASHTO maximum density. On the other hand, A-7 can only reach a density ratio of 88 percent and A-6 of up to 90 percent.

Figure 4. Consistency properties and AASHTO classifications for the specific soils described in this paper.

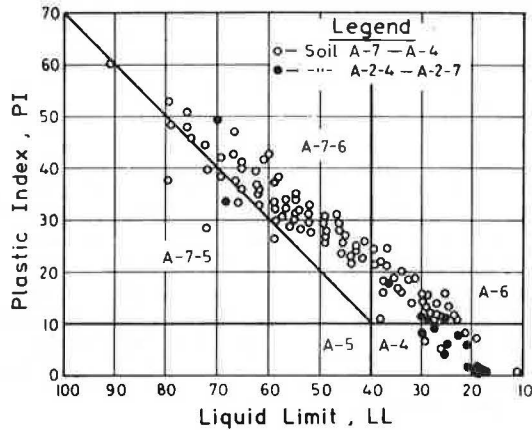


Figure 6. Optimum moisture contents for A-1 soils.

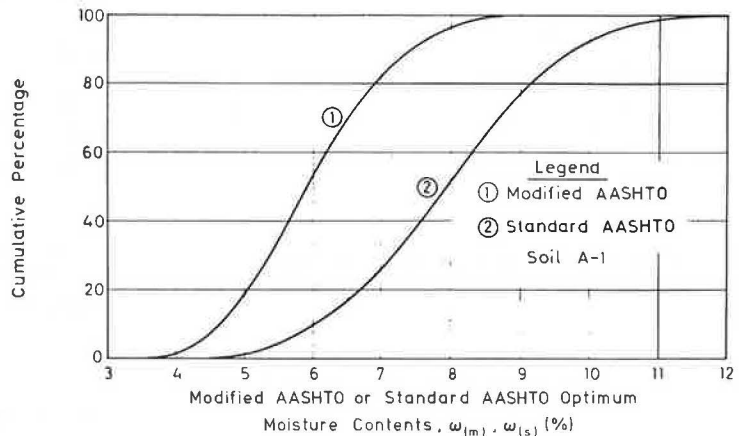


Figure 7. Relationship between the ratio of standard and modified AASHTO maximum densities [ $\gamma_{d(s)}/\gamma_{d(m)}$ ] and modified AASHTO maximum density [ $\gamma_{d(m)}$ ].

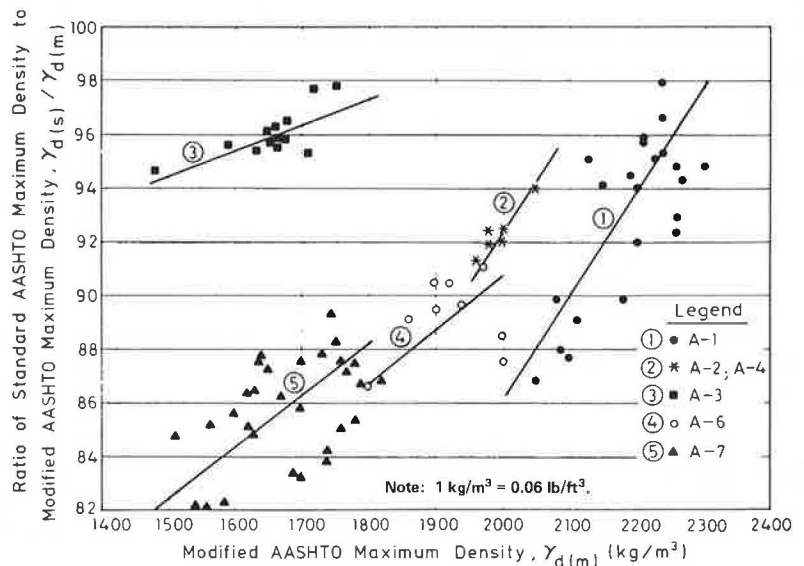


Figure 5. Relationship between plastic limit (PL) and modified AASHTO optimum moisture content [ $\omega_{(m)}$ ].

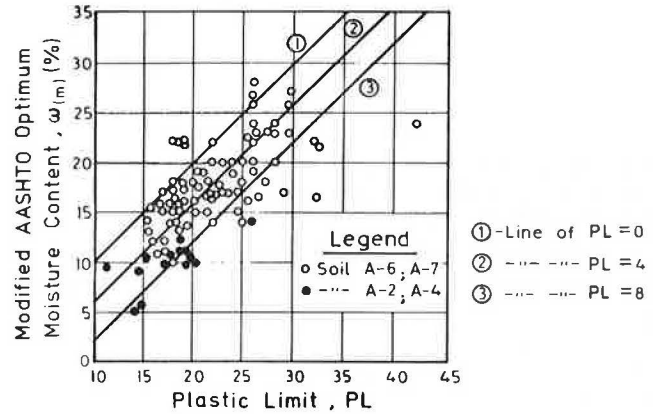


Figure 8. Relationship between the ratio of standard and modified AASHTO maximum densities [ $\gamma_{d(s)}/\gamma_{d(m)}$ ] and modified AASHTO maximum density [ $\gamma_{d(m)}$ ] according to Yoder.

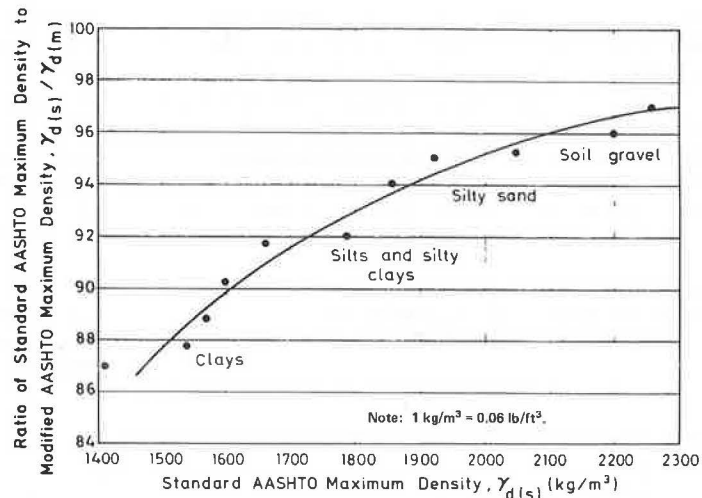


Figure 9. Relationship between liquid limit (LL) and the critical voids percentage obtained by modified AASHTO compaction effort [ $G_{v(m)}$ ].

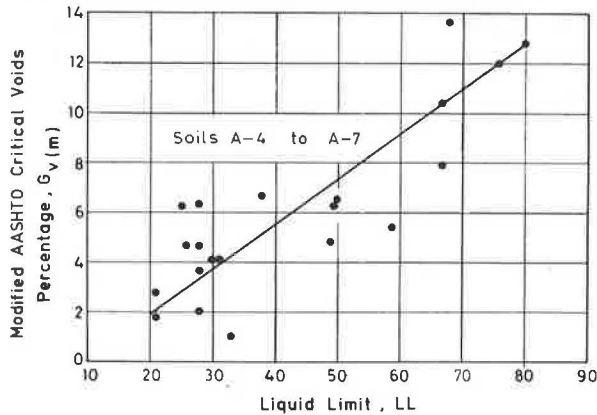
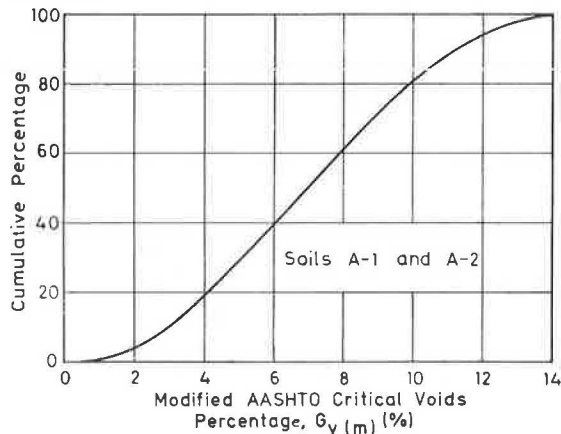


Figure 10. Distribution of critical voids percentage obtained by modified AASHTO compaction effort for A-1 and A-2 materials.



**PREDICTION OF THE CRITICAL VOIDS PERCENTAGE**

As discussed above, the critical voids percentage is the percentage of air voids in the specimen compacted to the maximum possible density at a given compaction effort. It is customary to assume that this voids percentage is

constant at a value of 5 percent (15). However, analysis of the findings presented in Figure 9 proves that the critical voids percentage obtained by modified AASHTO compaction effort is also a function of soil type. For cohesive soils its value increases with the increase in plasticity. Qualitatively, it is quite natural to assume that the critical voids percentage is also connected with a constant value of suction potential or, more precisely, with the effective suction potential,  $\bar{S}$ , as follows:

$$\bar{S} = S_r S = Q(E) \tag{4}$$

where

- S = suction of the material,
- $S_r$  = degree of saturation of the material, and
- Q = a factor depending on the level of compaction effort (E).

The relationship between the critical voids percentage,  $G_v$ , and the saturation degree,  $S_r$ , is expressed in the following equation:

$$G_v = [1 - (\gamma_d/G_s)] (100 - S_r) \tag{5}$$

where  $\gamma_d$  and  $G_s$  are defined in Equation 1 and  $G_v$  and  $S_r$  are percentages.

It was shown that the increase in soil plasticity leads to higher suction (S) and lower dry density. According to Equation 4, therefore, it will lead also to the decrease in the degree of saturation that is related to the maximum density conditions. Examination of Equation 5 will prove that the increase in the critical voids percentage is accompanied by a decrease in saturation degree and in dry density. This phenomenon can be observed in Figure 9 for A-4, A-6, and A-7 materials. For A-1 and A-2 materials, because the prediction cannot be made by using the liquid limit, the distribution of results shown in Figure 10 are used.

For the same reason, it is not necessary that the critical voids percentage be constant for every level of compaction effort. For a given soil, it is possible that a decrease of compaction effort will decrease the saturation degree under the new optimum conditions (see, for example, Figure 1, in which the saturation degree decreases from 92 to 82 percent with the reduction in compaction effort from modified AASHTO to standard AASHTO). However, at the same

Figure 11. Relationship between the critical voids percentage obtained by modified AASHTO compaction effort [ $G_{v(m)}$ ] and by standard AASHTO [ $G_{v(s)}$ ].

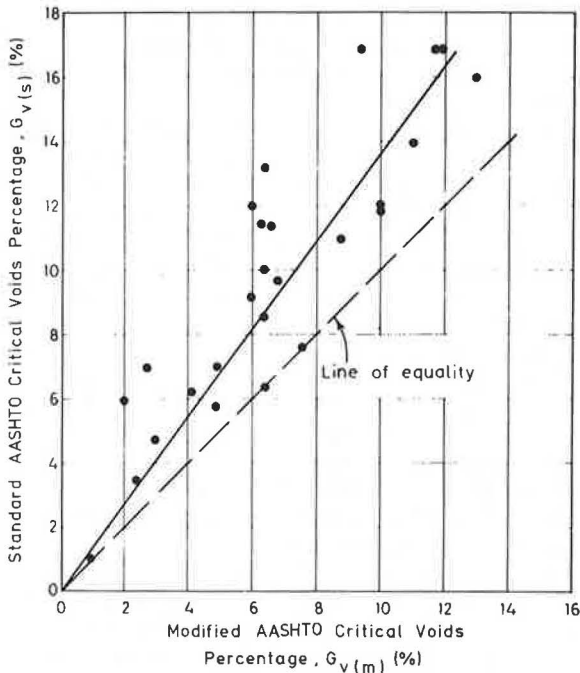


Figure 12. Flowchart for predicting the optimum line for a soil with given index properties.

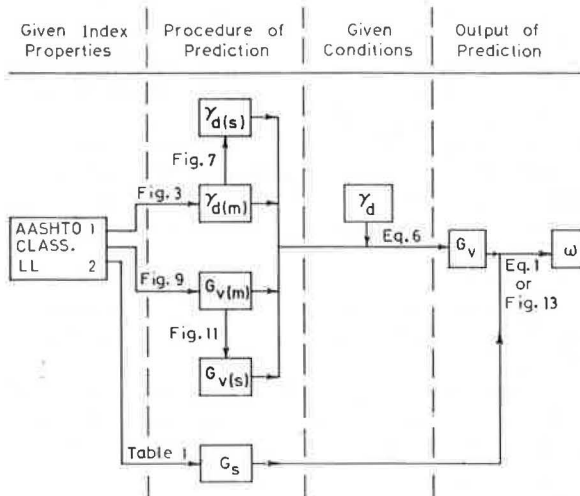
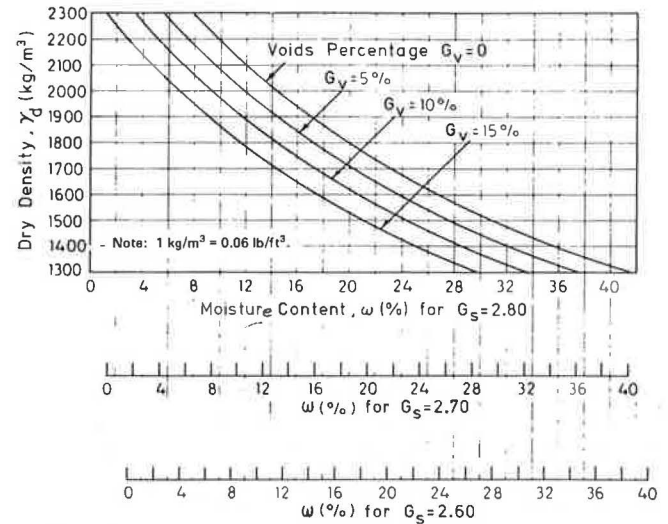


Table 2. Results of the calculated optimum line for an A-7 soil with a liquid limit of 60.

$\gamma_a/\gamma_{d(m)}$	Degree of Compaction			
	100 Percent [ $\gamma_d = \gamma_{d(m)}$ ]	95 Percent	90 Percent	86 Percent [ $\gamma_d = \gamma_{d(s)}$ ]
Air voids, % <sup>a</sup>	9.0 <sup>b</sup>	10.3	11.5	12.5 <sup>b</sup>
Optimum moisture content <sup>c</sup>	18.0	20.0	23.0	24.5

<sup>a</sup>According to Equation 6.  
<sup>b</sup>Values taken from Figures 9 and 11.  
<sup>c</sup>According to Equation 1 or Figure 13.

Figure 13. Determination of moisture content ( $\omega$ ) as a function of voids percentage ( $G_v$ ), dry density ( $\gamma_d$ ), and the specific gravity ( $G_s$ ).



time, this decrease is accompanied by a decrease in dry density, which in the end causes the increase in the critical voids percentage, as reflected in Equation 5.

The difference between the critical voids percentage obtained by standard AASHTO [ $G_{v(s)}$ ] and that obtained by modified AASHTO compaction effort [ $G_{v(m)}$ ] must, in fact, decrease as the densities obtained by the two compaction efforts become closer in values. This is also validated by Equation 5. As mentioned, this closeness of densities increases as the plasticity of the soil decreases. Therefore, for small values of the critical voids percentage (which usually are obtained from low-plasticity materials), the dependence of the critical voids percentage on compaction effort decreases. This fact is expressed in Figure 11, which shows the relationships between the critical voids percentage obtained by modified AASHTO compaction effort  $G_{v(m)}$ , and those obtained by standard AASHTO,  $G_{v(s)}$ .

PREDICTION OF THE OPTIMUM LINE

The optimum line is the curve that relates the maximum density to the optimum moisture content. In other words, this line connects the peaks of the density-moisture curves obtained from different compaction efforts. The material presented so far in the paper permits the prediction of the optimum line according to the flowchart given in Figure 12.

If one assumes that the variation of voids percentage,  $G_v$ , from the maximum density at different compaction efforts is linear, the following equation can be written:

$$G_v = [G_{v(s)} - G_{v(m)}] \left\{ \frac{1 - [\gamma_d/\gamma_{d(m)}]}{1 - [\gamma_{d(s)}/\gamma_{d(m)}]} \right\} + G_{v(m)} \quad (6)$$

where  $G_v$  is the critical voids percentage for maximum density  $\gamma_d$ , and  $G_{v(m)}$  and  $G_{v(s)}$  are the critical voids percentages for maximum densities  $\gamma_{d(m)}$  and  $\gamma_{d(s)}$  (obtained by modified AASHTO and standard AASHTO compaction efforts, respectively).

For illustrating the process of prediction, an A-7 soil with a liquid limit of 60 was checked.

Using the directive flowchart (Figure 12) and the appropriate figures, tables, and equations, the following values were determined:

1.  $\gamma_{d(m)} = 1690 \text{ kg/m}^3$  (Figure 3),
2.  $\gamma_{d(s)}/\gamma_{d(m)} = 86$  percent (Figure 7),
3.  $G_{v(m)} = 9$  percent (Figure 9),
4.  $G_{v(s)} = 12.5$  percent (Figure 11), and
5.  $G_a = 2.80$  (Table 1).

The results obtained for different degrees of compaction are summarized in Table 2. A comparison of these results with those obtained from the other correlations presented in this paper shows their adequacy.

#### SUMMARY

This paper presents a method for predicting the optimum line—the curve that connects the peaks of the density–moisture curves obtained at different levels of compaction effort. The object of this prediction is to enable preliminary evaluation of the compaction properties in materials to be used for subgrades and embankments of flexible pavements.

Predictions of density–moisture relationships are useful in preliminary design phases and feasibility studies of highways and airports for evaluating the earthwork and design parameters in terms of degree of natural density, maximum density, required molding water content, etc. They are also very important in cases where soil types are variable along the alignment. In this case a reliable field control requires moisture–density relationships and valid correlative relationships between parameters that are easy to determine. The correlation presented in this paper can serve as a guideline to similar correlations in other highway or airport projects (see Figure 13).

The existing methods for predicting moisture–density relationships usually estimate the moisture and density values only at modified and standard AASHTO compaction efforts and do not relate them to each other. Compared to these methods, the method suggested here is more general. It relates optimum moisture content and maximum density to any compaction effort and thus characterizes the entire optimum line and does not substitute the execution of the tests themselves. It proves to be a suitable method that enables one to obtain reliable preliminary information.

The correlations presented in this paper are qualitatively explained by using the suction criterion for defining the optimum condition in the compaction process.

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