Compacted Soil Strength Estimated From Grain Size Distribution and Soil Binder Analysis

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This paper presents a mathematical approach to the problem of estimating the strength of a compacted soil from a routine laboratory report on its grain size distribution and soil binder analysis. A means for estimating CBR for a soil obtained by the Alabama 2000-psi compaction method is also presented. This approach is suggested as providing the means for crossing state lines with soil strength data so that soil strength data measured in terms of other parameters for any given state might be converted into comparable data for any other state or agency.

•THIS PAPER is concerned with the development of a method for estimating strength characteristics of a compacted soil from a routine laboratory report on its grain size distribution and soil binder fraction analysis, without actually having to conduct strength characteristics tests in the laboratory. Also, a means for estimating the CBR for such a compacted soil obtained by the 2000-psi static-compaction method presently used in Alabama is presented. The 2000-psi static-compaction method is substantially the same as that originally presented in the late 1920's by O. J. Porter of the California Division of Highways. For design purposes, the Alabama Highway Department uses the lesser of the two CBR values reported for 0.1- and 0.2-in. penetrations. There is strong evidence that this same method also should apply to soil strengths measured by other procedures and parameters.

On a logical basis, the more coarse-grain material contained in a soil the higher the CBR and, conversely, the more fine-grain material the lower the CBR. Also, the plastic properties of a soil should have some influence on CBR. Research on properties of the binder fraction of soils at the University of Alabama indicates that the Atterberg limits of a particular soil are related to the percent clay in the binder fraction. It is recognized that the type of clay included in the binder fraction should have some bearing on compacted soil strength. However, the nature of Alabama soils in general, as well as those included in this study, are such that kaolinite is the predominant clay mineral. Illite and montmorillonite clays are rarely if ever encountered. For all practical purposes, the clays used as a basis for this study were assumed to be of the same type. The influence of the plastic properties of a soil, therefore, probably is some function of the percent clay, plastic limit and liquid limit. If it is assumed that each of these effects may be approximated by a parabolic curve, the resulting mathematical model could be written as follows:

$$\Phi(\text{CBR}) = a + bX_1 + cX_1^2 + dX_2 + eX_2^2 + fX_3 + gX_3^2 \qquad (1)$$

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where

$$\Phi(CBR) = \text{some function of CBR},$$
$$a, b, c, d, e, f \text{ and } g = \text{multiple-regression analysis constants},$$
$$X_1 = \text{some function of grain size distribution},$$
$$X_2 = \text{some function of percent clay, and}$$
$$X_3 = \text{some function of the Atterberg limits.}$$

The characteristic effect of grain size distribution on the value of CBR is illustrated by the gradation curves shown in Figure 1. The grain size data for each curve were taken from routine reports of the Alabama Highway Department soils laboratory. Examination of the 6 curves in Figure 1 will show that CBR is an inverse function of the area under a given curve. That is, the CBR values tend to decrease as the area under the curves increases.

Numerous multiple-regression analyses were made to determine the function $\Phi(CBR)$ that would correlate best with selected forms of the variables X_1, X_2 and X_3 (Eq. 1). The data used as a basis for these multiple-regression analyses were obtained from some 350 soil laboratory reports of the Alabama Highway Department in which the CBR values ranged from very low to very high. Of all the multiple-regression analyses investigated, the one that resulted in the highest correlation coefficient was the one in which the function $\Phi(CBR)$ and the variables X_1, X_2, and X_3 in Eq. 1 were defined as follows:

$$\Phi(CBR) = \log CBR \quad \text{(common logarithm)}$$

$$X_1 = \%4 + \%10 + \%40 + \%60 + \%200$$
(% of total sample passing each sieve size as indicated)

$$X_2 = \%\text{clay}$$
(% of No. 10 fraction as determined by elutriation test)

$$X_3 = (\text{plastic limit})/(\text{liquid limit} - 15) = PL/(LL-15)$$

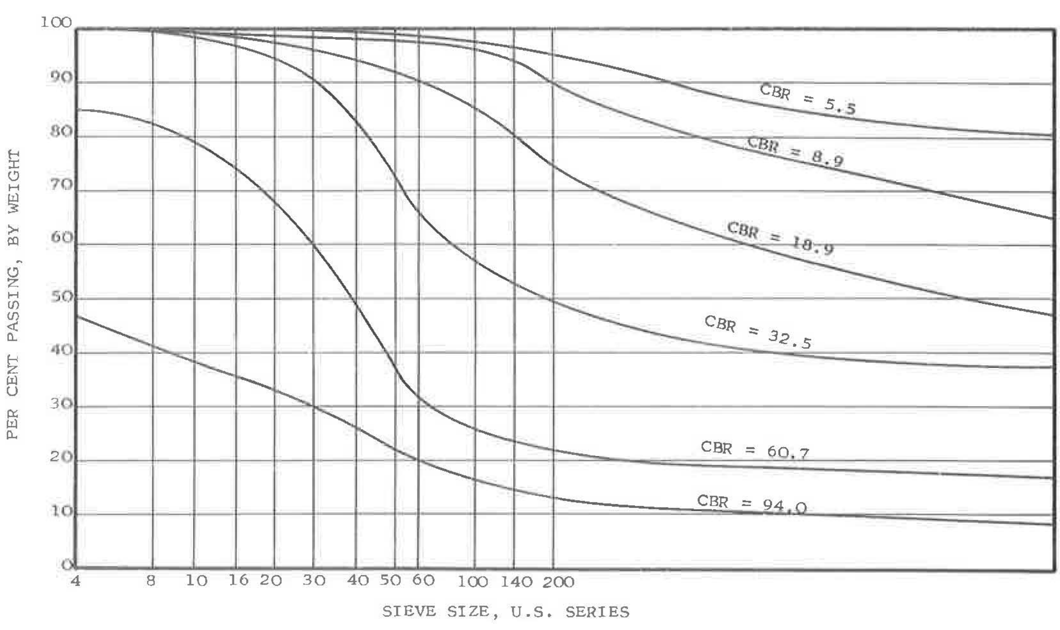

Figure 1. Typical grain size distribution curves.

together with the following multiple-regression constants:

a = 2.446826
b = -0.003272
c = 0.000001
d = -0.007582
e = 0.000003
f = -0.000184
g = 0.000000—negligible

which resulted in the following equation:

$$\log CBR = 2.446826 - 0.003272X_1 + 0.000001X_1^2 - 0.007582X_2 + 0.000003X_2^2 - 0.000184X_3 \quad (2)$$

This multiple-regression equation resulted in a correlation coefficient, $R = 0.878112$ with $R^2 = 0.7711$, which means that Eq. 2 explains 77.11 percent of the variation in log CBR.

Only a casual review of Eq. 2 is required to see that the terms involving X_1^2 and X_2^2 have very little effect on the value of log CBR. Similarly, the term involving X_3 has but little effect on the value of log CBR. By eliminating these relatively unimportant terms, it was decided that reasonably accurate values of CBR could be obtained from a simpler mathematical model such as:

$$\log CBR = a + bX_1 + cX_2 \quad (3)$$

where

X_1 = %4 + %10 + %40 + %60 + %200
(% of total sample passing each sieve size as indicated), and
X_2 = %clay
(% of No. 10 fraction as determined by elutriation test)

Based on the mathematical model in Eq. 3, a multiple-regression analysis was run using data from the same 350 soil laboratory reports employed in the multiple-regression analysis that resulted in Eq. 2. The constants resulting from this analysis were as follows:

a = 2.334984
b = -0.002425
c = -0.006920

which when substituted in Eq. 3 gives the following equation:

$$\log CBR = 2.334984 - 0.002425X_1 - 0.006920X_2 \quad (4)$$

The multiple-regression analysis that resulted in Eq. 4 had a correlation coefficient, $R = 0.8774$ with $R^2 = 0.770$, which means that Eq. 4 explains 77.0 percent of the variation in log CBR. By comparing this with the 77.11 percent of the variation in log CBR explained by Eq. 2, it will be seen that reasonably accurate CBR values should result from using Eq. 4. This is further evidenced in that the standard error of estimate of log CBR is 0.224 or standard error of estimate of CBR is 1.67. The principal advantage of using Eq. 4 is its simplicity, since all three of the terms can be shown graphically on one page, whereas Eq. 2 would require many pages. A graphical representation of Eq. 4 is given in Figure 2.

In Figure 2, the variable X_1 is shown on the horizontal scale; it is equal to the sum of the percentages of the entire sample passing the No. 4, 10, 40, 60 and 200 sieves. The variable X_2 = %clay (the percent of the fraction passing the No. 10 sieve, as determined by the elutriation test) is shown on the vertical scale. The use of Figure 2 may be illustrated by referring to the typical soils laboratory report shown in Figure 3.

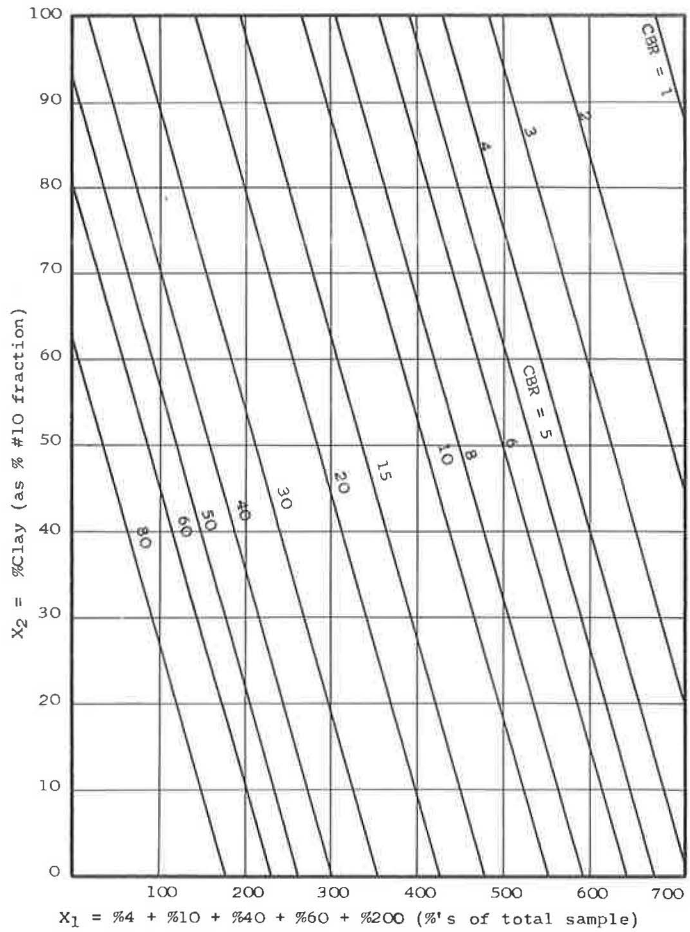

Figure 2. Chart for estimating CBR based on 2000-psi method used by Alabama Highway Department.

From the mechanical analysis, it will be found that $X_1 = 100 + 100 + 100(98 + 96 + 88.1)/100 = 482.1$ and the %clay, $X_2 = 70.4$. For these values of X_1 and X_2, Figure 2 indicates an estimated value of CBR = 4.9, which compares favorably with the design CBR = 5.1 at 0.2-in. penetration as determined by the Alabama Highway Department soils laboratory (Fig. 3).

The question now arises as to how well the observed CBR values agree with the calculated values obtained by use of Eq. 4. Figure 4 shows this relationship. Although this curve gives calculated values of CBR in the higher ranges which are on the conservative side, note that for values of CBR = 60 or less the calculated and observed agree quite well.

The observed CBR values, indicated by the dots in Figure 4, show considerable scatter about the regression curve. This, however, is to be expected since, in addition to grain size, soils in nature have other highly variable characteristics, such as grain angularity and surface roughness, which have a marked influence on soil strength. Research indicates that for sand-size soil grains, the effect of grain shape and roughness on the CBR is quite small compared to that of the coarser soil grains. Furthermore, it is well known that even small variations in compactive effort and molding moisture content will also have a marked influence on soil strength as indicated by the CBR.

STATE OF ALABAMA
HIGHWAY DEPARTMENT
MONTGOMERY

Form CBR-1

INFORMATION TO ACCOMPANY SAMPLE FOR TESTING	LAB NO. 414
Project F-352(13) Division 7 County Montgomery	Date 11-22-63
Materials Sub-Subgrade Marks	Density 116.9 Lbs. Cu. Ft.
Producer Left. R. W.	Optinium Moist 12.5 %
Source Sta. 837+00	Run By: Athey
Quantity Represented	Compressed at 2000 PSI
Remarks: BPR Check CBR	
Sampled By: Tatom & B. Wilkes Date 11-7-63	
Submitted By: Kilpatrick Address	
Title S. A. Cut	

BEARING VALUES

UNSOAKED					SOAKED				
Penetration Inch	Total Load Pounds	Pounds Per Sq. Inch	Standard	% Standard	Penetration Inch	Total Load Pounds	Pounds Per Sq. Inch	Standard	% Standard
0.1			1000		0.1	180	60	1000	6.0
0.2			1500		0.2	230	77	1500	5.1
0.3			1900		0.3	260	87	1900	4.6
0.4			2300		0.4	260	87	2300	3.8
0.5			2600		0.5	280	93	2600	3.6

SWELL DATA

Height in Mold	Inches	
Initial Reading	.100	
Reading After 1 Day	.	
Reading After 2 Days	.	
Reading After 3 Days	.	
Reading After 4 Days	.564	
Total Swell .464 Inches	9.28	%
Moisture-Top 1 Inch	33.7	%
Moisture Bottom 1 Inch	19.0	%
Moisture Average	26.4	%

ANALYSIS

Passing ¾ Screen	100.0	%
Passing # 4 Screen	1000	%
Passing # 10 Screen	100.0	%
Material Passing 10 M Sieve		
Clay	70.4	%
Silt	17.7	%
Total Sand	11.9	%
Pass 40 M	98.0	%
Pass 60 M	96.0	%
Pass 200 M	88.1	%
Field Moisture	37.1	%
Liquid Limit	56.9	%
Plastic Limit	23.0	%
Plasticity Index	33.9	%
Shrinkage Limit	18.9	%
Volume Change	31.9	%
Lineal Shrinkage	8.82	%
Shrinkage Ratio	1.75	%
	A-7	
	A-7-6(19)	

REMARKS: 10# Surcharge Used
Design CBR - 5.1
Std. P. D.
Max. Density - 99.6
Optimum Moisture - 21.6

Testing Engineer

Figure 3. Typical soils laboratory report.

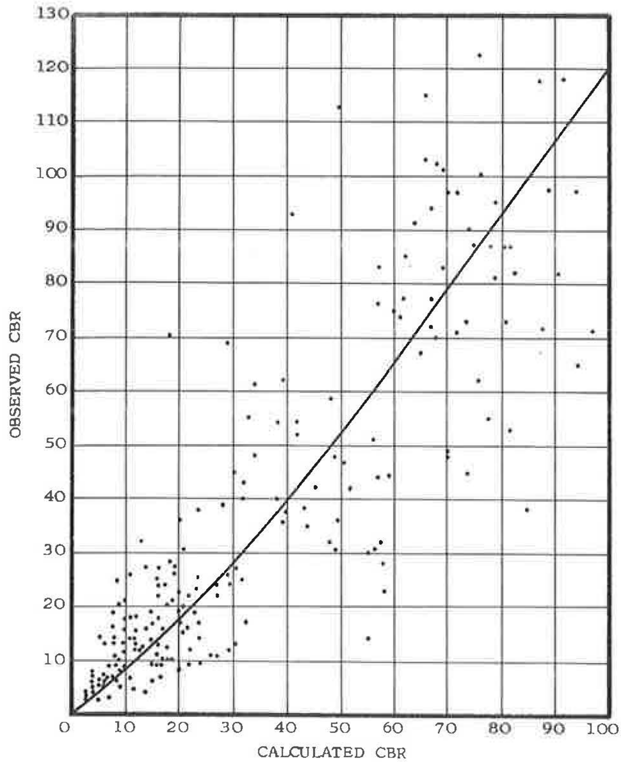

Figure 4. Regression curve showing relationship between observed and calculated CBR.

Experience has shown that replicate CBR tests, based on the 2000-psi static-compaction method, made under carefully controlled conditions have resulted in an average coefficient of variation of about 16 percent. This observation is illustrated by the data in Table 1 which resulted from a series of carefully controlled replicate CBR tests on twelve different materials, accounting for a total of 56 CBR tests. The soils for these tests were selected so that the CBR values would range from very low to very high. In the right hand column of Table 1, notice that the coefficient of variation ranged from a low of 7.1 percent to a high of 31.3 percent, with an average of 16.0 percent, which indicates a rather high degree of variability.

TABLE 1

RESULTS OF A REPLICATE CBR TESTING PROGRAM

Material	Number of Sample	Range of CBR Values	Average CBR	Standard Deviation	Coefficient of Variation (%)
1	5	4.67 to 8.00	6.44	1.29	20.0
2	4	1.20 to 2.00	1.63	0.26	15.9
3	7	4.16 to 5.00	4.66	0.40	8.6
4	5	46.60 to 70.00	57.82	8.50	14.7
5	5	72.80 to 112.00	93.14	12.73	13.7
6	5	50.00 to 100.00	70.00	17.89	25.6
7	5	79.33 to 183.33	115.20	36.05	31.3
8	4	66.50 to 80.00	74.45	5.29	7.1
9	4	80.90 to 107.90	87.70	11.64	13.3
10	4	62.50 to 90.00	77.50	9.85	12.7
11	4	81.00 to 102.50	87.50	8.72	10.0
12	4	72.50 to 113.50	93.63	16.68	17.8

NOTE: Average coefficient of variation = 16.0 percent.

It will be recalled that, on a statistical basis, Eq. 4 explained about 77 percent of the variation in log CBR. By comparing this with the difficulty of obtaining a reliable CBR value from a single test, it would seem that a CBR value obtained on a statistical basis, such as that resulting from Eq. 4 and shown in Figure 2, should provide a reasonably satisfactory estimate for a given soil under ordinary circumstances.

CONCLUSION

If the strength of a soil can be estimated satisfactorily from its physical characteristics by an approach similar to that suggested, it should provide a means for crossing state lines with soil-strength data. In other words, if this approach should prove to be feasible, soil-strength data from any given state or agency could be readily converted into comparable data from any other state or agency. Although this paper only illustrates a method for estimating the CBR resulting from the Alabama 2000-psi compaction method, it is believed that some function of grain size distribution, percent clay, and Atterberg limits could provide the means for estimating the CBR for any one of the many variant static and dynamic compaction methods now in use. Furthermore, such an approach might possibly be used for estimating soil strength obtained from the triaxial, stabilometer, or other test forms.