Method for Specifying Soil Compaction

M. F. Essigmann, Jr., Lincoln-Devore Testing Laboratory, Colorado Springs
A. G. Altschaeffl and C. W. Lovell, Department of Civil Engineering, Purdue University, West Lafayette, Indiana

Laboratory compaction data and associated strength test results have been generated for a study to improve predictability of compacted behavior. Statistical regression relationships were established for dry density, strength, and their respective variabilities. These relationships were then plotted as one combined nomograph. When mean water content, mean dry density, and variation in dry density are entered on the nomograph, the plot will yield a predicted mean compressive strength as well as the variability in the strength. Such a nomographic model based on field compaction relationships could be used to establish moisture and density ranges and thus the desired mean strength and tolerable variation in strength, i.e., the specification region. Field data are now being generated for various combinations of soils and rollers to allow this design tool to be tested for real embankments.

Soil compaction is performed to impart the desired engineering properties to the compacted mass. It is not, in general, practical to directly specify that the construction achieve these desired properties. Rather, the engineer must first specify descriptors of the compacted product, the compactive process, or both that are easy to measure and then be able to relate these to the desired properties. The requisite correlations are not simple and continue to challenge engineers seeking the best design.

Although the relationships among compacted properties and the variables of the compaction process are most directly studied in the field, this is expensive and time consuming. Accordingly, in the present state of the art, the above relationships are established in the laboratory. But this approach has serious intrinsic limitations, because field compaction is achieved by different modes and at different energy levels than in the laboratory and there is more variability in all variables in the field.

This paper reports a portion of a larger three-part study that (a) defines relationships among laboratory compaction variables and resulting properties and their variability, (b) defines these same relationships in the field, and (c) couples (a) and (b) so that the field-compacted properties and their variability can be predicted from laboratory testing only.

The part reported deals with the relationships among laboratory compaction variables and the as-compacted, unconfined compressive strength and its variability. A methodology is proposed by which the mean strength and its variability can be predicted from a knowledge of the levels of the compaction variables. By using the same technique, it is possible to decide how to specify (i.e., control) the compaction variables in order to produce a desired mean strength within a selected tolerable variability. Other laboratory data, such as soaked strength, as well as field values, could be handled in the same general way. Proof that the model proposed here will work awaits the results of field tests now under way.

BACKGROUND

Systematic studies of soil compaction date from Proctor (1); the impact-type laboratory test he developed is still by far the most popular one. Although the compacting action of this test is very different from that of common field rollers, the density and moisture content values of end-result specifications are based on it. Because large-scale studies by the Waterways Experiment Station (2) and the Road Research Laboratory (3), among others, show that the line of optimum is peculiar to the type of laboratory test or type of roller, the use of any one laboratory control test is arbitrary.

The consequences of bringing a soil to the same compacted density and moisture by different methods of compaction are not clear. Some believe that the soil fabric is strongly influenced by the compaction type and that properties such as strength will be peculiar to the method of achieving a given moisture and density. Others disagree, and, in fact, this study showed that, at common moisture-density values, impact- and kneading-compacted samples had about the same strength (4).

A number of previous studies have examined the variability in density, moisture content, or strength of laboratory- or field-compacted soils (5, 6, 7, 8, 9, 10, 11, 12, 13). These studies led to the conclusion that variability in the compacted property will depend primarily on soil type, compaction method, moisture content, and compaction energy. Accordingly, in this study, the above variables were suitably controlled and their effects on the magnitude and variability of density and unconfined compressive strength were established by statistical methods.

SUPPORTING DATA

A glacial silty clay, CL or A-4(5), was compacted at four levels of energy input in the impact or Proctor-type test. This soil has a liquid limit of 20, a plasticity index of 6, and a specific gravity of solids of 2.73. See Table 1 for the details of the compaction. Water content was controlled and both dry density and unconfined compressive strength were measured as dependent variables. The data are shown in Table 2.

DATA ANALYSIS

Statistical regression analysis was performed to develop functional relationships among the controlled compaction variables and both the magnitude and variability of the dependent variables. The data were placed in a single group for definition of the magnitude of density or strength. In the case of the variability regressions, the data were divided into subsets of 1 percent water content intervals about the optimum water content for each energy input level. Means and variances within each subset were calculated, and these reduced data were applied to the analysis.

To initially locate the important variables and variable interactions, an "all possible" regressions approach was used with the aid of the Purdue computer program DRRSQU, a part of the statistical applications library of computer programs. Analytical models so tested were considered to be potentially useful if (a) the square of the correlation coefficient was high ($R^2 > 65$ percent), (b) the confidence intervals for the regression coefficients were

Table 1. Compaction details and levels for 11.7 by 10.2-cm diameter mold.

Test Series	Height of Hammer Drop (cm)	No. of Layers	Weight of Hammer (kg)	No. of Blows per Layer	Energy Developed (kJ/m³)	Energy Ratio
15-blow Proctor	30.5	3	2.5	15	354	1.00
Standard Proctor	30.5	3	2.5	25	594	1.67
25-blow Proctor	45.7	3	4.5	25	1616	4.56
Modified Proctor	45.7	5	4.5	25	2696	7.61

Note: 1 cm = 0.39 in; 1 kg = 2.20 lb; and 1 kJ/m³ = 20.87 lb ft/ft³.

small, and (c) the confidence intervals did not cross zero.

The regressions summarized in Table 3 are probably the best simple ones. Density and variability in density equations had much better R^2 values and were simpler when the moisture contents were divided into dry- and wet-of-optimum groups. Significant models for strength and strength variability could be developed in this same manner, or for all moistures.

DISCUSSION OF RESULTS

The equations developed can be plotted. Figure 1 shows the plot of the relations for dry density; the data points shown are mean values for the data subsets described earlier.

Table 2. Results of four types of Proctor tests.

Test	Dry Density (kg/m³)	Water Content (%)	Unconfined Compression Strength (kPa)
15-blow Proctor	1704	7.0	93
	1722	7.1	104
	1715	7.1	85
	1765	8.2	110
	1734	8.2	97
	1781	8.3	132
	1809	9.5	124
	1851	9.5	186
	1770	9.5	112
	1874	10.2	146
	1859	10.3	182
	1861	10.3	158
	1843	11.1	112
	1917	11.3	246
	1916	11.4	231
	1917	11.4	240
	1933	12.0	217
	1910	12.1	210
	1931	12.2	190
	1946	12.8	193
	1934	12.8	183
	1934	12.9	190
	1936	13.7	110
	1918	13.9	82
	1907	13.9	105
	1886	15.2	47
	1885	15.3	49
Standard Proctor	1762	7.6	162
	1770	7.9	135
	1762	7.9	144
	1818	9.0	223
	1912	9.1	357
	1906	9.2	338
	1874	9.3	217
	1899	9.5	279

Test	Dry Density (kg/m³)	Water Content (%)	Unconfined Compression Strength (kPa)
Standard Proctor (continued)	1855	9.6	291
	1946	10.3	311
	1978	10.3	297
	1989	10.5	377
	1990	10.9	342
	1963	10.9	376
	1957	10.9	360
	1955	11.6	299
	1982	11.6	311
	1963	11.7	279
	1989	11.7	335
	1963	11.9	262
	1981	12.3	248
	1958	12.8	200
	1907	13.5	126
	1906	13.5	117
	1904	13.6	128
	1922	13.7	115
	1928	13.7	102
	1909	13.9	100
	1854	14.9	57
	1877	15.0	50
	1870	15.5	36
	1859	15.5	40
	1861	15.5	35
	1837	15.7	33
	1832	15.7	42
	1853	15.9	26
25-blow Proctor	1944	7.1	328
	1918	7.2	379
	1974	8.1	480
	1946	8.1	421
	1997	8.2	608
	1947	8.2	422
	1960	8.4	480

Test	Dry Density (kg/m³)	Water Content (%)	Unconfined Compression Strength (kPa)
25-blow Proctor (continued)	2021	9.8	533
	2016	9.8	387
	2010	9.9	472
	1995	9.9	468
	1997	10.0	497
	2008	10.0	552
	2000	10.0	477
	2003	10.1	476
	2030	10.2	518
	1994	10.8	404
	1982	10.8	345
	2014	10.8	464
	1942	13.2	121
	1926	13.4	114
	1906	13.5	109
Modified Proctor	2062	9.4	690
	2045	9.6	526
	2027	10.1	626
	2042	10.2	518
	2085	10.3	488
	1992	10.5	375
	2048	10.5	442
	2024	10.5	469
	2043	11.0	489
	2029	11.1	406
	2011	11.2	359
	1952	12.0	238
	1968	12.0	235
	2002	12.0	379
	1946	12.0	316
	1962	12.1	326
	1954	12.2	238
	1928	12.5	195
	1973	12.5	202
	1965	12.8	170

Note: 1 kg/m³ = 0.06 lb/ft³ and 1 kPa = 0.145 lbf/in².

Table 3. Results of regression equations.

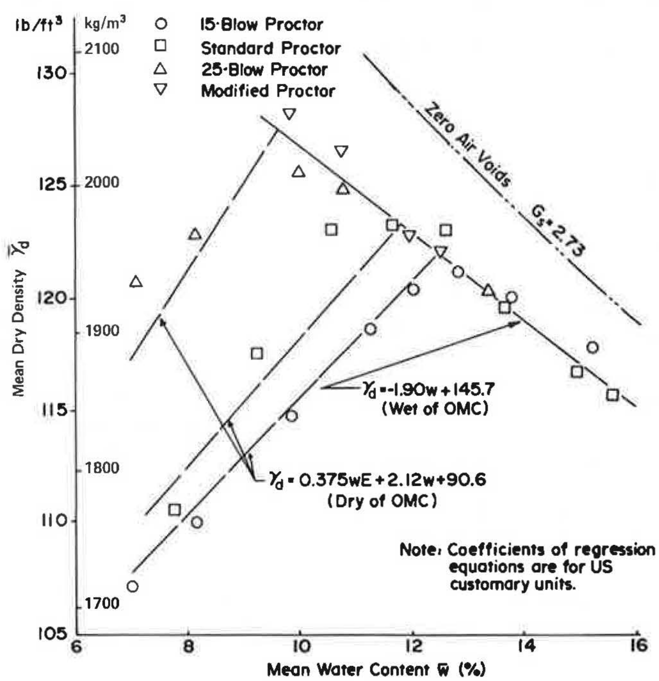
Dependent Variable	Moisture Range	Regression Relationship	R^2
Dry density	Dry of optimum	$\gamma_D = [0.375]\,[w]\,[E] + [2.12]\,[w] + [90.6]$	0.905
	Wet of optimum	$\gamma_D = [145.7] - [1.90]\,[w]$	0.919
Variation in dry density	Dry of optimum	$S(\gamma_D) = [3.02]\,[\overline{w}] - [1.06]\,[10^{-5}]\,[\overline{w}]^2\,[\overline{\gamma}_D]^2 + [0.142]\,[\overline{\gamma}_D]^2$	0.789
	Wet of optimum	$S(\gamma_D) = [0.55] + [9.16]\,[10^{-3}]\,[\overline{w}]\,[E]$	0.645
Unconfined compression strength	Dry of optimum	$q_u = [4.14]\,[\gamma_D] - [0.047]\,[\gamma_D]\,[w] - 396.2$	0.888
	Wet of optimum	$q_u = [3.10]\,[\gamma_D] - [0.073]\,[\gamma_D]\,[w] - 231.8$	0.943
Variation in unconfined compression strength	Dry of optimum	$S(q_u) = [0.124]\,[\overline{q}_u] + [2.88]\,[S(\gamma_D)] - 3.4$	0.814
	Wet of optimum	$S(q_u) = [0.129]\,[\overline{q}_u] + [1.88]\,[S(\gamma_D)] - 2.18$	0.891
	All water contents	$S(q_u) = [0.128]\,[\overline{q}_u] + [2.38]\,[S(\gamma_D)] - 2.6$	0.866

Notes: Coefficients of regression equations are for U.S. customary units.
w = water content (%), $\overline{w}$ = mean water content within data subset, E = energy ratio (see Table 1), γ_D = dry density (lb/ft³), $\overline{\gamma}_D$ = mean dry density within data subset, q_u = unconfined compression strength (lbf/in²), $S(\gamma_D)$ = standard deviation of dry density within data subset, $\overline{q}_u$ = mean unconfined compression strength within data subset, and $S(q_u)$ = standard deviation of unconfined compression strength within data subset.

The pattern of these relations follows that which is generally accepted, even to the observation that the dry-side slopes are functions of the energy-water content interaction. It should be noted that interaction terms are present in these relations; this precludes discussion of effects of variables in simple one-on-one fashion.

The relationships for the unconfined compression strength are plotted on Figure 2. Even though the energy variable does not appear directly, its presence is implicit in the dry-density term for dry of optimum. It would appear from Figures 1 and 2 that the maximum strength is obtained about 1 percent dry of optimum water content for the energy level involved. The relations suggest that, for wet-side compaction, the dry-density relations with water content could be substituted into that for strength; the result would be a relation for strength as a function of first- and second-order terms in water content only.

Figure 1. Moisture-density relationships.



Adequate description of the variability of dry density produced by compaction required a complex relation. That for the dry-side compaction differs markedly from that for wet-side compaction. Figure 3 shows these relations plotted against actual water contents (a) and against deviations from the optimum water content (b). Even though the energy term is not part of the dry-side relation, it is again there implicitly because energy is important in establishing the dry-density term. For dry-side compaction, an increase in compaction energy decreases the dry-density variability. At the water content associated with the maximum strength (about 1 percent dry of optimum), all levels exhibit the same variability. For the wet-side compaction, the variability is almost uniform for a given energy level.

These trends appear to support the multilevel soil structure concept suggested by Hodek (14), among others. This concept suggests that soil aggregations rather than individual particles are the most important structural units. Behavior then is described in terms of what happens within as well as between the aggregations.

The variation in unconfined compression strength is a function of the magnitude of the strength and the variation in dry density. Both an increase in the density variation and an increase in the strength magnitude are associated with a larger strength variation. Figure 4 shows these relations. A comparison of Figures 3a and 4a for dry-side compaction reveals that the lowest effort level (15-blow Proctor) with the highest variation in dry density has the lowest variation in strength. This lowest effort level also results in the lowest strengths, which indicates the impor-

Figure 2. Moisture-strength relationships.

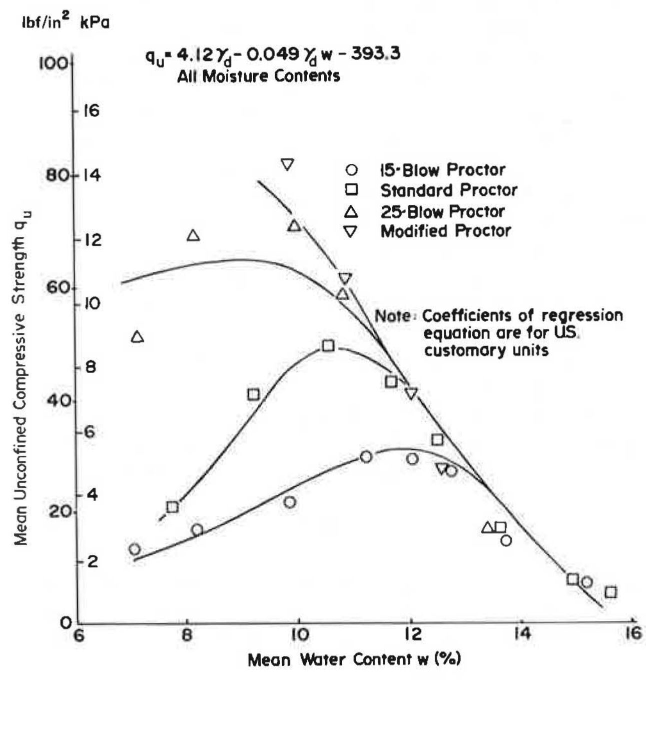


Figure 3. Variability in dry density.

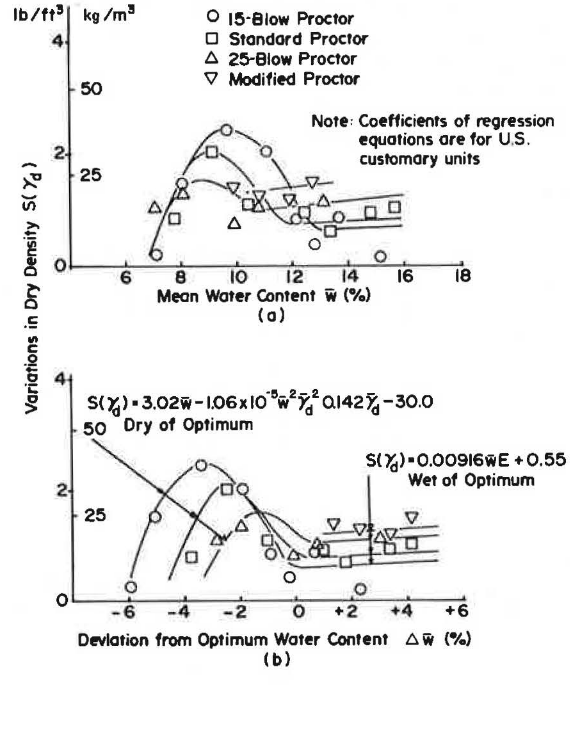


Figure 4. Variability in unconfined compression strength.

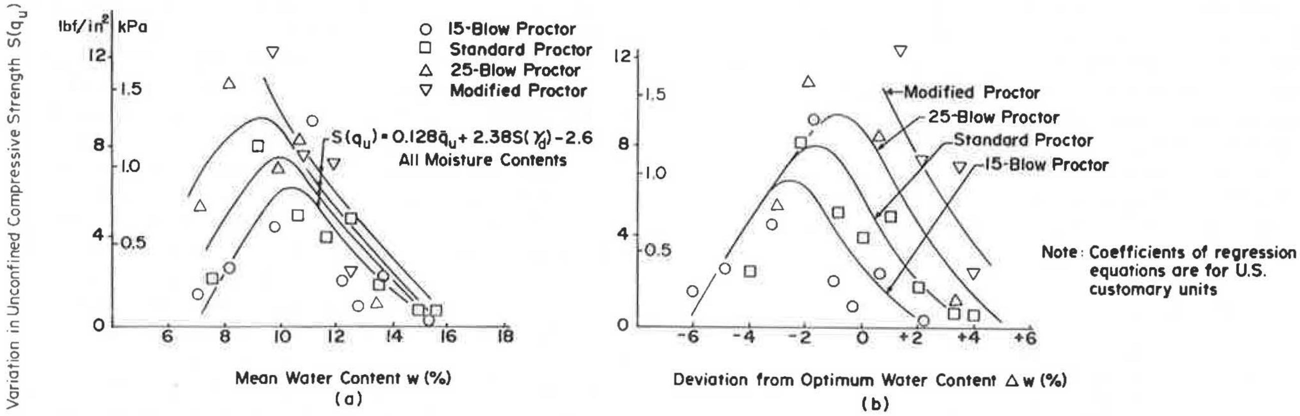
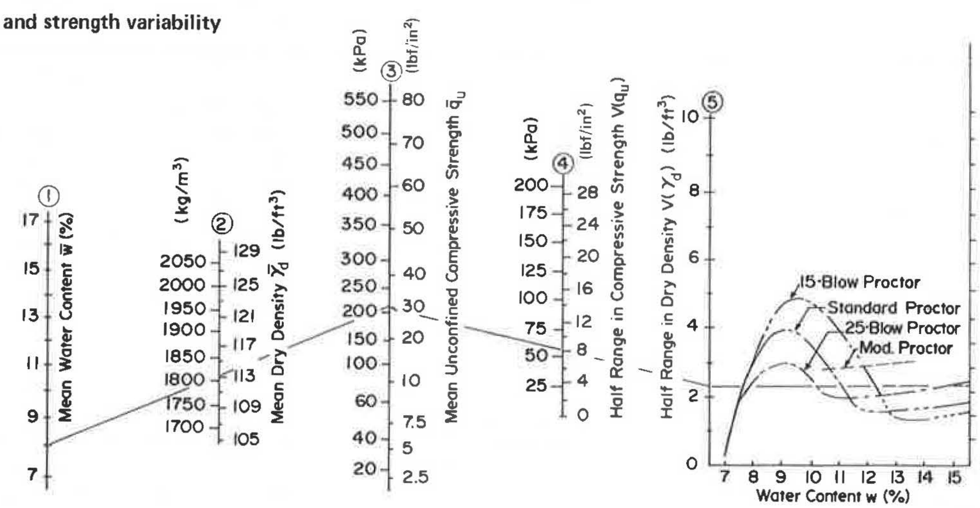


Figure 5. Nomograph for strength and strength variability prediction.



tance of the magnitude of strength for its variability. Thus, for dry-side compaction, increasing the compaction energy will decrease the dry-density variation but will increase the strength variation. Figures 3b and 4b show that the maximum strength variation occurs at the moisture content where the variation in dry density and the mean strength are at a maximum.

COMBINING THE RELATIONS

The unification of the foregoing relations was suggested by Hudson (15), who discussed concepts of reliability and variability as they related to pavement design. The analysis of the data suggested that all the results could be combined in a nomographic solution. Thus, Figure 5 was constructed from the relations shown in Table 2. It should be noted that the calculated variations in dry density and strength do not appear as such on the nomograph. These values have been converted to half-ranges, where the half-range equals two standard deviations. By doing this, a limiting range in values of four standard deviations is defined.

The nomograph can be used to predict strength, entering with mean water content, mean dry density, and half-range in dry density. On scale 3 the mean unconfined compression strength is obtained. Using curve 6, entering with the half-range in dry density, and using the result for mean strength, the half-range in strength is obtained on scale 4.

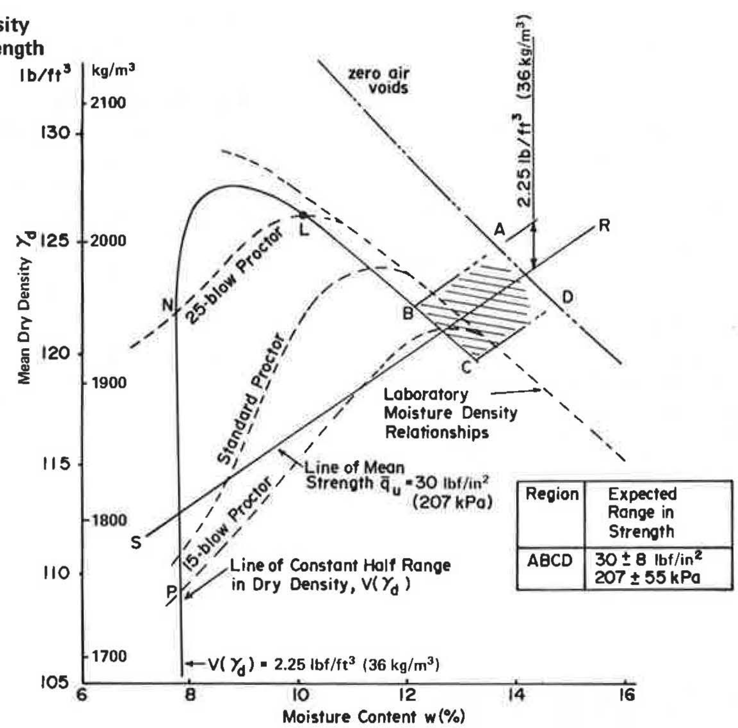
SPECIFYING COMPACTION

A more significant use can be made of the nomograph in establishing the ranges of moisture and density that will produce the strength properties desired.

Assume that a mean unconfined compressive strength ($\bar{q}_u$) of 207 kPa (30 lbf/in²) is desired. The use of scales 1, 2, and 3 on Figure 5 indicates this mean strength can be obtained at moisture-density combinations of 8 percent-1808 kg/m³ (113.0 lb/ft³), 11 percent-1896 kg/m³ (118.5 lb/ft³), and 14 percent-1968 kg/m³ (123 lb/ft³), among many others. These three points have been plotted on the basic moisture-density-energy compaction relations for this soil and appear as line RS on Figure 6. This line represents a constant mean strength of 207 kPa.

The variation in strength is a function of mean strength and variation in density. Scales 3, 4, and 5 on Figure 5 can be used to develop an allowable range of dry density to assure a specific variation (half-range) in strength. Assume the tolerable half-range in strength is ± 55 kPa (8 lbf/in²). Scale 6 indicates the allowable half-range in density is 36 kg/m³ (2.25 lb/ft³). This means that the area for compaction is bounded by lines (RS + 36) and (RS - 36); on Figure 6 these lines are labeled AB and CD. Of course, this variation in density can be obtained only at certain water contents. The appropriate water content regions can be isolated by use of scales 5 and 6 of Figure 5.

Figure 6. Acceptable moisture-density regions for desired strength and strength variability.



The intersections on Figure 5 of the constant half-range density value of 36 kg/m³ (2.25 lb/ft³) (scale 6) with the various energy curves have been transferred to Figure 6. For example, the half-range of 36 kg/m³ intersects the 25-blow Proctor curve on scale 6 of Figure 5 at 10 percent water content; this point plots as point L on Figure 6. Repeating this process produces line PNLBC, which represents a constant half-range in dry density of 36 kg/m³. The shaded region ABCD has thus been isolated as being associated with a strength of 207 kPa ± 55 kPa (30 lbf/in² ± 8 lbf/in²).

The size of the specification region is naturally determined by the range in strength that is tolerable. The availability of such a nomograph allows the compaction to be prescribed to produce the strength behavior deemed optimum.

SUMMARY

The systematic determination of the relations that exist among the laboratory compaction variables and the results of compaction for one soil and one compaction method has produced a solution to the question of how much compaction to specify.

Appropriate field studies (test pads) are required to develop a comparable nomograph for each combination of soil type and equipment. With both laboratory and field compaction functions available for the same soil, these relations can be coupled. When this has been accomplished, it will be possible to directly prepare the compaction specification so as to produce a desired field soil response with confidence.

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The contents of this paper reflect our views, and we alone are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the sponsors, the Federal Highway Administration and the Indiana State Highway Commission. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. R.R. Proctor. Design and Construction of Rolled-Earth Dams. Engineering News Record, Vol. 3, Aug. 31, 1933, pp. 245-248; Sept. 7, 1933, pp. 286-289; Sept. 21, 1933, pp. 348-351; Sept. 28, 1933, pp. 372-376.
2. Soil Compaction Investigation. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Technical Memorandum 3-271, Repts. 2 and 3, 1949.
3. Soil Mechanics for Road Engineers. British Road Research Laboratory, Her Majesty's Stationery Office, London, 1961.
4. M. F. Essigmann, Jr. An Examination of the Variability Resulting From Soil Compaction. Purdue Univ., West Lafayette, IN, master's thesis, Aug. 1976.
5. W.N. Carey, Jr. Discussion of paper, Maximum Density and Moisture of Soils, by F. M. Hveem. HRB, Bull. 159, 1957, p. 20.
6. C.P. Fischer, D.N. Bridges, and T.G. James. Moisture and Density Measurements in Engineering Soils. Highway Research Program, Engineering Research Department, North Carolina State Univ., Raleigh, 1962.
7. S. F. Hillis and D. Smith. Discussion of paper,

Portage Mountain Dam, II, by G.C. Morgan and M.L. Harris. Canadian Geotechnical Journal, Vol. 4, No. 2, May 1967, pp. 175-178.
8. T.G. Williamson. Embankment Compaction Variability—Control Techniques and Statistical Implications. HRB, Highway Research Record 290, 1969, pp. 9-22.
9. O.G. Ingles. Statistical Control in Pavement Design. Proc., 1st International Conference on Applications of Statistics and Probability to Soil and Structural Engineering, Hong Kong Univ. Press, 1972.
10. M.M. Johnson. Laboratory Compaction Tests Using Compacted Fine Grained Soils. Proc., 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico, Vol. 1, 1969, pp. 197-202.
11. J.A. Hooper and F.G. Butler. Some Numerical Results Concerning the Shear Strength of London Clay. Geotechnique, Vol. 16, No. 4, 1966, pp. 282-304.
12. P. Lumb. The Variability of Natural Soils. Canadian Geotechnical Journal, Vol. 3, No. 2, May 1966, pp. 74-97.
13. R.K. Morse. The Importance of Proper Soil Units for Statistical Analysis. Proc., 1st International Conference on Applications of Statistics and Probability to Soil and Structural Engineering, Hong Kong Univ. Press, 1972, pp. 347-357.
14. R.J. Hodek. Mechanism for the Compaction and Response of Kaolinite. Purdue Univ., West Lafayette, IN, PhD thesis, Dec. 1972.
15. W.R. Hudson. State-of-the-Art in Predicting Pavement Reliability From Input Variability. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Contract Rept. S-75-7, Aug. 1975.

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Base-Course Gravel-Compaction Control by the Comprimeter

Neville F. Allen, Stoll, Evans and Associates, Ann Arbor, Michigan

A new device called the comprimeter developed to measure in situ density of granular materials has been proved to effectively monitor the compactness of a typical gravel used as road base course. Its operation is quick and efficient, and it directly determines relative compactness at the test location.

Measurement and control of compaction of soil materials are very often an essential aspect of construction. The popular compaction-measuring methods that employ the drive cylinder, sand cone, and balloon tests have the inherent drawback of requiring a separate moisture determination and reference to previously determined Proctor density tests. The nuclear densiometer is very efficient and rapid, but the device is rather expensive to obtain and operate, and results also must be referenced to independent Proctor tests on comparable soils.

A new device called the comprimeter, developed by the Norwegian Geotechnical Institute in cooperation with A. Eggestad, Chief Engineer of the Geotechnical Division of the Municipality of Oslo, promises to allow quick and reasonably accurate monitoring of the state of field compaction of moist, cohesionless materials. Relative compaction is determined directly, without reference to companion Proctor tests. In the calibration of the instrument, extensive testing was done on sands, with a general size range of 0.06-2 mm. One grain-size distribution included 35 percent gravel in the 3-10 mm range.

Eggestad also mentioned some tests done on crushed stone with a gradation of 0-30 mm. Noting this, a series of tests was conducted on Michigan Department of State Highways (MDSH) 22-A gravel, which was typical of well-graded road base course, to determine the suitability of the comprimeter for monitoring the state of compaction under normal field construction circumstances.

THE COMPRIMETER

A complete description of the comprimeter is given by Eggestad elsewhere (1) and will not be reiterated here. The device and its principle of operation are diagramed in Figure 1. The operating principle is based on the fact that the denser a granular soil, the more it will dilate when subjected to large shear strains. With the comprimeter, the shear strains are produced by a rod of known volume that is driven into the material. The volume of heave is measured by the volume of water expelled from a water-filled membrane that covers the surface around the point where the rod is driven. This heave volume is empirically related to the degree of compactness by means of a series of controlled density tests. The instrument can be calibrated for both the standard and the modified Proctor compaction tests.

TESTING PROGRAM

Materials tested are representative of road base-course gravel and meet the requirements of Michigan Department of State Highways (MDSH 22-A). Gradations are shown on Figure 2 for field, ideal, and gap-graded distributions. Each contained a minimum of 25 percent of crushed material and consisted of natural glacial gravels obtained from a local commercial pit.

Standard and modified Proctor tests (AASHTO T99 and T180, respectively) were determined for each of the three particle distributions; results are summarized in Table 1. Maximum densities by the modified Proctor test range from 2256 to 2288 kg/m^3 (141 to 143 lb/ft^3), which are consistent with the well-graded character of the gravel.