PROCEEDINGS

TEXAS SECTION
AMERICAN SOCIETY
OF CIVIL ENGINEERS

FALL MEETING
EL PASO, TEXAS
OCTOBER 5-7, 1995

TABLE OF CONTENTS

CONSTRUCTION AND INDUSTRY

ENGINEERING EDUCATION

ENVIRONMENTAL

PRACTICE IMPROVEMENTS FOR THE DESIGN AND CONSTRUCTION OF EARTH FILLS

Ronald E. Langston, P.E., Member ASCE[1]
Philip A. Tritico, P.E., Member ASCE[2]

INTRODUCTION

Maximum dry density (MDD) and optimum moisture content (OMC) values for soils will vary significantly depending on the compaction energy delivered to the soil. Two specific unit cumulative compaction energies (developed in the laboratory) are typically used to simulate all field compaction energies today. The two unit cumulative compaction energies used in the laboratory [600 kN-m/m^3 (12,400 ft-lbs/cf) required by ASTM D698 and 2,700 kN-m/m^3 (56,000 ft-lbs/cf) required by ASTM D1557], were intended to be reasonably representative of compactive efforts covering the spectrum of construction equipment. The two laboratory compaction energies are significantly different and each will generate MDDs and OMCs that are significantly different. The cumulative field energies are often much different than the two lab energies, resulting in invalid construction specifications. Because of this disparity, many earth fill projects develop into contract or construction performance disputes. With today's practice, it is difficult to consistently and reliably simulate actual field compaction energies in the laboratory.

PURPOSES OF PAPER

The purposes of this technical paper are to:

- evaluate the total energy transfer (input and distribution) in a roller wheel/ground system without emphasis on force dynamics which are less quantifiable, practical, and useful,
- identify and quantify the disparity between the compaction energy used in the laboratory to estimate the MDD and OMC of a clay soil and the compaction energy delivered to the soil in the field with suitable compaction operations,
- show how the disparity between laboratory compaction energies and field compaction energies can result in significantly different MDDs/OMCs, resulting in impractical, sometimes impossible construction specification requirements,
- present a procedure for adjusting laboratory compaction energies to minimize the disparities between field/laboratory compaction

---

[1] President, HTS, Inc. Consultants, 416 Pickering, Houston, Texas 77091, (713) 692-8373
[2] Project Manager, Delta Environmental Consultants, Inc., 1400 Broadfield Boulevard, #114, Houston, Texas 77084, (713) 647-6263

energies,
- promote further research with varying soils and various compactors resulting in a matrix of multiplying factors which can be used to adjust laboratory test energies to better simulate field energies, and
- propose an addendum to ASTM laboratory compaction testing procedures to allow for adjusting laboratory compaction energy (using derived correlation factors) as an alternative test procedure in practice.

CURRENT PRACTICE AND BACKGROUND

In today's practice, the density/moisture of earth fill is typically controlled based on results of the standard proctor compaction test (ASTM D698) or modified proctor compaction test (ASTM D1557). The compaction energy used in ASTM D698 [600 kilonewton-meter per cubic meter (Kn-m/m^3), or 12,400 foot pounds per cubic foot (ft-lbs/cf)] is based on R.R. Proctor's estimate of field compaction energies for towed compactors (sheepsfoot rollers) used in the early 1930's. These field compaction energy estimates were based on drawbar pull values measured with the towed compactors. Subsequently, it was found that high fills constructed by using the standard proctor energy experienced substantial compression under their own weight. This fill compression combined with the development of aircraft and truck traffic with heavier wheel loadings led to the development of the modified proctor compaction test (ASTM D1557) (Hunt, 1986). The compaction energy used in ASTM D1557 (2,700 Kn-m/m^3, or 56,000 ft-lbs/cf), is about 4.5 times higher than the compaction energy used in ASTM D698.

It was recognized in the 1930's and 1940's that the laboratory compaction tests produced energies that were inconsistent with field compaction energies. Numerous attempts were made to develop test procedures which produced field and laboratory compaction curves which would be more comparable. Over the last 60 years, the laboratory test procedures now provided in ASTM D698 and ASTM D1557 have been utilized as standards in the industry even though the shortcomings of the tests are well known (Leonards, 1962).

EVALUATION OF WHEEL/GROUND ENERGY TRANSFER AND COMPACTION ENERGY

Proctor's work involved the simulation of field compaction energies for correlation purposes based on the drawbar pull of the compaction equipment. Drawbar pull (DBP) is defined as the available pull force which a tractor (or compactor) can exert on compaction equipment loads for mobilization. Proctor held that the drawbar pull of sheepsfoot type rollers ranges from 25 percent of the gross weight of the roller for sandy-textured soils to 40 percent of the gross roller weight for clayey-textured soils. The system energy conversion to compaction energy, can be expressed as a unit cumulative energy per unit volume as follows (Johnson and Sallberg, 1960; Williams, 1950; Proctor, 1948):

$$FCE = \frac{DBP \times NP \times UTL}{RW \times CLT \times UTL} \quad \ldots\ldots (1)$$

Where FCE = field compaction energy in Kn-m/m^3 (ft-lb/cf), DBP= drawbar pull in kN (lbs), NP = number of roller passes, UTL = unit travel length in m (ft), RW = roller width in m (ft), and CLT = compacted lift thickness in m (ft).

For example, say the drawbar pull of a 178 Kn (40,000 pound) roller based on a DBP factor of 35 percent, is equal to 62.3 Kn (14,000 pounds). If the roller is 2.75 m (9 ft.) wide and eight passes were required on 0.15 m (6 in.) thick compacted lifts; the field compactive effort would be estimated as follows:

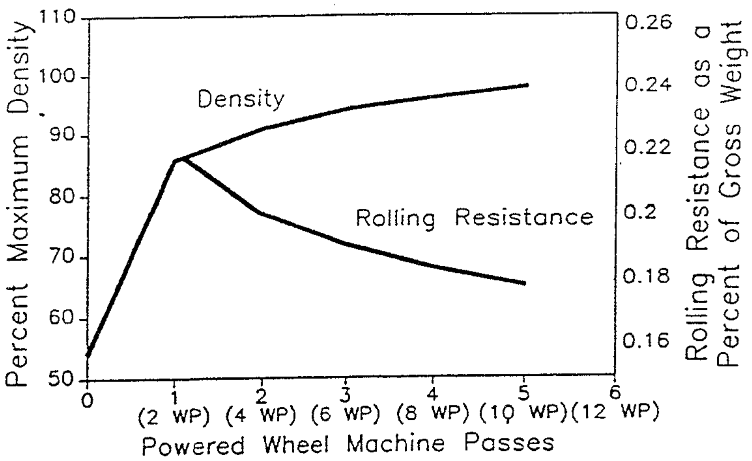
$$\frac{\text{62.3 Kn (14,000 pounds) x 8 passes x 0.305 linear m (1 linear foot)}}{\text{2.74 m (9 ft.) x 0.152 m (0.5 feet) x 0.305 linear m (1 linear ft)}}$$

$$= 1{,}200 \text{ Kn-m/m}^3 \text{ (24,900 ft-lbs/cf)}$$

This hypothetical value would compare to the Standard and Modified Proctor Test energy of 600 Kn-m/m^3 (12,400 ft-lbs/cf) and 2,700 Kn-m/m^3 (56,000 ft-lbs/cf), respectively.

This same principle, based on the measurement of energy transfer, should be used today, but the energy conversion factor should be modified to be more representative of energy transfer with today's variety of compactors. Instead of relating drawbar pull, the expression should incorporate rolling resistance which is today, more representative of energy transfer into the ground.

Figure 1 represents a typical illustration of rolling resistance vs. soil densification. As demonstrated in the figure, rolling resistance reduces, becoming asymptotic, as the soil densifies with each roller pass. This effect is the result of decreasing soil deformation with increasing compaction. Soil deformation consists of consolidation or densification and shear (which constitutes the required kneading action). Obviously, soil shear reduces as soil compaction/density increases and the roller "walks out". Therefore, the energy loss fraction associated with soil shear decreases as the energy loss fraction associated with soil consolidation (densification) increases. Accordingly, the rolling resistance becomes even more representative of the consolidation or densification energy component (or ground energy) as the rolling resistance and soil density become asymptotic during compaction. Beyond the asymptotic point, virtually all of the rolling resistance energy or ground energy, will be consumed by soil consolidation or densification.



(Courtesy of Caterpillar, Inc. – Peoria, Illinios)

FIG. 1. Representative Compaction and Rolling Resistance as Function of Machine Passes

In summary, the rolling resistance of a given roller wheel/ground system is considered to be more representative of field compaction energies than a given compactor's drawbar pull, because rolling resistance is representative of the energy input into the ground. Therefore, the unit conversion expression for field compaction energy presented by Proctor should be modified to utilize rolling resistance instead of drawbar pull. The recommended expression then becomes:

$$FCE = \frac{RR \times NP \times UTL}{RW \times CLT \times UTL} \quad \ldots\ldots (2)$$

Where FCE = field compaction energy in Kn-m/m^3 (ft-lb/cf), RR = rolling resistance in Kn (lbs), NP = number of roller passes, UTL = unit travel length in m (ft), RW = roller width in m (ft), and CLT = compacted lift thickness in m (ft).

FIELD TEST PROGRAM

A field test program was conducted to estimate energy transfer into the ground by measuring the rolling resistance of a wheel/ground system suitable for earth fill construction. The program was conducted at the construction site of a new landfill cell for the J.C. Elliot Landfill in Corpus Christi, Texas.

The test pad was built by using a relatively homogeneous tan fat clay containing calcareous nodules. The clay was classified as a CH material with a plasticity index of about 42 percent, a liquid limit of about 66 percent, and about 90 percent fines.

The compactor used for the test was a Caterpillar 815B which had approximately two hours of total operation time prior to the test program. The operating weight of the 815B is about 20,000 kgs (44,175 lbs).

The field test program consisted of a series of three trials. Each trial involved the estimation of rolling resistance, dry density, and moisture content with each roller pass. Each trial was conducted at a different initial moisture content with the intent to test a range covering the OMC for the energy being applied. Each trial was continued until the change in the field measurements clearly became asymptotic. Rolling resistance was measured by converting estimated speeds to rimpull and using rimpull performance curves for the 815B compactor. The rimpull curves were calculated at full throttle performance and therefore the test was conducted at full throttle to assure valid data. Moisture content tests using ASTM Method D2216 were conducted periodically as supplemental checks and to estimate pre-trial moisture contents.

The data from each trial are plotted in Figure 2. Rolling resistance was considered to be equal to rimpull energy measurements, less the estimated cleaner bar drawbar loads. The cleaner bar (drawbar) resistance was measured to be about 1.11 kN (250 lbs). These best fit curves represent averages of all data gathered for each data point shown. As reflected in the plots, this clay/compactor combination results in an asymptotic energy/density approach at around the eight to twelve pass range, which is considered to be consistent with expectations of today's equipment. This asymptotic approach is subject to interpretation, but the authors consider the eight to ten pass range to be a more refined representation of the approach to the asymptotic portion of the best fit curves. For simplicity and purposes of the paper, the eight to ten pass range will be referenced from this point forward as the asymptotic energy/density approach.

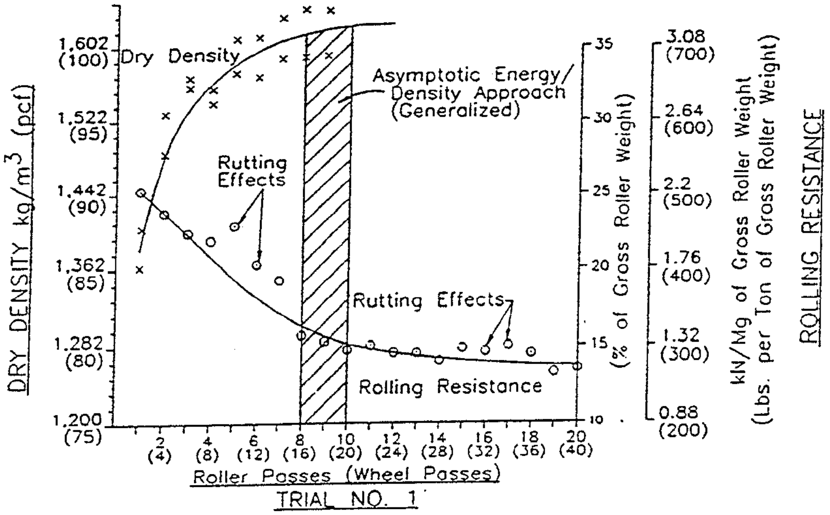


FIG. 2. Compacted Dry Density and Rolling Resistance vs. Roller Passes

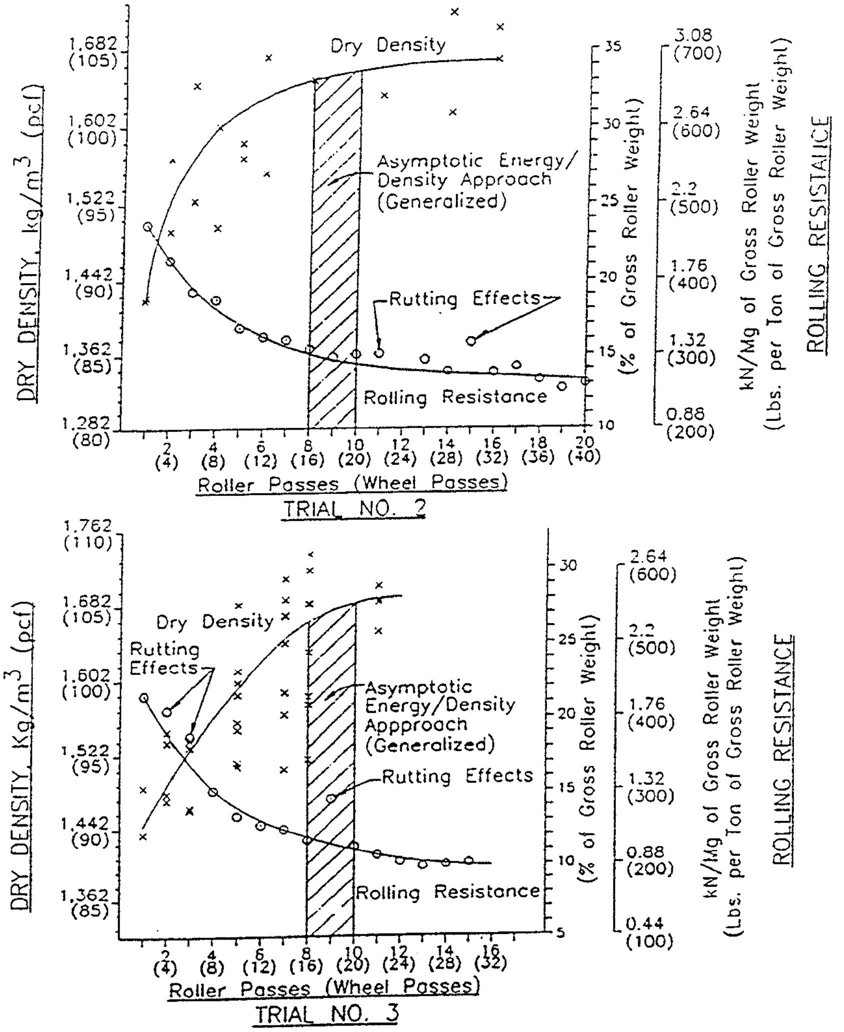


FIG. 2. Compacted Dry Density and Rolling Resistance vs. Roller Passes

For the field test program addressed by this paper, a field compaction curve and a laboratory compaction curve were generated for a field compaction energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf). As indicated in Figure 3, a field energy of about 1,250 kN-m/m^3 (26,000 ft-lbs/cf) is considered to be a conservative approximation of the average energy level, at the beginning of the asymptotic energy range, covering a practical range of moisture contents. For simplicity, this approximation is referred to as the "design" field compaction energy level achieved on CH soils with the 815B compactor. This design energy level is defined as the generalized compaction energy which:

- produces a compacted soil dry density which will not be appreciably increased with the application of additional compaction energy, and
- produces a compacted soil moisture content which will not be

appreciably decreased with the application of additional compaction energy.

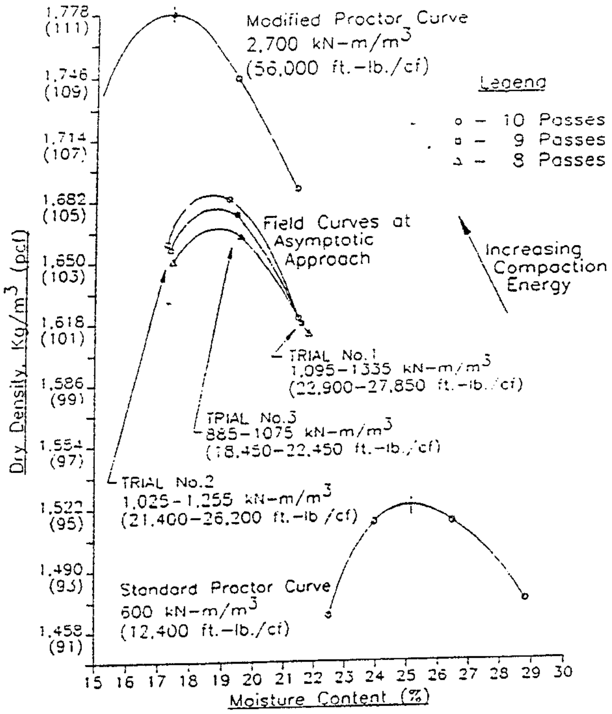


FIG. 3. Moisture/Density Relationship Comparisons, Apparent Field Curves (at Asymptotic Approach) vs. Laboratory Compaction Tests

The determination of the design energy level was based on observation of the rolling resistance (compaction energy) versus density curves shown in Figure 2. Although these figures are somewhat subject to interpretation, the asymptotic ranges in the curves provide a relatively clear definition of the design energy. By contrast, use of Proctor's equation [equation (1)] would yield a field compaction energy of about 3,700 kN-m/m^3 (77,000 ft-lbs/cf) versus a field compaction energy of about 1,250 kN-m/m^3 (26,000 ft-lbs/cf) computed with equation (2). The Proctor relationship [equation (1)] is based on a field energy correlation factor equal to about 35 percent of the gross roller weight versus a field energy correlation factor equal to about 12 percent of the gross roller weight which is computed with equation (2).

The data shown in Figures 2 and 3 were used to construct the field compaction curve shown in Figure 4 which is considered to be representative of the field moisture density relationship for an applied total energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf) with an 815B compactor.

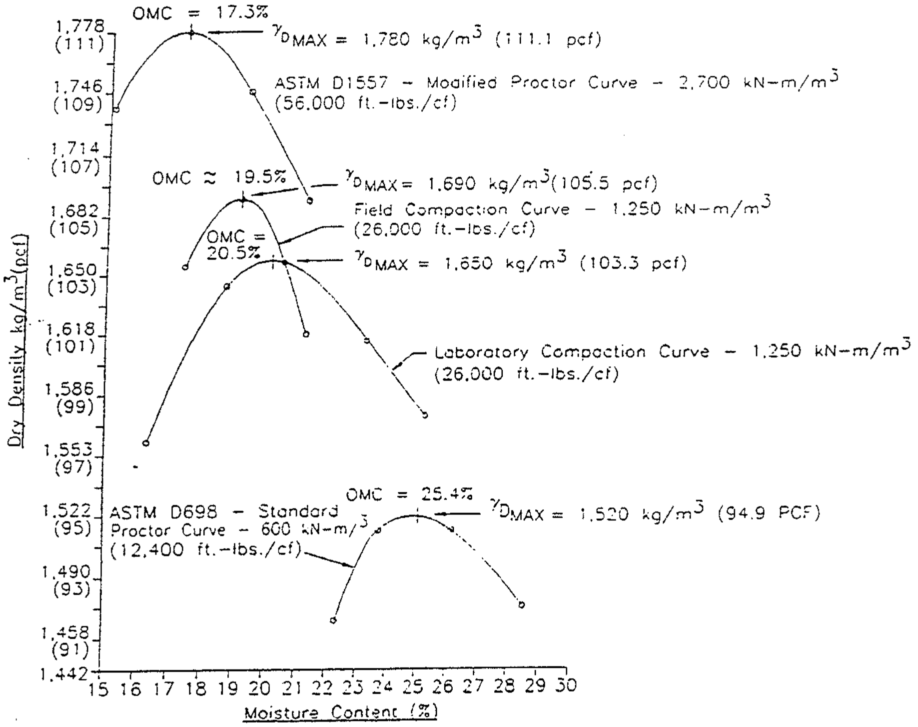


FIG. 4 **Moisture/Density Relationship Comparisons, Design Energy Curves (in Asymptotic Range) vs. Laboratory Compaction Tests**

As shown in Figure 4, comparison of the field compaction curve for the design compaction energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf) with the laboratory compaction curve developed by using a compaction energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf) indicated a relatively good comparison between the field and laboratory compaction curves, especially when compared with the standard and modified proctor curves. The MDD for the field compaction curve at the design compaction energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf) was 1,690 kg/m^3 (105.5 pcf) versus 1,650 kg/m^3 (103.3 pcf) for the laboratory compaction test. The OMC for the field compaction curve at the design compaction energy of 1,250 kN-m/m^3 (26,000 ft-lbs/cf) was about 19.5 percent versus 20.5 percent for the laboratory compaction curve. The disparity is considered to be primarily attributable to differences in energy transfer. In contrast, the MDD for the Standard Proctor Compaction test curve (ASTM D698) with a compaction energy of 600 kN-m/m^3 (12,400 ft-lbs/cf) was 1,520 kg/m^3 (94.9 pcf) and the OMC was 25.4 percent.

ALTERNATIVE SPECIFICATION GUIDANCE

Based on the aforementioned work, an alternative approach to construction specifications for earth fill projects should be considered. The modified approach should provide for:

- the contractor (or bidders) submitting product specifications for the compactor(s) to be used, i.e. comprehensive roller wheelfeet data, type of power train, and the gross roller weight,

- specifying that the number of passes necessary to achieve a steady-state "walk-out height" be used during construction and once the generalized (steady-state) total number of passes is established, the compaction operation should not deviate much from that throughout the project, and

- using amended laboratory compaction test procedures so that the field and laboratory compaction energies are comparable.

The estimated number of passes should be based on the range where asymptotic conditions are expected (steady state "walk-out"). Until rolling resistance values relating the suitable range of rollers to clays are produced, the authors recommend using a rolling resistance value equal to 1.09 kN/Mg (250 lbs/ton) to 1.32 kN/Mg (300 lbs/ton) of gross roller weight for today's powered wheel systems (especially for wheel/ground systems comparable to the Cat 815B on fat clays). More research is needed yet for a representative range of powered wheel rollers and towed wheel rollers.

CONCLUSIONS

- With good traction, compactor rolling resistance (energy consumption), provides a reasonably accurate correlation to total input of field compaction energy.
- Field estimates of total unit cumulative energy input per unit volume can be reasonably reproduced in the laboratory with Standard or Modified Proctor equipment/procedures but the energy transfer and distribution mechanisms cannot be reproduced.
- Laboratory simulation of total unit cumulative compaction energy levels in the field, approximated by using rolling resistance correlation (multiplying) factors, will produce moisture-density curves that are comparable to actual field curves, thereby enabling more reliable estimations of the true OMC.
- A rolling resistance correlation (multiplying) factor of 1.09 to 1.32 kN/Mg (250 to 300 lbs/ton) of gross roller weight is considered to provide a reasonable representation of field energy levels in a practical working range of moisture contents for relatively plastic to highly plastic clays and powered wheel compactors comparable to the Caterpillar 815B.
- A matrix of rolling resistance correlation (multiplying) factors covering the full range of clays and equipment suitable for earth fill construction should be prepared to enable global implementation of this improved practice.

REFERENCES

1. Caterpillar, Inc. (1991), Caterpillar® Performance Handbook, 22nd Edition, Caterpillar, Inc.
2. Hunt, Roy, E. (1986), Geotechnical Engineering Analysis and Evaluation," McGraw-Hill Book Co., pg. 211.
3. Johnson, A.W., Sallberg, J.R. (1960), "Factors that Influence Field Compaction of Soils, Compaction Characteristics of Field Equipment," Highway Research Board, Bulletin 272, National Academy of Sciences-Natural Research Council, Publication 810, pp. 39-48.
4. Leonards, (1962), Foundation Engineering, McGraw Hill Book Co., pg 1007.
5. Proctor, R.R. (1948), "The Relationship Between the Foot Pounds per Cubic Foot of Compactive Effort Expended in the Laboratory Compaction of Soils and the Required Compactive Efforts to Secure Similar Results with Sheepsfoot Rollers." Proceedings, Second International Conf. On Soil Mechanics and Foundation Eng. 5; 231-234, Rotterdam.
6. Proctor, R.R. (1948), "The Relationship Between the Foot Pounds per Cubic Foot of Compactive Effort and the Shear Strength of the Compacted Soils." Proceedings, Second International Conf. on Soil Mechanics and Foundation Eng. 5; 19-223, Rotterdam.
7. Williams, F.H.P., MacLean, D.J. (1950), "The Compaction of Soil, A Study of the Performance of Plant," Road Research Technical Paper No. 17, Department of Scientific and Industrial Research, Road Research Laboratory.