ENERGY-BASED DESIGN OF SUSTAINABLE EARTHWORKS COMPACTION

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ABSTRACT

The design of earthworks compaction has traditionally been guided by two distinct approaches: Method or End-Result Specifications. While Method specifications require the Contractor to deliver a product using specific materials, equipment and methods, the End-Result specifications require the Contractor to deliver a product that meets “pass/fail” criteria for specific requirements. This paper describes an innovative approach to compaction where laboratory testing and analytical modelling tools support the energy-based design of earthworks compaction. The sustainability criteria behind the proposed approach aims to design the earthworks by optimizing the compaction variables to achieve the most energy-efficient process that meets a target degree of compaction. This energy-based design tool relies on a 3-dimensional analysis where the Density Growth Curve (DGC) provides a supplement to the traditional 2-dimensional compaction (moisture vs density) curves. An interactive web-based application is being developed to identify sustainable compaction conditions for site-specific earthworks. The application can also be used to estimate productivity from dimensions and machine performance data.

RÉSUMÉ

La conception de compactage des travaux de terrassement ont traditionnellement été basées sur deux approches principales; les spécifications de la méthode exigent que l'entrepreneur livre un produit en utilisant des matériaux, des équipements et des méthodes spécifiées. Tandis que les spécifications des résultat final exigent de l'entrepreneur qu'il fournisse un produit répondant aux critères “de réussite ou d’échec” pour les tests spécifiés. Ce document décrit une approche innovante du compactage où des essais en laboratoire et des modèles analytiques appuient d'une approche énergétique pour la conception du terrassement et son compactage. Les critères de durabilité qui sous-tendent l’approche proposée visent à concevoir les travaux de terrassement en optimisant les variables de compactage afin d’obtenir le processus le plus économe en énergie respectant le degré de compactage cible. Cet outil de conception basé sur l’énergie repose sur une analyse tridimensionnelle dans laquelle la Courbe de Croissance de la Densité (CCD) constitue le supplément des courbes traditionnelles de compactage bidimensionnel (humidité vs densité). Une application Web interactive est en cours de développement pour identifier des méthodes écoénergétiques permettant de produire des résultats de compactage efficaces pour les travaux de terrassement spécifiques à un site. L'application peut également être utilisée pour estimer la productivité à partir des données de dimensions et de performances de la machine.

1 INTRODUCTION

Compaction quality control of earthworks has been traditionally driven by two distinct criteria: Method Specifications or End-Result Specifications. The Method specification stipulates that specific materials and construction operations be followed in delivering the earthworks. The contractor would be directed to the type of materials and equipment to use and in what manner they must be used in constructing the earthwork. In the End-Result specification the materials and the final characteristics of the earthwork product are specified, and the contractor has freedom to adopt equipment and methodologies for achieving the required results. Both criteria have significant limitations; The Method specification can stifle contractor innovation and incentive to develop more efficient or effective construction methods. The End-Result specification may stipulate a range of acceptable characteristics, but since it is impractical to measure every inch of constructed earthwork, the acceptance criteria must rely on statistical methods and a limited number of test locations.

As the construction industry embraces sustainability criteria such as the Leadership in Energy and Environmental Design (LEED) initiative, there is a growing need to implement energy-efficient and effective compaction processes. In recent years, the widespread use of earthwork compactors equipped with machine measurement and Global Positioning System (GPS) mapping has enabled the monitoring and documentation of the compaction process a supplementary criteria for compaction quality control. One of the technologies that provide continuous, real-time monitoring of the field compaction process is the Machine Drive Power (MDP). The energy-based MDP concept (Caterpillar, 2014) is illustrated schematically in Figure 1, suggesting that the power required to drive a machine decreases as the ground increases in bearing capacity during the compaction process. The MDP technology is based on the principle of energy transfer from the machine to the ground (Corcoran and Fernandez, 2001). Ground improvement (i.e. stiffness, bearing capacity or density growth) takes place progressively, as the compactor delivers additional compactive effort with each successive machine pass (Figure 1a).

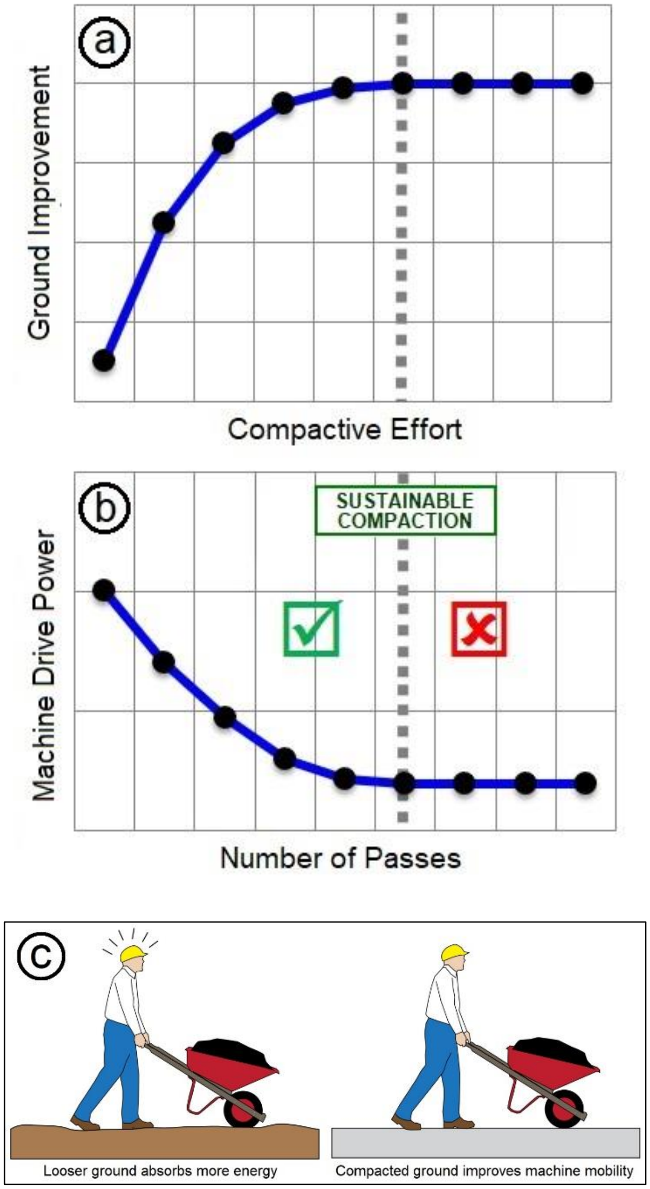


Figure 1. Energy transfer in earthworks compaction (adapted from Fernandez and Choma, 2017)

As demonstrated by Fernandez and Choma (2017) in laboratory CBR tests, an increased soil stiffness produces a decrease in energy absorption by the material being compacted. Consequently, ground improvement reduces the required power to drive the compaction machine (Figure 1b). This MDP concept is consistent with an intuitive visualization of hauling a wheelbarrow over loose and compacted ground as illustrated in Figure 1c.

Both curves shown in Figure 1a and 1b are non-linear and reach a "plateau" of minimal gains in ground improvement with additional compactive effort. The region prior to the plateau is characterized by beneficial use of the compactive effort (i.e. Energy) to produce ground improvement. However, upon reaching the plateau, additional compactive effort results in no further ground improvement and therefore the compaction process ceases to be sustainable. Further compactive effort results in waste of energy, as well as potential environmental impacts and losses in productivity. On that basis, the illustration in Figure 1b suggests that the compaction operation must stop once the plateau is reached, on the premise that a sustainable process of earthwork compaction requires beneficial use of energy resources.

This paper introduces a sustainable approach to the design of earthworks compaction based on analytical modelling and innovative laboratory testing methodologies. The proposed approach can be integrated with emerging technologies for field compaction monitoring to guide the sustainable design, construction quality control and maintenance of earthworks. The following sections of this manuscript describe a practical example with laboratory testing and modeling (Compac3D, 2014) conducted on granular material from the R.W. Tomlinson Rideau quarry located in Gloucester, Ontario. The particle size distribution for the test material is shown in Figure 2:

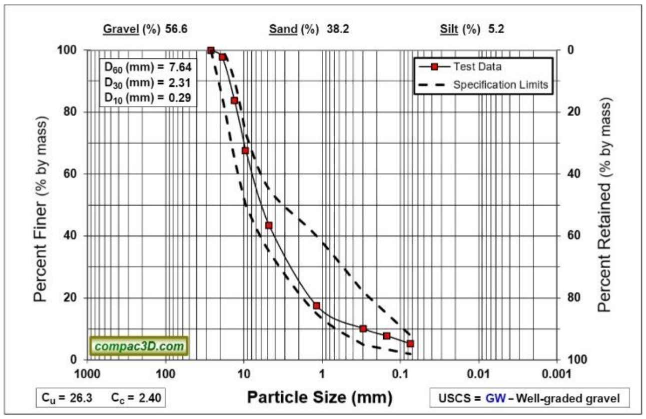


Figure 2. Particle size analysis for Granular "A" material (from Compac3D, 2014)

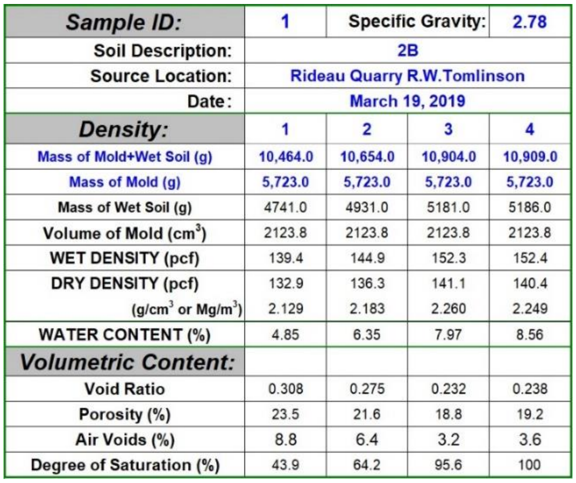
2 COMPACTION MODEL

Compac3D is a model based on 3 fundamental variables in earthworks compaction: the dry density (ρ_d), the water content (w) and the compactive effort (E). The analytical basis of Compac3D was introduced by Fernandez and Corcoran (2001). The model produces the typical compaction curve (moisture-density relationship) and expands along the energy (compactive effort) domain. The interrelations among these 3 parameters are discussed separately in the following sections.

2.1 Moisture-Density Relationship

In earthworks, compaction can be described as the process of densification resulting from the reduction in the volume of air (gas phase) as compactive effort is delivered to the material. For many decades, the moisture-density relationship has been the primary basis for compaction design and it is widely recognized that soil moisture content can have significant effects on its compaction behaviour. A systematic procedure for defining the density-moisture relationship was introduced by Proctor (1933) and has since been in use world-wide. The Standard and Modified Proctor tests (ASTM D698 and ASTM D1557) are well-established laboratory compaction methods used to determine the water content versus density relationship after a fixed levels of compactive effort are applied to the tested material. Both methods use standardized tools and procedures to ensure the delivery of a fixed compactive effort; 600 kJ/m^3 (12,400 lb$_f$-ft/ft^3) for ASTM D698 and 2,700 kJ/m^3 (56,000 lb$_f$-ft/ft^3) for ASTM D1557. Table 1 sumarizes the results of a standard laboratory compaction test conducted on the granular material previously described in Figure 2.

Table 1. Moisture-density relationship of soils (adapted from R.W.Tomlinson, 2014)



Sample ID:	1	Specific Gravity:		2.78
Soil Description:	2B			
Source Location:	Rideau Quarry R.W.Tomlinson			
Date:	March 19, 2019			
Density:	1	2	3	4
Mass of Mold+Wet Soil (g)	10,464.0	10,654.0	10,904.0	10,909.0
Mass of Mold (g)	5,723.0	5,723.0	5,723.0	5,723.0
Mass of Wet Soil (g)	4741.0	4931.0	5181.0	5186.0
Volume of Mold (cm^3)	2123.8	2123.8	2123.8	2123.8
WET DENSITY (pcf)	139.4	144.9	152.3	152.4
DRY DENSITY (pcf)	132.9	136.3	141.1	140.4
(g/cm^3 or Mg/m^3)	2.129	2.183	2.260	2.249
WATER CONTENT (%)	4.85	6.35	7.97	8.56
Volumetric Content:				
Void Ratio	0.308	0.275	0.232	0.238
Porosity (%)	23.5	21.6	18.8	19.2
Air Voids (%)	8.8	6.4	3.2	3.6
Degree of Saturation (%)	43.9	64.2	95.6	100

The results from Table 1 were processed by the Compac3D model and are shown graphically in Figure 3.

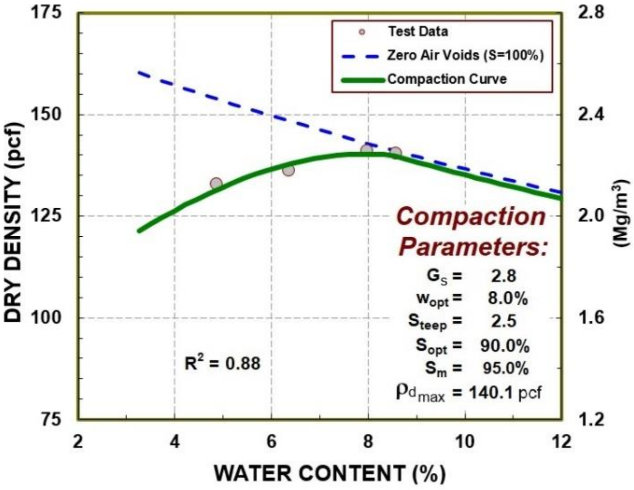


Figure 3. Standard compaction curve from Table 1

Figure 3 illustrates that soils compacted to fixed level of compactive effort exhibit a “bell-shape curve” relationship between water (moisture) content and dry density. The moisture-density relationship is commonly recognized as the “compaction curve” and it identifies a maximum dry density ($\rho_{d\,max}$ = 140.1pcf or 2.252Mg/m^3) and its optimum water content (w_{opt} = 8.0%).

An analytical 2-dimensional model of the compaction curve was proposed by Li and Sego (1999). Subsequemtly, Fernandez and Corcoran (2001) provided an alternate set of density-moisture relationships for the compactable moisture range, as follows:

$$\rho_d = C \div [(S_{teep}\, w^2 - 2S_{teep}\, w_{opt}\, w + S_{teep}\, w_{opt}^2 + (C \div \rho_{d\,max})] \quad [1]$$

where, ρ_d = Dry density (Mg/m^3 or pcf)
C = Unit conversion constant = 801.3 Mg/m^3 or 50,000pcf
S_{teep} = Shape factor for curve steepness
w = Water content (% by mass)
w_{opt} = Optimum water content (% by mass)
$\rho_{d\,max}$ = Maximum dry density (Mg/m^3 or pcf)

and,

$$\rho_{d\,max} = (G_s\, \mathbf{r}_w) / [1 + (G_s\, w_{opt} / S_{opt})] \quad [2]$$

where, ρ_w = Density of water = 1.000 Mg/m^3 or 62.43pcf
S_{opt} = Degree of saturation at w_{opt} (% by volume)
G_s = Specific gravity of soil particles

The Compac3D model combines Equations 1 and 2 to define moisture-density relationships fixed levels of laboratory compactive effort. The 2-dimensional compaction curve is well established and it has proven value in guiding the effectiveness of compaction. However, it does not address the efficiency of the compaction process.

2.2 Density Growth Curves

In order to assess the efficiency of the compaction process along the energy dimension, Fernandez and Corcoran (2001) introduced the Density Growth Curve (DGC) that provides the following relationship between dry density and compactive effort (E):

$$\rho_d = \rho_{d\,min} + (\rho_{d\,max} - \rho_{d\,min})\,(1 - 10^{-KE}) \quad [3]$$

where,

$\rho_{d\,min}$ = Uncompacted or loose dry density (Mg/m^3 or pcf)
$\rho_{d\,max}$ = Maximum dry density (Mg/m^3 or pcf)
E = Compactive effort (kJ/m^3 or lb$_f$-ft/ft^3)
K = Compactibility (m^3/kJ or ft^3/lb$_f$-ft)

The compactibility parameter (K) dictates the rate of density growth and is an indicator of compaction energy efficiency. The parameter K is determined as the inverse of the compactive effort E_{90}:

$$K = 1 / E_{90} \quad [4]$$

where,

E_{90} = Compactive effort required to achieve 90% of the density growth range ($\rho_{d\,max} - \rho_{d\,min}$)

Therefore, the DGC Equation 3 can be defined as follows:

$$\rho_d = \rho_{d\,min} + (\rho_{d\,max} - \rho_{d\,min})\,(1 - 10^{-E/E_{90}}) \qquad [5]$$

The granular material from Table 1 was prepared at a water content of about 5% under loose (uncompacted), standard and modified proctor levels of compactive effort. Figure 4 shows the test data and corresponding DGC produced by the Compac3D model based on Equation 5:

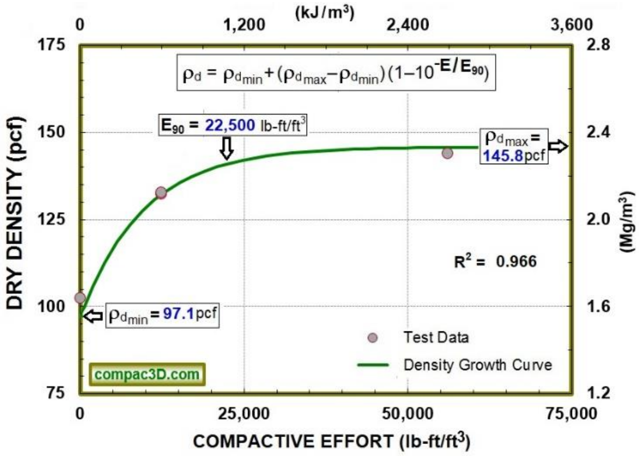


Figure 4. Density growth curve at w ≈ 5%.

The compaction parameters for the DGC curve ($\rho_{d\,min}$, $\rho_{d\,max}$ and E_{90}) are identified in Figure 4, where the dry density increases from a loose value $\rho_{d\,min}$ = 97.1pcf (1.56Mg/m^3) to a maximum dry density $\rho_{d\,max}$ = 145.8pcf (2.34Mg/m^3). As shown in Figure 4, a compactive effort of 22,500 lb$_f$-ft/ft^3 (1,077 kJ/m^3) is required to achieve 90% of the density growth range ($\rho_{d\,max} - \rho_{d\,min}$).

The DGC curve described in this section provides a convenient tool that can be used to assess the sustainability of the compaction process. Both parameters, K (or E_{90}) and $\rho_{d\,max}$ can be used as sustainability indicators in the compaction process. While the compactibility K parameter (or E_{90}) can be a direct indicator of energy efficiency, the maximum dry density ($\rho_{d\,max}$) can identify potential limitations (or lack of) for achieving a specified density target.

3 EXPERIMENTAL PROGRAM

A laboratory testing program was conducted to assess the earthworks compaction process in terms of dry density, water content and compactive effort. The compaction methodology included Standard and Modified Proctor tests (ASTM D698 and D1557) as well as an innovative vibratory compaction methodology. The test results were analyzed and presented using the Compac3D model.

3.1 Test Materials

The laboratory testing was conducted on granular material obtained from material from the R.W. Tomlinson Rideau quarry located in Gloucester, Ontario. The particle size distribution for the test soil is shown in the previous Figure 2 and it is considered a typical road base aggregate classified as a well-graded gravel (GW) in accordance with the Unified Soil Classification System (USCS).

3.2 Laboratory Compaction Tests

The material passing through the 3/8-inch (9.5mm) sieve was thoroughly mixed with sufficient water to obtain four (4) batches of increasing water contents and subjected to the following compaction tests:

- Standard Proctor testing in accordance with Method "B" of ASTM D698 standard.
- Modified Proctor testing in accordance with Method "B" of ASTM D1557 standard.
- Innovative Vibratory Compaction testing using equipment and procedures described in the following sub-section.

3.3 Vibratory Compaction Equipment

An innovative laboratory testing methodology was developed to assess the vibratory compaction process in a controlled laboratory environment. The test system (Figure 5) was enhanced after Fernandez and Osborne (2015) and it can substantially comply with standardized test methods (ASTM C1435 and ASTM D7382). Additionally, the proposed test methodology allows for continuous monitoring of the Density Growth Curve during the vibratory compaction process.

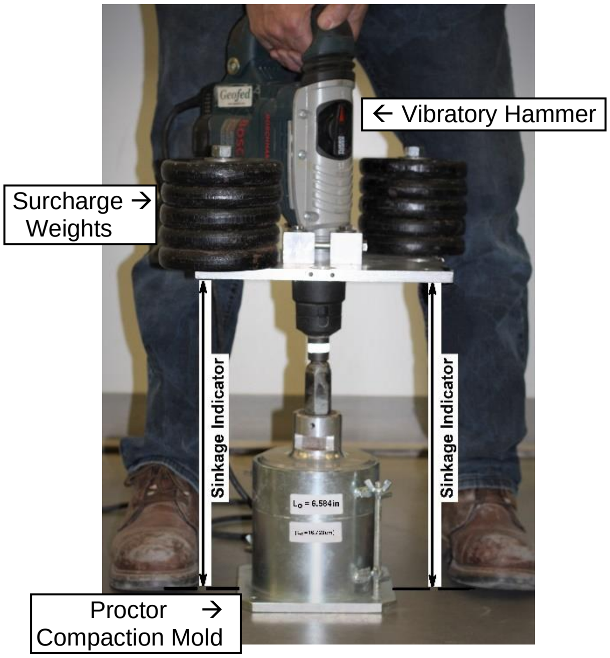


Figure 5. Vibratory energy test assembly

The mass of soil is determined using a standard scale prior to beginning compaction and it remains constant through the compaction process. As shown in Figure 5, sinkage indicators provide continuous monitoring of the compacted lift thickness, the sample volume and the soil density.

Sinkage of the tamping plate into the compaction mold can be determined using various devices such as dial gauges, linear variable displacement transducers (LVDT), non-contact distance sensors (laser or ultrasonic) or analysis of video imaging. In all cases, dual sinkage indicators allow for monitoring the average lift thickness and corresponding growth of soil density throughout the compaction process.

The vibratory hammer is affixed to the tamping plate by an aluminum plate and clamping blocks that can rigidly support various levels of surcharge weights. Table 2 details the operating characteristics of the Bosch 11248 hammer that can be operated at vibratory frequencies ranging from 28 to 55 Hertz.

Table 2. Vibratory hammer characteristics (adapted from Fernandez and Osborne, 2015)

Bosch 11248EVS	
Volts	120
Amps	11
Beats/min (rpm)	1700-3300
Beats/sec (Hz)	28-55
Impact Energy	7.4 ft·lb (10 m·N)
Impact Power at 1 Hz	7.4 ft·lb/s (10 W)
Impact Power at 28 Hz	207 ft·lb/s (280 W)
Impact Power at 55 Hz	407 ft·lb/s (550 W)

The compacive effort (E) can be tracked continuously based on the vibratory frequency selected. For example, a tests conducted at a frequency of 55 Hertz (i.e. 55 beats per second) imparts a vibratory power of 550 Watts (i.e. 550 Joules per second) of vibration. Then, the compactive effort is computed as the product of the vibratory power and the elapsed time of vibratory compaction, divided by the soil volume.

When equipped with digital sinkage indicators and a computerized data acquisition system, the Vibratory Compaction assembly (Figure 6) produce DGC curves expeditiously and allow for batch testing productivity.

Figure 6. Batch testing with vibratory compactor

In a typical vibratory compaction test the duration of vibration required to reach the “plateau” condition does not exceed 1 minute. It is then viable to use standard Proctor test molds arranged in batch configurations that permit expedient laboratory testing as shown in the following Figure 7:

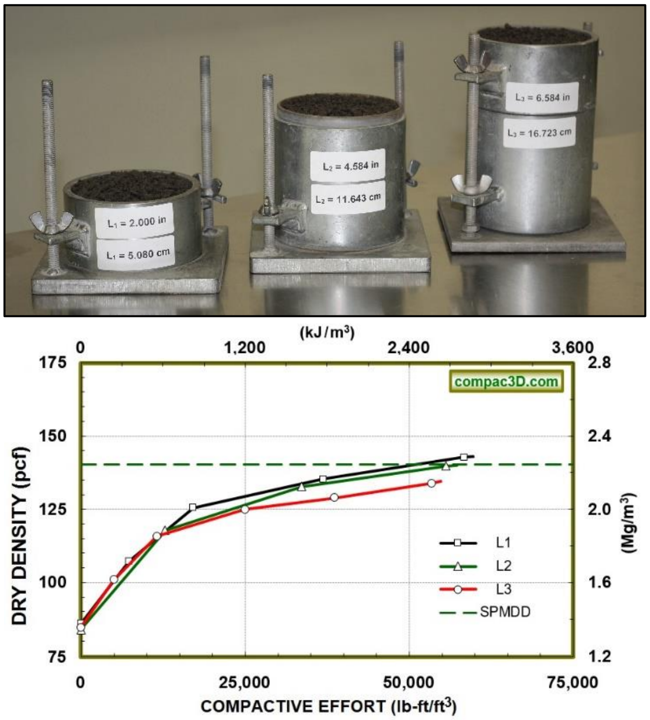


Figure 7 Vibratory compaction batch test for lift thickness.

The vibratory compaction method can provide a convenient and effective laboratory methodology to optimize the compaction design selecting process variables to produce an energy-efficiency and effective compaction. Thus, a variety of field compaction variables (e.g. water content, lift thickness, vibratory frequency and amplitude, surcharge pressure, etc.) can be assessed in the laboratory to produce sustainable design of earthworks.

4 TEST RESULTS

The following subsections present the results of dynamic (Proctor) compaction tests conducted on the granular material described in Section 3 and Figure 2.

4.1 Density-Moisture Relationship from Proctor Tests

The results from Standard and Modified Proctor compaction testing are shown in Figure 8 along with the uncompacted “loose” density values. The markers show the actual measurement points, while the solid lines correspond to the regression analysis curves produced by the Compac3D model. The moisture-density relationships in Figure 8 display a strong agreement between the data points and the regression curves with a coefficient of correlation $R^2 = 0.95$.

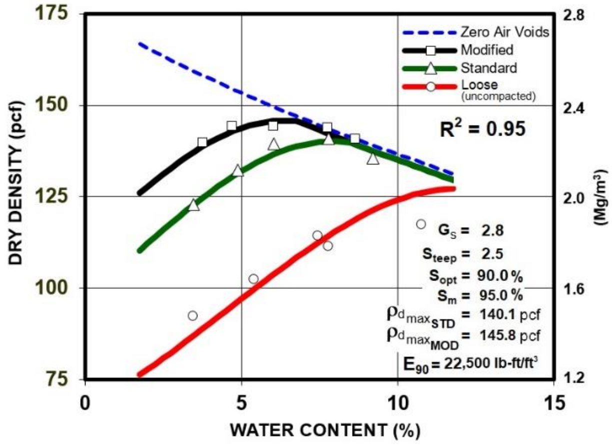


Figure 8. Moisture-density compaction curves

4.2 Density Growth Curves

The data points from Figure 8 are presented in Figure 9 as dry density values plotted versus their respective compactive efforts: 0, 12,400 and 56,000 lb_f-ft/ft^3 for loose, standard and modified Proctor compaction tests.

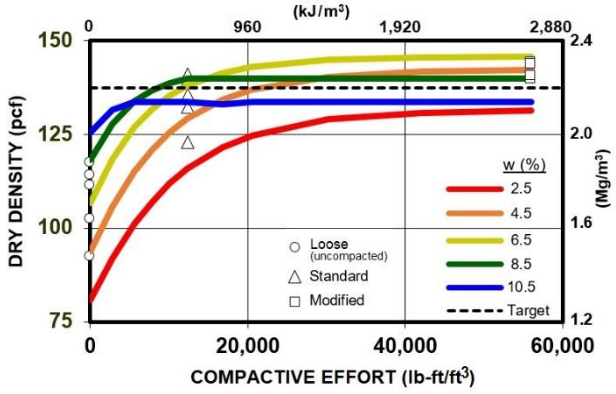


Figure 9. Density growth curves from Proctor tests

In Figure 9, the markers represent the actual measurement points, while the solid lines show the DGC curves produced by the Compac3D model. The dashed line corresponds to a target density or specified degree of compaction at 98% of the Standard Proctor Maximum Dry Density (98% SPMDD).

From the DGC curves it can be inferred that a water content of 8.5% produces the most sustainable compaction to achieve the specified density with the least compactive effort. At higher moisture contents (e.g. 10.5%) the compaction process is not effective in reaching the density target. Lower moisture would require additional compactive effort to achive the compaction specification.

4.3 Moisture-Compactive Effort Relationship

The following Figure 10 illustrates the moisture-compactive effort relationship from the Compac3D model for various levels of target density:

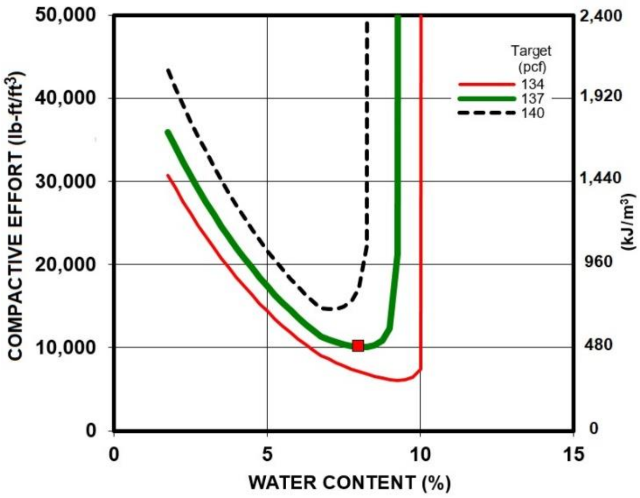


Figure 10. Compactive effort at various density targets

The thick green solid line in Figure 10 corresponds to a density target of 98% SPMDD. The reader can infer from Figures 9 or Figure 10 that the tested soil can produce the most sustainable compaction process at a water content of approximately 8%. The thinner red and dashed black lines in Figure 10 illustrate the sensitivity of varying the density target by +/-3pcf. In all of these cases, the compactive effort required to reach the density targets can double within a narrow (≈4%) range of moisture contents.

5 CONCLUSIONS

The earthwork compaction design process has traditionally been assessed using a 2-dimensional relation between the soil moisture content and its compacted dry density. However, energy is fundamental to the compaction process and optimizing the compactive effort required to reach a target result can lead to a more sustainable compaction design.

The following conclusions are supported from the findings presented in this paper:

1. The analytical model Compact3D characterizes the interrelationships between soil moisture, compactive effort and dry density, providing a useful tool to guide the sustainable design of compaction.
2. The Density Growth Curve supplements the traditional compaction curve (2D) along the energy domain (3D) for optimization of effectiveness and energy efficiency of the compaction process.
3. An innovative laboratory test methodology can be used to assess vibratory compaction processes on granular materials. The test procedures enhance current methods and leverage from standardized testing equipment that are readily available in geotechnical laboratories.

4. Laboratory compaction data can be processed by the Compact3D model to process variables (e.g. water content, lift thickness, vibratory frequency and amplitude, surcharge pressure, etc.) that produce energy-efficiency and effective compaction.

As the construction industry embraces sustainability criteria such as the LEED initiative, compaction of earthworks must be designed for energy-efficient and effective compaction processes. Optimizing the effectiveness and energy-efficiency can significantly improve compaction productivity, conserve non-renewable resources and reduce environmental impacts in support of sustainable earthwork construction.

ACKNOWLEDGEMENTS

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