

Preparing for Intelligent Compaction – The Importance of Degree of Saturation when Measuring Dry Density with Stiffness Indexes

R. Latimer¹, BEng, D. Airey², PhD

¹Higher Degree by Research Candidate, University of Sydney, School of Civil Engineering (Geotechnical), Sydney, Australia, email: rlat5653@uni.sydney.edu.au

²Professor, University of Sydney, School of Civil Engineering (Geotechnical), Sydney, Australia, email: david.airey@sydney.edu.au

ABSTRACT

Increasingly, the earthworks industry seeks to assess compaction through stiffness indexes, as it is both easier to measure, and is relatable to road design parameters such as soaked CBR. This interest in stiffness is not addressed in a conventional Proctor based approach to compaction. Furthermore, there is an often-held misconception that additional compaction improves stiffness. However, as shown in this paper, and by others, it is clear that stiffness is not related to density in a simple way.

During a recent compaction study undertaken at the University of Sydney, it has been shown that monitoring degree of saturation (S_r) is essential for understanding the relationship between small shear modulus (G_o) and dry density (ρ_d). Silty sand samples were prepared at differing moisture ratios before undergoing multi-staged compaction. First arrival shear wave velocity was measured via Bender Element (BE) to produce G_o at a range of ρ_d . Results presented in this paper show G_o increases with increasing ρ_d at a constant S_r rather than constant water content (w). Analysis indicates that additional compaction past the critical S_r range of 50% will reduce stiffness response G_o at constant w , and that when compacting across the typical range of S_r of 40-70% G_o is nearly constant and largely independent of ρ_d .

Keywords: compaction, degree of saturation, S_r , bender elements, shear modulus, G_o

1 INTRODUCTION

The compaction of soil embankments is a crucial component to major infrastructure projects. While the mechanics behind compaction are relatively well understood (such as Proctor, 1933), there is a desire within the earthwork's community to better control the engineering properties of the embankment, and also to automate the quality control and assurance process of its construction (Kodikara, 2018). The emerging field of Intelligent Compaction (IC) has been heralded as the long-awaited step change to earthworks' practices. IC involves the combination of compactor mounted global positioning systems (GPS) and stiffness index measuring devices making use of accelerometers to produce complete coverage and pass-by-pass stiffness index maps in real-time for an earthworks' lot. However, counter to expectations, during a recent field trial conducted in Australia, a common IC unit Compaction Meter Value (CMV) was found to have scattered and independent relationship to density and compaction.

The motivation for the work described in this paper has been to understand the soil mechanics responsible for the constant stiffness observed in the field data. There has been almost thirty years of research, such as Sandström (1994), White (2011), and Pistol and Adams (2021), showing that CMV can produce a reliable, but noisy, stiffness index with a properly implemented construction method. But, given CMV has been found to be largely independent of ρ_d during compaction, what is the explanation? This paper presents findings from a compaction study undertaken at the University of Sydney and explores what factors affect stiffness as soil is compacted.

1.1 The case for S_r and the stiffness / density relationship

Due to the consistent increase of ρ_d during compaction, the expectation is that IC measurement values should also increase with compaction. This has been shown to be not the case (Latimer et al, 2022).

The work of Tatsuoka et al (2021) offers an updated framework for compaction, one in which stiffness is controlled by S_r and ρ_d , rather than solely ρ_d . To test this framework, a consistent and controlled approach for measuring compaction and stiffness is required. Measuring of shear wave velocity through bender elements (BE) has been shown to be one of the simplest, non-destructive ways to measure small strain shear modulus (G_o) (Heitor, 2013; Airey and Mohsin, 2013). The general relationship between shear wave velocity (V_s in m/s) to elastic shear modulus (G_o in kPa) where ρ_b is the bulk density (kN/m^3) is shown in Equation 1.

Equation 1: G_o relationship to V_s

$$G_o = V_s^2 \cdot \rho_b$$

2 LABORATORY TRIAL: THE EFFECT COMPACTION HAS ON SHEAR MODULUS G_o

To compare the effects S_r and ρ_d have on G_o , and to test the framework developed by Tatsuoka et al. (2021), a test apparatus was constructed to statically compact soil at various moisture contents while taking shear wave velocity using bender elements at regular intervals.

2.1 Methodology

All works have been conducted in general accordance with AS1289 (2017) Methods of Testing Soils for Engineering Purposes, unless otherwise stated. Due to its current popularity in earthworks' projects around Sydney (NSW) (Sutton et al. 2018), a tunnel sourced crushed Hawksbury Sandstone, sieved to 1.18mm, was selected as the test soil. Typical particle size distribution (PSD) curve from wet sieve and hydrometer is shown in Figure 1. Specific gravity of the soil was $G_s = 2.65$.

Samples were moisture conditioned to desired levels and homogenised by mixing thoroughly. The prepared sample was rained loosely into a PVC mould and placed into the test set up as shown in Figure 2. The sample was compacted in stages using the triaxial ram. Bender elements were mounted in the top and bottom platens to monitor the shear wave velocity throughout the experiment. Soil was compressed one-dimensionally, and displacement of the upper platen used to update ρ_d and S_r . Compaction proceeded in stages: the soil was compressed to a target dry density, the shear wave velocity and load recorded, and then the stress was then reduced to zero and the shear wave velocity measured again. Soil relaxation during unloading was found to have a negligible impact on ρ_d . The process was then repeated for progressively higher target densities until the limiting stress of 5 MPa was reached.

The PVC mould was not sealed at the top, allowing PVC moisture to be expelled from soil once optimum S_r was passed. The soil was compacted slowly and controlled by a combination of stress and displacement to prevent pore water pressure build up and ensure drained conditions. When water was expelled from the soil due to approaching the nil air voids line, this displaced water was captured and measured, adjusting the soil moisture accordingly. The PVC mould diameter was 16 cm and compacted sample thickness typically 5-10 cm. This aspect ratio is such that friction on the sides is not expected to be significant.

G_o was calculated from shear wave velocity measured by Bender Elements using the first arrival method (Heitor, 2013). It was checked against cross-correlation method (Airey and Mohsin, 2013) and found to give essentially the same V_s .

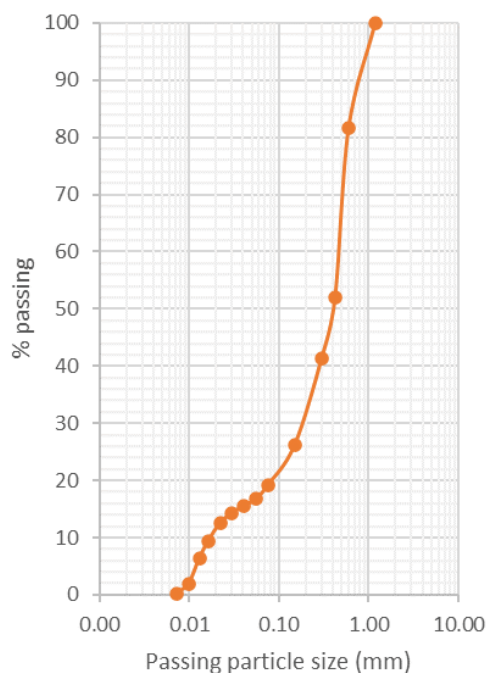


Figure 1: Typical particle size distribution of trial soil

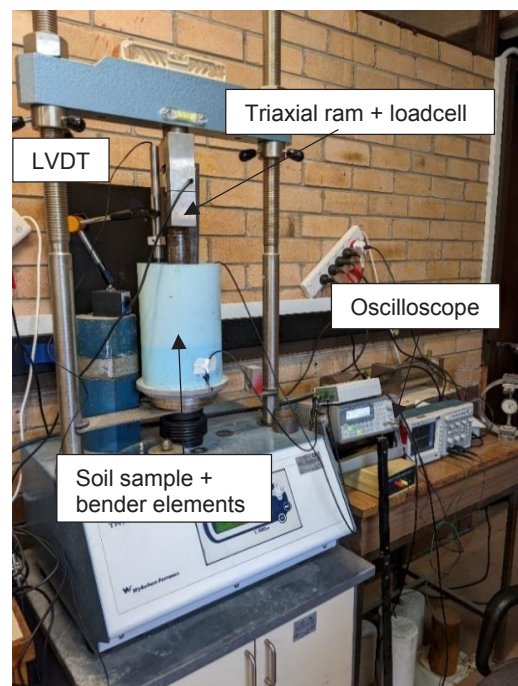


Figure 2: University of Sydney bender element compaction test apparatus set-up

A total of 16 test iterations were completed at varying moisture contents from dry, partially saturated and saturated conditions.

3 RESULTS

Because V_s is strongly dependant on stress level, a consistent stress is needed to enable comparison of the effects of density and moisture content. To achieve this, the soil was unloaded to zero vertical applied stress and the results presented below are only from this zero applied stress state. It is noted that G_o measured while under load increased by an order of magnitude compared to unloaded G_o during final stages of compaction approximately when $S_r > 50\%$. The relevancy of comparing unloaded G_o to CMV (which essentially a stiffness measurement taken while under load from the roller drum) is not addressed by this paper, however, the effects of density and moisture are expected to be qualitatively similar.

A sample of the data captured during the test is presented in Figure 3 and Figure 4 below. Figure 3 shows that for a constant w , G_o increases as ρ_d increases, and the rate appears to be increasing with density. However, as shown in Figure 4, this increasing trend does not continue indefinitely, and as the soil approaches the no air voids line, further change can only occur if moisture drains from the soil. This $w=10-15\%$ result shows the relationship between G_o and ρ_d for a fixed w ratio is not unique. It can also be noted on Figure 3 that as the soil is compressed, S_r is increasing because of the reduced void space while the volume of water remains constant.

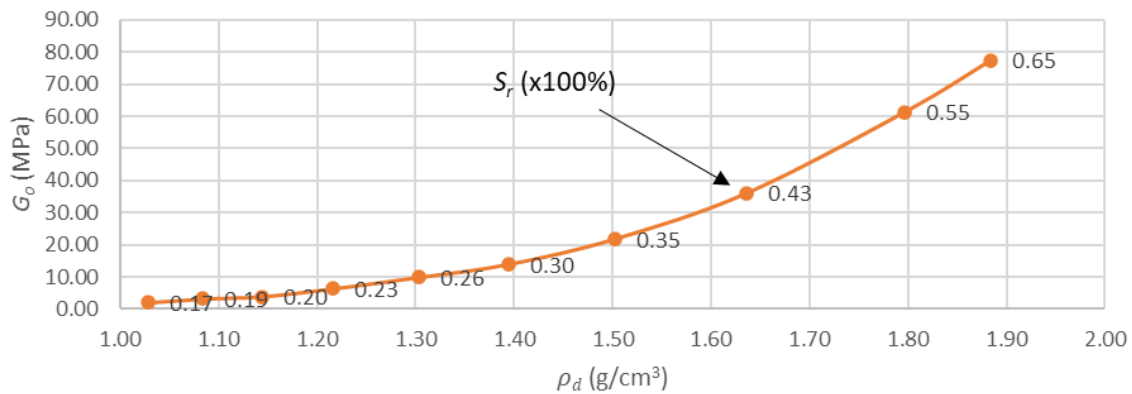


Figure 3: Typical G_o to dry density correlation seen during compaction in trial ($w= 10\%$, under zero confining pressure conditions)

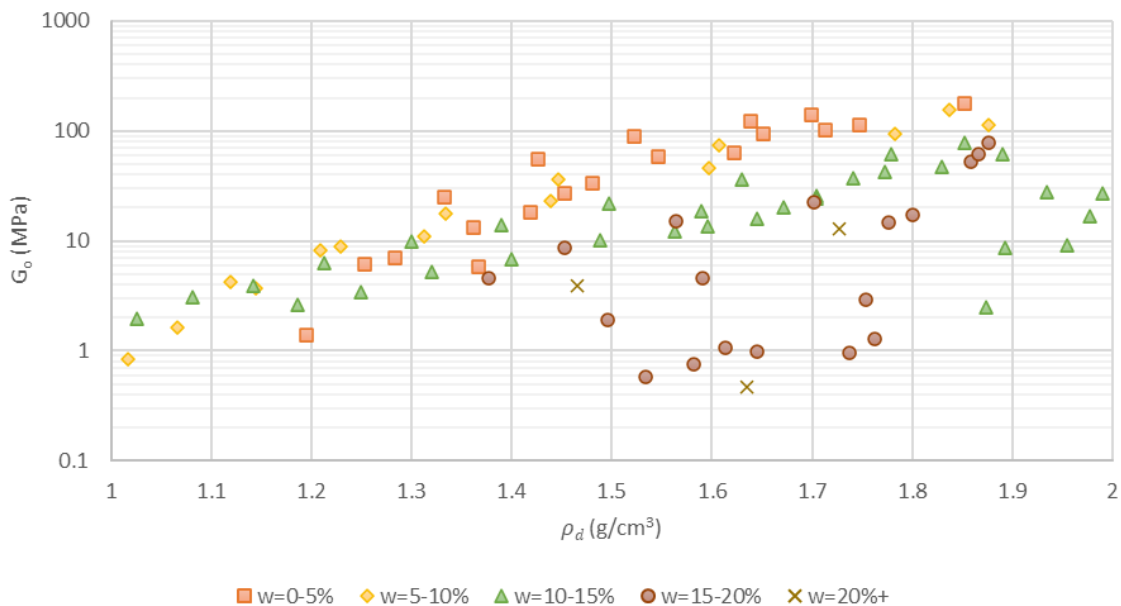


Figure 4: G_o to dry density correlation seen across all compaction trials (zero confining pressure)

Figure 5 shows a distinct and unique relationship where G_o is increasing exponentially with increasing ρ_d when sorted by S_r . Broadly Figure 5 shows G_o is increasing with ρ_d for fixed S_r , and in Figure 6 G_o decreasing with S_r for fixed ρ_d . R^2 trend between G_o and S_r when sorted by ρ_d in Figure 6 are convincing at 0.56 to 0.84. These results are similar to those of Tatsuoka et al. (2018 and 2021).

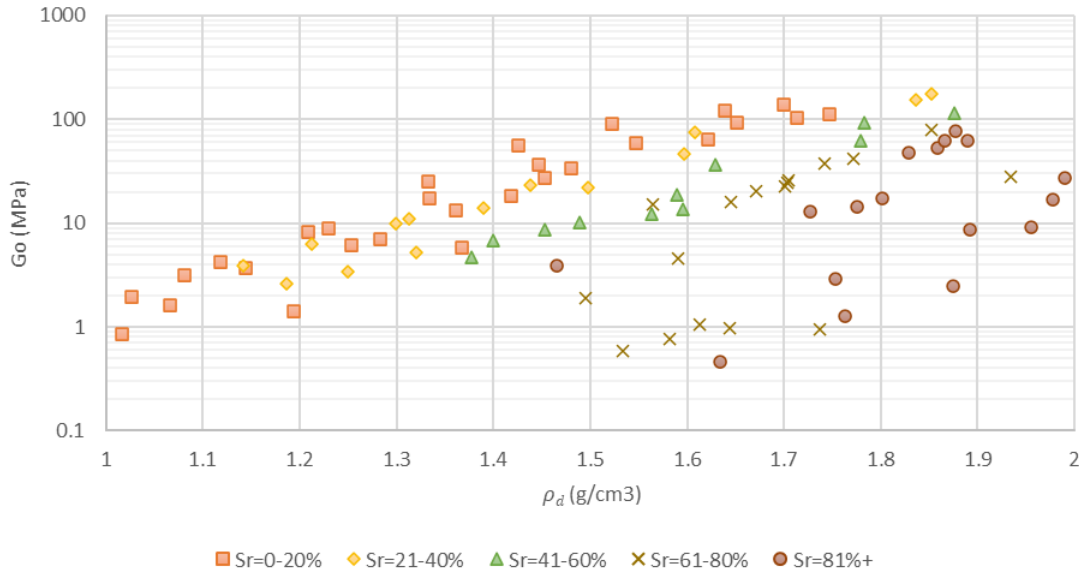


Figure 5: Increasing relationship between G_o and ρ_d for fixed S_r^1

¹Note: data variation seen above optimum S_r (around 80%) and at high water content is likely due to miscalculations of S_r and slight variation in ρ_d as water and small amounts of soil particles are expelled from the mould. Improving the testing method to produce a higher quality data set is part of an ongoing research effort.

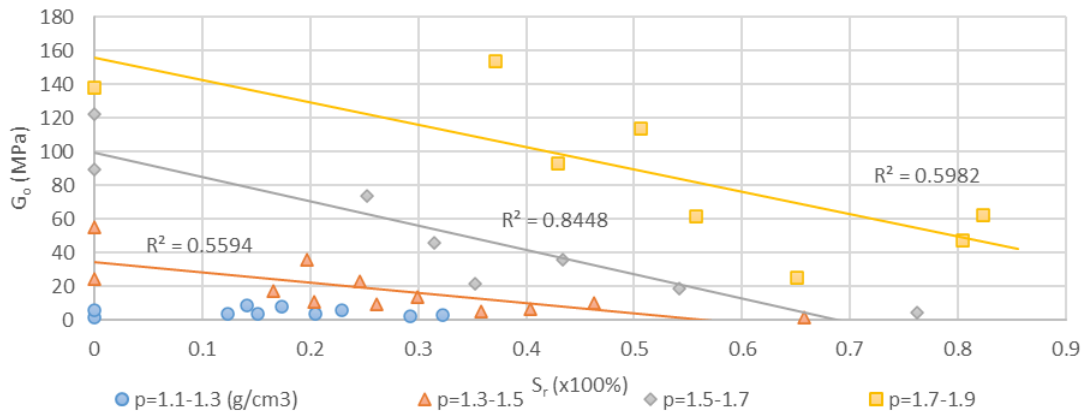


Figure 6: Decreasing relationship between G_o and S_r for fixed ρ_d

4 DISCUSSION

Building upon empirical framework developed by Tatsuoka et al. (2021) and assuming a relationship for G_o described in Equation 2, where soil specific variable a is a function of S_r , and soil specific parameters b and c are a fixed function of ρ_d .

Equation 2: Empirical G_o relationship to S_r and ρ_d (Tatsuoka et al. 2021)

$$G_o = a * \left(\frac{\rho_d}{\rho_w} - b \right)^c$$

A series of best fit graphs such as Figure 7 have been plotted to empirically estimate variables a , b and c . Variable a has then been plotted to produce a best fit Boltzmann equation for a generalised function relating G_o to S_r in Figure 8. The Boltzmann fit for data from this BE trial fits the theoretical framework of Tatsuoka et al. (2021), it is noted that it also fits a polynomial trend.

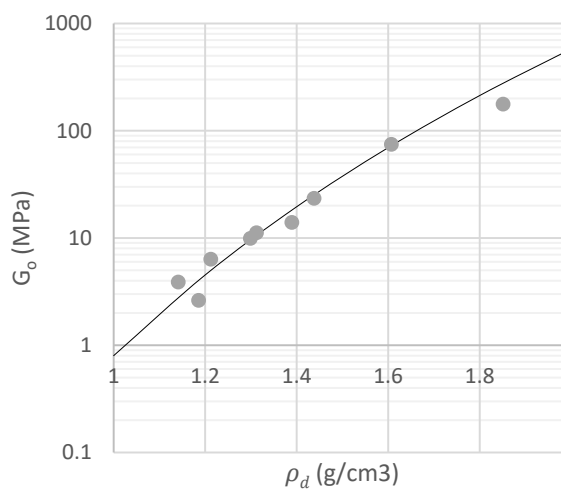


Figure 7: Sample correlation of S_r 21-30% relating ρ_d to G_o , the fitted equation is $G_o=0.8(\rho_d/\rho_w-0)^{9.5}$

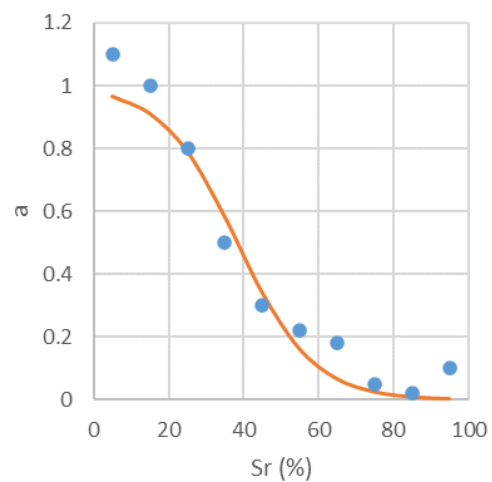


Figure 8: Boltzmann correlation of G_o and S_r by a generalised function for “a”

Using this generalised equation for G_o and plotting for compaction at constant w , as shown in Figure 9, the trial saw an initial increase in stiffness due to densification. However, consistently as S_r approaches a key range of 50% G_o plateaus before reducing. Practical applications of this process are twofold:

1. This trial’s results show during compaction at fixed w , maximum G_o is found around 50% S_r , and further compaction past this range of S_r leads to a reduction in G_o .
2. Current earthwork’s practices such as R44 (TfNSW, 2013), aim to achieve maximum dry density at 60-90% optimum moisture content. This process typically sees compaction undertaken across a range of S_r 40% to 70%. If attempting to use a stiffness index to monitor the compaction process, it is expected practitioners would see very little change in IC value and potentially even a reduction in measurement value.

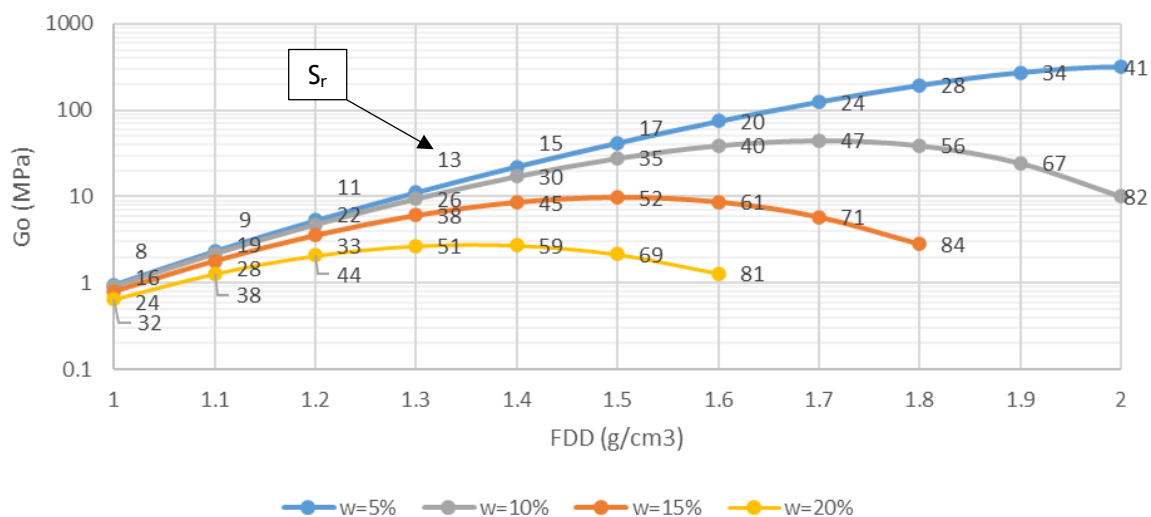


Figure 9: Calculated values of G_o during compaction for fixed w ratios²

²Note: The Boltzmann best fit equation used by Tatsuoka et al. (2021) expects that variable “a” should continue to zero for $S_r > 85\%$ in Figure 8, however, an increase is seen at $S_r = 95\%$. This is likely due to accuracy and testing control issues as soil nears complete saturation during data acquisition. This is part of on-going research and will be investigated with a revision of this work. Results presented in Figure 9 are limited to $S_r < 85\%$.

Tatsuoka et al (2021) have found similar correlations between soil stiffness and density when using a lightweight falling deflectometer (LWFD) and in California Bearing Ratio (CBR) tests. CBR is used as an industry standard road design parameter (from which “ $E=10\text{CBR}$ ” is often adopted). However, these tests are performed using a specified relative density/moisture content followed by soaking to account

for reduced stiffness due to wetting/inundation, and thus the design stiffness is not directly related to values measured during compaction.

5 CONCLUSION

Simple application of the Proctor approach to earthworks compaction control is outdated, and it is time to upgrade. To achieve this, a more thorough understanding of soil compaction is required. Intelligent Compaction offers a promising solution to the modernising demands of the earthwork's market, however, during recent field trials, a popular Intelligent Compaction measuring unit, CMV, was found to be unusable for proving current specifications due to dry density ρ_d being independent of CMV across typical ranges of compaction.

To properly understand how stiffness indexes such as CMV are related to ρ_d , a series of laboratory-based compaction trials were conducted to test the importance of degree of saturation S_r to shear modulus G_o (a stiffness index) during the compaction process. These trials have shown G_o is empirically related to ρ_d via S_r , rather than w . The results presented in this paper show that, as expected, G_o initially increases during compaction for low S_r . However, importantly, this trial indicates that at the critical range of 50% S_r , further compaction leads to a decrease in G_o . Furthermore, when attempting to use stiffness indexes such as G_o to measure ρ_d during compaction across a typical range of 40-70% S_r , G_o will be largely independent of ρ_d , and that careful control of S_r would be required to calibrate this G_o to ρ_d relationship.

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