ASSESSMENT OF FIELD COMPACTION OF SUBBASE MATERIAL DURING CONSTRUCTION AND TRAFFICKING OF HEAVY AIRCRAFT USING THE SUPERPAVE GYRATORY COMPACTOR

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ABSTRACT

Past full-scale pavement testing at the National Airport Pavement Test Facility (NAPTF) of the Federal Aviation Administration (FAA) has shown excessive compaction of the subbase layer during trafficking. Modern construction compaction equipment is capable of achieving densities higher than maximum Proctor values at moisture contents drier than optimum conditions. Laboratory testing has been conducted at different moisture contents and confining pressures using the Superpave Gyratory Compactor (SGC). SGC results were found to be similar to that achieved by modern construction compaction equipment in the field. Different from the Proctor method, the shear work component added by the SGC closely replicates the aggregate crushing mechanisms observed in the field during construction and trafficking. Results suggest that the excessive compaction reported for the subbase after trafficking is, in part, due to abrasion and attrition of the aggregate which reduces particle interlock and promotes additional compaction. Based on the test results, it is recommended to implement SGC based construction specifications in order to prevent excessive compaction from construction and trafficking. After achieving field construction density, the additional compaction observed in SGC test samples was found to be significantly smaller than the actual compaction observed in the pavement during trafficking. The suitability of the SGC to reproduce trafficking compaction in the field due to heavy aircraft loading is still under evaluation. Research efforts are currently directed to find a rational method for determining field compaction energy, which will lead to the development of a correlation between SGC test results and material field performance during compaction and trafficking. Using compaction energy principles this correlation would allow determination of the number of roller passes required during construction in order to achieve any desired density-moisture condition. Preliminary results on the development of this approach are presented in this study.

INTRODUCTION

The NAPTF was constructed by the FAA to study the impact of large and heavy aircraft such as the Boeing-777, 747 and Airbus A-380 on modern airport pavements. Different pavement sections are constructed using techniques typical for runway construction after which instrumentation is installed within the pavement structure to monitor responses in the subbase, and subgrade due to repeated trafficking. The main purpose of this indoor test facility is to accelerate life cycle testing of a simulated airport pavement in a more controlled and cost effective environment in comparison to building a full size outdoor runway to test empirical methods and runway design modifications [1]. According to Garg and Hayhoe, field results from past full-scale testing at the NAPTF have shown excessive compaction of the subbase layer after trafficking [1]. In order to understand the compaction characteristics of the subbase layer in response to construction and trafficking, the material was compacted in the SGC at various stress levels and at different moisture contents. The NAPTF construction cycle 5 (CC5) is the most recent construction cycle of interest. CC5 is being utilized to study the effects of various gear configurations as well as subbase material depth and quality on the flexible pavement's performance. The granular subbase material is comprised of two different materials including crushed quarry screenings, P-154, and densely graded aggregate (DGA).

In this study, the use of the SGC over the Modified Proctor method for determining the compaction characteristics of aggregates is explored. An attempt to develop a SGC-based approach to predict field performance of P-154 and DGA subbase materials for both construction and trafficking stages is presented. This approach will allow determination of the number of roller passes required during construction in order to achieve any desired density-moisture condition. Most important, this approach will contribute to minimizing field trafficking compaction.

OBJECTIVES

The objectives of this paper were: a) To assess the feasibility of replacing the Modified Proctor method by SGC based construction specifications in order to prevent excessive compaction from construction and trafficking, b) To determine the crushing mechanisms leading to excessive compaction of subbase materials, c) To develop a rational approach for correlating SGC laboratory test results with field compaction from construction, and d) To explore the feasibility of using SGC laboratory test results for predicting field compaction from trafficking.

LABORATORY TESTING PROGRAM

Materials

Two materials are utilized as granular subbase at the NAPTF: a crushed quarry screenings, and a densely graded aggregate denominated P-154 and DGA respectively. Additionally, a crushed stone used as granular base material denominated P-209 was included for evaluation in this project. However, the present paper focuses only on the results obtained for the P-154 and DGA materials. Testing of material P-209 has not been completed. Upon completion of P-209, relevant findings will be reported and published.

Subbase material P-154 is a crushed quarry screenings with 9.5% of fines and a plasticity index of 3.1. The Modified Proctor test results report an optimum moisture content (OMC) of 6.5% and a maximum dry density (MDD) of 128.3 pcf. DGA subbase material is a non-plastic densely graded aggregate with 4.6% of fines. According to the Modified Proctor test the OMC is 4.9% and a MDD of 155.7 pcf. Such index properties meet the FAA specifications for subbase materials.

Superpave Gyratory Compactor

In the last two decades, the SGC has been a key tool in the compaction and analysis of hot mix asphalt (HMA) samples. The SGC equipment is shown in Figure 1. The standards for testing of HMA mixtures have been properly established by the American Society for Testing and Materials, ASTM, and the American Association of State Highway and Transportation Officials, AASHTO. Details on SGC samples compaction can be found elsewhere [2]. The use of the SGC for compaction of soil samples ranging from granular soils to clays has been investigated and documented in the literature Ping 2002, Ping 2003, and Mokwa 2008 [3, 4, 5].

The Standard and Modified Proctor testing methods have been around since the 1930's. The Proctor tests determine the moisture-density relationship for soils. This relationship defines the optimum moisture contents (OMC) and maximum theoretical dry densities (MDD) for soils to be achieved during construction. However, recent improvements in the construction equipment capabilities have made it possible to achieve greater densities than Proctor tests are capable of producing in the laboratory. Therefore, there is an increasing interest in using the SGC to determine the moisture-density relationship, as well as the potential to simulate the life cycle of these soils in an accelerated manner. The SGC closely simulates the actual field compaction process during construction since its gyratory action imparts shear work similar to the rollers in the field. A comprehensive analysis of compacted soil specimens in the SGC could also allow for a better understanding of the mechanisms of compaction and how different variables affect the compaction process.

A device called the Pressure Distribution Analyzer (PDA) was run simultaneously with the SGC during sample compaction. The PDA has a set of three load cells which measure and analyze all the forces applied to the sample during compaction. The shear and vertical energies being imparted to the sample can be calculated using the PDA output. Vertical displacement resulting from compaction is recorded by the SGC and then correlated with the PDA data to gain insight in to the different types of energy input by the SGC. The PDA device is shown in Figure 2.

Figure 1. Superpave Gyratory Compactor, SGC.

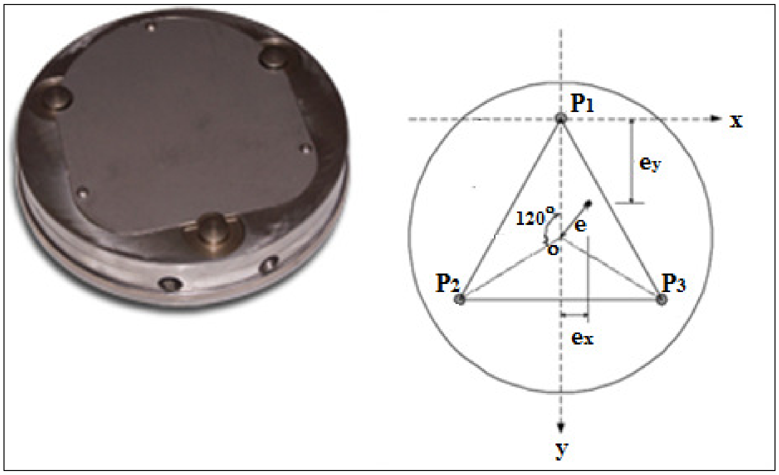

Figure 2. Pressure Distribution Analyzer (PDA) (left). Schematic representation of the PDA unit layout (right).

SGC Test Results

In this section the SGC test results for both P-154 and DGA subbase materials are presented. The dry soil mass utilized for all testing was 3000 grams. Once weighed, the dry material was thoroughly mixed with water and compacted in the SGC with a vertical pressure of 600 kPa. During preliminary testing, the specimens were subjected to 800 gyrations. Later, it was decided to increase the gyrations to 2400 in order to input more energy and achieve higher densities. Figures 3 and 4 show the density achieved in each specimen at different number of gyrations, N for P-154 and DGA material respectively. The Modified Proctor curve is included in the plots for purposes of comparison. It should be noted in both charts, that similar to modern field compaction equipment, the SGC is capable of achieving higher densities than the Modified Proctor method even at moisture contents lower than optimum conditions.

Also, as discussed later, the SGC seems to reproduce the compaction mechanism observed in trafficked field samples. Thus, the SGC appears to be a more suitable method for characterizing the compaction of subbase materials. A total of 16 SGC test results at different moisture contents were considered for the analysis of P-154 material. For DGA, a total of 18 SGC tests were included in the analysis. Note that due to the SGC mechanism of compaction and the particle size distribution of the aggregates, there is a limit in the maximum moisture content the samples can be tested. The coarser the aggregate the lower the potential for moisture retention under the shear work imparted by the SGC. As a consequence, water simply seeps out of the SGC mold during the test, which prevents compacting samples at moisture contents greater than those shown in Figures 3 and 4.

The test results were subsequently used to develop a predictive model for estimating the energy input required to achieve any desired moisture-density condition in the laboratory. Theoretically, by applying the same energy level in the field using heavy compaction equipment, the desired moisture-density condition should be achieved. The final step in the process is to determine the feasibility of expressing input energy in terms of roller passes. Therefore a rational method to quantify the energy applied by the rollers in the field is being developed by the study.

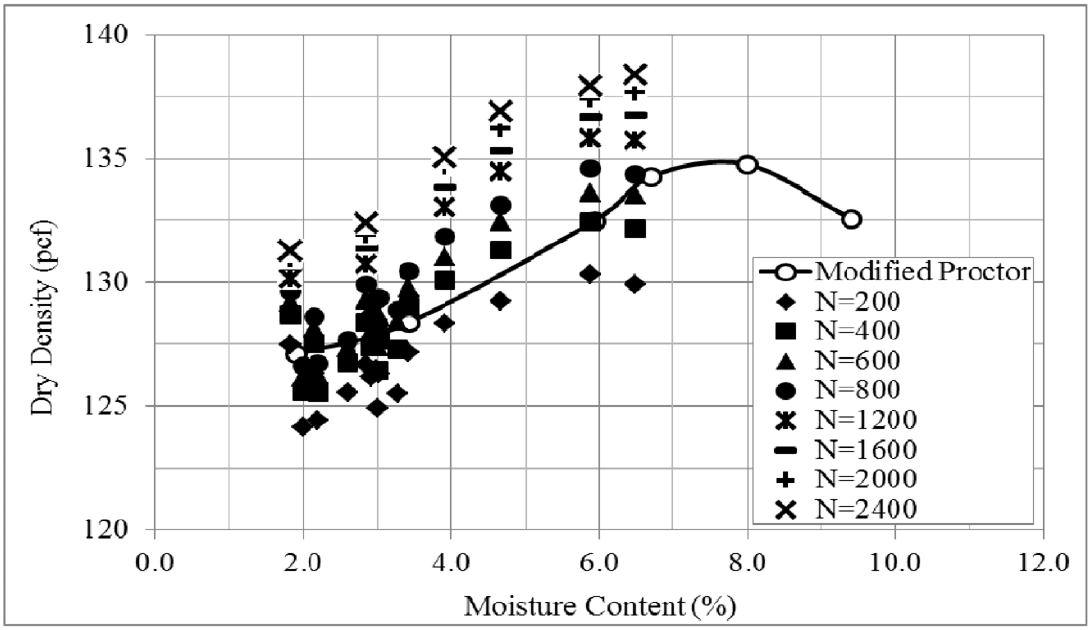

Figure 3. SGC Moisture-Density Relationship for P-154 Material.

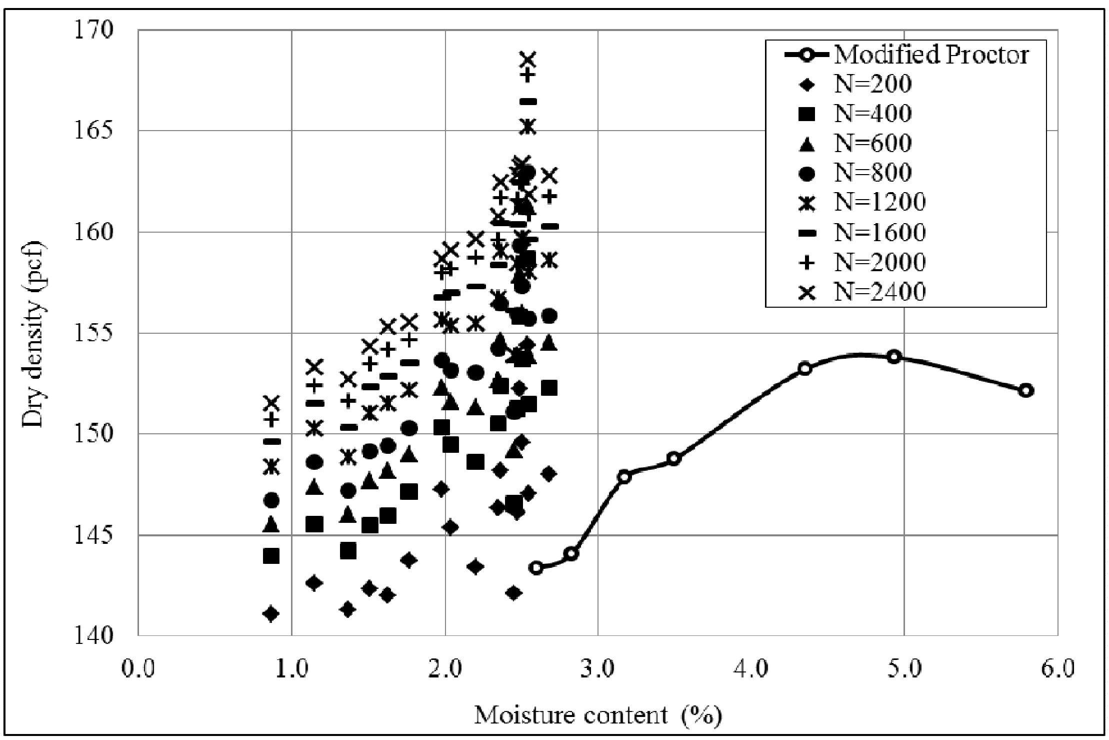

Figure 4. SGC Moisture-Density Relationship for DGA material.

AGGREGATES PERFORMANCE CHARACTERISTICS

Further compaction after construction is heavily influenced by the interlock between particles. Interlocking is affected by particle crushing during construction compaction in the field and subsequent trafficking. According to Ramamurthy et al., there are three different crushing mechanisms of crushing: fracture, attrition, and abrasion [6]. Fracture of a particle occurs when it splits into two or more particles of similar size. Attrition takes place when the particle remains intact with the exception of the sharp points or edges being broken off. Finally abrasion occurs when any part of the particle is removed from the surface, resulting in the production of fines.

Both breakage and rounding of the subbase aggregate appear to lead the material to excessive compaction during trafficking. Any reduction in angularity and therefore interlock allows for the aggregate pieces to move more easily causing particle rearrangement into a denser state than that achieved during construction. Nowadays, as aircraft become heavier and gear configurations become more complex, the potential for aggregate breakage leading to excessive compaction increases. For this reason, there is a great deal of interest in investigating the different particle crushing mechanisms.

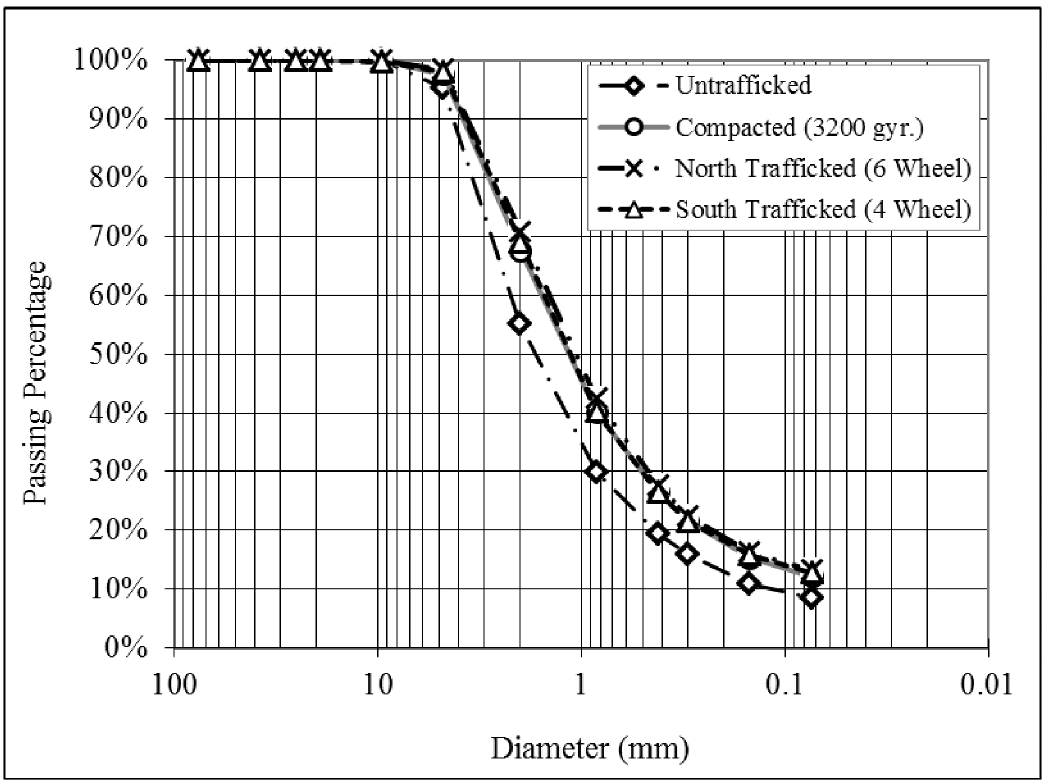

Figure 5. P-154 Grain Size Distribution for Different Compaction Conditions.

The grain size distribution (GSD) following the wash-sieve method was obtained for virgin, compacted, and trafficked P-154 material to evaluate the mechanisms of compaction seen during construction and trafficking. GSD for the virgin material was selected as the baseline for the investigation. The GSD of the trafficked material revealed the presence of 4-5% more fines than the baseline sample. The baseline material was subsequently compacted at 1000 kPa for 3200 gyrations to obtain a compacted material for evaluation. The GSD of this material also produced an increase in fines of 4-5%, which indicates that the mechanism of compaction is the same as that seen in trafficking. Figure 5 shows the GSD curves for each material condition. The figure shows the close relationship of the trafficked and compacted gradation analyses. This further suggests that the shear work imparted by the gyratory action and pressure applied by the SGC may be well-suited for the evaluation of compaction characteristics of trafficking. The increase in fine material indicates that attrition and abrasion of the aggregate took place during trafficking and compaction in the SGC.

LABORATORY VERSUS FIELD COMPACTION

As noted in previous sections, the SGC closely simulates the actual field compaction process during construction due to the shear work imparted by its gyratory action. Therefore, there is a need to develop a rational SGC based approach for estimating the energy per unit volume required in the field to achieve any given moisture-density condition. In order to accomplish this goal, the SGC laboratory test results presented in previous sections were used to characterize the compaction of P-154 and DGA subbase materials.

Preliminary data fitting applying non-linear estimation methods was conducted on P-154 and DGA data to find a suitable mathematical function capable of capturing the moisture-density relation observed in the SGC test results. From observation of the experimental results, it can be concluded that a sigmoid function with intercept reasonably describes the existing relationship. Equation 1 below describes the sigmoid function:

$$DD = \left(a + \frac{b}{1 + \exp\left(- \frac{MC - c}{d} \right)} \right) \qquad (1)$$

where *DD* = dry density; *MC* = moisture content; and *a, b, c, d* = regression parameters.

Moisture-density values from the raw data corresponding to different number of gyrations, *N* were collected for every sample. For every value of *N*, a set of regression parameters for the sigmoidal function was obtained. Linear relationships were found between parameters *a*, *b* and *d*, and the logarithm of *N*. A relationship between *c* and logarithm of *N* was not found for P-154 material. The relationship between *c* and logarithm of *N* for DGA was found to be linear with *c* varying within a relatively narrow range. Therefore, it was decided to leave *c* in the model as a constant.

The linear relationships between the sigmoid parameters and logarithm of *N* were incorporated into the sigmoidal function and global regressions using all data available for each material were conducted. Note that the final moisture-density relationship captures the influence of gyration number as shown in Equation 2:

$$DD = \left((\alpha \log N + \beta) + \frac{(\gamma \log N + \delta)}{1 + \exp\left(- \frac{MC - \mu}{(\varphi \log N + \omega)} \right)} \right) \quad (2)$$

where *DD* = dry density; *MC* = moisture content; and *α, β, γ, δ, μ, φ, ω* = regression parameters.

Figure 6 and 7 show the predictions given by the model in Equation 2 for materials P-154 and DGA respectively. Note that the model fits the data well with adjusted coefficients of determination, R^2_{adj} of 0.955 and 0.944 for P-154 and DGA material respectively. Even when the model does not capture the wet-side of the compaction curve, the predictions are well suited for field conditions as construction specifications for subbase or base layer call for the use of moisture contents about optimum, if not lower than, particularly when dealing with coarse aggregates compacted with modern heavy equipment. Any water exceeding the potential for moisture retention of the aggregate will seep towards the subbase-subgrade interface decreasing the subgrade strength. Thus, the proposed model captures the moisture range of interest in the construction of airfields..

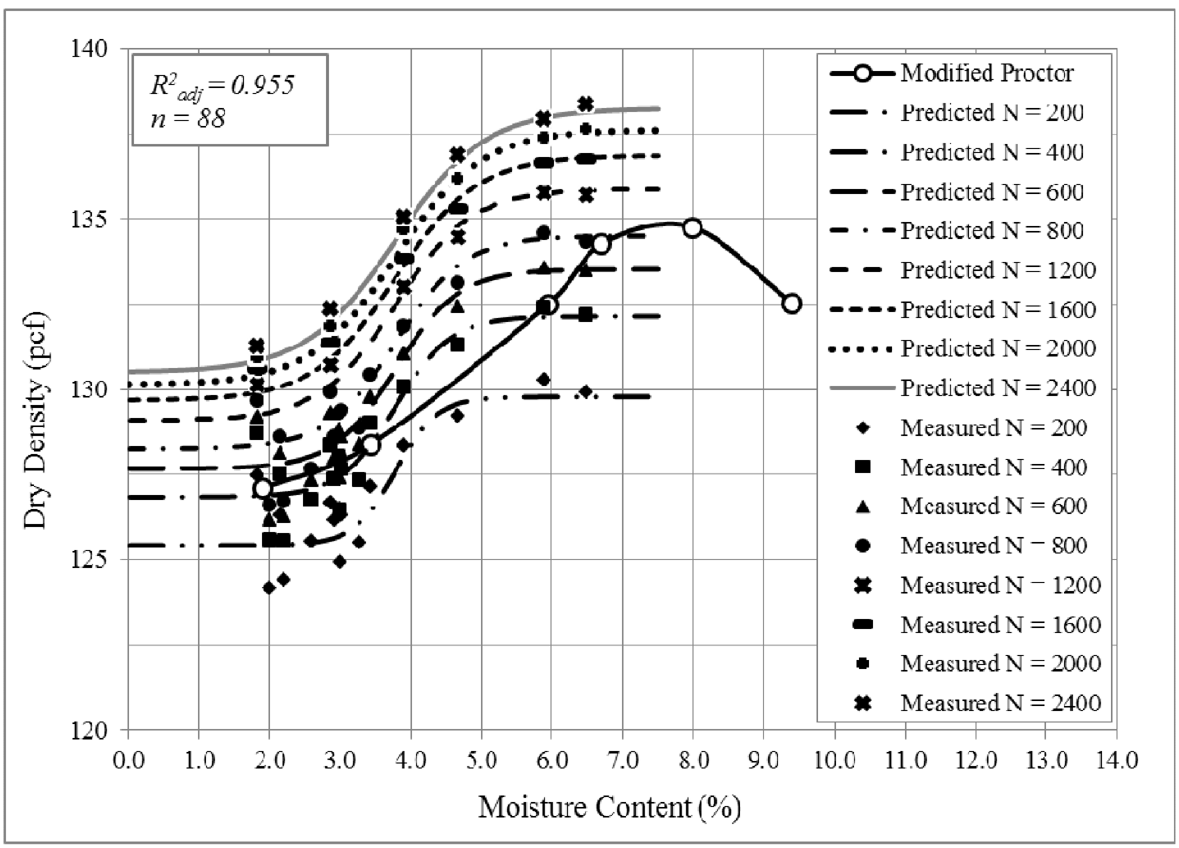

Figure 6. Measured and Predicted Values Using the Proposed Model for P-154 Material.

Table 1 summarizes the global regression constants found for both P-154 and DGA materials. Note that the constants are material dependent. Using these sets of constants, it is possible to determine the number of gyrations, *N* required to achieve any given moisture-density condition in the laboratory.

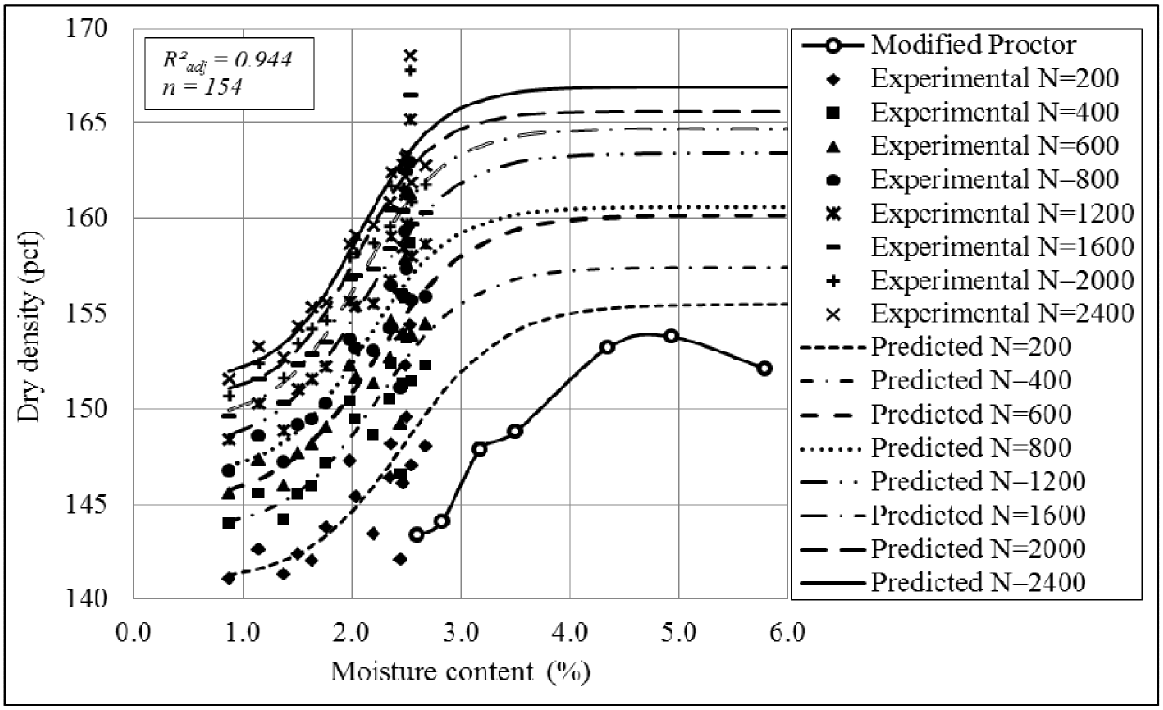

Figure 7. Measured and Predicted Values Using the Proposed Model for DGA Material.

Table 1.
Global Parameters for Equation 2.

Parameter/Material	P-154	DGA
α	4.699	9.297
β	114.619	119.500
γ	3.138	7.063
δ	-2.868	6.170
μ	3.782	2.139
φ	0.317	0.069
ω	-0.435	0.192
n	88	154
R^2_{adj}	0.955	0.944

Compaction energy was measured during the SGC compaction test using the PDA. The data collected during testing was used to obtain a relationship between cumulative total compaction energy and number of gyrations. Note that the total energy is the sum of the vertical and shear energy imparted to the soil specimen during laboratory compaction. In Figures 8 and 9, the relationship between cumulative total compaction energy and number of gyrations is shown for

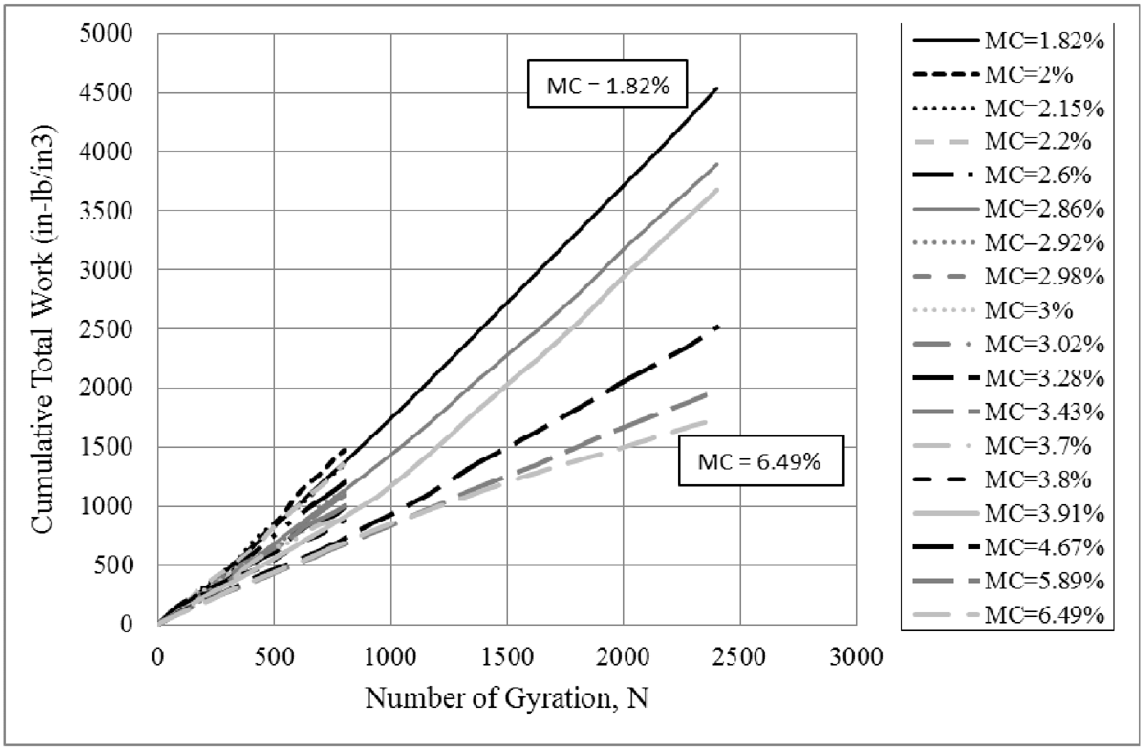

Figure 8. Relationship Between Gyrations and Cumulative Work for P-154 Material

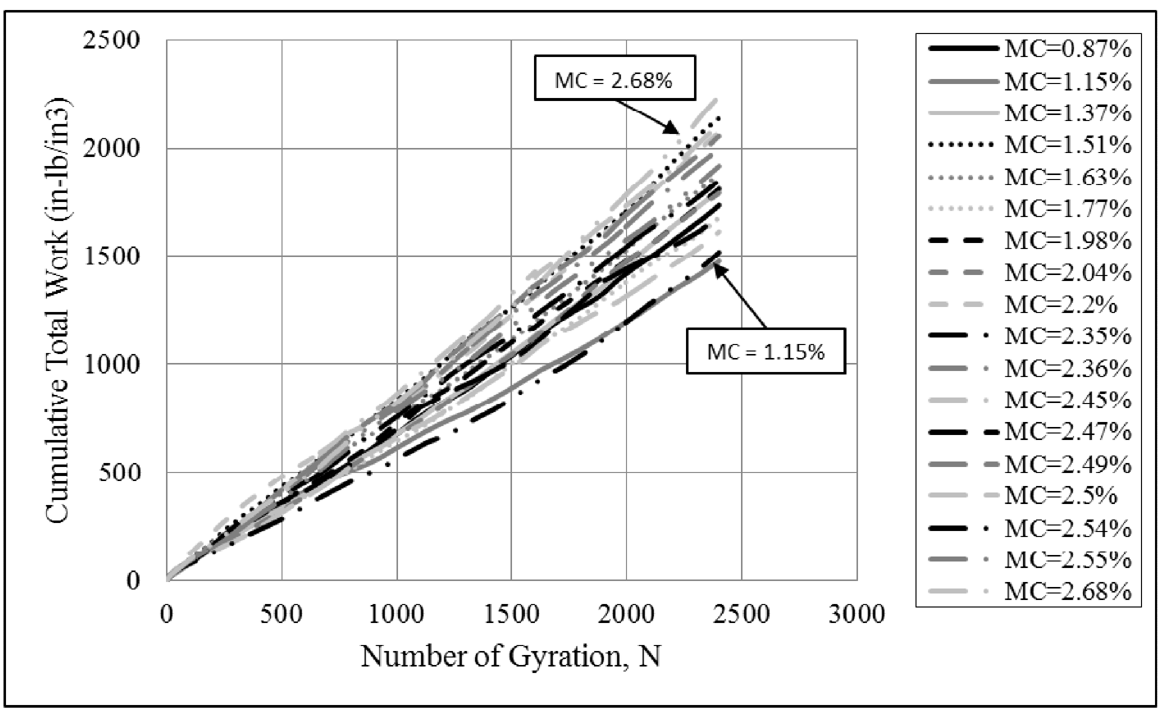

Figure 9. Relationship Between Gyrations and Cumulative Work for DGA Material

P-154 and DGA materials respectively. As observed in Figure 8, the total cumulative energy at any given *N* decreases with increasing *MC* for P-154 material. It is hypothesized that for finer aggregate mixes, higher moisture content allow the aggregates to rearrange into a denser state with less energy. The trend of change in total energy with moisture content for DGA material appears to be opposite to the trend observed for P-154. The higher the water content the higher the total compaction energy at 800 gyrations. However, the rate of increase in energy input with respect to increasing moisture contents in coarse materials such as DGA seems to be insignificant compared to the rate of decrease in energy input with increasing moisture content for finer materials such as P-154.

The near linear relationship between gyrations and total work observed in Figures 8 and 9 are useful for determining an equivalency between laboratory and field compaction energy. By correlating total work input with number of gyrations, it might be possible to control the moisture-density condition in the field provided that a method for quantifying the energy input from rollers is established. The relationships shown in Figures 8 and 9 can be expressed as shown in Equation 3 below:

$$E = \left(p \cdot \ln\left(MC\right) + q\right) \cdot N \qquad (3)$$

where E = cumulative total energy; MC = moisture content; N = gyration number; and p, q = regression constants.

Therefore, once the number of SGC gyrations required to achieve any desired moisture-density condition is estimated using Equation 2 the required field compaction energy can be easily obtained by using Equation 3. The global regression constants p and q for P-154 material were found to be 0.866 and 2.415 respectively. The R^2_{adj} for P-154 was found to be 0.976 based on 88 observations. For DGA material, the global regression constants p and q were found to be 0.076 and 0.708 respectively. The R^2_{adj} for DGA was found to be 0.953 based on 144 observations.

Theoretically, the energy estimated using this SGC based approach should be the same energy required in the field to achieve similar, if not the same, moisture-density condition. A rational method to quantify compaction energy in the field is needed in order to implement this approach.

LABORATORY COMPACTION VERSUS FIELD TRAFFICKING

During trafficking of the CC5 pavement, various gages including Multi Depth Deflectometers (MDD's) were used to monitor the performance. MDD's were located in the subbase and subgrade of the pavement, and the deflection over about 13,000 vehicle passes was measured. Each MDD consisted of six sensors located at different depths within the structure. Each sensor measures the total vertical deflection of the material above the depth to the point where the sensor was installed. Only four out of the seven MDD's installed in test items where P-154 material was used as subbase reported good data for the analysis. These MDD's are: MDD's 3, 4, 10 and 12. In this section, MDD measurements are compared to SGC test results.

All MDD's mentioned above have two sensors located within the subbase layer or at least at the subbase-subgrade interface. The subbase layer compaction was estimated as the deflections difference between these two sensors. In the case of MDD's 3 and 4, this difference reflects the compaction of the subbase for 33 inches of material since the deepest sensor is located at the subbase-subgrade interface and the shallowest sensor is located 1in below the top of a 34in subbase layer. In the case of MDD-10 the compaction obtained corresponds to 19 inches out of a 38 inch subbase layer. For MDD-12, the compaction obtained corresponds to 17 inches out of a 34 inch subbase layer. Figure 10 illustrates pavement cross sections where MDD's were installed. In Figure 10, the actual MDD device is not shown entirely. However, the depth to the points where the deflections were measured within the subbase layer is shown.

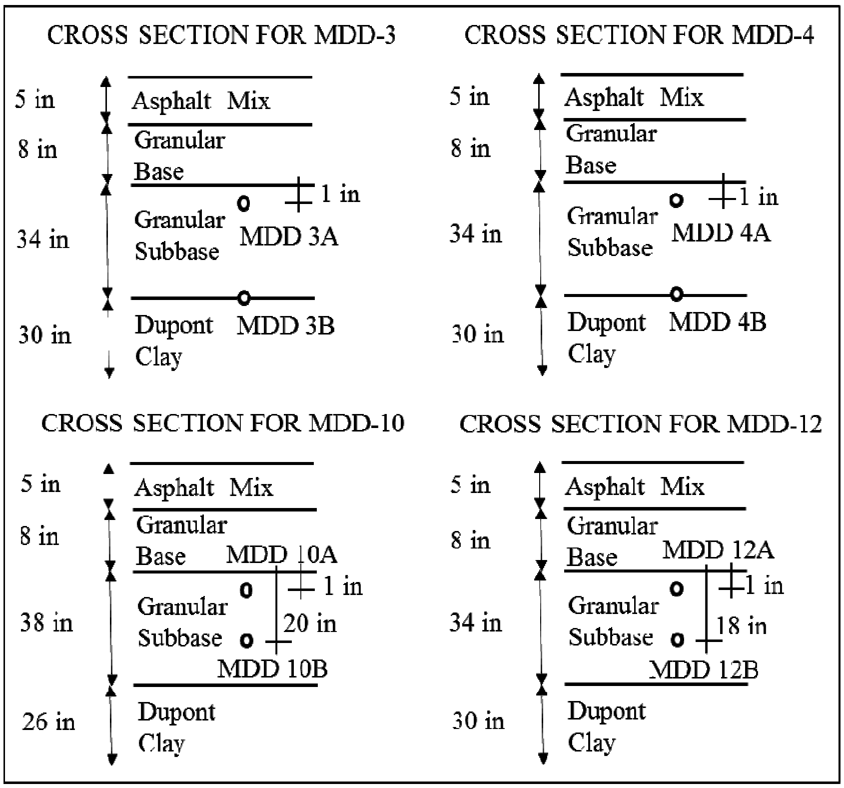

Figure 10. Pavement Cross Sections for the MDD's Used for Comparison with Laboratory Data.

A comparison attempt between field trafficking and SGC vertical deformations is shown in Figure 11. Ideally the number of trafficking events for the field data should be expressed in terms of compaction energy in order to establish an equivalency between the traffic count in the field and the SGC gyrations in the laboratory. In contrast with field testing, the compaction energy was measured during SGC laboratory testing. Figure 11 presents the laboratory compaction of the material in terms of vertical displacement versus cumulative work. Note that only data after the initial compaction was considered for the plot, rather than all of the SGC data. The samples tested in the SGC are virgin material. Only the vertical displacement taking place after the sample reached the construction density measured in the field is plotted. Thus, in Figure 11 trafficking compaction of both laboratory samples and field material started at the same density.

Figure 11 may suggest that the vertical displacement in the field is considerably more than the vertical displacement observed in the laboratory. However, some factors need to be considered before attempting a direct comparison. The moisture content of the material during construction ranged from 2.5 to 3.5%. Therefore it can be considered that most of the laboratory results shown in Figure 11 are comparable to field trafficking in terms of moisture content. In terms of sample size, care should be taken when attempting to compare laboratory versus field results. Laboratory samples were 3 inches height in average while field compaction was measured over thicker layers. Thus, a correction due to sample thickness should be incorporated in order to make results directly comparable.

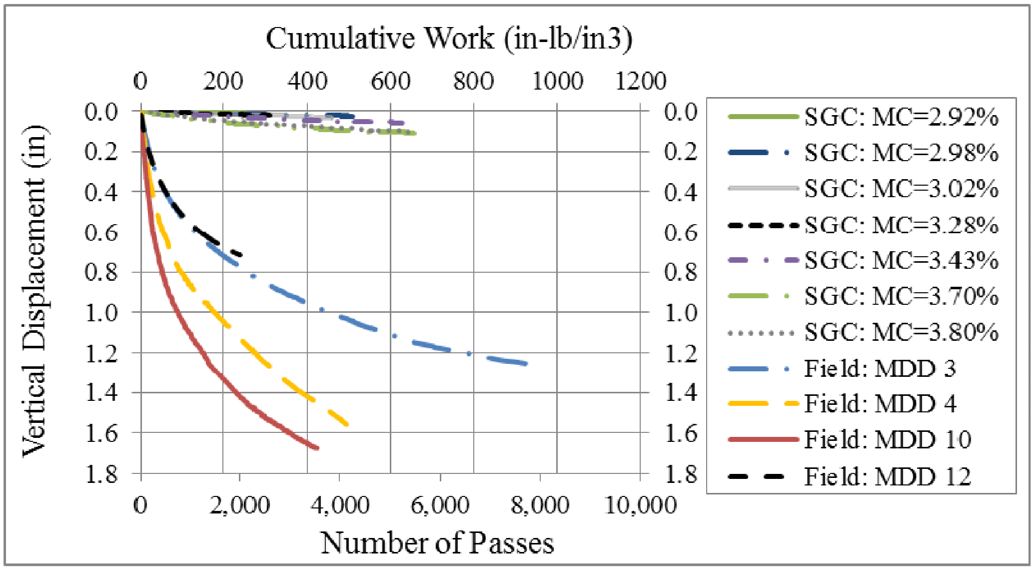

Figure 11. Comparison of SGC Laboratory Test and Field Trafficking Results for Material P-154.

Compaction energy is another parameter to take into account when comparing field versus laboratory test results. It is impossible to establish an equivalency between number of passes in the field and cumulative work measured in the laboratory without first developing a rational method to determine the compaction energy in the field resulting from heavy aircraft traffic. Once a reasonable approach is developed, then it will be feasible to determine the extent to which the laboratory and field compaction curves can be compared. At this point Figure 11 is just referential and more conclusive observations regarding comparability of results will be provided in the future. Even when Figure 11 seems to indicate that SGC and field trafficking results are not directly comparable, it is also true that a thorough evaluation of the factors mentioned above has to be conducted before stating any incompatibility between the SGC test and field trafficking results.

CONCLUSIONS AND RECOMMENDATIONS

A series of SGC compaction tests was conducted on unbound materials used at the NAPTF of FAA as the subbase course. Laboratory test samples at different moisture contents were subjected to the SGC gyratory action using a vertical pressure of 600 kPa. Results indicate that the SGC is capable of achieving higher densities than the Modified Proctor method even at moisture contents lower than optimum conditions. These density levels are similar to those achieved by modern heavy compaction equipment in the field. The use of the SGC over the Modified Proctor method for determining the compaction characteristics of aggregates is recommended. The implementation of SGC-based compaction specifications is expected to minimize excessive compaction observed during pavement trafficking.

The SGC appears to reproduce the compaction mechanism observed in trafficked field samples. Comparison of sieve analysis results on virgin, compacted and trafficked samples indicate that the gyratory action and pressure in the SGC may be well-suited for the evaluation of compaction characteristics resulting from field compaction and trafficking. The increase in the percent of fine fractions suggest that attrition and abrasion are crushing mechanisms occurring during compaction and trafficking in the field as well as during SGC testing.

An energy-based method for predicting aggregates performance during construction using the SGC was proposed. Predictive models for determining the compaction energy required in the field to achieve any desired moisture-density condition in P-154 and DGA materials were presented. A rational approach to determine the equivalency between SGC compaction energy and number of roller passes in the field is needed to fully implement the proposed methodology into practice.

An attempt to compare SGC compaction results with subbase field compaction data collected by MDD's during trafficking was discussed. The compaction observed in the field appears to be much higher than the compaction observed in the laboratory. However, the influence of factors such as sample thickness and confinement conditions need to be investigated before providing conclusive observations. Also, a relationship between traffic count and traffic compaction energy needs to be determined in order to establish parameters for a direct comparison between laboratory and field data.

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