



ALASKA DEPARTMENT OF TRANSPORTATION

Evaluating A Simlified Method To Estimate Compaction Of Soils & Aggregates

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13. ABSTRACT (Maximum 200 words) Southeast Region personnel of the Alaska Department of Transportation & Public Facilities (DOT&PF) have proposed a simplified method for estimating percent compaction of soil, aggregate, and asphalt concrete materials during construction. In simplest terms, percent compaction is obtained by dividing the field-measured dry density of a material by the maximum dry density of that same material, then multiplying the result by 100. Nowadays, field-measured density is usually determined by DOT&PF technicians with a nuclear moisture-density gauge (called nuclear density gauge or densometer in the following text), while the maximum, i.e., target density has been determined using any one of several standardized laboratory compaction tests. The Southeast Region percent compaction calculation proposes that γ_{MAX} might be estimated with reasonable accuracy without performing Alaska DOT&PF's WAQTC* versions of AASHTO** T 99 / T 180 or ATM*** 212 (for soil/aggregate materials) or WAQTC version of AASHTO T 209 (for asphalt concrete materials). The objective of this report is to identify the basic operating characteristics and limitations of the method. The report also addresses the potential for improving, i.e., optimizing the method so that it might consistently provide maximum density values closely matching those determined by standard DOT&PF methods.				
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Evaluating A Simplified Method To Estimate Compaction Of Soils & Aggregates

Statewide Research Section
Department of Transportation
& Public Facilities

Research Technical Note: No. 1

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1 Background & Objectives

Southeast Region personnel of the Alaska Department of Transportation & Public Facilities (DOT&PF) have proposed a simplified method for estimating percent compaction of soil, aggregate, and asphalt concrete materials during construction.

In simplest terms, percent compaction is obtained by dividing the field-measured dry density of a material by the maximum dry density of that same material, then multiplying the result by 100. In equation form:

$$\% \text{ Compaction} = (\gamma_{\text{FIELD}} / \gamma_{\text{MAX}}) \times 100$$

Where: γ_{FIELD} and γ_{MAX} are, respectively, the field-measured dry density and laboratory-determined maximum density (DOT&PF usually uses units of lbs/ft³ for density).

Nowadays, field-measured density is usually determined by DOT&PF technicians with a nuclear moisture-density gauge (called nuclear density gauge or densometer in the following text), while the maximum, i.e., target density has been determined using any one of several standardized laboratory compaction tests. The Southeast Region percent compaction calculation proposes that γ_{MAX} might be estimated with reasonable accuracy without performing Alaska DOT&PF's WAQTC* versions of AASHTO** T 99 / T 180 or ATM*** 212 (for soil/aggregate materials) or WAQTC version of AASHTO T 209 (for asphalt concrete materials).

* WAQTC is the Western Alliance for Quality in Transportation Construction organization that regulates standard materials testing methods in Alaska and several other western states.

** American Association of State Highway and Transportation Officials

*** Alaska Test Method

The Southeast Region asserts that maximum densities can be estimated using field dry density and voids data collected during nuclear density gauge testing and perhaps one or more other known material properties such as aggregate specific gravity. To date, the Southeast Region calculation has calculated maximum densities using one of the following equations depending on material type:

Equation 1 $\gamma_{\text{MAX}} \text{ lbs/ft}^3 = [(\% \text{ voids}^*) \times (\text{air void ratio}^*) \times (\text{coarse aggregate specific gravity})] + (\text{field dry density}^*)$

— or —

Equation 2 $\gamma_{\text{MAX}} \text{ lbs/ft}^3 = [(\% \text{ voids}^*) \times (\text{air void ratio}^*)] + (\text{field dry density}^*)$
* indicates nuclear gauge test data.

Where * : % Air Voids = $100 \times (1 - (\text{vol. soil} / \text{total vol.}) - (\text{vol. water} / \text{total vol.}))$
Void Ratio = $((\text{Sp.G. of soil particles} \times \text{water density}) - \text{field dry density}) / \text{field dry density}$

* Defined by Troxler Electronic Laboratories, Inc. in the edition 8.1 (2006) operator's manual for the Troxler Model 3430 nuclear moisture-density gauge

According to Southeast Region personnel, Equation 1 appears to work best for estimating maximum densities of well graded soils and asphalt concrete aggregate materials containing significant amounts of fine particles, i.e., mass fraction passing the # 200 sieve. Such materials tend to be sensitive to the fluids (water or asphalt cement) content during compaction. Such materials might include gravel surfacing, silty embankment fill, and asphalt concrete aggregate. Maximum density for soils of this type is usually determined using the AASHTO T 99 or T 180 "Proctor" method. AASHTO T 209, the "Rice" method is used to determine the maximum density of asphalt concrete mixes.

Similarly, Equation 2 appears to apply to certain manufactured aggregates and soils exhibiting coarser gradations that are insensitive to fluids content during compaction. Such materials might include open-graded base courses and low-fines embankment fill. Maximum density for soils or aggregates of this type is usually determined using the ATM 212. The ATM 212 method employs a vibratory "hammer" for compacting material into a standard mold instead of the impact-type hammers used in the T 99 and T 180 Proctor methods.

Does such a simple computational method have merit? The method seems to "work" to the extent that calculated maximum densities are sometimes very close or equal to maximum density values obtained by standard laboratory methods. Other times calculated and laboratory maximum densities have been shown to differ by $\pm 6 \text{ lbs/ft}^3$ or more. Initial investigation stalled when the method could not be easily "explained" in an engineering sense based on volumetric analysis.

The objective of this report is to identify the basic operating characteristics and limitations of the method. The report also addresses the potential for improving, i.e., optimizing the method so that it might consistently provide maximum density values closely matching those determined by standard DOT&PF methods.

2 Methods

2.1 Use of Statistics

Statistics methods provided the framework within which the Southeast Region's method could be understood, discussed, and (hopefully) improved. Statistics were used to quantify the method's accuracy. Statistics also shed light on some of the method's inherent problems.

Why were statistical methods so relevant to this study? The units of the multiplied variables in the above equation are computationally inconsistent with the lbs/ft^3 units of the added or computed density. The authors recognized that regression analysis might be a good tool for evaluating empirical equations with inconsistent units. Of course equations derived using regression techniques do not necessarily require any consistency of units. Regression equations simply rely on the quality of correlations between the predictor variables and predicted variables.

Using standard regression methods, one derives an equation between the variable to be predicted (dependent variable) and the one or more predictor variables (independent variables) that are used to estimate the dependent variable. More specifically, the *dependent* variable, usually designated “y”, is the *predicted* value in a regression equation—in this case = γ_{MAX} . One or more *independent* “x” variables are the *predictors*—in this case = voids, γ_{FIELD} , specific gravity, etc. The general form of a linear regression equation with multiple independent “x” variables is:

Equation 3 $Y = A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + \dots + A_iX_i + B$
Where : $A_1 \dots A_i$ = regression coefficients, derived by analysis
 $X_1 \dots X_i$ = predictor variables
B = regression constant, derived by analysis

Notice that Equation 1 can be converted to the format of Equation 3 if we define:

$$X_1 = [(\% \text{ voids}) \times (\text{air void ratio}) \times (\text{coarse aggregate specific gravity})]$$

$$X_2 = \gamma_{FIELD}, A_1 = 1, A_2 = 1, \text{ and } B = 0$$

Therefore: $Y = A_1X_1 + A_2X_2 + B$ or $Y = 1X_1 + 1X_2 + 0$ or $Y = X_1 + X_2$

And finally: $\gamma_{MAX} \text{ lbs/ft}^3 = [(\% \text{ voids}) \times (\text{air void ratio}) \times (\text{coarse aggregate specific gravity})] + (\gamma_{FIELD})$

Recognize that Equation 1 is defined as a linear regression equation even though the X_1 variable results from multiplying together 3 other variables.

Detailed explanation of the regression analysis process is beyond the scope of this report. Any statistics text that covers regression principles through the basics of linear multiple regression would treat the subject to more than sufficient depth. Recommended reading is: Berk and Carey's, *Data Analysis with Microsoft Excel*, Brooks/Cole, 2004. Statistical analyses for this project were done using Microsoft Excel 2002 including the StatPlus statistical “add-in” described in the Berk & Carey text.

The gist of this report can be followed by anyone even vaguely familiar with regression analysis without reference to statistics books. However, two concepts (regression residuals and R^2 values) are very important to understanding this report. These concepts are presented here for the reader's convenience.

Residual — A residual is the difference between the y-value predicted by a regression equation and the actual y-value. In generating a regression equation, the regression coefficients ($A_1 \dots A_i$) and regression constant (B) are selected so that the sum of the squares of the residuals from the actual y-values of the regression data set is minimized. Such a regression equation is said to best-fit that data set. Most regression analysis programs provide a table of residual values for each case in the data set used to generate the regression equation, i.e., a list of differences between the actual y-value for that case and the calculated

y-value for that case. In a well behaved regression equation, the statistical distribution of the residual values should be normal with a mean of zero.

Residuals are used to quantify the precision of the regression equation estimate. For example, if the statistical distribution of the residuals has a standard deviation = 2 lbs/ft³, then the expected precision of the regression will be approximately $\pm 2 \text{ lbs/ft}^3 \times 3 = \pm 6 \text{ lbs/ft}^3$. Remember that nearly 100% of values are contained within about ± 3 standard deviations if the values are normally distributed. Assuming the $\pm 6 \text{ lbs/ft}^3$ precision indicated in this example, we would say that a regression equation result of 145 lbs/ft³ should be stated more properly as $145 \pm 6 \text{ lbs/ft}^3$. Or, we can say that the actual value will probably lie somewhere between 139 and 151 lbs/ft³. Analysis of residuals was very important in this study.

R² — An R² value is derived for each regression equation. In simple terms, the R² value (coefficient of determination) defines the general quality of the regression equation. R² ranges in value from 0 to 1. An R² = 0 indicates that the one or more independent x-values have no functional relationship to the dependent y-value. If R² = 0, the regression equation does not fit the data and is therefore of no use. If R² = 1, the regression equation provides essentially a perfect functional relationship (fit) between y and x variables, and the regression equation may be very useful. Viewed a different way, the R² quantifies how much of the variation in the data set's dependent variables (in this study, laboratory maximum density) is accounted for by the regression equation. An example of the latter definition would be to say that a regression equation having an R² of 0.45 accounts for about 45% of the variation of the actual dependent y-value, leaving 100% – 45%, i.e., 55% of the variation unexplained. Obviously a regression equation with an R² of 0.45 provides a poor fit to the real data. Many statisticians consider that an R² of less than say .85 to .90 indicates a poor fit between regression equation values and the real world.

2.2 Analytical Approach

The authors are fully aware that neither Equation 1 nor Equation 2 were derived by performing formal regression analyses. Equations 1 and 2 were developed from observation and study of available data sets followed by trial and error combining of data variables into equations with the objective of predicting maximum density (γ_{MAX}). To test the hypothesis that Equations 1 and 2 are operating like regression equations:

1. A multiple linear regression equation (Equation 4) was developed using the same “training” data used by Southeast Region personnel to develop their equations. The data set contained 379 samples (cases). All cases used in this study were for soils and aggregate materials. A few cases representing asphalt concrete materials were available but were not used in this study.
2. The computational capabilities and general operating characteristics of the regression equation were compared with those of the Southeast Region equations. Both methods were found to function almost identically.

The 379-case data set is not included with this report. A Microsoft Excel file of these data can be obtained at the 2301 Peger Road office of DOT&PF's Research section, from Mr. Clint Adler, acting Statewide Research Manager (Contact: 907-451-5321 or clint_adler@dot.state.ak.us).

Each case contains the following eight (8) variables:

1. % Air Voids—measured in the field using a nuclear densometer
2. Air Void Ratio—measured in the field using a nuclear densometer
3. Coarse Aggregate Specific Gravity—determined in the laboratory
4. Field Dry Density (γ_{FIELD})—measured in the field using a nuclear densometer
5. Actual Maximum Density (γ_{MAX})—determined in the laboratory
6. Actual % Compaction—calculated from field and laboratory data as
7. Maximum Density (γ_{MAX})—calculated using Southeast Region's method
8. % Compaction—calculated using Southeast Region's γ_{MAX} .

Variables 1, 2, 3, 6, and 8 are dimensionless. Units for variables 4, 5, and 7 are lbs/ft³.

The authors were able to establish an equivalency between their regression equation and the Southeast Region's method. This finding made it possible to evaluate and discuss the Southeast Region's method in the same way one would evaluate and discuss any regression equation. Using this approach, the authors addressed the question of whether the Southeast Region's method can reliably estimate percent compaction determined by standard methods. Following along this line of reasoning and analysis, the authors were able to address the possibility of improving the method.

It is significant that the authors developed a single regression equation, Equation 4, for estimating γ_{MAX} . Equation 4 is a "best-fit" for the entire 379-case data set. On the other hand, the Southeast Region developed two separate equations (Equations 1 and 2) to address different materials types within the data set. Initially, the authors thought that two regression equations might be necessary to cover the entire data set. However, the single regression equation proved to be reasonably equivalent to both of the Southeast Region equations at estimating values of γ_{MAX} throughout the entire data set. Use of one regression equation reduced the amount of work in the following analysis.

3 Analysis

3.1 Correlations & Regression

A regression equation was necessary for calculating γ_{MAX} . This task began by examining correlations between available data set variables and γ_{MAX} . Table 1 provides a matrix of Pearson's Correlation coefficients created using Microsoft Excel. It is a simple matter to compare the correlation coefficients between column 5 (actual γ_{MAX} = dependent variable = y) and the few perspective independent variables. Variables having the highest correlations with γ_{MAX} were selected as independent (x) variables for the regression equation. In Table 1, the

higher the absolute value of the correlation coefficient, the better the correlation between the two variables. An absolute value approaching zero indicates no correlation between the variables.

In Table 1, variables in columns 1 (% air voids), 3 (coarse aggregate specific gravity), and 4 (field density) are best correlated with γ_{MAX} of column 5. These correlation coefficients are -0.59362, 0.647409, and 0.930311 respectively. Column 2 (air void ratio) exhibits a correlation coefficient of only -0.03253, about an order of magnitude lower than the others. The negative coefficient between % air voids and γ_{MAX} (-0.59362) indicates an inverse correlation where increasing % air voids predicts decreasing γ_{MAX} .

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Column 1	1					
Column 2	0.019088	1				
Column 3	-0.51525	-0.05416	1			
Column 4	-0.67849	-0.0763	0.561425	1		
Column 5	-0.59362	-0.03253	0.647409	0.930311	1	
Column 6	-0.42389	-0.12715	-0.01965	0.493996	0.141265	1
	% air voids	air void ratio	coarse agg.Sp. G.	field density	actual max. density	actual % comp.

Table 1. Correlation table (Microsoft Excel output)

Independent variables selected for use in the regression equation were obviously:

$$\begin{aligned} X_1 &= \% \text{ Air Voids} \\ X_2 &= \text{Coarse Aggregate Specific Gravity} \\ X_3 &= \text{Field Density} \end{aligned}$$

A multiple regression analysis was performed using Microsoft Excel's Data Analysis tools. The resulting regression equation is of the form: $Y = A_1X_1 + A_2X_2 + A_3X_3 + B$, or specifically:

Equation 4 $\gamma_{MAX} \text{ lbs/ft}^3 = (0.165 \times \% \text{ voids}) + (25.6 \times \text{coarse aggregate specific gravity}) + (0.820 \times \text{field density}) - 44.2$

Table 2 contains the statistical summary of Excel's regression analysis.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.946496
R Square	0.895855
Adjusted R Square	0.895022
Standard Error	2.261458
Observations	379

ANOVA					
	df	SS	MS	F	Significance F
Regression	3	16497.05832	5499.019	1075.246	9.408E-184
Residual	375	1917.822945	5.114195		
Total	378	18414.88127			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-44.2378	6.800132486	-6.50544	2.48E-10	-57.6090072	-30.8666789	-57.60900717	-30.86667892
X Variable 1	0.164807	0.031671803	5.203584	3.23E-07	0.102530334	0.227083459	0.102530334	0.227083459
X Variable 2	25.59333	2.559964036	9.997537	5.11E-21	20.55965332	30.62701579	20.55965332	30.62701579
X Variable 3	0.819833	0.022029044	37.216	5.8E-128	0.776516981	0.863148813	0.776516981	0.863148813

Table 2. Regression equation statistics (Microsoft Excel output)

Table 2 identifies the coefficients of the regression equation and indicates that the equation itself provides a statistically valid estimate of γ_{MAX} . Several of the values contained in Table 2 are worthwhile discussing. An $R^2 \approx 0.90$ was achieved for the regression equation, i.e., a fairly solid correlation. The slightly lower “Adjusted R Square” compensates for the fact that the regression uses more than one independent variable. The “Standard Error” addresses the expected precision of the regression equation. For this analysis it indicates that the real value of γ_{MAX} is expected to lie within about ± 2.3 lbs/ft³ of the calculated value about half of the time. It is not necessary to explain the “ANOVA” portion of Table 2 except that the **AN**alysis **Of** **VA**riance indicates the ability of the regression to estimate the actual γ_{MAX} is significant—in other words, the equation is meaningful. The “Coefficients” column of the bottom part of Table 1 displays the A_1 (0.165), A_2 (25.6), A_3 (0.820), and B (-44.2) coefficients used in Equation 4. The remaining columns at the bottom of Table 2 indicate that these coefficients are statistically valid.

3.2 Characterizing the Southeast Region’s Method

Having identified a statistically valid regression equation, the authors compared its operational characteristics to those of the Southeast Region’s method.

3.2.1 Calculating Maximum Density (γ_{MAX})

Calculating γ_{MAX} is the first step in calculating % compaction. Compare the Southeast Regions calculation of γ_{MAX} to γ_{MAX} calculated with the regression equation. Figures 1 and 2 provide this comparison. Figure 1 plots actual (laboratory) γ_{MAX} against γ_{MAX} calculated using the Southeast Region’s method (note that the pcf = lbs/ft³ in Figures 1, 2 and 3). Figure 2 plots actual (laboratory) γ_{MAX} against the regression equation γ_{MAX} . In both figures we are interested in the amount of scatter in the calculated γ_{MAX} values (y-values) with respect to actual γ_{MAX} (x-value). A best-fit line through the data points is provided for both figures. Both methods of calculating γ_{MAX} provide very similar results. This is obvious through visual

inspection as well as by the quantitative quality of correlation between actual and calculated value (note the $R^2 = 0.90$ for in both figures).

The statistical variation of the residuals in both figures (the y-distances between data points and the best-fit line) are normally distributed with a means of about zero about the best-fit lines. Because the vertical distribution of the data points is normal, calculated values of γ_{MAX} are expected to predict actual γ_{MAX} with a precision that can be guaranteed to be no better than about ± 3 standard deviations. In this case, since 1 standard deviation = 2.13 lbs/ft³ in both Figures 1 and 2, the expected precision of ± 3 standard deviations = ± 6.4 lbs/ft³.

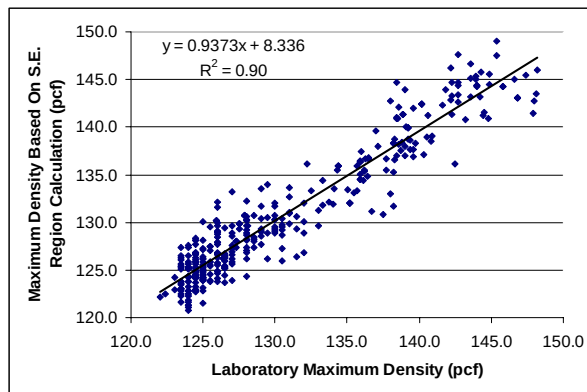


Figure 1. Actual Vs. S.E. calculation γ_{MAX}

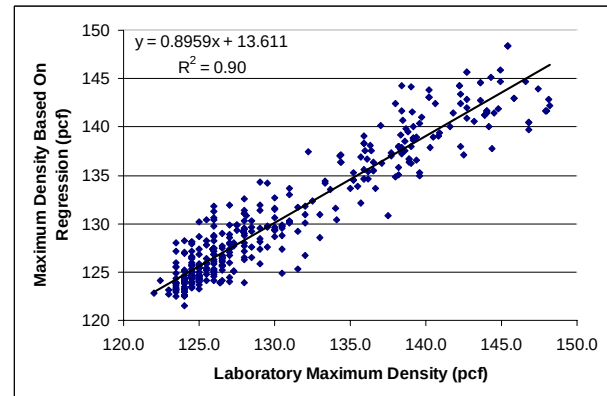


Figure 2. Actual Vs. regression equation γ_{MAX}

Table 3 tabulates a comparison between the Southeast Region and the regression methods of calculating γ_{MAX} . Table 3 shows minor differences but leaves no doubt that both methods operate almost identically.

Calculated Maximum Density Ranges Compared to Actual Values – Based on Observed Variation Shown in Figures 1 and 2

	If <u>Actual</u> Maximum Densities Are:		
	125 pcf	135 pcf	145 pcf
S.E. Region Calculation Will Produce:	A range of 119.1 – 131.9 pcf	A range of 128.5 – 141.3 pcf	A range of 137.8 – 150.6 pcf
Regression Equation Will Produce:	A range of 119.2 – 132.0 pcf	A range of 128.2 – 141.0 pcf	A range of 137.1 – 149.9 pcf

Table 3. Expected ranges of calculated γ_{MAX} given actual γ_{MAX} values

Although both methods provide equivalent “ballpark” estimates of actual γ_{MAX} , the poor precision of the estimate is quantifiable. For example, Table 3 shows that for an actual γ_{MAX} of 135 lbs/ft³, computed values using either method are expected to range between 128 + lbs/ft³ and 141 + lbs/ft³.

Notice also for actual γ_{MAX} values as far apart as say 135 and 145 lbs/ft³, the calculated values can actually overlap. For example (see Southeast Region data in Table 3) if the actual density is 135 lbs/ft³ the calculated value can run as high as about 141 lbs/ft³ and for an actual density of 145 lbs/ft³, the calculated value may run as low as about 138 lbs/ft³. These ranges overlap by about 3 lbs/ft³. Table 3 indicates that the regression equation method can produce similar overlap. Table 3 data shows that it is not possible to discriminate between actual densities of 125 and 135 lbs/ft³ or between actual densities of 135 and 145 lbs/ft³.

It is a simple matter to define precision in terms of other ranges. Above we defined precision in terms of a ± 3 -standard deviation (± 6.4 lbs/ft³) range. The wide ± 3 -deviation range allows us to say with almost 100% certainty that the actual value of γ_{MAX} lies somewhere within ± 6.4 lbs/ft³ of the calculated γ_{MAX} value. Table 3 demonstrates use of this range with real numbers. A narrower ± 0.67 standard deviation range allows us to say with 50% certainty that the actual value of γ_{MAX} lies within only $\pm 0.67 \times 2.13 \approx \pm 1.4$ lbs/ft³ of the calculated value.

So far the subject of discussion has primarily been precision, i.e., in this study the expected $\pm$ scatter of actual values above and below a calculated value. However, accuracy is another matter of concern. With reference to Figures 1 and 2, the Southeast Region and regression methods would be perfectly accurate only if the best-fit lines ($y = Ax + B$) shown on the figures were of the form $y = x$, thus indicating a 1:1 functional correspondence. Of course this requires that $A = 1$ and $B = 0$. Evidence of the slight inaccuracies of Southeast Region and regression calculations of γ_{MAX} are apparent in the ranges of values listed in Table 3. Notice that the calculated ranges are not perfectly centered on actual γ_{MAX} values shown at the top of Table 3.

Above we compared calculated γ_{MAX} values with actual values. We now directly compare γ_{MAX} calculation of the Southeast Region with the γ_{MAX} calculation of the regression equation. Figure 3 provides a plot of this relationship. The R^2 of 0.96 indicates a very strong correlative relationship between the two methods of calculation. Correlation between the two γ_{MAX} calculation techniques is in fact significantly higher than between either technique and the actual γ_{MAX} . It is correct to say that the computation methods are significantly better at predicting one another than they are at predicting actual γ_{MAX} .

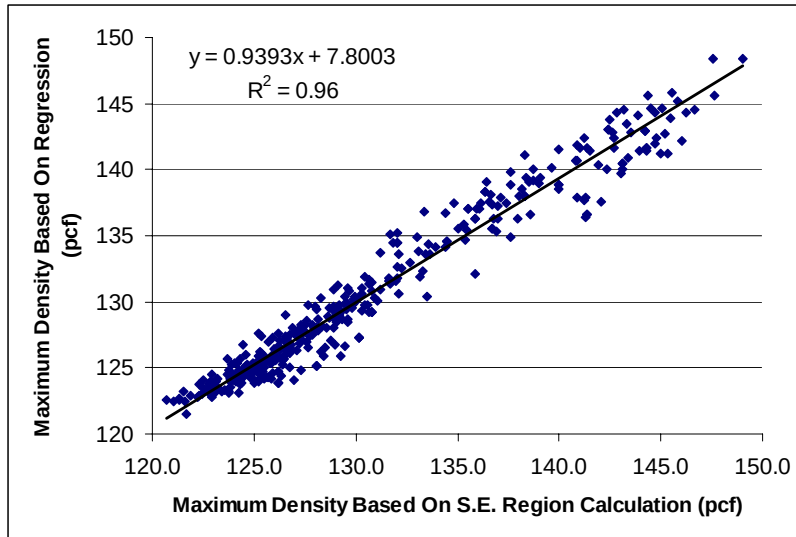


Figure 3. S.E. Region calculated Vs. regression equation γ_{MAX}

As previously done for Figures 1 and 2, Figure 3 information is summarized in Table 4. The statistical variation of the residuals in Figure 3 (the y-distances between data points and the best-fit line) is normally distributed with a mean of about zero about the best-fit line. A standard deviation of only about 1.37 characterizes the vertical spread of data points in the y-axis direction. Because the vertical distribution of the data points is normal, calculated values of γ_{MAX} are expected to predict regression equation values of γ_{MAX} with a precision that can be guaranteed to no better than about ± 3 standard deviations. Since 1 standard deviation = 1.37 lbs/ft³ in Figure 3, the expected precision of ± 3 standard deviations is therefore $\approx \pm 4.1$ lbs/ft³.

Table 4 summarizes the relationship depicted in Figure 3. For example, Table 4 shows that if the Southeast Region's calculated $\gamma_{MAX} = 135$ lbs/ft³, the regression equation is expected to produce a γ_{MAX} somewhere 130.5 and 138.7 lbs/ft³.

Regression Equation Maximum Density Ranges Compared to Calculated Values Using the S.E. Region Method – Based on Observed Variation Shown in Figure 3

	If Calculated Maximum Densities Using S.E. Region Method Are:		
	125 pcf	135 pcf	145 pcf
Regression Equation Will Produce:	A range of 121.1 – 129.3 pcf	A range of 130.5 – 138.7 pcf	A range of 139.9 – 148.1 pcf

Table 4. Comparing S.E. Region Vs. regression calculated γ_{MAX} values

The preceding analysis indicates:

1. The Southeast Region and regression methods for estimating actual γ_{MAX} are roughly equivalent to one another.
2. Neither method can be counted on to estimate actual γ_{MAX} with a precision of better than about ± 6 lbs/ft³.

3. The Southeast Region and regression equation calculations predict one another more precisely than either method can predict actual γ_{MAX} .

3.2.2 Calculating % Compaction

Now we will compare Southeast Region and regression equation estimates of actual % compaction. Figures 4 and 5 compare actual % compaction versus calculated values of % compaction. Figure 4 plots actual % compaction versus % compaction estimated by Southeast Region's calculations. Figure 5 plots actual % compaction against % compaction estimated with the regression equation. Obviously interesting is the large amount of scatter and similar scatter patterns seen in the data of both figures. Low R^2 values for best-fit lines in Figures 4 and 5 (both less than 0.50) confirm and quantify the visual observation that both methods of calculating % compaction are similarly poor estimators of actual % compaction.

The statistical variation of the residuals in both figures (the y-distances between data points and the best-fit line) are normally distributed with a means of about zero around the best-fit lines. Because the vertical distribution of the data points is normal, calculated values of % compaction are expected to predict actual % compaction to a precision of no better than about ± 3 standard deviations. Standard deviations for the Southeast Region and regression equation calculation of % compaction are about 1.34% and 1.03% respectively. The Southeast Region's method can be expected therefore to estimate the actual % compaction with precision of about $\pm 3 \times 1.34\% \approx 4.1\%$. By similar calculation, the regression is expected to estimate actual % compaction to within about $\pm 3.1\%$.

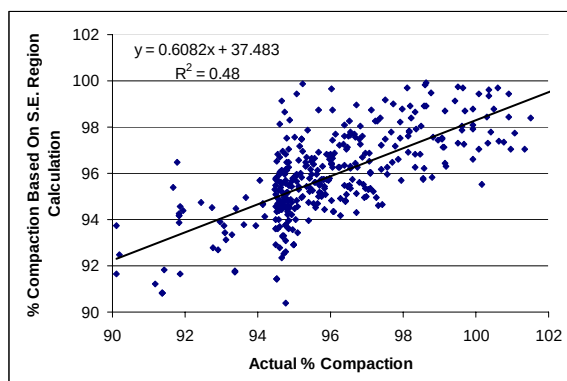


Figure 4. Actual Vs. S.E. Region's % compaction

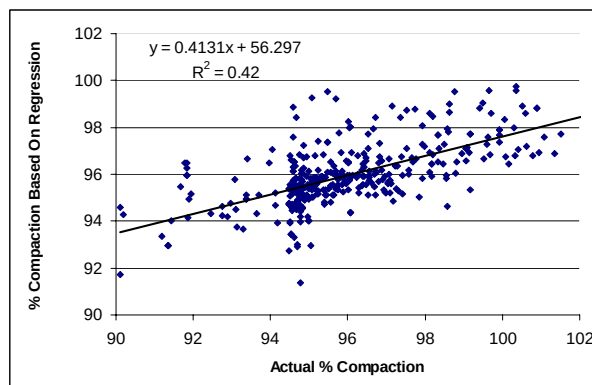


Figure 5. Actual Vs. regression equation % compaction

Table 5 tabulates the comparison between the Southeast Region and the regression methods of calculating % compaction. As in Table 3, Table 5 shows minor differences but leaves no doubt that both methods operate nearly identically.

Calculated % Compaction Ranges Compared to Actual Values – Based on Observed Variation Shown in Figures 4 and 5			
	If Actual % Compactions Are:		
	92%	96%	100%
S.E. Region Calculation Will Produce:	A range of 89.4 – 97.4%	A range of 91.9 – 99.9%	A range of 94.3 – 102.3%
Regression Equation Will Produce:	A range of 91.2 – 97.4%	A range of 92.9 – 99.1%	A range of 94.5 – 100.7%

Table 5. Expected ranges of calculated % compaction given actual % compaction

As with calculation of γ_{MAX} , both methods provide rough estimates of actual % compaction, and the poor precision of the estimate is again quantifiable. For example, Table 5 shows that for an actual compaction of 96%, Southeast Region computed values may range from as low as 91.9% to as high 99.9%.

A narrower ± 0.67 standard deviation range allows us to say with 50% certainty that the actual value of % compaction lies within only $\pm 0.67 \times 1.34 \approx \pm 0.9\%$ of the calculated value for the Southeast Region's calculation, and within $\pm 0.67 \times 1.03 \approx \pm 0.7\%$ of the calculated value for the regression equation.

Accuracy in estimating % compaction is worse than for estimating γ_{MAX} . In Figures 4 and 5 notice that the best-fit lines do not approach the $y = x$ ideal (where $A = 1$ and $B = 0$). Most of the ranges listed in Table 5 are off-center by 1% or more with respect to actual values shown at the top of the table.

Again as in Table 3, notice that the calculated ranges of % compaction overlap. Table 5 indicates that it may not be possible to discriminate between actual values of 96% and 100% compaction. Ranges of calculated values for the Southeast method shown in Table 5 indicate that an actual compaction of 96% may be estimated as high as 99.9 and that an actual value of 100% may be estimated as low as 94.3%.

The preceding analysis indicates:

1. The computational methods for estimating % compaction are roughly equivalent to one another.
2. Neither method can estimate % compaction with a precision of better than about ± 3 or 4%.

4 Discussion

4.1 *Estimated Versus Actual Values*

DOT&PF's WAQTC testing standards require that percent compaction be determined based on standard laboratory and field methods and reported within certain limits of precision. For example, soil/aggregate density is calculated and reported to the nearest 0.1 lbs/ft³.

Soil/aggregate compaction is calculated to the nearest 0.1 percent and reported to the nearest 1 percent. Similar calculation and reporting precision is required for asphalt concrete materials.

Analysis indicates:

1. The operating characteristics of Southeast Region's empirical method can be reasonably simulated by a simple linear multiple regression equation with three independent variables.
2. The actual value of γ_{MAX} may differ by as much as ± 6.4 lbs/ft³ from calculated values. The difference between calculated and actual γ_{MAX} will be within ± 1.4 lbs/ft³ no more than 50% of the time.
3. The actual value of % compaction may vary as much as $\pm 4.1\%$ (Southeast Region method) or $\pm 3.1\%$ (regression method) from the calculated value. The difference between calculated and actual % compaction will be within $\pm 0.9\%$ (Southeast method) and $\pm 0.7\%$ (regression method) no more than 50% of the time.
4. A very low R^2 (< 0.5) was found between calculated and actual % compaction, based on the 379-case data set available for this research effort.

4.2 *Does the Method Make Sense?*

Can nuclear densometer measurements be used as a basis to predict the unit weight of a soil or aggregate in its densest state? One major problem with any such assumption is that a standardized compaction method plays no part in estimating maximum density. In other words, densometer readings are obtained after an unknown amount of compaction has taken place.

How well compacted is the soil at the time of the densometer measurement? The following variables are known to affect compaction but are unaccounted for in the empirical methods discussed in this report.

- Soil type, gradation, and particle morphology (shape and angularity)
- Soil moisture (most soils and manufactured aggregates)

- Weight and type of roller
- Static versus vibratory action
- Number of roller passes

There are inherent problems in extrapolating empirical methods, including regression equations, beyond conditions used in “training” those methods. It would make more sense if empirical methods and equations are developed to cover limited, standard sets of conditions with respect to soil type and equipment type/operation. For example, empirical methods have been developed using test strips for: 1) HMA pavement compaction and 2) compacting aggregate/recycled asphalt concrete mixes. An example of one such empirical method is described in the Standard Specifications for Highway Construction 2004 Edition Section 308-3.04.

4.3 Can the Method be Improved?

The short answer is yes. Empirical methods, including regression equations, can nearly always be improved if better-correlating variables and a larger data bases are used to develop those methods. Additional variables, such as those listed in the bulleted list in section 4.2, could perhaps greatly improve the precision of the % compaction estimate.

How many and what kind of new variables would need to be added to see significant improvement over the empirical methods studied in this report? New variables may require new or modified laboratory tests. Different soil types will almost certainly require different sets of variables. Keep in mind that the cost and inconvenience of obtaining the additional data may easily exceed the cost and time required to simply determine maximum density using a standard laboratory compaction test.

4.4 Method Using a Family of Compaction Curves

Empirical methods discussed in this report are somewhat analogous to the empirical family of curves methods used in some states. WAQTC standard procedure for AASHTO T 272 describes how to construct and use a family of compaction curves that are applicable to certain soil types that rely on AASHTO T 99/T 180 compaction standards. Figure 6 illustrates the normal appearance of a family of curves. The family of curves is a simple but elegant way of presenting a large number Proctor compaction curves for similar materials usually found within a rather localized area.

Using a family of curves is simple. The in-place density of the material is measured using a nuclear gauge or some other method. A sample of the material is taken from the location of the field density measurement. The sample is placed in a standard mold and subjected to standard compaction effort. This compaction is done with the sample at its field moisture content. The density of the compacted material is determined. The moisture content of the material is also determined. This laboratory process is referred to as a 1-point compaction test. A family of curves is selected that conforms to the soil type being tested as well as the

compaction equipment and test standards used for the 1-point test. With laboratory density and moisture content now known, a single point is plotted within the family of density curves. Figure 7 illustrates the process of estimating maximum density based on interpolation of the single plotted point.

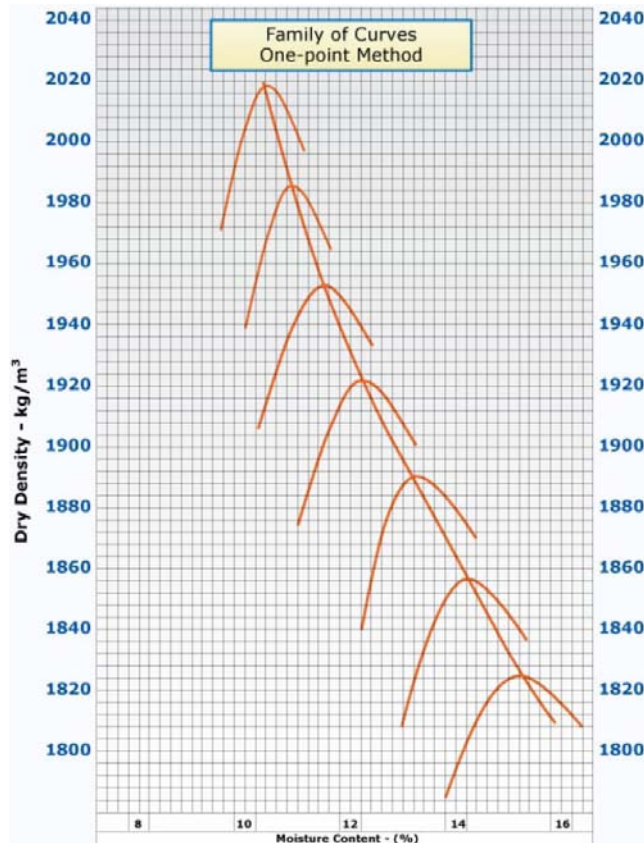


Figure 6. Family of density curves (example from WAQTC training information)

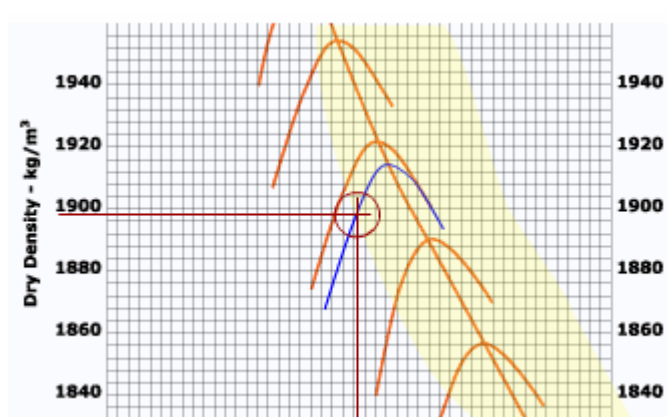


Figure 7. Illustrates use of family of curves (example from WAQTC training information)

The field dry density is divided by the estimated maximum density obtained from the family of curves. The result (multiplied by 100) is the % compaction.

The advantage of using a family of curves method versus a completely new empirical method is that the methodology for creating and using the family of curves has been standardized. Family of curves methods benefit from a history of application and acceptance. Perhaps the most appealing aspects of the family of curves method is that it: 1) recognizes applicability of specific curve families only to certain materials, e.g., local area soils, and 2) requires a standardized compaction effort as part of estimating maximum density.

5 Conclusions & Implementation

5.1 Conclusions

Empirical methods examined during this research are not precise enough to replace current standard methods for any level of practical application for estimating maximum density of soils or manufactured aggregates.

- Accuracy—acceptable
- Precision—not acceptable

Empirical methods examined during this research are not precise or accurate enough to replace current standard methods for any level of practical application for estimating % compaction of soils or manufactured aggregates.

- Accuracy—not acceptable
- Precision—not acceptable

Further literature and laboratory research is necessary to determine if it is possible to develop empirical methods that can replace the laboratory density standard as the basis for gauging compaction of soils and manufactured aggregates in Alaska.

5.2 Implementation

Do not use empirical equations addressed in this report for estimating maximum density or % compaction of soils or manufactured aggregates.

If the State of Alaska desires to use empirical methods as part of determining % compaction, the authors recommend that regional DOT&PF materials laboratories develop families of T 99/T 180 curves for determining maximum density characteristics of various, local, Alaska soil types. See section 4.4 of this report for a brief discussion of the AASHTO T 272 methods. It is possible and in fact common practice in some states, to estimate maximum density using empirical methods IF a standard compaction effort is used as part of that determination.

To augment development of T 99/T 180 families of curves, the authors recommend that DOT&PF investigate the possibility of developing families of T 212 (vibratory) maximum density curves. Unlike AASHTO T 272 for Proctor density curves, there is no standard practice for developing a family of vibratory compaction density curves.