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Compaction Control of Granular Soils

WA-RD 230.1

Final Report
January 1991

Washington State Department of Transportation
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16. ABSTRACT

This report looks at the effect of gravel size particles on the maximum dry density of granular soils. The procedures which the Washington State Department of Transportation use for the determination of maximum dry density sometimes produce density standards which cannot be obtained in the field.

Eight soil samples were tested to determine the influence of angularity of rock particles on the density. The samples were selected to provide a variation of rounded to angular particles. The method (WTM 606) WSDOT uses to determine a maximum density curve was found to overpredict the maximum dry density test results as compared to one point maximum density tests (Modified Proctor).

It is recommended that modifications be made to the current WSDOT method (WTM 606) and that a gravel size correction method, described in the report, be added to WSDOT procedures for soils with gravel contents above 50 percent.

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COMPACTION CONTROL OF GRANULAR SOILS

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The contents of this report reflects the view of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington state Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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ABSTRACT

The project described herein concerns the effect of gravel size particles on the maximum dry density of granular soils. The Washington State Department of Transportation (WSDOT) currently uses Washington Test Method No. 606 (WTM 606) which is a vibratory compaction method and Humphres' procedure for determining maximum dry density as a function of gravel content. This occasionally produces density standards which cannot be obtained in the field. This report presents the results of an investigation of WTM 606 and, in particular, Humphres' method with the objective of suggesting modifications to reduce or eliminate the possibility of unobtainable density standards.

Eight soil samples were used in this investigation. The influence of angularity of rock particles on test results was a concern. As a result, samples were selected to provide a variation of rounded to angular particles. In addition to the WTM 606 test, one point maximum density tests were performed at various gravel contents (by percentage) for each soil sample. The WTM 606 maximum density curve results gave higher densities than the one point maximum density test results. Sometimes this overprediction was a much as 8%. The ASTM D-1557 and AASHTO T 224-86 maximum soil density tests were also performed on the soil samples.

Because of the differences in maximum densities, WSDOT should consider modifying WTM 606. A gravel size correction method, described in the report, that also produces a maximum density curve is recommended instead. Additional testing of this method is strongly suggested.

CONCLUSIONS AND RECOMMENDATIONS

Based on a limited number of tests it appears that variability in the test results from the compaction method specified in WTM 606 may be as large as approximately 6 pcf between laboratories. Differences in test results obtained in Olympia and Spokane are higher, on average, than differences between duplicate tests in the same laboratory.

Humphres' method for determining maximum dry density as a function of gravel content tends to overpredict maximum density, especially when there is more than approximately 50% gravel present. The overprediction can be quite significant (8% or more) and could result in compaction specifications which are unrealistically high. For soils containing less than approximately 50% gravel, Humphres' method still tends to overpredict density, but not as consistently and not by as large a percentage.

The AASHTO rock correction method, when used with the WTM 606 compaction test, overpredicts density, especially at gravel contents over approximately 40%. As with the Humphres' method, overprediction can be very significant.

For gravel contents up to approximately 50%, maximum density can be estimated with reasonable accuracy by interpolating linearly between test results for 0% and 50% gravel. For gravel contents above 50%, density variation can be accurately predicted for some soils by determining the value of alpha (the ratio of the volume of the gravel solids to the volume they occupy when mixed with finer soil) for 50% and

100% gravel content and calculating the density at percentages between 50% and 100% by using a linear variation in alpha.

Based on this study, the following recommendation are made:

1) WSDOT should evaluate variability in WTM 606 results by testing identical samples in each of their laboratories which conduct these tests.

2) WSDOT should consider modifying the use of Humphres' method, especially for estimating maximum dry density when the gravel content of the soil exceeds 50%.

3) When evaluating maximum dry density variation with gravel content, WSDOT should, on a routine basis, conduct WTM 606 compaction tests at 0%, 50% and 100% gravel. In the range between 0% and 50% gravel, linear interpolation of test results should be used. If the range between 50% and 100% gravel is expected to be important, the alpha method should be used to determine the density. Additional WTM 606 tests at approximately 65% and 85% gravel are strongly suggested.

4) Additional study of the difference between the Modified Proctor (ASTM D-1557) and the WTM 606 compaction tests should be conducted with emphasis on the effect of particle crushing and the correlation between laboratory test results and field compaction.

I. INTRODUCTION

Compaction control of granular fill is a crucial element in the construction and repair of pavements and other transportation structures. Insufficient compaction leads to settlement or inadequate stiffness which often causes significant structural distress. Unrealistically high compaction specifications can lead to excessive cost and construction delays.

To determine the required placement density of granular fill materials it is necessary to determine compaction characteristics of the material. The two methods most commonly used in the United States are the Standard Proctor Test (ASTM Test No. D-698; AASHTO Test No. T 99-86), and the Modified Proctor Test (ASTM Test Procedure D-1557; AASHTO Test No. T 180-86). These tests use an impact method to densify the soil; only the compactive energy per unit volume of soil differs. Some federal and state agencies, including the Washington State Department of Transportation (WSDOT), have their own test method. WSDOT uses the Washington Test Method No. 606 (WTM 606). This method uses vibration under a static load to densify the soil, in a manner similar to that of the ASTM Maximum Density test (ASTM D-4253).

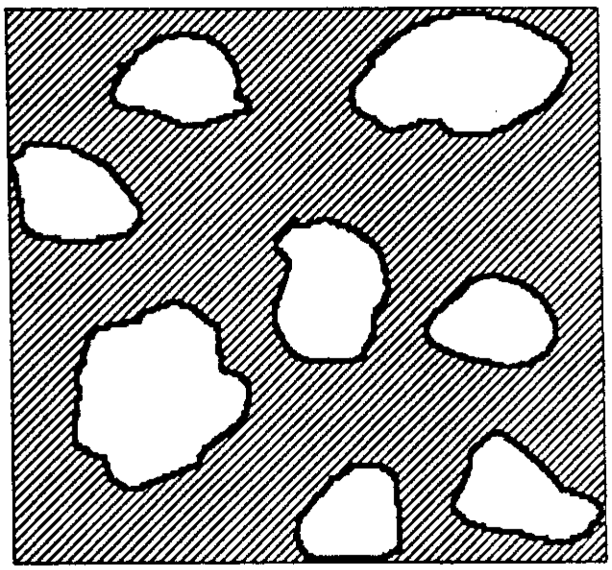
For convenience we will refer WTM 606 as the method that specifies the laboratory procedure for obtaining the maximum density of a given soil sample. Humphres' method will be considered as the procedure that constructs the maximum density curve (Humphres' curve) from the WTM 606 results.

A common difficulty encountered when specifying compaction requirements is the natural variation in the gradation of the fill material. Of particular interest to this study is the variation in the percentage of gravel size material (defined as material which does not pass the No. 4 sieve). Unfortunately, the maximum density will vary, sometimes very significantly, as the amount of gravel size particles changes. Because it can be quite time consuming to conduct a new laboratory compaction test whenever the fill gradation changes, methods have been developed to estimate maximum dry density changes as a function of percent gravel in the fill. For example, AASHTO specifications for compaction include a rock correction factor which can be used when the percentage of gravel size particles is less than or equal to 70% (AASHTO T 224-86). WSDOT uses Humphres' method to accomplish this correction (Humphres, 1957). A curve of maximum density vs. percentage of gravel can quickly be determined based on minimal laboratory testing so that the field engineer does not need a new compaction test every time the gradation of the material changes. There are, unfortunately, several disadvantages associated with the use of Humphres' method. The major one is that it sometimes gives maximum densities which can not be obtained in the field. This has led to complications on construction jobs where the contractor has been unable to achieve the required density. When this occurs, it is not always clear if the inability to achieve the required density is the fault of the contractor or is a result of an incorrect density standard. This problem may result in added testing costs and possible delays to the contractor.

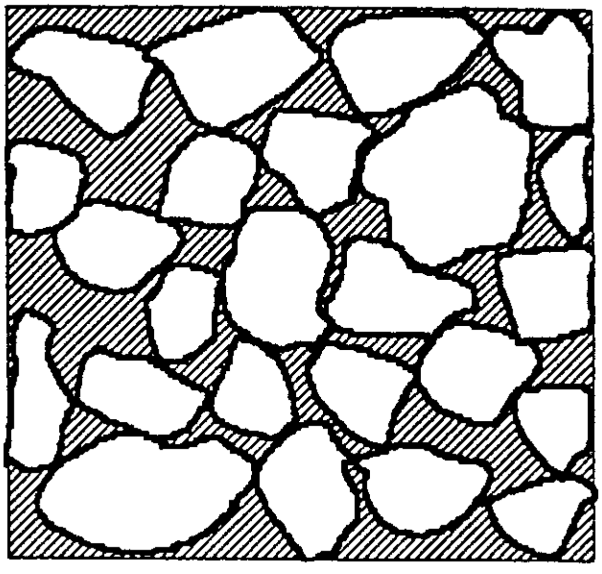
The principles upon which the Humphres' method is based have not been vigorously investigated or documented by WSDOT; therefore, it is difficult to understand which specific properties of a fill material lead to the development of erroneous density curves. The objective of this study was to investigate the use of Humphres' method and to suggest improvements and/or alternatives to its use.

II. BACKGROUND

The Humphres method, the AASHTO rock correction method and an "alpha" method developed by the writers and described below are all methods to predict maximum densities of soils containing gravel size material. Before discussing these methods in detail, it is useful to discuss the structure of soils containing gravel size material mixed with sand and silt size granular particles. Fragaszy et al (1989) have defined three states describing the interaction of gravel size particles with smaller grains -- the floating, non-floating and intermediate states. The floating state occurs in a soil mixture when there is little or no contact among the gravel size particles and the gravel floats in a matrix of finer particles as illustrated schematically in Fig. 1(a). This state describes mixtures of up to approximately 40-50% gravel. In the floating state the behavior of the soil (strength, deformation and compaction characteristics) are controlled by the soil matrix. On the other extreme, when enough gravel size particles are present, they form their own structure and the finer sand and silt particles only fill the voids created by the gravel structure. This state, illustrated in Fig. 1(b), forms when the percentage of gravel exceeds approximately 70%. In the non-floating case the behavior of the soil is dominated by the gravel structure. In the range of approximately 40-70% gravel there is considerable gravel to gravel



(a) Floating Case



(b) Non-floating Case

Fig. 1. Schematic Diagram of Soil With Oversize Particles

(Fragaszy et al, 1988)

contact, but a continuous structure is not formed. This intermediate state is a transition between the floating and non-floating states and the structures of both the gravel and the fines are important. Any method to determine the changing compaction behavior of a gravel/sand mixture will have to account, explicitly or implicitly, for the changing structure of the soil mixture.

Humphres' method of predicting maximum dry density as a function of gravel content is an empirical, graphical method. Although a computer program is used to calculate the maximum density curve, the computer program is derived from this empirical, graphical method. The first step in the Humphres' method is to divide a given soil sample into two specimens -- plus No. 4 and minus No. 4. Specific gravity and WTM 606 tests are performed on each specimen to determine specific gravity and maximum dry density. Also, the minimum dry density for each specimen is estimated by an empirical relationship between the maximum compacted dry density and the percentage of minus No. 4. material (Humphres, 1957). The maximum density tests provide two points in a plot of maximum dry density vs. gravel content (0% and 100% gravel). Four other points are determined as described below and a complete curve of maximum dry density vs. gravel content is fitted through the points.

The graphical solution is based on the interactions of the eight theoretical curves A, B, C, D, E, F, G, and H, shown in Fig. 2 (a). These curves provide upper and lower bounds for the maximum density. Two assumptions are used to develop equations that define the eight theoretical curves. The first assumption is that mixing a coarser

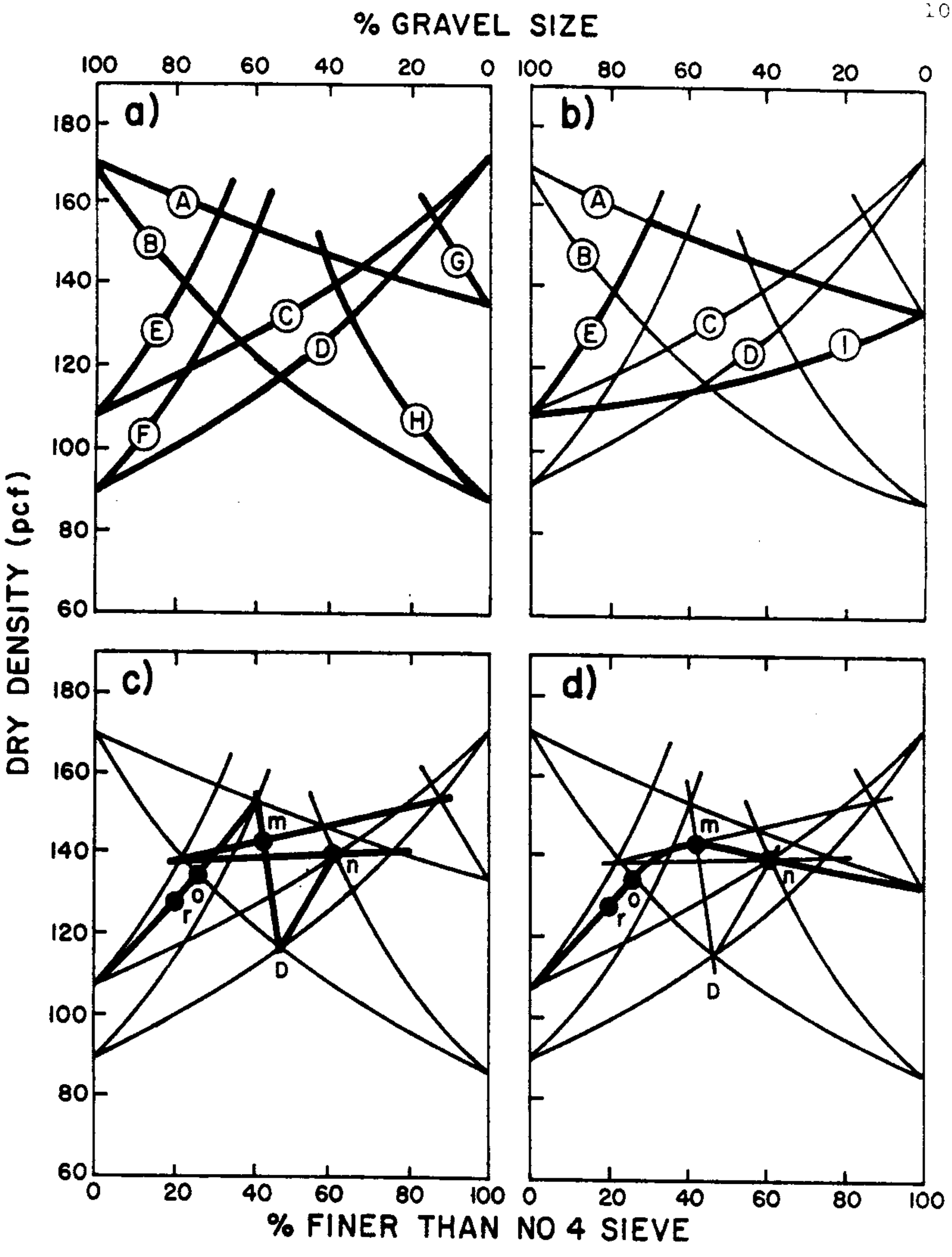


Fig. 2. Derivation of Humphres Maximum Density Curve

(Humphres, 1957)

material into a finer material and also a finer material into a coarser material introduces no extra void space. In other words, to obtain the volume added to a sand specimen when 100 grams of gravel are mixed in, one merely adds the volume of the gravel (i.e., the mass of the gravel divided by the mass density of the gravel). This assumption allows Eqns. 1-4 to define curves A, B, C and D, respectively:

Curve A $$D_p = \{D_c D_s\}/\{(1-p)D_s+pD_c\} \quad (1)$$

Curve B $$D_p = \{D_l D_s\}/\{(1-p)D_s+pD_l\} \quad (2)$$

Curve C $$D_p = \{D_c D_s\}/\{pD_s+(1-p)D_c\} \quad (3)$$

Curve D $$D_p = \{D_l D_s\}/\{pD_s+(1-p)D_l\} \quad (4)$$

Where:

D_p = density of mixture at a given percent gravel

D_c = compacted density

D_s = solids density (SPG * 62.4))

D_l = loose density.

p = percent gravel

Note that Eqns. 1-2 use D_c and D_l of the minus No. 4 material and D_s of the plus No. 4 material. Conversely, Eqns. 3-4 use D_c and D_l of the plus No. 4 material and D_s of the minus No. 4 material.

The second assumption is that when mixing a coarser material into a finer material and also a finer material into a coarser material only the voids are filled and no volume change occurs. This allows equations 5, 6, 7, and 8 to define curves E, F, G, and H, respectively:

Curve E $$D_p = D_c/p \quad (5)$$

Curve F $$D_p = D_l/p \quad (6)$$

Curve G $$D_p = D_c/\{1-p\} \quad (7)$$

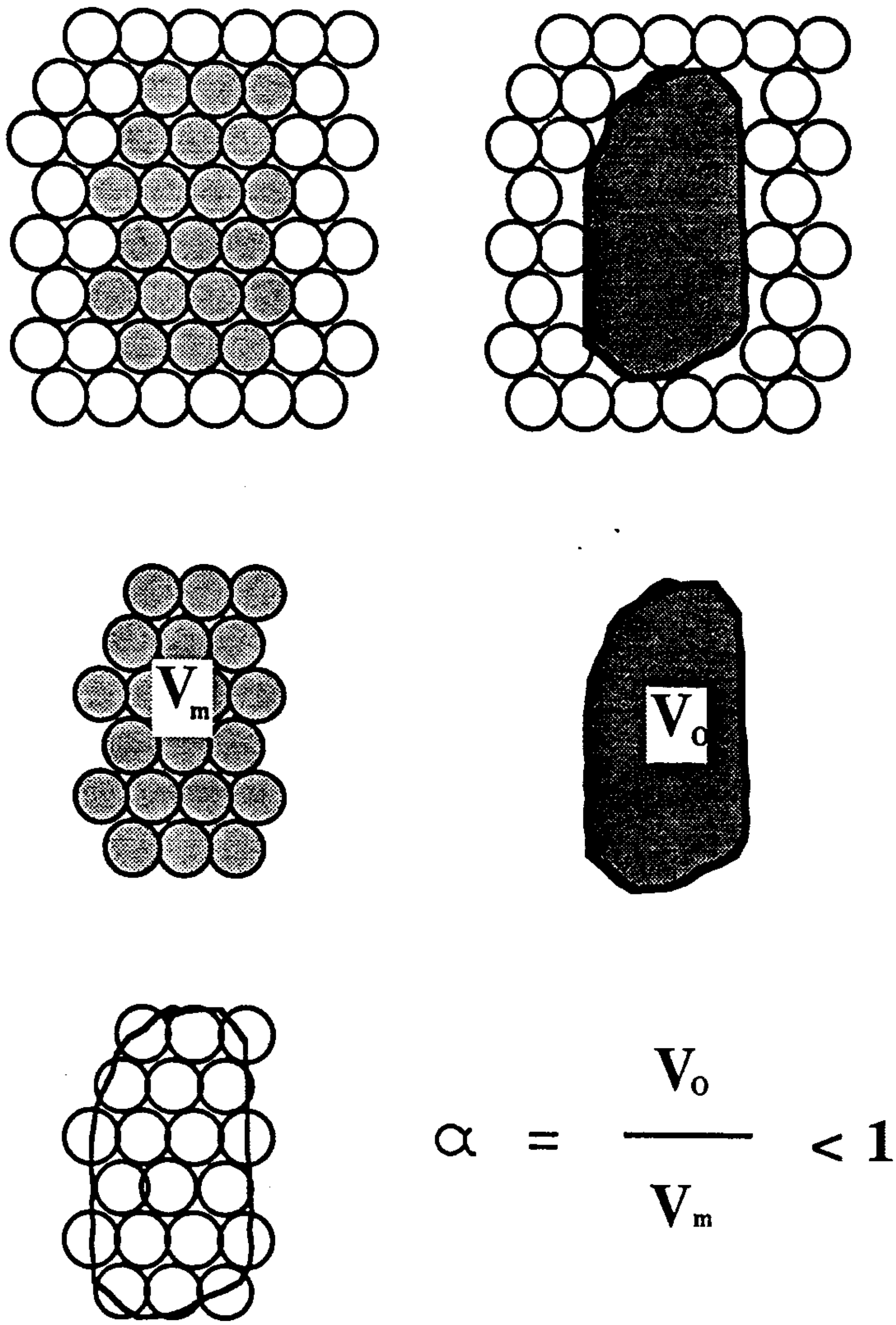
Curve H $D_p = D_l/(1-p)$ (8)

Note that D_c and D_l in Eqns. 5-6 refer to the minus No. 4 material, whereas in Eqns. 7-8 they refer to the plus No. 4 material.

Both the upper and lower bounds are shown in Fig. 2 (b) as thick lines. The first assumption defines the A portion of the upper bound. The second assumption defines the E portion of upper bound. Of course neither assumption is correct; however, Humphres assumed that they result in a reasonable upper bound. Concerning the lower bound Humphres' states, "curves D and B represent theoretical density curves based on the loose, or minimum densities of the two fractions. The intercept of these curves at point D, therefore, can be said to be a point common to both fractions on the theoretical lower limiting density curve, which starts at D_c No. 4-plus and terminates at D_c No. 4-minus" (Humphres, 1957).

Empirical relations among the eight theoretical curves determine four interior points r, o, m, and n on the maximum density curve. These relations are shown in Fig. 2 (c). The maximum density curve is drawn from the 0% gravel compacted density through the four points and ends at the 100% gravel compacted density as shown in Fig. 2 (d).

Eqns. 1-8 do not accurately predict the total density of real soil mixtures because they do not take into account soil interaction which reduces the density. Fragaszy et al (1989) have defined a factor, α, which quantifies this effect. Alpha is the ratio of the volume of a gravel size particle divided by the volume it occupies in a matrix of smaller particles. This is illustrated in Fig. 3.



$$\alpha = \frac{V_o}{V_m} < 1$$

Fig. 3. Illustration Showing Derivation of Alpha Term

(Fragaszy et al, 1989)

Rearranging Eqn. 1 so that D_s is contained in one term gives:

$$D_p = 1/\{(p/D_s)+(1-p)/D_c\}. \quad (9)$$

This assumed density combined with the alpha term can now define the true density, D_t, as follows:

$$D_t = 1/\{p\alpha D_s+(1-p)/D_c\}. \quad (10)$$

The major factors that influence alpha are gradation, particle surface roughness, and particle shape.

In a manner similar to the alpha method, AASHTO uses method T 224-86. This method is used to predict the density for a finer material containing 70% or less gravel size particles by use of the following equation:

$$D_t = 62.4/\{p/G_s+62.4(1-p)/rD_s\} \quad (11)$$

where G_s is the specific gravity of the gravel size material and D_s is the compacted density of the finer size material. Instead of using alpha, this method uses a rock correction coefficient, r, based on percent gravel in the soil mixture.

To further complicate the problem, the method of compaction testing will also affect the relationship between maximum dry density and gravel content. Methods such as the Proctor test can result in crushing of individual grains of soil, especially at high gravel contents. In contrast, WTM 606 does not produce significant particle crushing due to the static nature of the load and small dynamic stress amplitude. Similar to WTM 606, field compaction of coarse grained soils tends to be static and vibratory. The writers, therefore believe that WTM 606 better emulates field conditions than the proctor test.

III. DESCRIPTION OF WORK

To accomplish the objectives of this project a study was made of the theoretical basis for the construction of Humphres' curve. The validity of the assumptions made by Humphres, both explicit and implicit was examined.

The bulk of the experimental work consisted of laboratory compaction tests using WTM 606 which were conducted on eight soils provided by the WSDOT Materials Laboratory in Olympia. For each soil the Humphres' curve was constructed in the manner described above. Each soil was then divided into a gravel portion (plus #4 sieve) and a fines portion (minus #4 sieve). These two components were then mixed in various percentages and compaction tests were conducted to compare the actual maximum dry density with that predicted by the Humphres' curve.

During this investigation questions arose concerning the WTM 606 compaction test. These concerned whether there are significant differences in results when tests on identical samples are performed at different laboratories and/or by different people. Although not addressed in the research proposal, it was felt that some testing should be done to investigate these questions. Therefore, a brief study of the variability of test results using WTM 606 was performed. Comparisons were made between test results obtained by the second author utilizing the same equipment. Comparisons were also made between tests performed in Olympia by WSDOT personnel and by the second author in Spokane.

IV. SOIL DESCRIPTION

The soils used in this study were provided by the WSDOT Materials Laboratory and were selected to cover a range of typical granular soils encountered in WSDOT projects. Grain size distribution curves for the gravel and fines components of each soil are presented in Figs. 4-11. The gravel portions of all soils are poorly graded and are classified GP according to the Unified Soil Classification System (USCS). The minus #4 fraction of four soils is classified SW-SM, two are classified SM, and the remaining two are classified SP and SM. Table 1 presents a summary of pertinent soil properties.

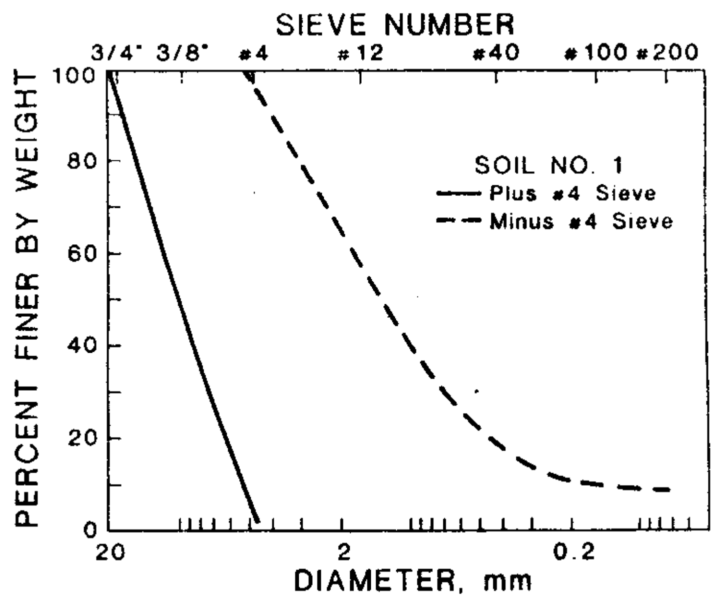


Fig. 4. Grain Size Distribution Curves for Soil No. 1

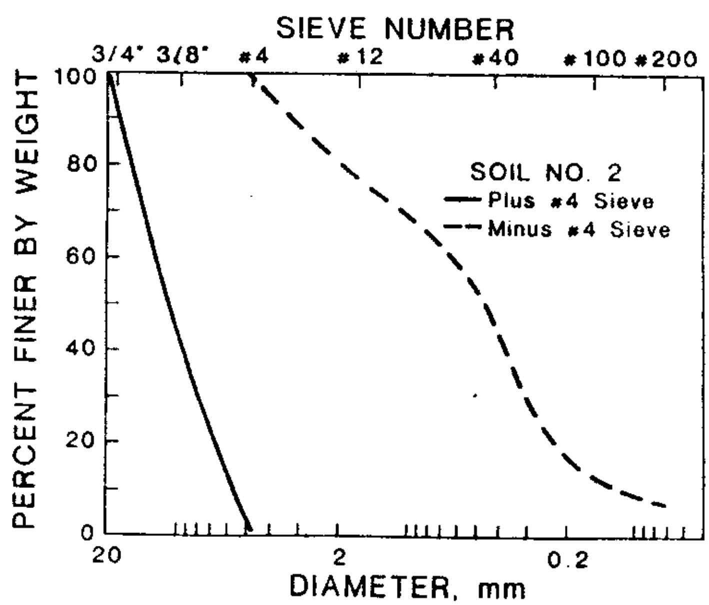


Fig. 5. Grain Size Distribution Curves for Soil No. 2

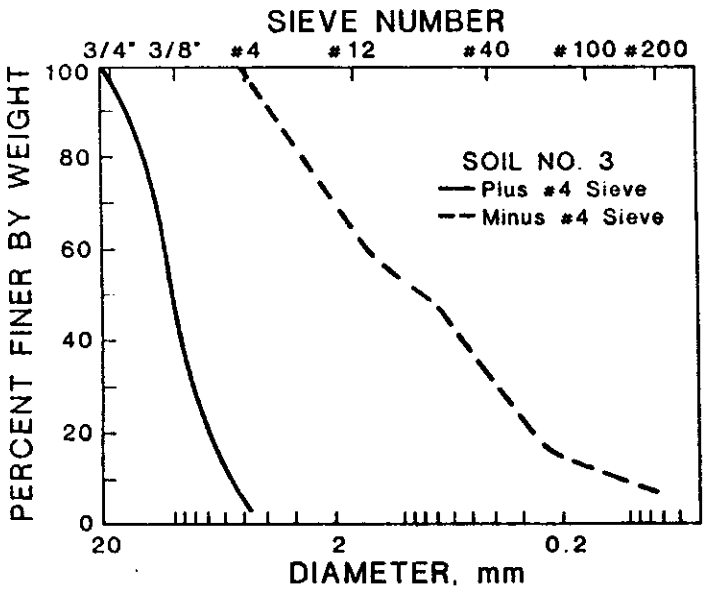


Fig. 6. Grain Size Distribution Curves for Soil No. 3

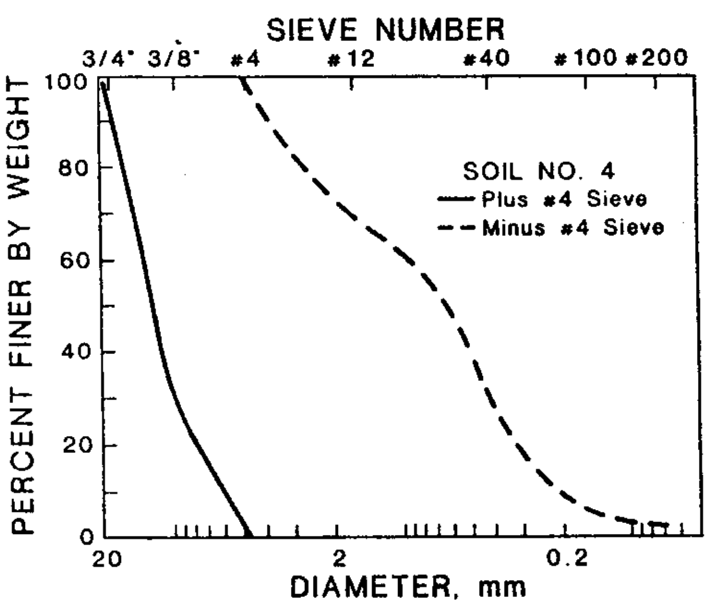


Fig. 7. Grain Size Distribution Curves for Soil No. 4

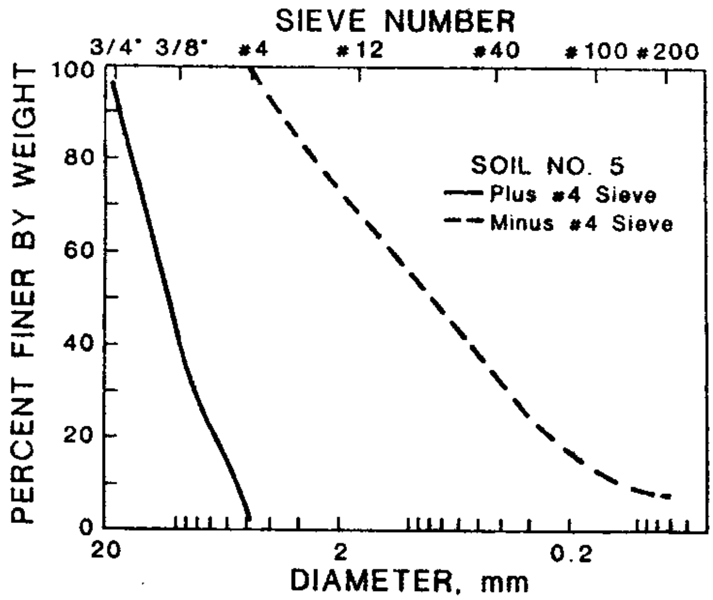


Fig. 8. Grain Size Distribution Curves for Soil No. 5

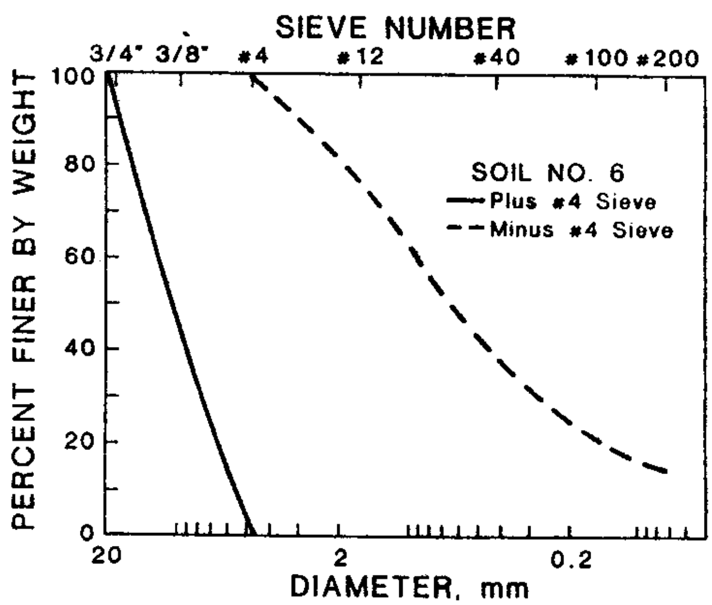


Fig. 9. Grain Size Distribution Curves for Soil No. 6

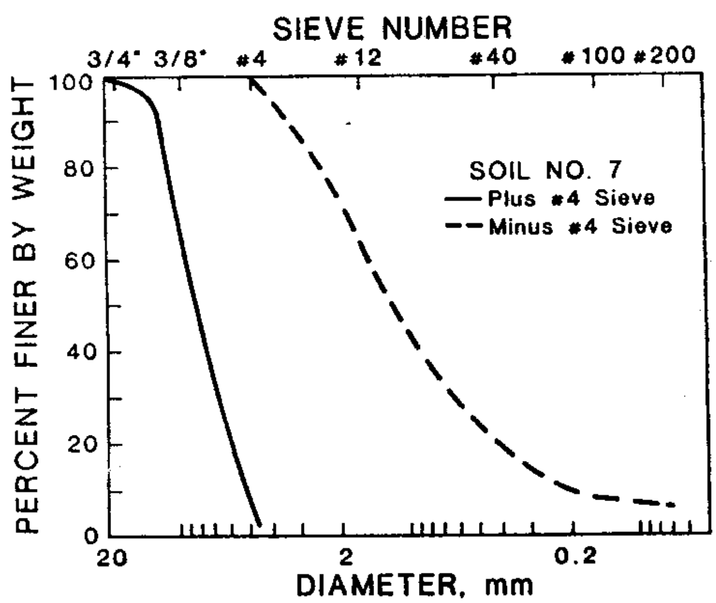


Fig. 10. Grain Size Distribution Curves for Soil No. 7

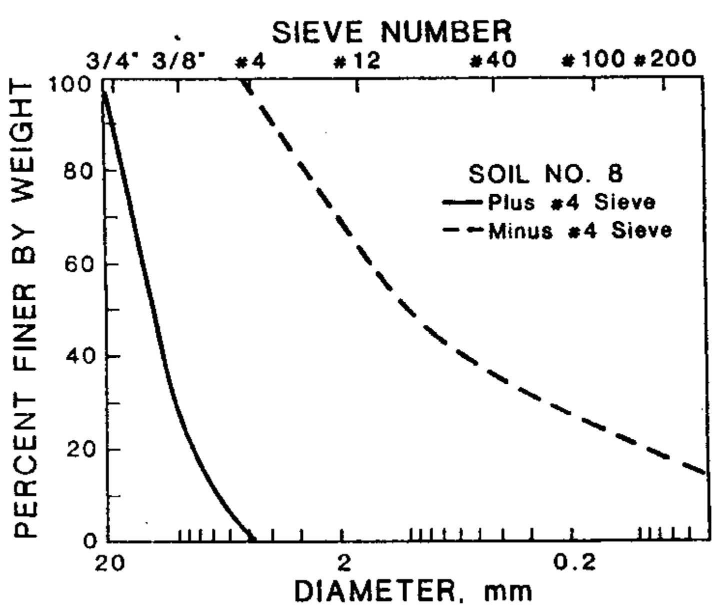


Fig. 11. Grain Size Distribution Curves for Soil No. 8

TABLE 1
Properties of Test Soils

Soil No	USCS Symbol	G_s[1]	C_c[2]	C_u[3]	% Passing #200 sieve	Particle shape/roughess
1						
Gravel	GP	2.70	0.9	2.1	-	round (smooth)
Fines	SW-SM	2.67	9.6	1.7	8.5%	round (smooth)
2						
Gravel	GP	2.71	0.9	2.1	-	round (smooth)
Fines	SP-SM	2.71	1.3	5.3	7.7%	round (smooth)
3						
Gravel	GP	2.73	1.1	1.8	-	angular (rough)
Fines	SW-SM	2.74	0.9	11.3	7.8%	angular (rough)
4						
Gravel	GP	2.73	1.2	2.2	-	round (smooth)
Fines	SP	2.71	0.9	4.2	2.9%	round (smooth)
5						
Gravel	GP	2.70	1.1	2.3	-	sub-angular (average)
Fines	SW-SM	2.62	1.0	10.1	8.3%	sub-angular (average)
6						
Gravel	GP	2.70	0.9	2.1	-	round (smooth)
Fines	SM	2.65	2.1	22	15.6%	round (smooth)
7						
Gravel	GP	2.68	1.0	1.7	-	sub-angular (average)
Fines	SW-SM	2.67	1.3	6.9	6.6%	sub-angular (average)
8						
Gravel	GP	2.71	1.5	1.6	-	angular (rough)
Fines	SM	2.70	1.1	34.5	18.5%	angular (rough)

[1] Specific Gravity
[2] Coefficient of Curvature = $D_{30}^2/(D_{60}*D_{10})$
[3] Coefficient of Uniformity = D_{60}/D_{10}

V. RESULTS

The investigation of the theoretical basis for Humphres' method found that although some of the method is based on correct and/or logical assumptions, these assumptions do not explicitly or implicitly define the maximum density curve. They only define boundaries where the maximum density curve must lie.

Tables 2 and 3 present the results of WTM 606 tests performed to evaluate inherent variability, and variability arising from test equipment and personnel. As seen in Table 2, the results of W.S.U. tests performed in Spokane are higher than the results obtained by WSDOT personnel in Olympia. On average, W.S.U. results were higher were 1.8% higher (based on deviation from the mean value). As shown in Table 3, with tests performed using the same lab equipment and by the same individual, this difference is reduced to 1.3%. The number of tests performed is fewer than needed to do meaningful statistical analyses. However based on these few tests, it does appear that these variations may be allowable according to ASTM Standards (ASTM D698 - D1557). It is felt, though, that the magnitudes of the actual differences (up to 5.7 pcf) merit addition investigation.

The results of WTM 606 compaction tests used to compare with predictions based on Humphres' method are presented in Table 4. Also presented in this Table are the ratios of the actual maximum dry density obtained from testing to the density predicted by the Humphres' curve. A ratio less than 1.0 means that the density predicted by the

TABLE 2

Humphres Test Variability
(Different Laboratories & Personnel)

Soil No	Density, pcf Olympia	Spokane	difference	mean value % error
1				
Gravel	107.6	111.5	3.9	1.8
2				
Gravel	109.9	114.7	4.8	2.2
Fines	119.8	122.2	2.4	2.0
3				
Gravel	100.6	106.3	5.7	2.8
Fines	123.4	126.0	2.6	2.1
4				
Gravel	114.2	118.6	4.4	1.9
5				
Gravel	102.9	106.3	3.4	1.7
Fines	122.4	122.1	0.3	0.0

TABLE 3
Humphres Test Variability
(Same Laboratory & Personnel)

Soil No	Density, pcf Spokane (1)	Spokane (2)	Spokane (3)	difference	mean % error
6					
Gravel	109.1	111.4	-	2.3	1.1
Fines	135.3	134.7	132.3	3.0	1.4
7					
Gravel	104.1	105.2	-	1.1	0.5
Fines	128.7	123.8	127.4	4.9	2.3
8					
Fines	139.8	139.7	137.4	2.4	1.1

TABLE 4

Compaction Test Results and Corresponding Predictions Based on Humphres' Method

Soil No.	% gravel	Density, pcf 606	Density, pcf Humphres	difference	Ratio 606/Humphres
1	40	128.2	130.5	2.3	0.98
	70	124.8	137.5	12.7	0.91
	85	116.0	124.8	8.8	0.93
2	20	127.3	127.0	0.3	1.00
	40	132.3	133.3	1.0	0.99
	70	136.6	141.6	5.0	0.96
	85	125.4	127.2	1.8	0.96
3	20	131.0	129.7	1.3	1.01
	40	133.9	135.0	1.1	0.99
	70	131.6	135.1	3.5	0.97
	85	114.4	119.0	4.6	0.96
4	40	132.7	132.1	0.6	1.00
	70	138.5	144.4	5.9	0.96
	85	128.7	130.8	2.1	0.98
5	20	127.0	125.7	1.3	1.01
	40	130.5	132.0	1.5	0.99
	70	126.2	134.0	7.8	0.94
	85	116.2	119.0	2.8	0.98
6	20	136.5	138.7	2.2	0.98
	50	137.2	142.0	4.8	0.97
	70	129.6	138.2	8.6	0.94
	85	124.2	122.1	2.1	1.02
7	20	129.6	132.0	2.4	0.98
	50	130.7	138.6	7.9	0.94
	70	124.6	133.1	8.5	0.94
	85	111.0	117.1	6.1	0.95
8	20	140.7	141.0	0.3	1.00
	40	137.6	142.3	4.7	0.97
	50	135.4	142.5	7.1	0.95
	70	125.3	130.1	4.8	0.96
	85	111.4	114.9	3.5	0.97

Humphres' curve was not achieved by the WTM 606 compaction test. It is, therefore, more likely that problems may result in the field if the contractor is required to achieve a density equal to or near the Humphres' maximum density.

Because the Humphres' curve is based partially on actual test results for 0% and 100% gravel, these values will always agree with test results. As the percentage of gravel increases, however, the Humphres' curve deviates in many cases from the results of laboratory tests. This can be seen in Figs. 12-19 in which the Humphres' curve for each soil is presented along with the actual test data. Included on these figures are curves showing the predicted values of maximum dry density using the AASHTO rock correction method and using a suggested new method based on the alpha factor. Discussion of these other methods will be presented below.

For soil Nos. 1, 7 and 8, the Humphres' curve is everywhere above the test data and, therefore, overpredicts the maximum dry density. For soil No. 6, Humphres' curve overestimates the actual test result for all tests other than the one for 15% passing the #4 sieve. For the remaining four soils, Humphres' curve either closely matches or slightly underestimates the test data in the range between 50 and 100% minus #4 material. However, for all soils except No. 6, the Humphres' curve overestimates, frequently by a significant amount, the maximum dry density, as determined by the WTM 606, in the range between 0 and 50% minus #4 material.

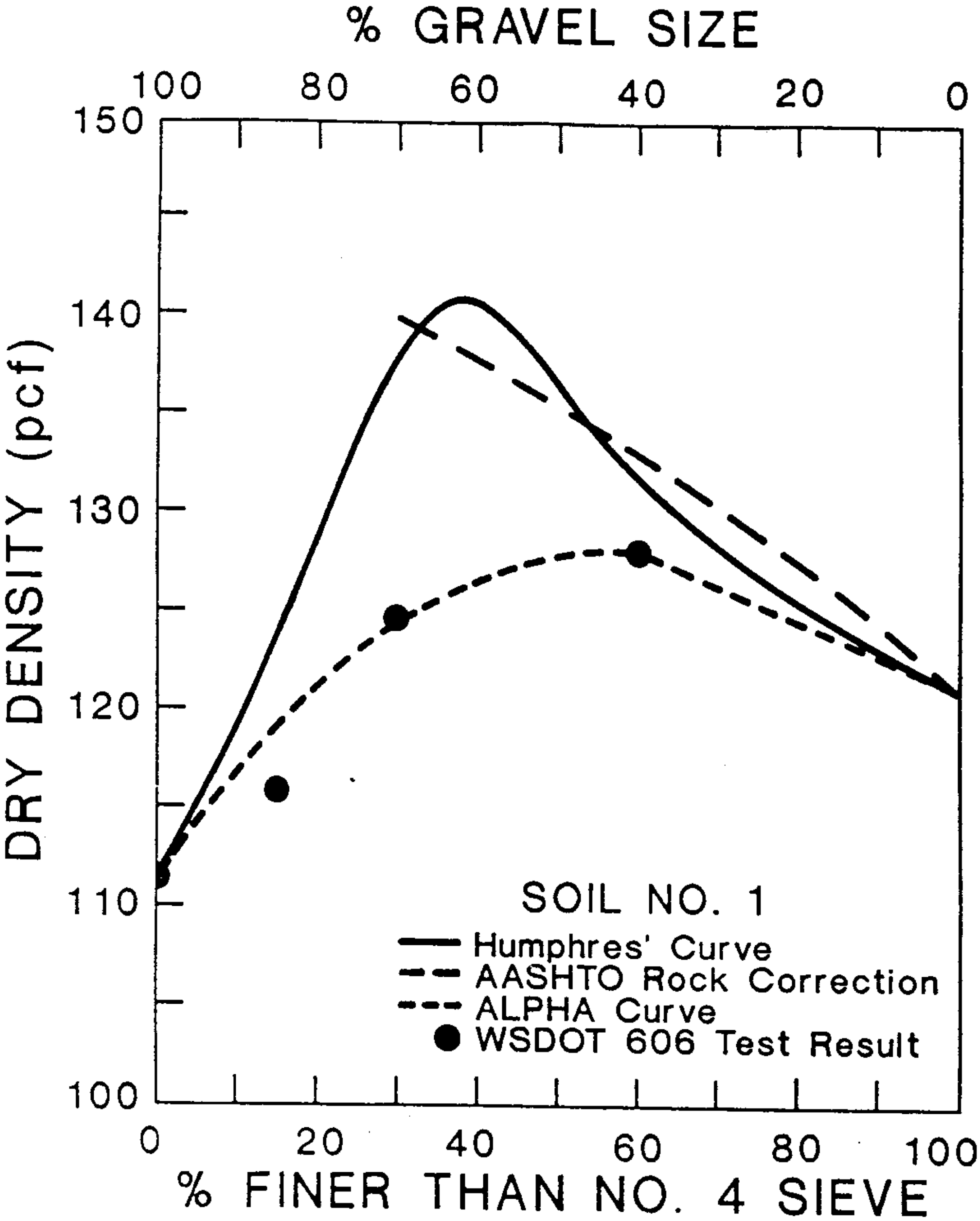


Fig. 12. Maximum Density Curves and Data Points (Soil No. 1)

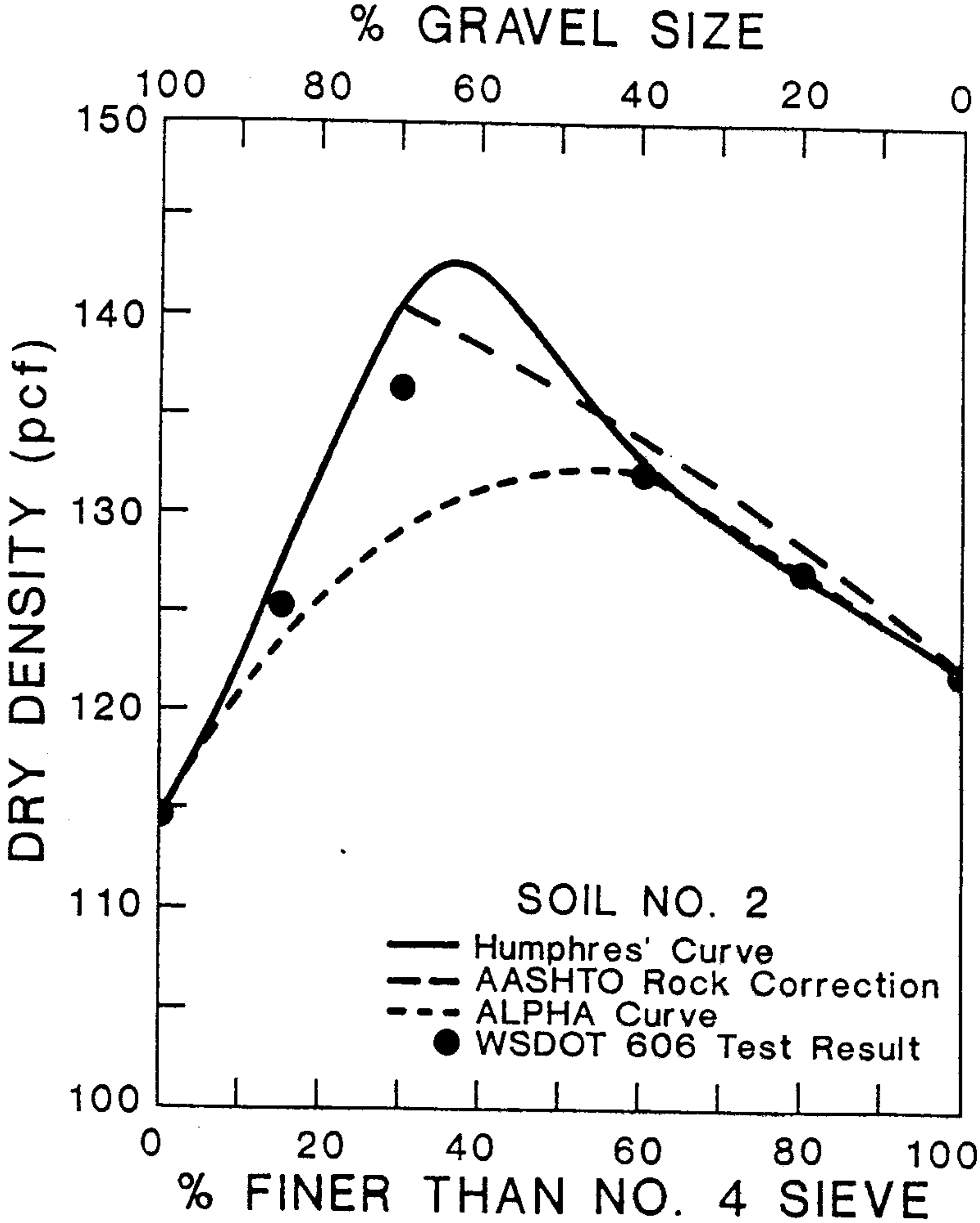


Fig. 13. Maximum Density Curves and Data Points (Soil No. 2)

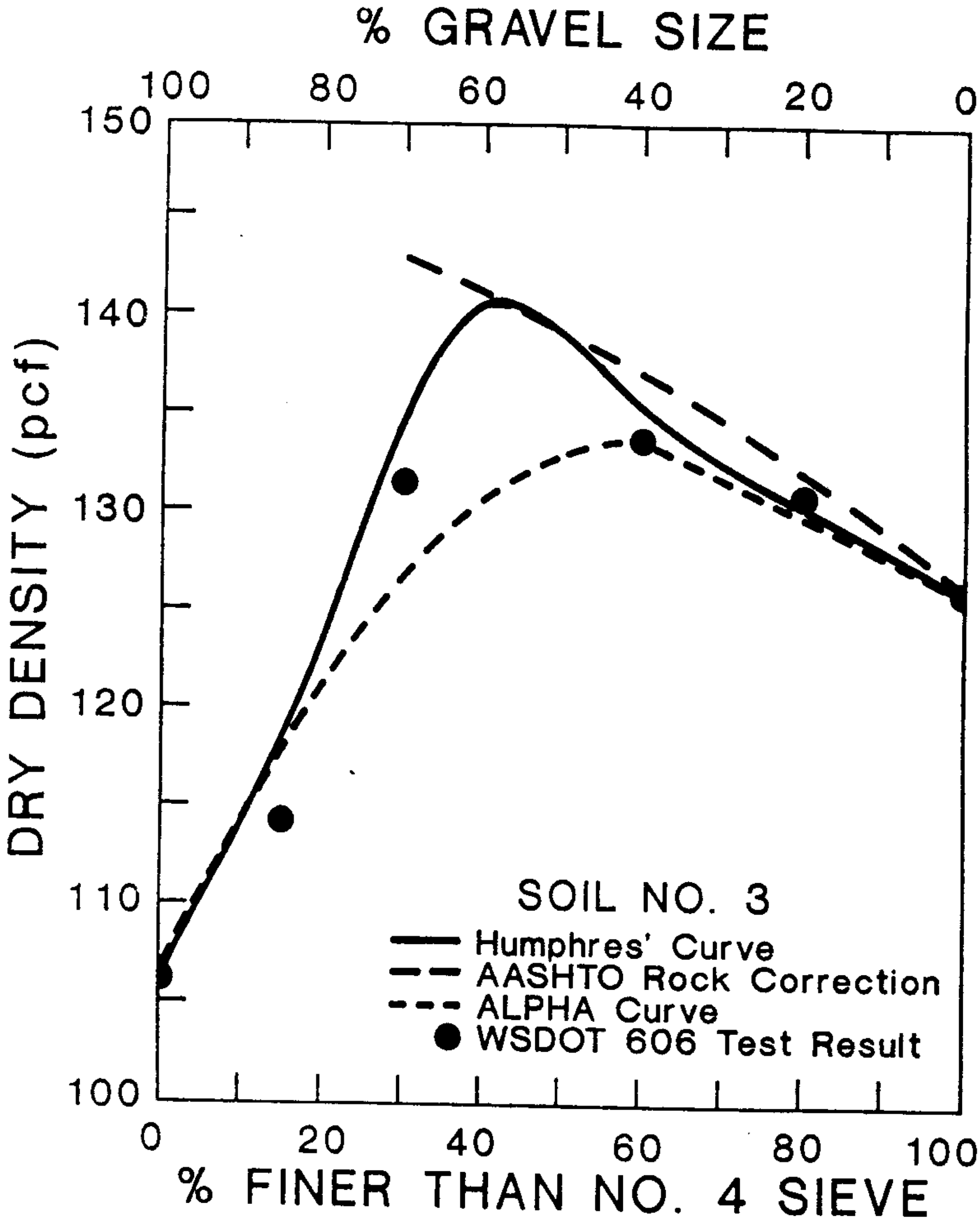


Fig. 14. Maximum Density Curves and Data Points (Soil No. 3)

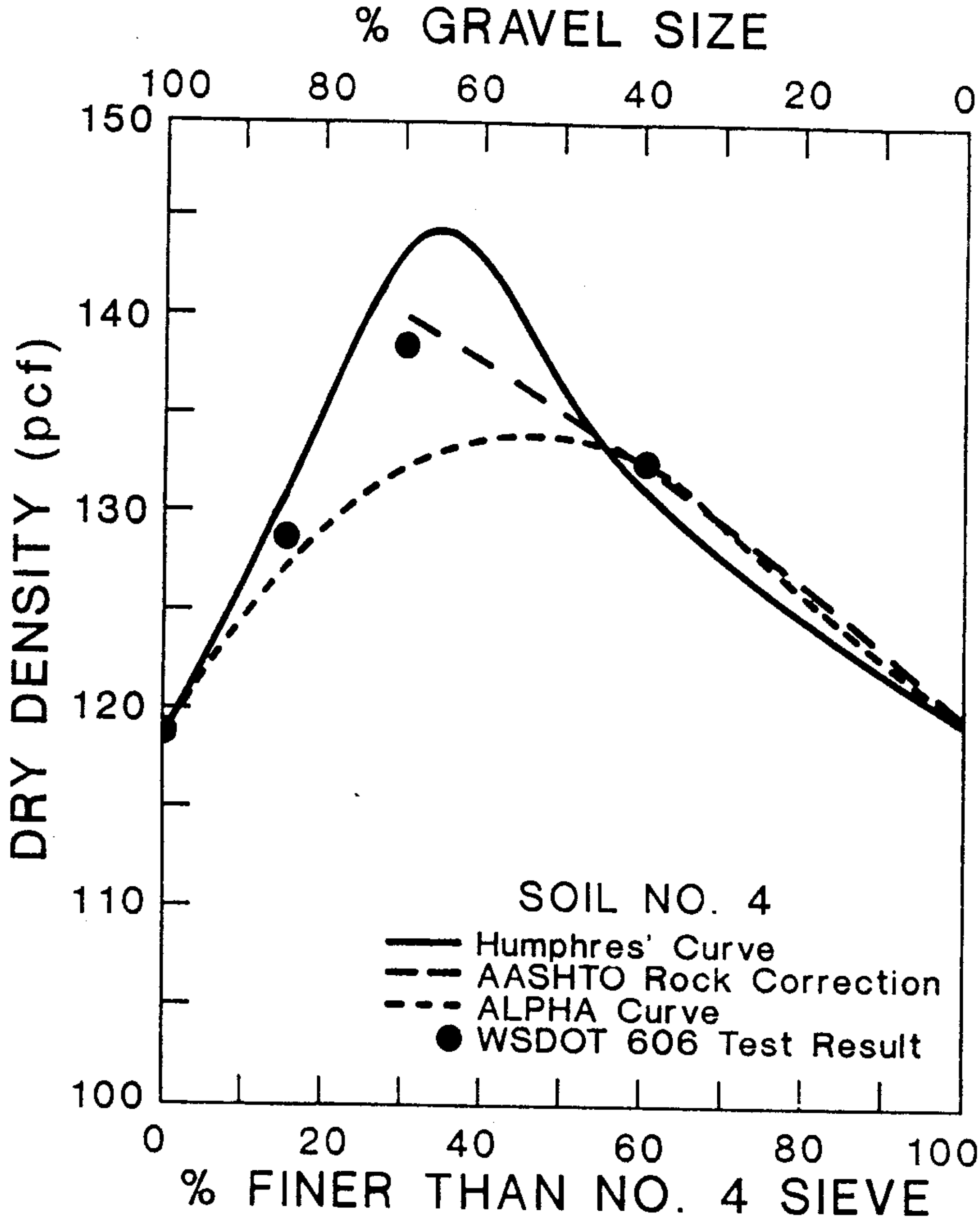


Fig. 15. Maximum Density Curves and Data Points (Soil No. 4)

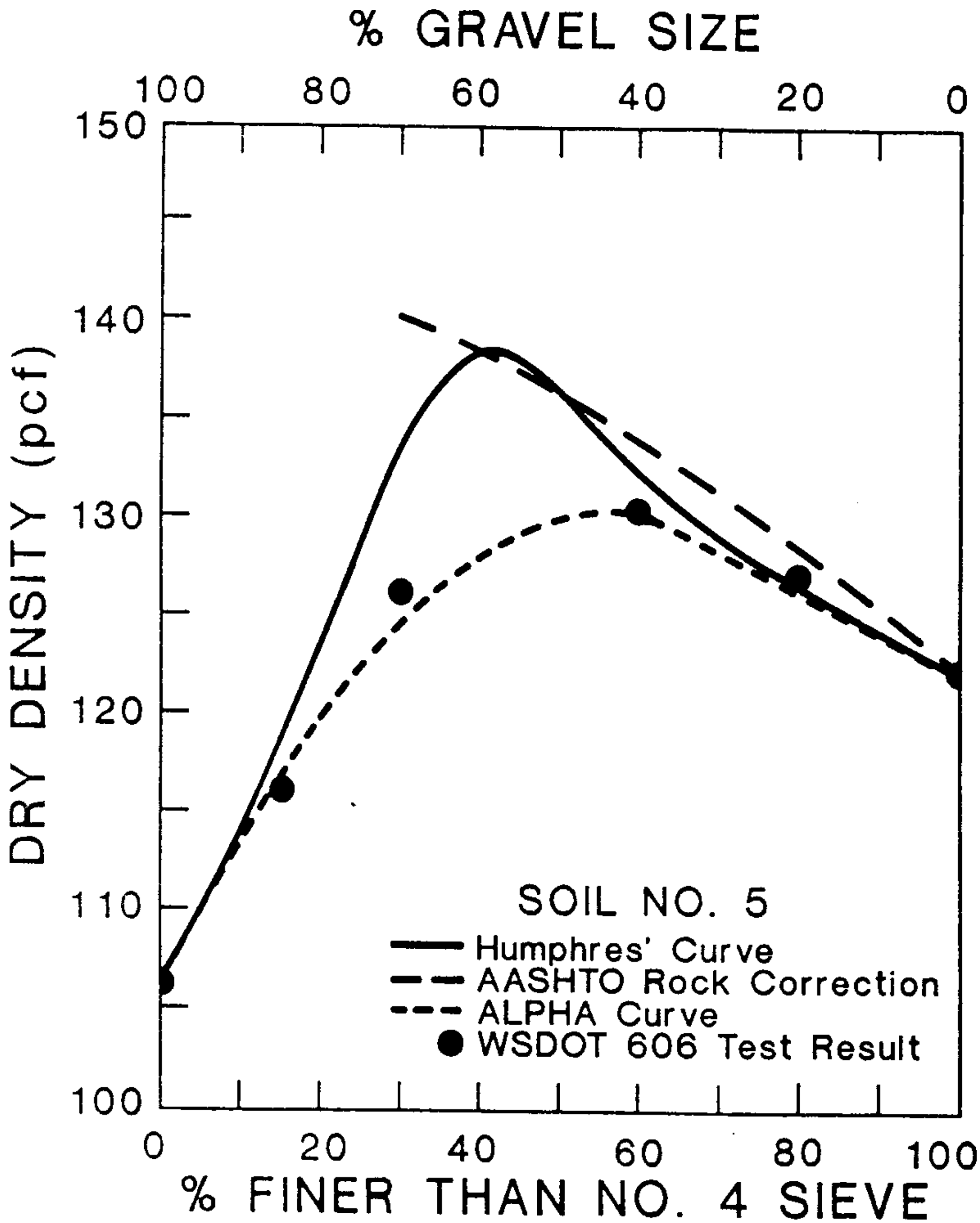


Fig. 16. Maximum Density Curves and Data Points (Soil No. 5)

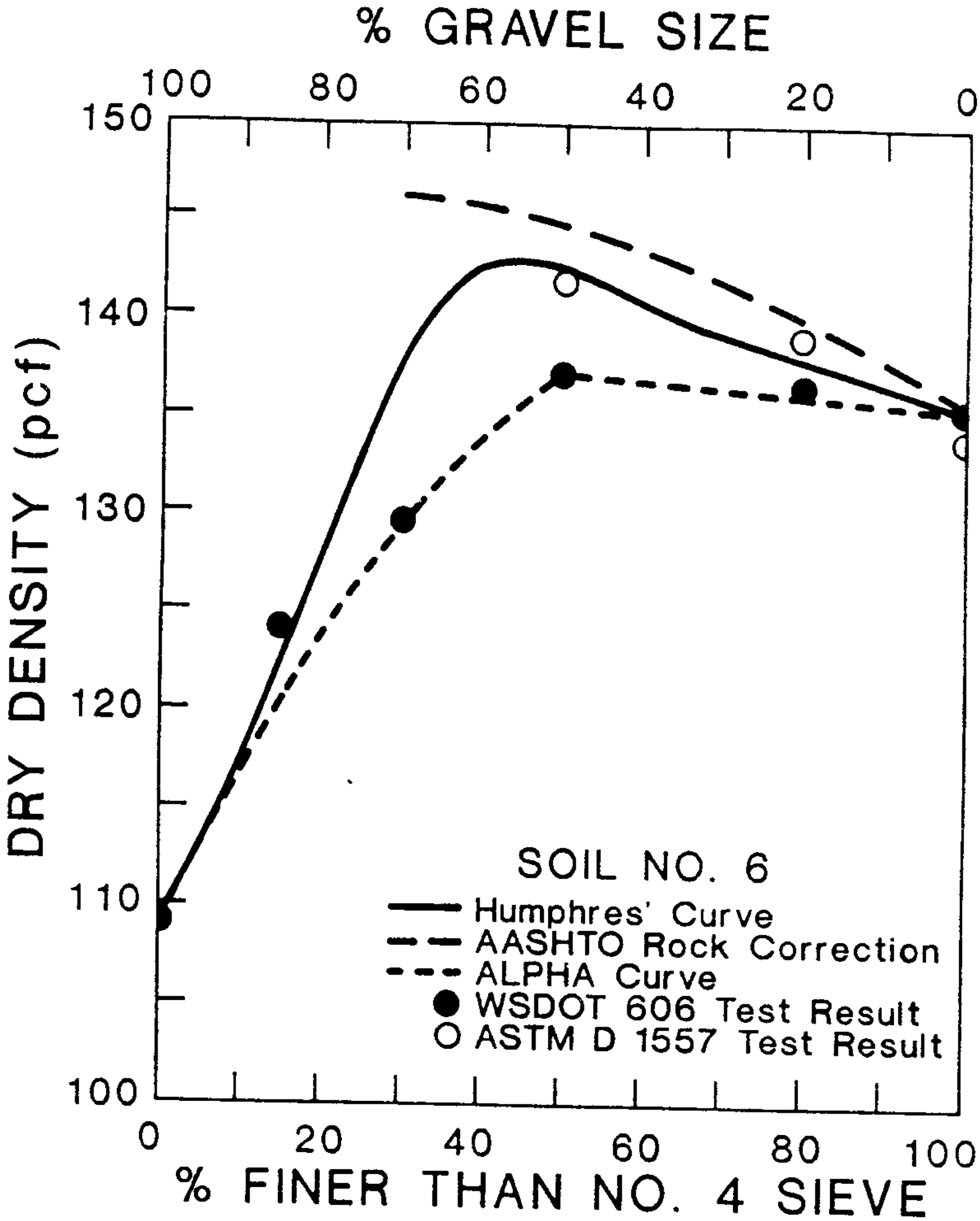


Fig. 17. Maximum Density Curves and Data Points (Soil No. 6)

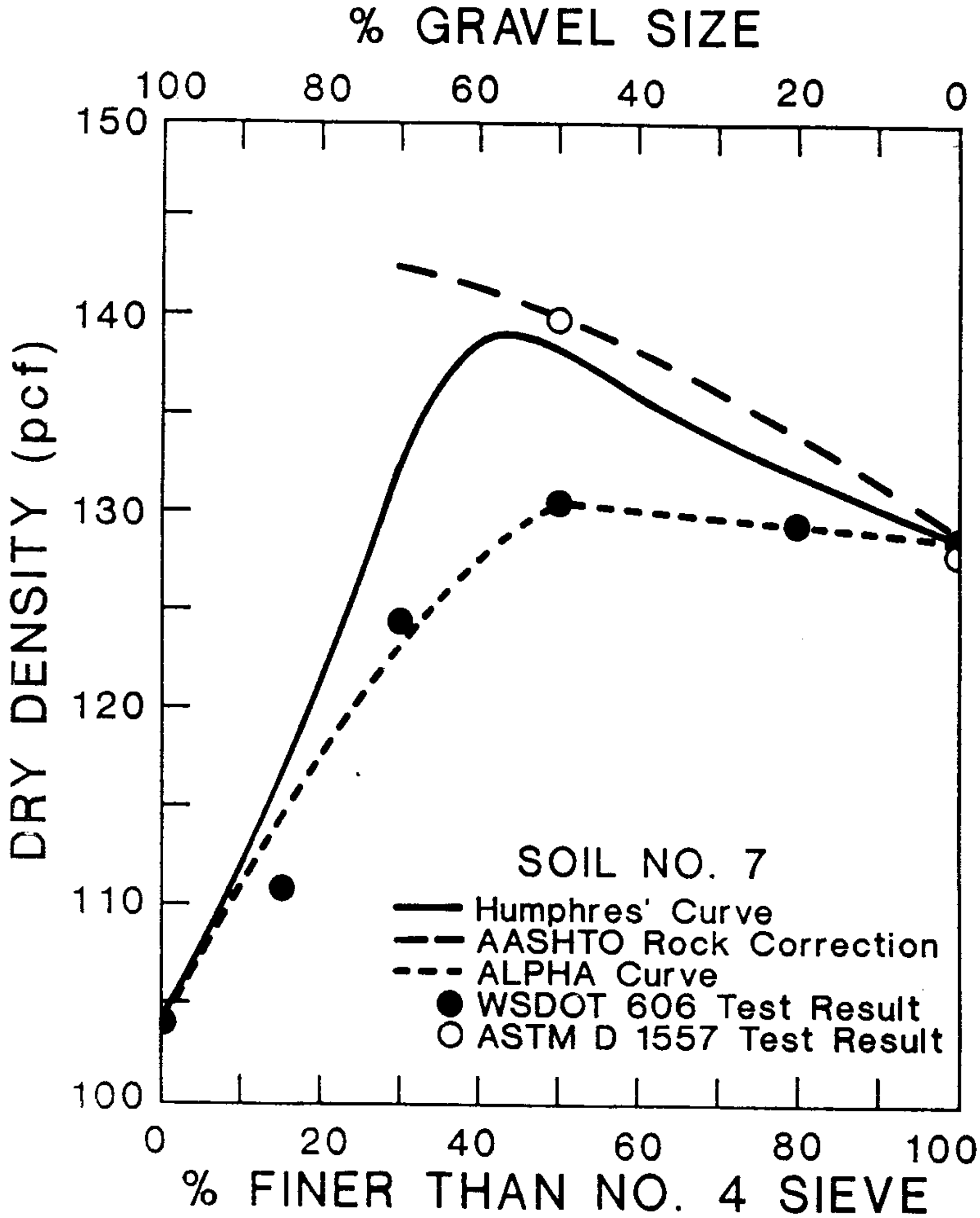


Fig. 18. Maximum Density Curves and Data Points (Soil No. 7)

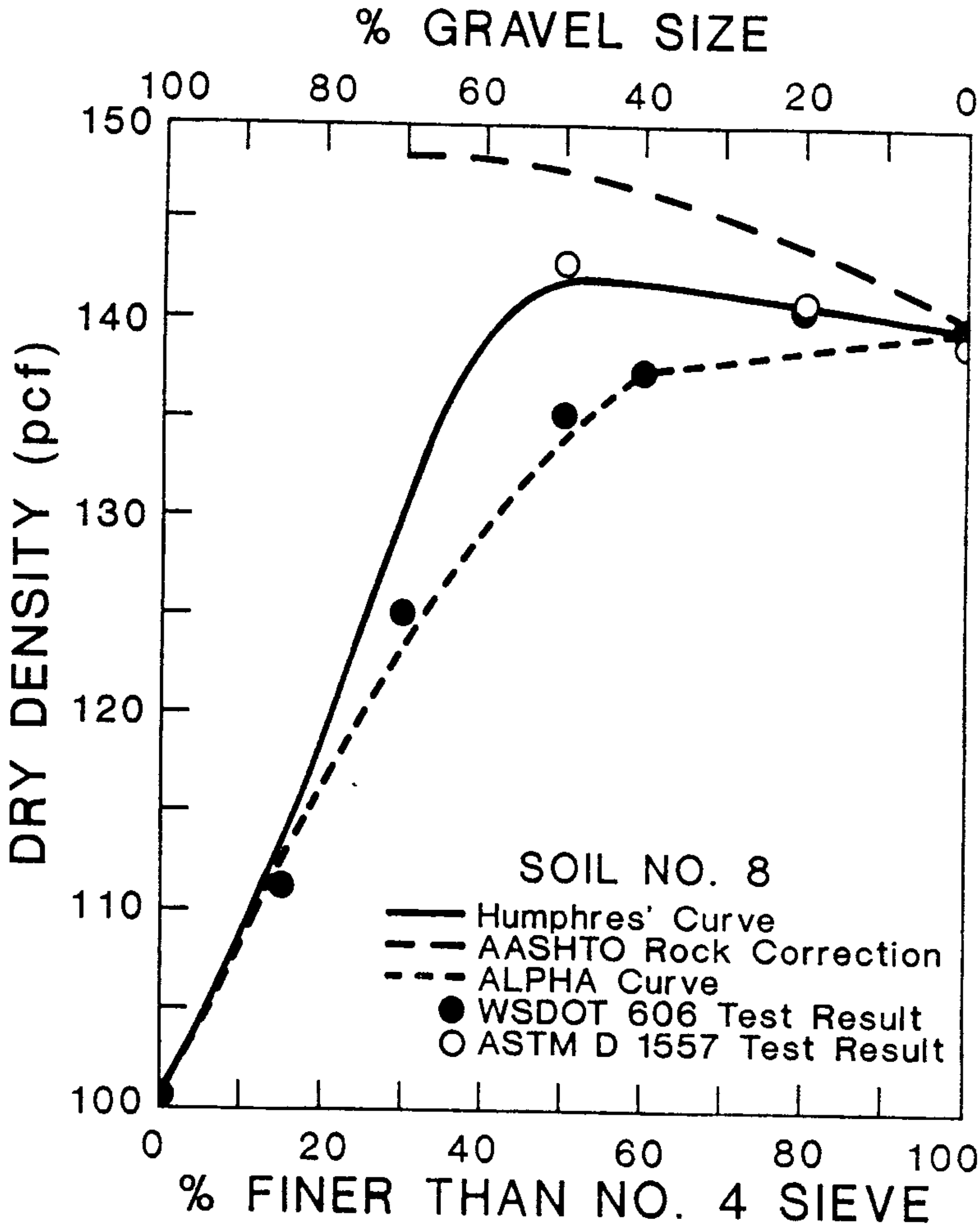


Fig. 19. Maximum Density Curves and Data Points (Soil No 8)

In terms of the concepts described in the Background section, it appears that the Humphres' method works best in the situation where the gravel size particles are floating in a matrix of sand and silt. In this floating condition the value of alpha is relatively constant, as expected. Its actual value will depend on the specific soil being considered. As the number of gravel particles increases to the intermediate and non-floating case, the Humphres' curve overpredicts density. Here, the structure formed by the gravel particles dominates and appears to inhibit the compaction of the minus #4 material. This is reflected in a decrease in the alpha value and an accompanying drop in dry density.

The AASHTO rock correction method of predicting maximum dry density is based on impact compaction (AASHTO specifications T99 and T180, essentially the same as ASTM D-698 and 1557) and a concept similar to the alpha factor. Rock correction factors are only given for soils with more than 30% minus #4 material. The use of these factors, in combination with WTM 606 results for the minus #4 material only, leads to the curves shown on Figs. 12-19. Because the rock correction factor is not a continuous function of the percentage of gravel in the soil, some smoothing was done using a second order regression to generate these curves; however, the error this introduces is less than 1 pcf.

It is clear that the use of AASHTO rock correction significantly overpredicts WTM 606 results for all the soils tested. This overprediction increases as the amount of gravel in the soil increases. In fact, the ever present decrease in maximum dry density as the percent gravel passes approximately 50% is not reflected in the rock correction method.

Using the alpha factor concept, an attempt was made to develop a method of maximum density prediction which better fits the data for the entire range of gravel contents. As mentioned above, the alpha factor is relatively constant between approximately 0 and 50% gravel content. Therefore, if one performed a compaction test with approximately 40-50% gravel and back-calculated, using Eqn. 10, the value of alpha, this alpha value could be used to calculate the dry density over the range of approximately 0-50% gravel. With more than 50% gravel, the value of alpha decreases. For the case of 100% gravel one could back-calculate, again using Eqn. 10, to obtain the value of alpha. As a first attempt to model the variation in density in this range it was assumed that the value of alpha varies linearly between its values at 50% (or 40%) and 100% gravel. Using these assumptions, constant alpha from 0 to 50% (or 40%) gravel and linearly decreasing alpha to 100% gravel, curves of dry density vs. percent gravel where developed and are shown in Figs. 12-19. In the range between 0 and 50% gravel, the alpha curves compare favorably with test data. These curves appear to be as good to considerably better than the Humphres' curves. In the range between 50 and 100% gravel, the comparison with test data is mixed; however, the alpha curves tend to be closer to the test data than the Humphres' curves and overpredict less often than the Humphres' curves. Overall, it is felt that the alpha curves provide a better match to the data than Humphres' curves. Additional developmental work may improve the ability of the alpha curves to predict maximum density in the 50 to 100% gravel range.

A few ASTM D1557 maximum density tests were performed on soils 6, 7, and 8. The results of these tests are plotted on Figs. 17-19. These tests produced higher maximum densities than the WTM 606 tests on the same soils and appear to better match the Humphres' and AASHTO rock correction curves. It is felt that the higher densities may have resulted from particle crushing in the ASTM test. Although grain size distribution tests were not performed after each ASTM test, the soils appeared to contain additional fines after testing. If this is the case, it is important to ask if field compaction will also result in a similar amount of particle crushing. If not, the ASTM test results may not be achievable in the field.

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GLOSSARY OF SELECTED TERMS

D_p -- the density of a mixture at a given percent gravel.

D_c -- the compacted density.

D_s -- the density of the solids only (obtained from multiplying the specific gravity of the solids by the mass density of water).

D_l -- the loose density.

D_t -- the true density.

α -- the alpha term (obtained from the ratio of the volume of a gravel size particle divided by the volume it occupies in a matrix of smaller particles).