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REVIEW OF MAXIMUM DRY DENSITY DETERMINATION METHODS

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MATERIALS TESTING REQUIREMENTS
AND PROCEDURES R&D
PHASE II

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REVIEW OF MAXIMUM DRY DENSITY DETERMINATION METHODS

1. INTRODUCTION

A review of Public Works and Government Services Canada (PWGSC) Architectural and Engineering (A&ES), Air Transportation, construction manual ASG-06[1] was carried out in 1995 by a Standards Review Board (SRB). The SRB consisted of members from the private sector and PWGSC, A&ES, Air Transportation. The purpose of the above noted review was to update the manual with current industry practices and developments in technology. Recommendations of the SRB were incorporated in the revised ASG-06 (September 1996) manual[2]. Some of the recommendations were not included and it was agreed that further evaluation would be required before their implementation. The National Office of PWGSC, A&ES Air Transportation, requested assistance from the Atlantic Region to evaluate and report on these outstanding recommendations.

2. SCOPE OF WORK

The scope of work included the following three items:

- Evaluation of the test method ASTM D1557[3] and ASTM D4718[4] compared to "Laboratory Density Determination" as defined in section 2.4.1 of ASG - 06[2].
- Investigation of the Modified Rice Test Method as put forward by the Canadian Asphalt Mix Exchange Program (CAMEP), compared to the test method for Maximum Specific Gravity of Bituminous Paving Mixtures (ASTM D2041-95). A report has been prepared and is submitted under separate cover.
- Review and evaluation of the Micro-Deval test. A report has been prepared and is submitted under separate cover.

This report summarizes a literature search and review of the test methods put forth by several material testing associations for determining the laboratory maximum dry density of aggregate layers. A survey of other Agencies including several Canadian Provincial Departments of Transportation was carried out to compare the different methods actually being used. The report also includes results obtained from laboratory testing carried out by PWGSC on a typical granular base aggregate and discussions on which method PWGSC should recommend in determining the laboratory maximum dry density of aggregate layers.

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1 ASG-06, Sept 1994. Pavement Construction Materials and Testing, Canadian Standards and Recommended Practices Airport Engineering, PWGSC, A&ES, Air Transportation.

2 ASG-06, Sept 1996. Pavement Construction Materials and Testing, Canadian Standards and Recommended Practices Airport Engineering, PWGSC, A&ES, Air Transportation.

3 D1557-91. Test Method for Laboratory Compaction Characteristics of Soils Using Modified Effort, 1996 ASTM Annual Book of Standards.

4 D4718-94. Standard Practice for Correction of Unit Weight and Water Contents for Soils Containing Oversize Particles, 1996 ASTM Annual Book of Standards.

3. PWGSC STANDARD TEST PROCEDURE

The PWGSC compaction standards for airfield pavement aggregate layers are presently specified in section 2.3 and Appendix H of ASG-06[2]. These compaction requirements are based on the corrected laboratory maximum dry density as specified in section 2.4.1 of ASG-06[2]. The corrected maximum dry density is calculated using the following empirical equation:

$$D = (F1 \times D1) + (0.9 \times D2 \times F2) \qquad (1)$$

D = corrected maximum dry density (kg/m^3).

F1 = fraction (decimal) of total field sample passing the 4.75 mm sieve.

F2 = fraction (decimal) of total field sample retained on the 4.75 mm sieve (equal to 1.00 - F1).

D1 = maximum dry density (kg/m^3) of material passing the 4.75 mm sieve in accordance with method A of ASTM D1557[3] (regardless of percent oversize fraction F2)

D2 = bulk density (kg/m^3) of material retained on the 4.75 mm sieve, equal to 1000 G where G is the bulk specific gravity (dry basis) of material when tested to ASTM C127[5].

No historical data could be found to explain exactly when or why the maximum dry density correction, as shown in equation (1) above was adopted. Reference to equation (1) can be found in the Canadian Department of Transport Engineering Design Manual[6] thus it would appear that equation (1) has been specified on Canadian Airfield Pavements at least since 1965.

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5 C127-93. Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate, 1996 ASTM Annual Book of Standards.

6 Section 7 (1965). Construction Control of Base, Sub-base and Subgrade. Engineering Design, Air Services, Department of Transport, Canada.

A reference to the origin of equation (1) was traced back to a paper by Norman McLeod[7] who carried out research work for the Department of Transport in the mid 40's. Because of the considerable influence of the subgrade and granular base layers shear strength on airfield pavement thickness design, stringent compaction requirements have historically been specified in North America. The shear strength of the sub-base and base layers must be high enough that failure will not occur within the pavement structure itself. To develop their inherent stability, sub-base and base course layers must be compacted to a high density during construction.

It would appear that the maximum dry density D1 in equation (1) was based on AASHTO standard T180[8,7]. The T180[8] test procedure is similar to the earlier version of the ASTM D1557[3] (pre 1991) test, commonly referred to as the Modified Proctor test, which included a scalp and replace option[9]. It would appear that the scalp and replace option was not adopted in Canadian Airfield standards. The maximum dry density D1 is based on material passing the 4.75 mm sieve regardless of the percent coarse fraction (> 4.75 mm) in the total sample. The corrected maximum dry density (D) appears to be based on AASHTO standard T224[10] which describes a procedure whereby the maximum dry density (D1) is adjusted to compensate for differing percentages of the coarse fraction retained on the 4.75 mm sieve in the total sample.

7 Norman W. McLeod, "Flexible Pavement Thickness Requirements", The Association of Asphalt Paving Technologists Proceedings (1956).

8 AASHTO T180. Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54kg Rammer and a 457mm Drop, American Association of State Highway and State Officials.

9 Rock Correction Issues in Compaction Specifications for High Gravel Content Soil. Transportation Research Record 1462, Kenneth D. Walsh. (Reference USBR 5515-89).

10 AASHTO T224. Standard Method of Test for Correction for Coarse Particles in the Soil Compaction Test, American Association of State Highway and State Officials.

4. OTHER AGENCIES

4.1 New Brunswick Department of Transportation (NBDOT)

Contact: Lester Foreman, Materials Laboratory (506-453-2619).

NBDOT's standards[11] specify the compaction of granular base layers to ASTM D698[12] commonly referred to as the Standard Proctor test. The use of ASTM D1557[3] is only specified on structural fills by special request. The choice of testing procedures (A, B or C) is based on material gradation and the oversize correction is carried out following ASTM D4718[4].

4.2 Nova Scotia Department of Transportation and Communications (NSDOT)

Contact: Wayne MacAskill, Technical Services (902-860-2999).

NSDOT's standard specifications[13] recommend compaction of granular base materials to ASTM D698[12]. The choice of testing procedures (A, B or C) is based on material gradation. The oversize correction is carried out following a Humphres solution[14]. The department is presently considering the use of field control test strips for all compaction control of granular base layers.

4.3 Prince Edward Island Department of Transportation and Public Works (PEIDOT)

Contact: Terry Kelly (902-368-4750).

PEIDOT's standard specifications[15] recommend compaction of granular base materials to AASHTO T-99[16] also commonly referred to as the Standard Proctor test. Method A procedure is specified regardless of percent oversize greater than 4.75 mm. The oversize correction (> 4.75 mm) is calculate following ASSHTO T-224[10].

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11 New Brunswick Department of Transportation, General Specification Book, January 1995.

12 ASTM D698. Laboratory Compaction Characteristics of Soil Using Standard Effort, ASTM Annual Book of Standards.

13 Nova Scotia Department of Transportation and Public Works. Standard Specification Highway Construction and Maintenance, April 1996.

14 Hubert W. Humphres, A Method for controlling Compaction of Granular Materials.

15 Prince Edward Island Department of Transportation and Public Works, Contract Specifications for Highway Construction, April 1994.

16 AASHTO T99. Standard Method of Test for the Moisture-Density Relations of Soils Using a 2.5 kg Rammer and a 305 mm Drop, American Association of State Highway and State Officials.

4.4 Newfoundland and Labrador Department of Works, Services and Transportation (NDOT)

Contact: Keith S. Foster (709-729-2441).

NDOT's standard specifications[17] recommend compaction of granular base materials to ASTM D698[12]. The choice of testing procedures (A, B or C) is based on material gradation and the oversize correction is carried out following ASTM D4718[4].

4.5 Ministry of Transport of Quebec (MTQ)

Contact: Claude Robert, Laboratoire des Chaussees (418-644-0181).

MTQ's standard specifications[18] recommend compaction of natural granular base materials to BNQ-2501-255[19] which is similar to the pre 1991 ASTM D1557 including the scalp and replace method. The choice of testing procedures A, B, C or D is based on material gradation and the oversize correction is carried out following ASTM D4718[4]. When quarried materials are used, field control strips are carried out as a reference.

4.6 Ministry of Transportation of Ontario (MTO)

Contact: Stephen A. Senior, Senior Aggregate Engineer (416-235-3743).

MTO has been specifying, since summer of 1996, field test strips for compaction control of granular base and fill materials.

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[17] Newfoundland Department of Works, Services and Transportation, Highway Design Division, Specifications Book, April 1995.

[18] Ministere des Transport du Quebec, Cahier des charges et devis Generaux, 1993.

[19] BNQ-2501-255, 1993, Determination de la teneur en eau/ masse volumique, Essai Proctor Modifie.

5. LABORATORY RESEARCH WORK

5.1 Introduction

Compaction control of engineered fills is usually provided by specifying that the in place dry density of the fill be a predetermined percentage of a reference dry density. Most of the current methods in determining a reference dry density in the laboratory are derived from one developed by the California Highway Department[20] in the early 1930's known as the Standard Proctor test ASTM D-698[12]. This procedure determines the relationship between water content and dry density (compaction curve).

The purpose of the laboratory compaction test is to determine in the laboratory a moisture-density curve comparable to that for the same material when compacted in the field by the equipment and procedures likely to be used. The Standard Proctor test was established for general road construction with relatively lightweight field compaction equipment. For increased traffic loads and heavier construction equipment, ASTM D1557[3] (AASHTO T180[8]), known as the Modified Proctor test, was developed. Based on the literature review, the Modified Proctor test is widely accepted as a benchmark for the determination of a laboratory reference dry density for airfield pavement compaction control[21,20,7]. For the purpose of this study the use of test method ASTM D1557[3] for the determination of a laboratory reference dry density is considered an appropriate method.

The use of a laboratory reference dry density for compaction control is based on the assumption that the material compacted in the laboratory is the same as the material compacted in the field. The laboratory molds (101.6 mm or 152.4 mm) used in the Modified Proctor test place a physical restriction on the maximum particle size that can be practically tested. For this reason the effect of coarse particles on the laboratory maximum dry density must be considered. SRB discussions on the different methods of determining the corrected maximum dry density, resulted in a need to further reassess the influence of coarse particles in the determination of a reference maximum dry density. Both SRB members from the private sector recommended in their review [22,23] that equation (1) be replaced by ASTM D4718[4] in conjunction with ASTM D1557[3] for the determination of the corrected maximum dry density. Their recommendations also included that test method ASTM D1557[3] be based on the material gradation. Based on these recommendations a limited laboratory testing program was carried by PWGSC to evaluate the corrected maximum dry density as obtained with equation (1) compared to ASTM D1557[3] in conjunction with ASTM D4718[4].

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[20] Soils Mechanic in Engineering Practice, Terzaghi and Peck, John Wiley and Sons, 1967.

[21] NAVFAC, Naval Facilities Engineering Command, Design Manual 7.1 and 7.2, 1986.

[22] Review and Recommendations to PWGSC Pavement Construction Manuals, Terra Engineering Ltd, February 14, 1995.

[23] Recommended Technical Changes, PWGSC Pavement Construction Manual ASG-06, JEGEL, February 21, 1995

5.2 Testing program

Three bulk samples of crushed Gabbro rock were obtained from existing stockpiles at the Moncton Crushed Stone, Gorge Road Quarry, Moncton, N.B. The three samples are locally identified as 75 mm minus, 37.5 mm minus and 19 mm minus. These materials are locally used for structural fills and road bases. The quarry has previously supplied granular base materials for several Airfield pavement projects.

Preliminary sieve analyses were carried out on each bulk sample to determine which one would provide the most representative gradation for further testing. The 19 mm minus bulk sample was selected to carry out the comparative testing along with representative oversize material (4.75 mm to 19 mm) selected from the 75 mm minus and 37.5 mm minus bulk samples. The average results of two sieve analyses carried out on the 19 mm minus bulk samples are summarized in table 1.

Table 1
Average Gradation (19 mm minus)
Bulk Sample

Sieve Size (mm)	Percent Passing (%)
37.500	100.000
19.000	98.900
9.500	71.500
4.750	51.800
2.000	33.100
0.425	14.700
0.075	7.000

The 19 mm minus bulk sample was then processed on the 4.75 mm sieve. The average results of two representative sieve analyses carried out on the minus 4.75 material prior to carrying out the Proctors are summarized in table 2. Sufficient material representative of the 4.75 mm to 19.0 mm fraction was then prepared to complete the Proctor tests.

Table 2
Average Gradation (4.75 mm minus)

Sieve Size (mm)	Percent Passing (%)
9.5	100.000
4.750	99.400
2.000	60.900
0.425	24.800
0.075	10.300

The laboratory program consisted of carrying out 18 separate Modified Proctor tests. The ASTM D1557-91 method was carried out following procedures A and C. For the purpose of this study it was assumed that these two methods would provide sufficient data for assessment. Procedure B was not included in the laboratory program. Airfield Pavement granular base layers typically contain more than 20% by weight of material retained on the 9.5 mm thus procedure B would not normally be used if PWGSC fully adopted ASTM D1557-91[3].

It should be noted that procedures for scalp-and-replace are no longer included in ASTM D1557-91. The scalp-and-replace method involved the removal of all material larger than 19 mm and replacement in the mold with an equal amount of 4.75 mm to 19 mm.

Procedure A

Three separate tests were carried out following ASTM D1557 procedure A (material passing the 4.75 mm sieve). The material was compacted in a 101.6 mm diameter mold with a 4.5 kg hammer dropped from a height of 457 mm. The molds were filled in five separate layers with 25 blows per layer. The material was processed at 5 incremental water contents for each test. The maximum (optimum) dry densities were determined from the compaction curves.

Procedure C

Fifteen separate tests were carried out following ASTM D1557 procedure C. The material was compacted in a 152.4 mm diameter mold with a 4.5 kg hammer dropped from a height of 457 mm. The molds were filled in five separate layers with 56 blows per layer. The material was processed at 5 incremental water contents for each test. The maximum (optimum) dry densities were determined from the compaction curves.

Five groups of three tests were carried out with rock contents varying between 10 to 60 percent (10, 20, 30, 40 and 60). The rock fractions consisted of material ranging between 4.75 mm and 19.0 mm. The gradation of the minus 4.75 mm was left unchanged and the percentage by weight of the plus 4.75 mm was incrementally increased. The maximum dry density results obtained from the testing program are summarized in table 4.

Table 4
Laboratory Program
Test Results - ASTM D1557-91

Procedure	% Coarse Fraction 4.75-19 mm	Maximum Dry Density kg/m^3	Average Max Dry Density kg/m^3
A	0	2152	
		2145	
		2145	2147
C	10	2158	
		2155	
		2147	2153
C	20	2175	
		2173	
		2165	2171
C	30	2204	
		2206	
		2198	2203
C	40	2209	
		2202	
		2195	2202
C	60	2236	
		2239	2238

The quality of the material was assessed by carrying out three Atterberg limits[24], two Abrasion Tests[25] and four Specific Gravities and Absorptions[26]. The average results of the these tests are summarized in table 3.

[24] ASTM D4318-95, Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, 1996 ASTM Annual Book of Standards.

[25] ASTM C131-89, Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.

[26] ASTM C127-88, Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate, 1996 ASTM Annual Book of Standards.

Table 3
Material Quality Test Results

Test		Result
Atterberg Limits[24]		Non Plastic Fines
Los Angeles Abrasion[25]		22.0%
Bulk Specific Gravity[26]		
	4.75 mm to 19.0 mm	2.67
	19.0 mm to 75.0 mm	2.64
Absorption[26]		
	4.75 mm to 19.0 mm	1.25%
	19.0 mm to 75 mm	0.8%

6. DISCUSSION AND RECOMMENDATIONS

6.1 Rock Correction Equations

Several empirical equations have been developed by different material testing associations to account for the effect of coarse particles on a laboratory reference dry density. These are commonly called rock, oversize or coarse fraction correction equations. In these empirical equations, factors such as the maximum dry density of the fine fraction, the percentage of coarse fraction and sometimes the character of the fine fraction are used to approximate the maximum dry density of the total material. Commonly used rock correction equations are presented in table 5.

Table 5
Rock Correction Equations

Reference		Equation	Comments
AASHTO T224[10] / PWGSC ASG-06[2]	(1)	D= (F1xD1)+(0.9* x F2 x D2)	D1 determined on the 4.75 mm fraction, using ASTM D1557 / AASHTO T180.
AASHTO T224[10]	(2)	D= 1 / ((F2/D2)+(F1/r D1))	D1 determined on the 4.75 mm fraction, using AASHTO T180.
ASTM D4718[4]	(3)	D= 1 / ((F2/D2)+(F1/D1))	D1 determined using ASTM D1557.
USBR 5515[9]	(4)	D= 1 / ((F2/D2)+(F1/r_u D1))	D1 determined using USBR 5500.
NAVFAC[21]	(5)	D= (1- (.05 x F2)) / ((F2/D2)+(F1/D1))	D1 determined using ASTM D1557. For F2 greater than 60% further adjustments may be required.

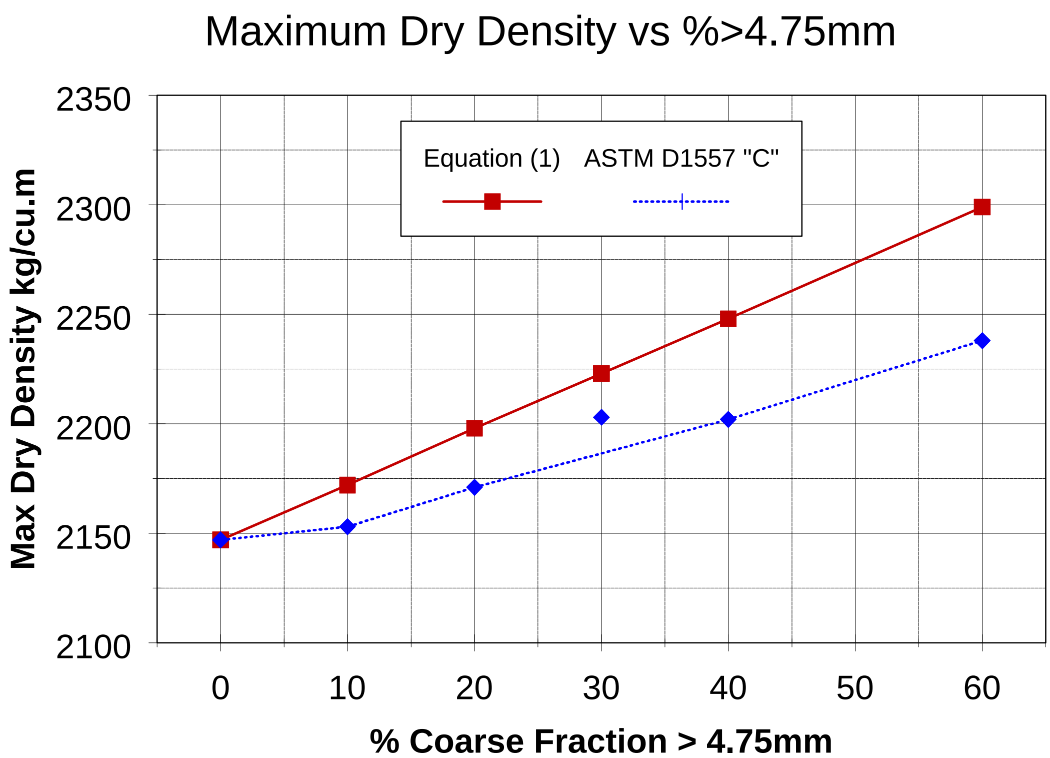
D = Corrected maximum dry density (kg/m^3)
D1 = Maximum dry density of fine fraction (kg/m^3)
D2 = Density of coarse particles (1000 x Bulk Specific Gravity) (kg/m^3)
F1 = Fine fraction (decimal) of total field sample.
F2 = Coarse fraction (decimal) of total field sample (equal to 1.00 - F1).
* = 0.9 is an empirical coefficient that is dependent on the value of F2. A coefficient of 0.9 is normally considered to be adequate in field control of granular base compaction control however if a more exact adjustment is desired AASHTO recommends the use of equation (2).
r = Coefficient having a value dependent on F2.
r_u = Coefficient having a value dependent on F2 and plasticity of fines.

Some agency standards such as method AASHTO T180-93 and the previous edition of ASTM D1557 (pre 1991) include a scalp-and-replace method.

6.2 Laboratory Program

The laboratory program carried out for this study was limited to comparing the results obtained from the PWGSC equation (1) with the results obtained from method C of ASTM D1557-91[3]. Figure 1 shows the effect of coarse particles on the corrected maximum dry densities calculated by equations (1) and obtained with ASTM D1557 (method C)[3].

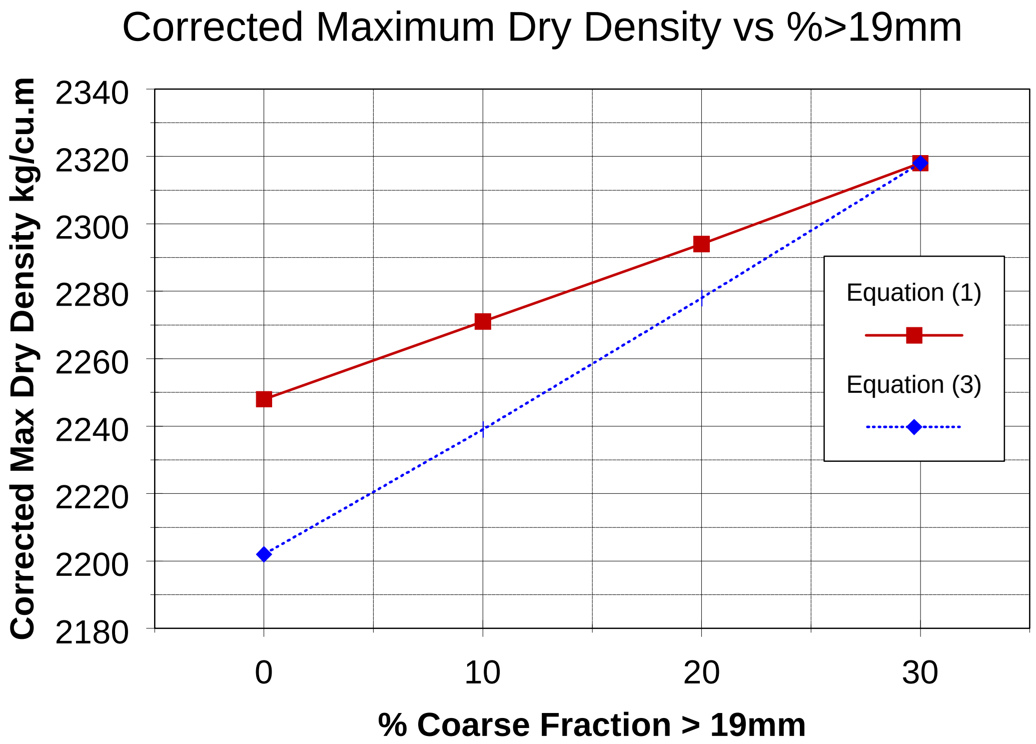
Figure 1



In all cases the corrected maximum dry density calculated with equation (1) was greater than the maximum dry density obtained with ASTM D1557 (procedure C)[3]. Figure 1 also shows that the percent increase in corrected maximum dry density generally increases as the percent coarse particles increases. The results obtained from equation (1) were 1.0 to 2.7% higher than ASTM D1557 method C[3]. This trend has also been observed in studies carried out by others[9].

The PWGSC granular base gradation limits range from a maximum of 50 percent to a minimum of 25 percent retained on the 19 mm. Figure 2 shows the effect of coarse particles (> 19 mm < 75 mm) on the corrected maximum dry densities as calculated by equations (1) and (3).

Figure 2



The corrected maximum dry densities calculated by equation (3) as shown in figure 2 are based on the premise that a typical granular base material contains approximately 40% material between particle sizes 4.75 mm and 19 mm when oversize particles (>19 mm) are removed. Therefore for comparison purposes a value of 2201 kg/m^3 (D1) obtained from figure 1 was used in equation (3). Figure 2 clearly demonstrates that the percent increase in the corrected maximum dry density obtained from equation (3) increases as the percent coarse particles (>19 mm) increase. This is due to the fact that an empirical reduction factor is applied to the coarse fraction density in equation (1) and none in equation (3). The equation (1) values were 2.7% higher than the equation (3) values at low coarse fractions (>19 mm) however it can also be seen that equation (3) would result in increasingly higher values than equation (1) when the coarse fraction (>19 mm) exceeds 30%.

Based on the results of this study it is concluded that the adoption of ASTM D1557-91[3] with correction for oversize particles based on ASTM D4718-94[4] would result in the reporting of an increase of up to 2.7% in calculated compaction results for exactly the same compacted material compared to results calculated using the corrected maximum dry density equation as recommended in ASG-06[2]. This would mean that in the field, granular base materials would be accepted in-place with up to 2.7% lower density than currently accepted.

6.3 Recommendations

Some of the advantages of maintaining equation (1) rather than fully adopting ASTM D1557 and D4718 in PWGSC airfield pavement standards are: based on the laboratory testing program the corrected maximum dry density obtained from equation (1) requires more field compaction effort to achieve and thus ensures maximum shear strength; laboratory processing of the field sample is limited to only two fractions (< 4.75 mm and > 4.75 mm) and one mold size while the full ASTM D1557 method would theoretically require splitting and processing the material on a variation of three fractions (< 4.75 mm, < 9.5 mm and < 19 mm) and the use of two mold sizes; and in theory could require carrying out different procedures depending on the variability of percent coarse fraction in the total material.

Most rock correction equations are considered suitable when the percent of oversize material (> 4.75 mm) is less than 60% by weight[9,21] however ASTM[4] limits it to less than 40%. ASTM[4] considers the rock correction practice valid for material having up to 30% oversize particles when the oversize fraction is greater than 19 mm. The factor controlling the maximum permissible percentage of oversize particles is whether the interference between the oversize particles affects the density of the finer fraction when compacted in the field. This interference may occur at different percentages of oversize particles for different types of material. For this reason the use of a corrected maximum dry density as a reference density for increasing rock percentages will have to be evaluated on an individual basis particularly for coarse granular sub-base materials . The use of field control test strips should be used as an alternate for these coarse materials to ensure representative and achievable compaction control in the field.

It has been observed on numerous Canadian Airport projects that achieving 100% of the corrected maximum dry density as specified in ASG-06 requires optimal conditions and equipment. Seldom are there compaction results above 100%.

In conclusion equation (1) has historically provided a conservative approach in determining a reference maximum density for airfield pavement compaction control on granular layers and has been used successfully to achieve the high granular base layer densities required using the construction methods and equipment available. It is therefore recommended that PWGSC maintain equation (1) for compaction control of airfield pavement granular base and sub-base materials with a provision for the use of field control test strips where the oversize fraction correction does not accurately reflect the maximum dry density achievable in the field.