VALIDATION OF THE COREDRY™ AND COREREADER™ APPRATUS

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COREREADER™ APPRATUS

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CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

The determination of the bulk specific gravity (Gmb) of bituminous paving mixture is an important part of the superpave mix design system and construction quality control/ quality assurance program. The bulk specific gravity is used to determine the air void content (VTM), voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and percent density after compaction of bituminous mixtures. The Gmb of pavement cores are used in determining the percent compaction of hot-mix asphalt (HMA) pavements. All of the above parameters are monitored closely during production to ensure satisfactory pavement performance. Problems or errors in measuring the Gmb can lead to pavement distresses such as rutting, stripping, bleeding, cracking, age hardening, and excessive permeability which finally have impact on pavement performance.

With the introduction of coarser superpave mixtures and open graded specialty mixes, the ability of current procedures to accurately measure Gmb is being questioned. This is due to increased interconnected voids of coarse and open graded mixes, which can result in over-approximations of density and under approximation of VTM. Repeatability and consistency problem in Gmb test values are also more pronounced for coarse graded mixes. AASHTO T166 is used to determine the Gmb for samples with less than two percent moisture absorption. AASHTO TP69, the CoreLok^{TM} procedure, is recommended for samples with greater than two percent moisture absorption.

Troxler® has developed the CoreReader^{TM} apparatus which can overcome all the drawbacks of AASHTO T166 and AASHTO TP69. The manufacturer claims that this device, when properly calibrated, provides repeatable and accurate measurements that are not operator dependent (1). The Troxler® 3660 CoreReader^{TM} uses gamma ray technology to determine the density and Gmb of HMA samples without using water displacement methods or dimensional analysis procedures. Initial results indicate that the CoreReader^{TM} has potential to accurately measure Gmb of HMA samples with interconnected voids (1). An evaluation of the CoreReader^{TM} could result in a more accurate measurement of Gmb, resulting in improved pavement performance.

A second problem with AASHTO T166 is the time it takes to dry the sample and potential damage to the sample caused by drying at elevated temperatures. InstroTek® has developed the CoreDry^{TM} apparatus that dries a core without heat, reducing testing time and allowing further testing of the sample without concern of damage to or artificial hardening of the sample due to heat of drying (2). The test procedure is listed in ASTM D7227. However, there was little published literature verifying that the dry mass determined from CoreDry^{TM} is the same as determined using AASHTO T166.

OBJECTIVES

There were two main objectives of this study. The first objective was to determine if the Gmb of pavement cores determine using the CoreDry^{TM} apparatus produces statistically similar results to AASHTO T166, resulting is substantial time savings to contractors and for quality control and quality assurance works. The second objective was to determine if the CoreReader™ produces statistically similar bulk specific gravities to AASHTO T166. If the results are different, correlations will be developed between the CoreReader™ and AASHTO T166 Gmb. The effect of parallel surface and roughness of sample faces on CoreReader™ Gmb will also be evaluated.

SCOPE

As the CoreDry™ and CoreReaer™ apparatus are new in determination of bulk specific gravity of HMA samples, there was little much literature available on the procedures to review. Only guidelines given by manufacturer and three unpublished articles were found and reviewed for this study. For the true comparison of AASHTO T166 Gmb with the Gmb obtained either by CoreDry™ or CoreReaer™, a wide variety of samples ranging from dense to loose mix is needed. Different mixes with different void contents are necessary to evaluate the efficiency of the apparatus. The test results and analysis were done using lab compacted samples which were limited to ODOT S3, S4 and SMA mixes and field cores of diameter100 mm and 150 mm of unknown volumetric properties.

CHAPTER 2

REVIEW OF LITERATURE

BULK SPECIFIC GRAVITY OF ASPHALT MIXES (Gmb)

AASHTO defines the bulk specific gravity (Gmb) of an asphalt mix as the ratio of the weight in air of a unit volume of material (including both permeable and impermeable voids) at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature (3).

The accurate measurement of bulk specific gravity (Gmb) of hot-mix asphalt (HMA) is critical in mix design and determination of volumetric properties. The accurate determination of Gmb has been a topic of research for many DOTs and agencies for many years. The introduction of Superpave mix design methods in the late 1980's resulted in the use of more coarse graded mixtures. With the use of coarse graded mixtures, agencies began noticing difficulty in accurately determining the Gmb of these coarse graded HMA mixes.

There are several methods available for determination of Gmb of asphalt mixes. Common procedures are SSD method as outlined in AASHTO T166, Height–diameter or dimensional analysis method, CoreReader™ (using Gamma rays), CoreLok™ (a vacuum sealing device) method as outlined in ASTM D6752 and AASHTO TP 69, and paraffin and Para film methods (AASHTO T275).

AASHTO T166

AASHTO T166 outlines the laboratory determination of bulk specific gravity by water displacement. The method consists of determination of dry weight and volume of the lab compacted as well as field core sample. AASHTO T166 uses the following formulas to calculate the bulk specific gravity and percent water absorption of asphalt mixture (1).

$$\text{Bulk specific gravity (Gmb)} = \frac{A}{B - C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\text{Percent water absorption} = \frac{B - A}{B - C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, A= mass in grams of dry specimen in air

B= mass in grams of the saturated surface-dry (SSD) specimen in air

C= mass in grams of the specimen in water

Method A

For lab compacted samples, dry mass is the mass of the sample after cooling to room temperature at 25±5ºC (77±9ºF). The determination of the volume of the sample is by water displacement. In this method, the mass of sample immersed in water at 25±1ºC (77±1.8ºF) for 4±1 minute is the submerged mass (C) and the mass of specimen by blotting with a damp towel quickly is the surface-dry mass (B) (3).

For filed core samples the dry mass (A) is defined as the mass at which further drying at 52±3ºC (125±5ºF) does not alter the mass by more than 0.05 %. Samples partially saturated with water are dried overnight at 52±3ºC (125±5ºF) and then weighed at two-hour drying intervals until the mass loss is less than 0.05 %.

Method B

This method outlines the measurement of Gmb by volumeter. Method B consists of determining the dry mass (A) of lab compacted sample by cooling to 25±5ºC (77±9ºF) and saturated-dry mass (B) by blotting a sample with a damp towel, immersed in water at

25±1ºC (77±1.8ºF) for 10 minutes. The mass of the volumeter filled with water at 25±1ºC (77±1.8ºF) (E) is taken and the following formula is used to calculate the Gmb (3).

$$\text{Bulk specific gravity (Gmb)} = \frac{A}{B + D - E} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

D= mass in grams of the volumeter filled with water at 25±1ºC (77±1.8ºF)

E= mass in grams of the volumeter filled with specimen and water at 25±1ºC (77±1.8ºF)

A and B are as previously defined.

If the percent water absorption is greater than 2 %, AASHTO T166 method B recommends using AASHTO T275 to determine the bulk specific gravity.

Method C (Rapid Test)

AASHTO T166 Method C outlines the procedure of determining the Gmb of lab compacted and field core samples which have a substantial amount of moisture and are not required for further testing. In this method, the determination of volume is similar to Method A. The only difference in this method is the dry mass (A). The sample is dried at 110±5ºC (230±9ºF) to a constant mass. Constant mass in this case is mass loss does not alter by more than 0.05 percent when weighed at 2-hour intervals. The dry mass (A) is the mass of sample at room temperature when mass loss is less than 0.05 % (3). The only disadvantage of this method is it can damage the sample for further testing.

ASTM D2726

ASTM D2726 outlines the procedure for determination of Gmb of asphalt mix (4). For the laboratory prepared sample, the dry mass (A), surface-dry mass (B) and submerged mass (C) are determined as in AASHTO T166. For the laboratory drilled and field drilled cores ASTM D2726 recommends drying the sample at 110±5ºC (230±9ºF) to a constant mass. Constant mass in this case is mass loss does not alter by more than 0.1 percent when weighed at 2-hour intervals. ASTM D2726 does not allow drying the drilled cores at reduced temperature such as 52ºC (4).

COREDRY™

The best method to determine the dry state or constant mass of field or laboratory cut cores is still in question as there are a number of methods available and the accurate determination of the dry mass is necessary in calculating the bulk specific gravity of asphalt mixes. According to InstroTek ® (2), the CoreDry™ apparatus was introduced to overcome the problem. The CoreDry™ system uses high vacuum in conjunction with a thermoelectric cold trap to draw moisture out of a sample, evaporate the moisture, and subsequently condense the moisture in a separate chamber. It provides a constant mass in relatively less time than traditional oven-drying techniques. The vacuum system lowers the vapor pressure in the chamber holding the specimen to draw out and evaporate trapped moisture. As such, the specimen remains at or near room temperature, which helps to retain the HMA characteristics due to prolonged exposure to the heat and oxidation potential present in forced-draft ovens (5).

The CoreDry™ is already accepted by ASTM and the test procedure is available as ASTM D7227. The apparatus consists of sample chamber, water trap system and key pad. The apparatus performs a self test when it is started. The operation of CoreDry™ is simple and easy. A sample is placed in the sample chamber and drying operation can be completed by hitting the start button. During the drying operation, the apparatus runs through a series of drying cycles at a reduced pressure until the dry condition is met. The number of cycles depends on the amount of moisture present in sample. The cold trap system collects all the water drawn by vacuum action which needs to remove after each drying operation. Sucking of water from the sample by vacuum action and collecting trapped water in water chamber constitutes a cycle. The apparatus goes through a number of such cycles to remove the water present in sample (2). The CoreDry^{TM} apparatus is shown in figure 2.1

FIGURE 2.1 InstroTek® CoreDry^{TM} apparatus.

COREREADER™

The Troxler Model 3660 CoreReader™ is a laboratory nuclear device used to measure the bulk specific gravity and density of laboratory and field specimens (4). The CoreReader™ uses gamma rays for determination of the pavement density and bulk specific gravity. The gamma ray method of density measurement is based on the scattering and absorption properties of gamma rays with matter. When a gamma ray source of primary energy in the Compton range is placed near a material, and energy selective gamma ray detector is used for gamma ray counting, the scattered and unscattered gamma rays with energies in the Compton range can be counted exclusively and directly converted to the density or bulk specific gravity of the material (1).

CoreReader™ bulk specific measurement is a non destructive, operator independent test and does not harm the mix property for further testing. CoreReader™ can be used for hot specimens, resulting in a time saving for cooling of laboratory compacted samples (6).

The apparatus consists of sample chamber and key pad. A sample size of 100 mm or 150 mm fits into the sample chamber. The operator selects the sample size and inputs the height of specimen. The manufacturer recommends the input height should be the average height measured at six evenly spaced locations by a caliper having precision of ±0.1mm. The height of the sample should be 110-120 mm for 150 mm diameter laboratory sample. Once this information has been entered and the START button pressed, the CoreReader™ measures the specimen specific gravity (Gmb) and density and displays the results on the screen. If the operator enters a maximum specific gravity (Gmm), it also calculates and displays the air void content (VTM). CoreReader™

calculates Gmb using the entered height and diameter of the specimen. This requires that specimens need to be parallel with smooth edges for testing. The allowable angle between two faces is 3°. The apparatus needs calibration with the standard set of calibrating cylinders when moved to new place or used after long time (6). The CoreReader™ apparatus is shown in figure 2.2.

FIGURE 2.2 Troxler CoreReader™ Model 3660.

The non-destructive bulk specific gravity (Gmb) determination of laboratory prepared and cored pavement specimens allow for performance tests to be conducted on the same specimens used in the Gmb determinations. In addition to the time savings, more reliable correlation between densities and moduli of specimens may be achieved.

Troxler claims the following measurement precision,

Repeatability (Single Laboratory)	0.006 Sp. Gravity	6 kg/m^3 (0.3744 pcf)
Reproducibility (Multi laboratory)	0.009 Sp. Gravity	9 kg/m^3 (0.5616 pcf)

Troxler also states that the researcher does not have to prepare as many sample replicates to measure both volumetric and mechanical properties (1).

PREVIOUS RESEARCH

As both products, the CoreDry™ and CoreReader™ are only few years old, there has not been much research on the devices. There were few published articles on CoreDry™ and CoreReader ™ found in the literature. Only three published articles, one on CoreReader™ and two on CoreDry™, were found. Although there is not much published data on CoreDry™, it has been accepted for use and the procedure is found in ASTM D7227.

CoreDry™

In 2006, Kevin D. Hall (5) performed a study to investigate the ability of the CoreDry™ vacuum drying system to provide consistent and accurate estimates of constant mass for compacted HMA specimens. The study focused on the efficacy of the drying system-provision of constant mass condition for a range of initial saturation conditions, and the practicality of the drying system, regarding the time required for obtaining the constant mass determination. A total of 29 gyratory compacted specimens of three different aggregate sizes (NMAS) were used in the analysis. Two different sets, one with 24-26 hours soaking at 25ºC (77ºF) and another with vacuum saturation were used in the evaluation. Further, 20 drilled cores of 100mm diameter and approximately

150 mm height were vacuum saturated and subsequently used for the analysis. Each set were fed in to the CoreDry™ for drying. Drying time and drying efficiency were evaluated based on the previously determined dry weight from AASHTO T166.

The result of this study in second attempt of drying with CoreDry™ for 24 hour soaked samples, removed 0.002 to 0.032 percent of water which is well below the 0.05 percent threshold value used in oven-drying constant mass definition. For the vacuum saturated specimens, the dry mass obtained after CoreDry™ showed that the degree of drying was less than the 0.2 % of the original dry mass and the difference in dry mass ranged from 0.043 to 0.211 percent of dry mass. The increased percentage of difference in dry mass was higher for the higher saturation. CoreDry™ produces the same results, but with the increased drying time and number of attempts for the vacuum saturated specimens. This study concluded with the following remarks (5):

i) The CoreDry™ vacuum drying system consistently provides a reasonable estimate of constant mass in its initial attempt.

ii) The CoreDry™ vacuum drying system provides reasonable estimates of constant mass for specimens with degree of saturation ranging up to 'fully saturated'.

Neal Retzer (7) conducted a review of InstroTek®'s CoreDry™ apparatus in 2005. The research objective was to evaluate if the CoreDry™ compares well enough with the conventional oven dry method. Both 100 mm and 150 mm diameter field cut cores were used in the analysis. Cores were first tested in CoreDry™ and tested in rapid oven drying at 110±5ºC (AASHTO T166, Method C) for dry mass. This study reported that the average difference in density came out to be 0.17 % and never exceeded 0.6 %.

Similarly, the difference in bulk specific gravity difference averaged 0.004 and never exceeded 0.016. CoreDry™ removed 86.9 % of the water while oven drying removed 91.2 % after drying in CoreDry™. This shows the rapid drying is more effective than CoreDry™ drying method. The results seem to be bias as oven drying is followed by CoreDry™ for all of the samples. To overcome the bias results, 12 more samples with 90 seconds vacuum saturation were tested. This time comparison of weight of the sample before saturation, after saturation, after drying with CoreDry™ and oven drying were made. The average efficiency of CoreDry™ in removing water from the vacuum saturated samples was found to be 86.9% where as the average efficiency was found to be 91.2 % for oven drying. Based on efficiency in removing the water from the samples, the final conclusion was made in favor of CoreDry™ apparatus and can be accepted as an alternative to oven drying method (7).

CoreReader™

In July 2006, Stacy G. Williams (7) evaluated the bulk specific gravity obtained from CoreReader™. The comparison was done among the specific gravities obtained by AASHTO T166, CoreLok™, CoreReader™ and Height-Diameter procedure. The study was carried out using two different aggregate sizes and three different levels of compaction to account the effect of aggregate size and compactive effort on Gmb. All together, 72 samples were used in this study. A two way ANOVA with Duncan's ranking indicated the AASHTO T166 method being most repeatable and consistent where as CoreReader™ was statistically different, and seemed to be more variable. Individually, minimum variability was found in AASHTO T166 method (coefficient of variance 0.317) where as maximum variability in case of CoreReader™ method (coefficient of variance

2.200). The CoreReader™ Gmb was found to be statistically different than the AASHTO T166 and other methods. The study has also indicated that the variability in measured Gmb using CoreReader™ is more for mixes with larger aggregate size (NMAS 25.0 mm and 37.5 mm). In this study, some samples were with heights which were out of range required for CoreReader™ Gmb testing and alternative proportional height calculation was utilized (8).

In another independent study by the Highway Materials Lab at North Carolina State University, (9) data were collected on 108 different specimens. Among the data collected were repeated specific gravity measurements with the CoreReader™ at different measurement intervals. The average standard deviation of all 108 specimens comparing 4-minute and 8-minute counts was 0.0018. The test results also indicated that the CoreReader™ is more precise than other methods currently used because of the increased sensitivity to the volumetric differences.

SUMMARY

After the review of the available literature, CoreDry™ apparatus seems promising in drying the lab compacted as well as field core samples for Gmb determination. The Gmb determined using CoreReader™ apparatus seems different than AASHTO T166. Gmb from CoreReader™ apparatus is expected to be less repeatable than AASHTO T166.

CHAPTER 3

TEST PLAN

MATERIALS

Lab Samples

Two types of samples were evaluated, lab compacted and field cores. For the lab compacted samples, three types of mixes were used, an ODOT S3 mix, an ODOT S4 mix and an ODOT stone matrix asphalt (SMA) mix . The S3 and S4 mixes were prepared in the OSU bituminous laboratory. The SMA samples were obtained from a contractor's lab. For the lab compacted S3 and S4 mixes, two different sample heights, 95±5 mm and 115±5 mm were prepared. The 95±5 mm and 115±5 mm high specimens were compacted at 7±0.5% and 4±0.5% VTM. Table 3.1 shows the heights and VTMs of the S3 and S4 mixes prepared in the laboratory.

Table 3.1. Test Specimens of S3 and S4 Mix

Mix	Sample Height (mm)	Diameter (mm)	VTM (%)
S3	95±5	150	7±0.5
	115±5	150	4±0.5
S4	95±5	150	7±0.5
	115±5	150	4±0.5

Determination of bulk specific gravity (Gmb) of lab compacted samples is important for different laboratory distress evaluation tests. Distresses are directly related to pavement performance. Moisture Induced Damage Test (AASHTO T283), Hamburg Wheel Track Testing (AASHTO T324) etc are used to evaluate pavement performance. These tests need samples with specific volumetric properties, which are ultimately based on Gmb of test specimens. The laboratory compacted 95±5mm high, 7±0.5% VTM samples were used to simulate AASHTO T283 test specimens and the 115±5mm high, and 4±0.5% VTM samples were selected to simulate the AASHTO T324 test specimens**.**

S3 and S4 Mixes

ODOT S3 and S4 mixes are fine graded mixes with nominal maximum aggregate size (NMAS) of 19.0 mm (3/4 inches) and 12.5 mm (1/2 inches), respectively. The S3 and S4 mixture were made with PG 64-22 asphalt. The gradation of aggregate used in preparation of test specimens and ODOT mix specifications are presented in table 3.2. The grain size distribution curve of aggregates used for S3 and S4 mixes are presented in figure 3.1.

TABLE 3.2. S3 and S4 Mix Design

Sieve Size	**% Passing**		**ODOT Specification**	
	S3	**S4**	**S3**	**S4**
1"	100	100	100	
3/4"	100	100	90-100	100
1/2"	85	94	<90	90-100
3/8"	69	89		<90
No.4	47	62		
No.8	32	40	31-49	34-58
No.16	23	28		
No.30	19	20		
No.50	8	12		
No.100	5	7		
No.200	4	5.2	2-8	2-10
P_b (%)	4.1	4.95	4.1 min.	4.6 min

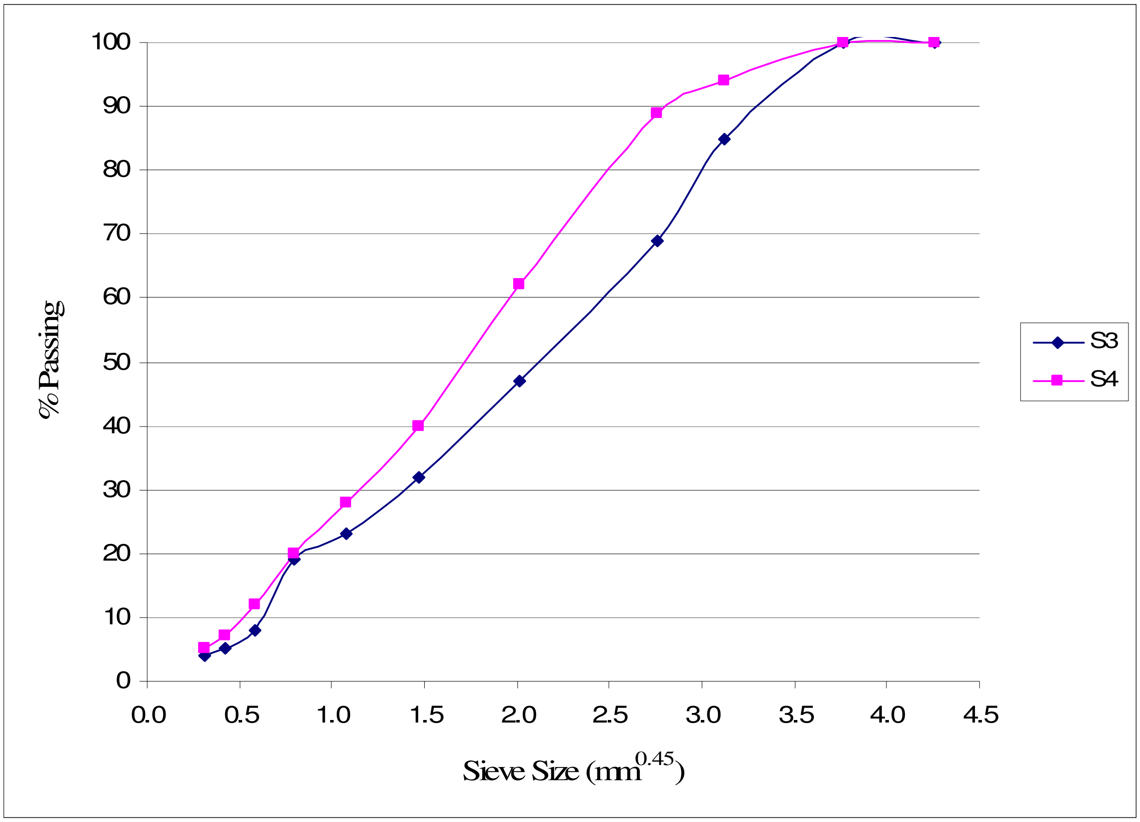

FIGURE 3.1 Grain size distribution curve of aggregate for S3 and S4 mixes.

Stone Matrix Asphalt (SMA) Mix

Stone Matrix Asphalt (SMA) is a special type of mix consisting of coarse aggregate with fines as mineral filler. It relies on stone on-stone contact to provide strength. Generally, gap-graded aggregates are used to produce such a mix. The percentage of asphalt in an SMA mix is generally higher than a regular mix. The SMA specimens were obtained from a contractor's lab, and the physical properties were not determined. A typical aggregate gradation for an SMA mix is shown in table 3.3 and typical grain size distribution curve in figure 3.2.

TABLE 3.3. Typical Gradation of Aggregate for SMA

Sieve Size	% passing
3/4"	100
1/2"	90-97
3/8"	60-85
No.4	25-35
No.8	15-25
No.200	8-12

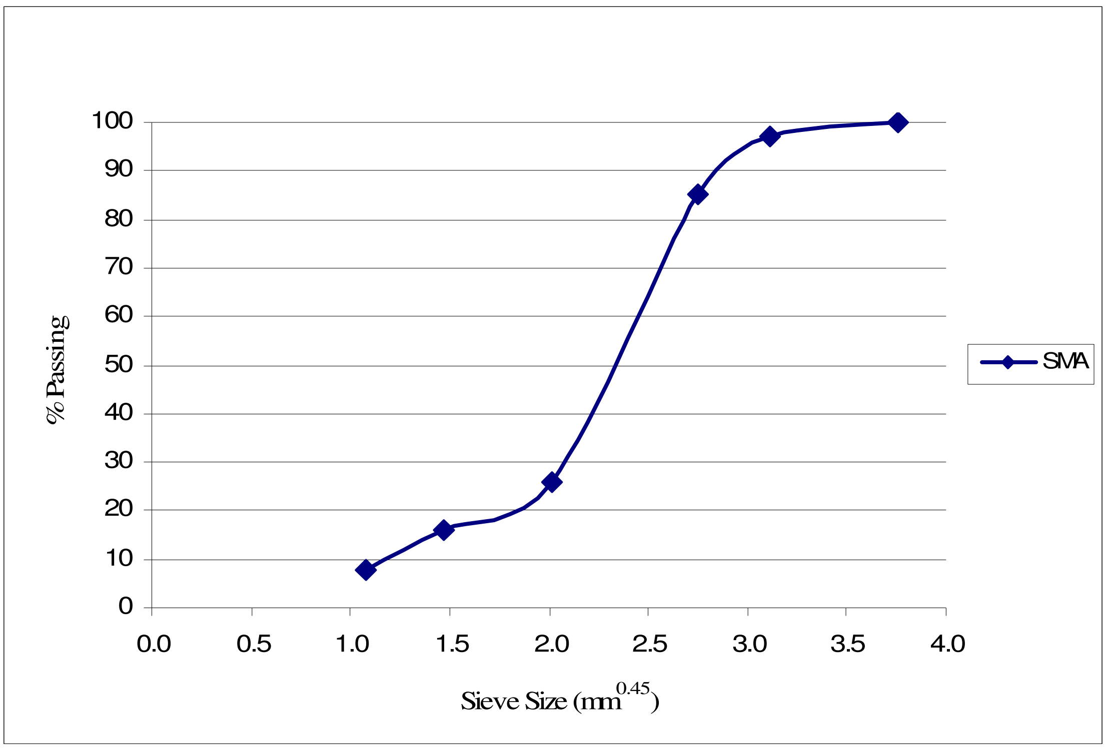

FIGURE 3.2 Typical grain size distribution curve for SMA mix.

Field Cores

Field cores of HMA were provided from various projects by a testing lab. There were two different sizes of cores provided, approximately 100 mm (4 inches) diameter and approximately 150mm (6 inches) diameter. All the cores upon arrival were numbered with a sample marker and sorted into two sets. One set consisted of cores having both ends smooth and parallel and the other consisted of cores with one or both edges irregular. The set with both ends smooth were tested directly whereas the other set, with one or both the faces irregular, were first tested for CoreReader^{TM} Gmb using the average height and retested after being sawed to make the edges smooth and parallel.

TEST PROCEDURES

Lab Samples

Two different sets of samples were prepared in the laboratory, one with 95±5 mm height of 7±0.5 % VTM to match the test specimens used for AASHTO T283 test and other set of specimens with 115±5 mm height of 4±0.5 % air void content to match the superpave mix design void requirements. Samples were compacted according to AASHTO T312. After compacting the samples, they were allowed to cool at room temperature overnight. After cooling to room temperature, the height of each sample was recorded at six evenly spaced locations using a digital caliper having precision of ±0.1mm. The average of six readings was reported as the height of the specimen. Samples were next tested in the CoreReader^{TM} apparatus using the measured height and reported as CoreReader^{TM} bulk specific gravity. After the CoreReader^{TM} Gmb measurement, the dry (initial dry), submerged and saturated surface dry (SSD) masses were obtained in accordance with AASHTO T166. The bulk specific gravity was calculated using the formula given below,

$$\text{Bulk Specific Gravity(Gmb)} = \frac{\text{Dry mass}}{\text{SSD mass} - \text{Submerged mass}} \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.1$$

The Gmb obtained using the initial dry mass is reported as T166 Gmb. The percent absorption of each sample was also calculated using the formula

$$\% \text{ absorption} = \frac{\text{SSD mass} - \text{Dry mass}}{\text{SSD mass} - \text{Submerged mass}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.2$$

If the percent absorption was above 2 %, the Gmb was determined using the CoreLok™ apparatus in accordance with AASHTO TP69 (ASTM D6752), and the bulk specific gravity obtained was reported as AASHTO T166 Gmb. For further testing, each set of 95mm and 115mm high samples of S3, S4 and SMA mixes were divided in to two groups, namely group A and B, and tested in two different sequences.

Group A:

After determining the SSD mass**,** samples were placed in an oven at 52±3ºC (125±5ºF) overnight. After oven drying overnight, the mass was measured at 2 hour intervals until the difference in mass was less than 0.05 %. This was reported as the slow oven dry mass of the sample. The bulk specific gravity calculated using equation 3.1 using the slow oven dry mass, and previously measured submerged and SSD mass in accordance with AASHTO T166, was reported as slow oven Gmb. When the slow oven drying was completed, the same sample was dried in the CoreDry™ apparatus (CoreDry™ mass). Finally, the sample was placed in an oven at 110±5ºC (230±9ºF) and the mass checked every 2 hours until the sample reached a constant mass, which is a mass loss of less than 0.05 % in a two hour period. The bulk specific gravity obtained at 110±5ºC is recorded as fast oven Gmb.

Group B

A second set of samples of equal number were tested in a similar method as group A. The only difference being the order of testing between the CoreDry™ and slow oven procedures. The initial dry, submerged and SSD masses were obtained and the Gmb obtained based on initial dry mass is reported as T166 Gmb. After T166 Gmb, the same samples were dried in the CoreDry™ to get the CoreDry™ Gmb. Finally samples were processed for slow oven and then fast oven drying and reported as slow oven and fast oven Gmb. The sequence of testing for group A and group B lab samples is illustrated in the flow chart shown in figure 3.3.

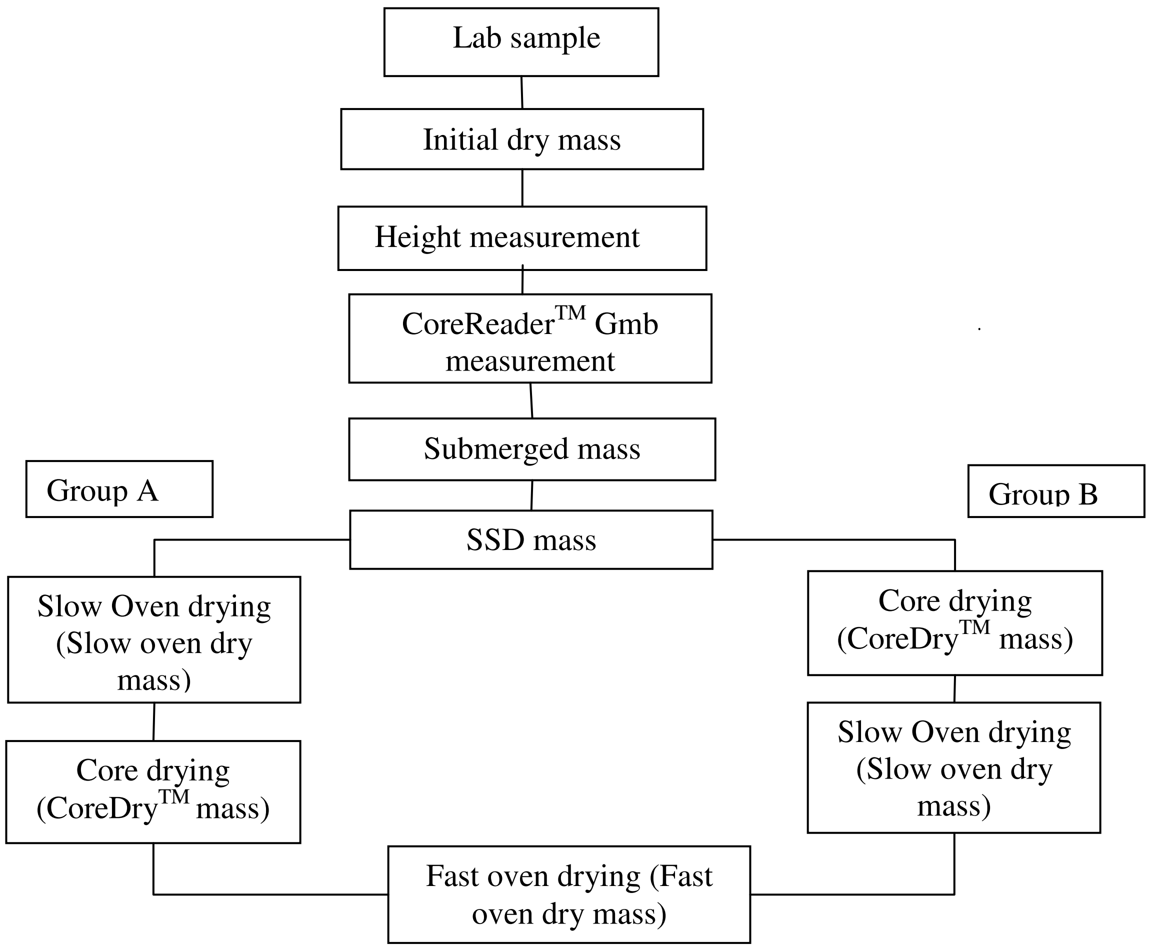

FIGURE 3.3 Test procedures for lab compacted sample.

Field Cores

The field cores had varying heights and diameters of either approximately 100 mm (4 inches) or approximately 150 mm (6 inches). The actual diameter for the small size cores ranged from 95.3 mm (3.75 inches) to 97.0 mm (3.82 inches) and the diameter of large size cores range from 143.6 mm (5.65 inches) to 154.0 mm (6.06 inches). The specified diameter of samples for the CoreReader^{TM} is either exactly 100 mm (4 inches) or exactly 150 mm (6 inches). Cores were assumed as 100 mm for all small size cores and 150 mm for all large size cores.

Cores cannot be considered dry as lab compacted samples. Therefore, the cores were placed in the CoreDry^{TM} apparatus prior to testing to reach the dry condition. After drying using the CoreDry^{TM}, heights were measured and then testing followed. The CoreReader^{TM} testing, submerged mass, SSD mass, slow oven drying mass and fast oven drying mass were determined in the same group A and group B sequence as followed for laboratory prepared samples.

Effect of Parallel Faces

Before Sawing

One of the objectives of this study was to determine the effect of end treatment on CoreReader^{TM} Gmb. For cores with one or both ends uneven, they were first dried in CoreDry^{TM} and height was measured using a dial gauge at 12 different locations. The cores were then tested in CoreReader^{TM} using the average height obtained from dial gauge measurement. The Gmb so obtained is reported as CoreReader^{TM} Gmb before sawing.

After Sawing

The same cores tested above were then sawed to make the faces parallel and smooth. During the sawing care was taken to minimize the reduction in height. After sawing the cores, heights at six different locations were obtained with a digital caliper. The Gmb so obtained is reported is CoreReader^{TM} Gmb after sawing. These cores were then placed in to regular testing described in phase II. The sequence of testing for group A and group B field cores is illustrated in the flow chart shown in figure 3.4.

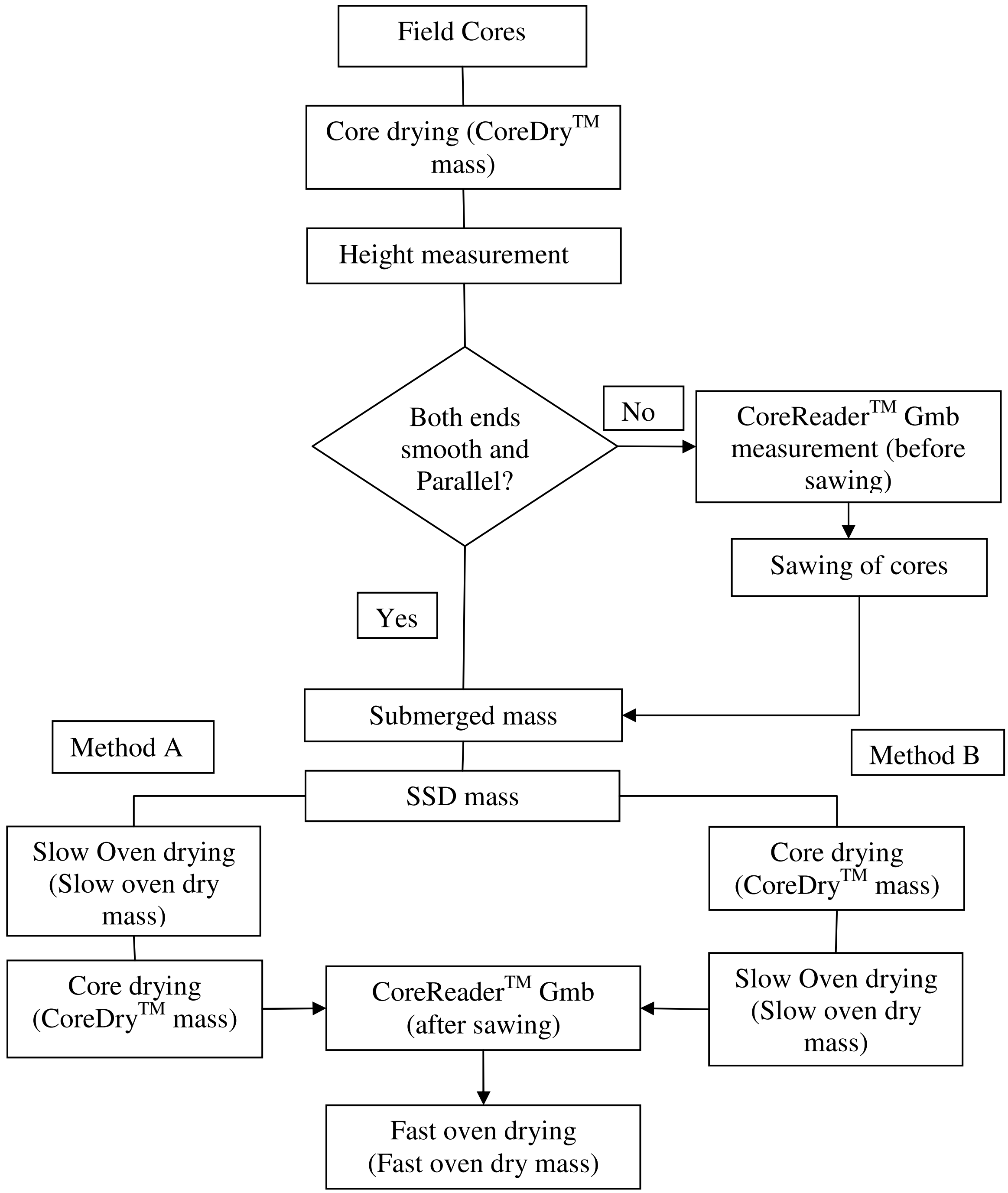

FIGURE 3.4 Test procedures for field core samples.

ANALYSIS

The main objectives of this study were to determine the drying efficiency of CoreDry™ and to evaluate the CoreReader™ apparatus in determining the bulk specific gravity (Gmb) of asphalt paving mixtures. To meet the objectives, ANOVA with Duncan's multiple range tests along with paired t-testing were used. Practical significance of any statistically different results was also taken into account while analyzing the test results. A correlation will be developed by regression analysis if the test results are found statistically as well as practically different.

Phase I CoreDry™

In this phase the dry mass of field cores and lab compacted samples obtained using the CoreDry™ apparatus were compared with the dry mass obtained by slow oven and fast oven drying. For lab samples, one extra dry mass measurement was obtained, dry mass after cooling to room temperature, and was used in the analysis.

Phase II CoreReader™

This phase of the project concentrated on evaluation of Gmb obtained from the CoreReader™ to that obtained from conventional water displacement method (AASHTO T166). The Gmb obtained after drying by CoreDry™, slow oven and fast oven operation were used in this analysis phase.

Phase III

This phase of analysis consists of evaluation of effect of sample height and parallel faces on CoreReader™ Gmb. This was accomplished by comparing the CoreReader™ Gmb before sawing and CoreReader™ Gmb after sawing. Paired t-test and t-test assuming equal variances were used in this analysis.

CHAPTER 4

TEST RESULTS

The determination of bulk specific gravity of asphalt paving mixture was divided into two major parts, one using the CoreReader™ apparatus and another using the AASHTO T166 procedure. Four different drying techniques were used in the AASHTO T166 procedure. The drying method used in AASHTO T166 includes:

i) Drying the sample at room temperature for 24 hours (only applicable to lab compacted samples)

ii) Drying using CoreDry™ apparatus

iii) Drying at 52±3ºC (125±5ºF) for constant mass (Slow oven drying method)

iv) Drying at 110±5ºC (230±9ºF) for constant mass (Fast oven or rapid drying method)

Laboratory compacted ODOT S3, S4 and SMA mixes and field cores obtained from a contractor's lab were used for testing.

PHASE I COREDRY™

In this phase, lab compacted samples and field cores were tested for dry mass. For the lab compacted specimens, dry mass after cooling to room temperature (initial dry mass), submerged and SSD mass and dry mass after slow oven and fast oven drying were obtained in accordance with AASHTO T166 and reported as initial dry mass, sub mass, SSD mass, slow oven dry mass and fast oven dry mass, respectively. In addition, dry mass of test specimens were obtained after drying in CoreDry^{TM} and reported as CoreDry^{TM} mass. In this phase, 59 laboratory compacted samples and 219 field cores were used. To prevent bias, the samples were divided into two sets for testing, group A and group B.

Group A

The lab compacted samples and field cores were tested for dry mass according to the following sequence of tests of group A samples: (i) CoreReader^{TM} Gmb, (ii) measurement of dry mass after cooling to room temperature (for lab compacted samples only), (iii) measurement of submerged mass, (iv) measurement of SSD mass, (v) measurement of dry mass after slow oven drying, (vi) measurement of dry mass after drying in CoreDry^{TM} apparatus, and (vii) measurement of dry mass after fast oven drying. A total of 30 lab compacted samples and 103 field cores were tested. The test results for lab samples and field cores are presented in Table 4.1 and 4.2, respectively.

Group B

For this group, the lab compacted and field cores were tested for dry mass according to the following sequence: (i) CoreReader^{TM} Gmb, (ii) measurement of dry mass after cooling to room temperature (for lab compacted samples only), (iii) measurement of submerged mass, (iv) measurement of SSD mass, (v) measurement of dry mass after drying in CoreDry^{TM} apparatus(vi) measurement of dry mass after slow oven drying, and (vii) measurement of dry mass after fast oven drying. A total of 29 lab compacted samples and 116 field cores were tested. The test results for lab samples and field cores are presented in Tables 4.3 and 4.4, respectively.

PHASE II COREREADER^{TM}

This phase of the project is the evaluation of Gmb obtained using the CoreReader^{TM}. The dry masses for lab compacted samples and field cores used in phase I were used in Gmb calculations for phase II. Therefore, the group A and B samples were the same as in phase I. All together, 59 laboratory compacted samples and 219 field cores were used in this phase, out of which 30 lab compacted samples and 103 field cores were tested in group A and 29 lab samples and 116 field cores were tested in group B. The results include the Gmb obtained after initial drying (T166 Gmb), slow oven drying (Slow oven Gmb), Fast oven drying (Fast oven Gmb), Gmb after drying in CoreDry^{TM} (CoreDry^{TM} Gmb) and Gmb obtained from CoreReader^{TM} apparatus (CoreReader^{TM} Gmb). The test results for lab samples and field cores for group A are presented in tables 4.5 and 4.6, respectively. Similarly, test results for group B lab samples and field cores are presented in tables 4.7 and 4.8, respectively.

PHASE III

This phase is the evaluation of the effect of height and parallel faces on CoreReader^{TM} Gmb. This section of test results consists of field cores only. The CoreReader^{TM} Gmb before sawing (CRD Gmb, before sawing) and CoreReader^{TM} Gmb after sawing (CRD Gmb, after sawing) were obtained according to test procedures for field cores. A total of 94 field cores were tested. The test results are presented in table 4.9.

TABLE 4.1. Lab Test Result of Lab Compacted Samples, Phase I, Group A

Sample ID	Mix	Initial dry mass (g)	Sub. mass (g)	SSD mass (g)	Slow oven dry mass (g)	CoreDry™ dry mass (g)	Fast oven dry mass (g)
95 (1)	S3	3883.3	2283.3	3910.7	3886.7	3883.8	3883.2
95 (6)	S3	3873.0	2272.5	3905.4	3874.1	3874.0	3874.0
95 (7)	S3	3871.3	2275.9	3900.2	3871.3	3870.8	3870.8
95 (8)	S3	3877.5	2277.2	3906.2	3879.1	3878.2	3877.8
115 (3)	S3	4927.2	2943.5	4939.0	4927.5	4927.2	4923.6
115 (4)	S3	4912.6	2936.1	4928.2	4914.6	4913.3	4910.4
115 (5)	S3	4919.5	2934.9	4930.6	4920.6	4919.8	4916.5
115 (7)	S3	4913.2	2935.1	4924.2	4913.7	4913.7	4913.7
115 (8)	S3	4902.1	2928.7	4917.7	4902.6	4902.2	4902.2
95(2)	S4	3591.3	2026.7	3615.0	3596.0	3593.2	3592.3
95(3)	S4	3603.7	2033.8	3627.9	3609.0	3605.7	3604.9
95(4)	S4	3595.6	2028.2	3620.0	3601.0	3597.7	3596.7
95(5)	S4	3602.1	2033.1	3623.9	3605.9	3603.7	3603.0
115(1)	S4	4515.0	2581.2	4520.9	4515.2	4515.1	4515.0
115(2)	S4	4504.7	2578.1	4510.8	4504.8	4504.8	4504.7
115(3)	S4	4502.1	2572.0	4508.9	4502.4	4502.3	4502.1
115(4)	S4	4505.9	2577.4	4511.5	4506.1	4506.1	4506.0
S(1)	SMA	4755.7	2771.1	4759.7	4755.9	4755.9	4755.7
S(2)	SMA	4768.8	2719.3	4783.5	4770.1	4769.0	4768.6
S(3)	SMA	4762.0	2744.9	4767.9	4762.3	4762.2	4762.0
S(4)	SMA	4780.9	2730.8	4792.5	4781.5	4781.1	4780.8
S(5)	SMA	4767.5	2755.5	4772.0	4767.8	4767.7	4767.6
S(6)	SMA	4765.2	2713.3	4784.0	4767.2	4765.5	4765.0
S(7)	SMA	4761.1	2717.7	4771.5	4762.3	4761.1	4760.8
S(8)	SMA	4776.3	2717.1	4789.7	4777.9	4776.5	4776.2
S(9)	SMA	4769.0	2770.5	4775.6	4769.4	4769.2	4769.0
S(10)	SMA	4763.1	2738.7	4767.5	4763.4	4763.3	4763.1
S(11)	SMA	4763.2	2736.2	4768.7	4763.3	4763.3	4763.2
S(12)	SMA	4772.7	2721.0	4781.8	4773.5	4772.9	4772.7
S(13)	SMA	4752.4	2766.7	4757.9	4752.6	4752.5	4752.3

TABLE 4.2. Lab Test Results of Field Cores, Phase I, Group A

Sample ID	Sub. mass (g)	SSD mass (g)	Slow oven dry mass (g)	CoreDry™ dry mass (g)	Fast oven dry mass (g)
A-1	820.8	1493.2	1482.9	1482.9	1481.4
A-2	745.7	1338.2	1330.9	1330.9	1329.8
A-3	828.2	1512.6	1500.0	1500.0	1498.2
A-4	617.0	1120.0	1108.1	1108.1	1107.1
A-5	677.3	1228.9	1215.5	1215.5	1214.5
A-6	682.1	1235.5	1226.3	1226.3	1224.1
A-7	807.8	1448.2	1444.4	1444.4	1443.8
A-8	747.3	1357.2	1346.5	1346.5	1345.2
A-9	613.3	1120.9	1112.6	1112.6	1111.5
B-1	265.8	478.7	476.5	476.4	476.1
B-2	267.4	480.3	478.4	478.4	478.2
B-3	384.7	701.9	691.7	691.1	689.7
B-4	387.5	704.2	694.7	694.4	693.5
B-5	441.9	800.2	796.6	796.5	796.2
B-6	589.5	1078.8	1071.9	1071.5	1071.0
B-7	662.5	1196.1	1192.2	1191.6	1191.1
B-8	624.3	1133.7	1128.7	1128.7	1127.9
B-9	642.0	1161.0	1156.5	1156.1	1155.3
B-10	587.0	1075.7	1069.2	1068.4	1067.7
B-11	683.0	1237.4	1231.9	1231.5	1230.9
T1-15	890.9	1551.7	1550.5	1550.5	1550.2
T1-16	969.3	1712.2	1709.3	1709.2	1708.4
T1-17	735.3	1286.1	1283.9	1283.8	1283.3
T1-18	833.7	1502.2	1480.6	1481.3	1480.3
T1-19	961.0	1688.9	1685.5	1685.4	1685.1
T1-20	2371.3	4085.1	4072.3	4071.1	4069.7
T1-21	646.7	1161.2	1148.8	1147.3	1145.8
T1-22	882.4	1552.1	1549.0	1549.0	1548.7
T1-23	713.5	1249.0	1247.4	1247.5	1247.2
T1-24	685.0	1204.4	1202.6	1202.6	1202.3
T1-25	1000.5	1779.6	1772.5	1772.2	1771.2
T1-26	662.3	1172.1	1172.1	1170.9	1169.9
T1-27	862.7	1535.9	1529.4	1529.3	1528.5
T2-1	731.8	1278.8	1277.2	1277.1	1277.1
T2-2	723.9	1281.6	1277.8	1277.7	1277.7

TABLE 4.2. (Con't.) Lab Test Results of Field Cores, Phase I, Group A

Sample ID	Sub. mass (g)	SSD mass (g)	Slow oven dry mass (g)	CoreDry^{TM} dry mass (g)	Fast oven dry mass (g)
T2-3	864.3	1531.2	1528.6	1528.4	1528.4
T2-4	795.0	1403.3	1399.7	1399.7	1399.6
T2-5	941.6	1672.7	1665.5	1664.7	1663.6
T2-6	783.4	1430.5	1404.9	1399.9	1393.6
T2-7	1000.8	1730.0	1728.8	1728.7	1728.7
T2-8	903.1	1581.6	1578.9	1578.8	1578.5
T2-9	896.7	1582.3	1578.1	1578.0	1577.8
T2-10	1454.3	2569.9	2563.5	2563.1	2562.1
T2-11	814.2	1435.5	1432.1	1432.1	1431.9
T2-12	798.8	1409.3	1405.6	1405.6	1405.4
T2-13	1033.4	1787.1	1785.5	1785.5	1785.5
T2-14	996.7	1739.6	1738.3	1738.3	1738.1
T2-15	1281.6	2235.8	2232.2	2232.2	2231.6
T2-16	788.4	1379.9	1378.3	1378.3	1378.2
T2-17	741.5	1310.8	1307.9	1307.9	1307.8
T2-18	861.8	1496.9	1495.7	1495.7	1495.6
T2-19	869.8	1550.5	1541.9	1541.9	1541.2
T2-20	1001.5	1745.9	1742.3	1742.3	1742.0
T2-21	717.4	1261.2	1259.2	1259.2	1259.2
T2-22	772.7	1374.7	1371.5	1371.5	1371.2
T2-23	892.4	1544.9	1544.0	1544.0	1543.9
T2-24	1354.6	2398.2	2386.2	2386.2	2385.3
SC-1	1122.0	1957.7	1954.8	1954.8	1954.7
SC-2	1311.5	2289.9	2286.6	2286.6	2286.5
SC-3	1231.1	2177.5	2171.9	2171.5	2171.4
SC-4	1129.7	1975.1	1971.1	1971.6	1971.5
SC-5	1045.8	1839.7	1835.6	1835.5	1835.3
B-32	932.3	1669.9	1664.7	1664.5	1663.9
B-33	832.2	1504.6	1496.9	1496.4	1494.6
B-34	857.7	1523.9	1520.8	1520.8	1520.5
B-35	1180.2	2111.5	2105.3	2104.7	2104.1
B-36	1006.1	1803.9	1798.0	1797.9	1797.4
B-37	570.7	1040.5	1033.5	1032.7	1032.4
B-38	879.9	1557.8	1554.4	1554.4	1554.1
B-39	536.4	970.8	966.9	966.7	966.6
T1-36	981.8	1740.0	1734.1	1734.1	1733.6

TABLE 4.2. (Con't.) Lab Test Results of Field Cores, Phase I, Group A

Sample ID	Sub. mass (g)	SSD mass (g)	Slow oven dry mass (g)	CoreDry™ dry mass (g)	Fast oven dry mass (g)
T1-37	1572.6	2721.0	2715.3	2714.4	2713.6
T1-38	1759.7	3034.8	3032.1	3032.1	3031.7
T1-39	1520.5	2616.0	2613.2	2613.1	2612.8
T1-40	2167.9	3787.2	3770.9	3765.7	3762.8
T1-41	2217.6	3815.5	3808.9	3808.1	3807.1
T1-42	1692.6	2903.8	2900.5	2900.5	2900.0
T1-43	1961.5	3373.5	3368.4	3368.0	3366.9
T1-44	1418.9	2459.0	2453.4	2453.3	2452.9
T2-71	1780.7	3070.9	3061.4	3061.2	3060.6
T2-72	1257.9	2227.4	2207.2	2207.1	2204.6
T2-73	970.4	1765.4	1751.6	1750.8	1749.0
T2-74	1799.6	3290.0	3264.1	3257.2	3256.9
T2-75	1512.4	2608.7	2604.5	2604.5	2604.0
T2-76	1479.3	2608.5	2604	2603.5	2603.1
T2-77	1756.2	3025.2	3019	3017.8	3015.0
T2-78	1441.1	2499.0	2491.8	2491.0	2490.2
T2-79	1416.6	2437.5	2435.2	2435.3	2435.1
T2-80	1469.7	2547.1	2532.9	2530.4	2529.2
T2-81	1483.7	2696.0	2674.1	2670.2	2666.9
T2-82	1333.7	2338.8	2330.7	2329.6	2328.6
T2-83	1060.9	1908.8	1900.9	1900.9	1899.3
T2-84	946.8	1632.9	1630.3	1630.3	1629.9
T2-85	2318.5	4129.3	4120.8	4120.7	4119.1
T2-86	2291.8	4021.0	4016.4	4016.2	4014.7
T2-87	1830.9	3152.8	3144.1	3142.9	3141.7
T2-88	967.3	1742.6	1739.8	1739.8	1739.6
T2-89	1149.6	1987.5	1983.7	1983.7	1983.2
T2-90	1284.9	2249.7	2247.4	2247.0	2246.5
T2-91	1114.8	1939.9	1933.8	1933.1	1932.4
T2-92	2311.5	4015.4	3999.6	3995.4	3994.1
T2-93	2126.0	3740.0	3732.8	3731.1	3728.7

TABLE 4.3. Lab Test Results of Lab Compacted Samples, Phase I, Group B

Sample ID	Mix	Initial dry mass (g)	Sub. mass (g)	SSD mass (g)	CoreDryTM dry mass (g)	Slow oven dry mass (g)	Fast oven dry mass (g)
95 (10)	S3	3857.3	2262.1	3888.3	3858.3	3857.4	3857.2
95(11)	S3	3887.2	2280.0	3914.6	3887.8	3887.3	3887.3
95(12)	S3	3862.8	2261.1	3893.0	3863.1	3862.9	3862.8
95(13)	S3	3879.0	2279.0	3907.2	3879.8	3878.1	3878.1
115(9)	S3	4928.6	2942.5	4938.7	4928.7	4928.6	4928.5
115(10)	S3	4907.3	2935.6	4919.1	4907.8	4907.3	4907.2
115 (11)	S3	4921.8	2941.7	4930.8	4922.2	4921.8	4921.5
115(12)	S3	4912.9	2926.7	4920.1	4913.1	4913.0	4913
115(13)	S3	4921.6	2940.4	4931.4	4921.7	4921.6	4921.6
95(6)	S4	3596.7	2029.5	3618.5	3597.2	3596.8	3596.7
95(8)	S4	3607.4	2036.9	3627.9	3608.1	3607.5	3607.4
95(9)	S4	3594.2	2029.3	3620.6	3594.9	3594.2	3594.1
95(10)	S4	3605.1	2036.1	3626.4	3606.0	3605.2	3605.1
115(5)	S4	4505.3	2583.4	4513.9	4505.7	4505.5	4505.3
115(6)	S4	4521.4	2591.3	4529.0	4521.4	4521.4	4521.4
115(7)	S4	4510.1	2581.9	4519.2	4510.2	4510.2	4510.1
115(8)	S4	4518.3	2587.3	4524.6	4518.3	4518.3	4518.3
S(14)	SMA	4768.8	2714.9	4786.9	4769.2	4768.5	4768.2
S(15)	SMA	4764.9	2780.0	4769.2	4764.9	4764.7	4764.5
S(16)	SMA	4774.1	2749.0	4784.4	4774.3	4773.9	4773.6
S(17)	SMA	4762.7	2778.3	4767.3	4762.7	4762.5	4762.2
S(18)	SMA	4772.0	2739.9	4780.6	4772.2	4771.8	4771.6
S(19)	SMA	4773.7	2778.6	4779.8	4773.7	4773.3	4773.1
S(20)	SMA	4765.0	2774.2	4769.0	4765.1	4764.8	4764.5
S(21)	SMA	4766.1	2773.7	4771.8	4766.1	4765.8	4765.5
S(22)	SMA	4773.0	2776.6	4779.9	4773	4772.7	4772.4
S(23)	SMA	4765.4	2744.9	4770.8	4765.4	4765.2	4764.9
S(24)	SMA	4777.3	2749.7	4787.1	4777.4	4777.0	4776.6
S(25)	SMA	4766.7	2772.3	4772.6	4766.7	4766.4	4766.2

TABLE 4.4. Lab Test Results of Field Cores, Phase I, Group B

Sample ID	Sub. mass (g)	SSD mass (g)	CoreDry™ dry mass (g)	Slow oven dry mass (g)	Fast oven dry mass (g)
A-10	689.4	1240.5	1234.3	1233.6	1232.9
A-11	730.6	1326.7	1316.7	1316.0	1315.4
B-12	1006.0	1791.2	1791.2	1790.3	1789.9
B-13	1003.3	1788.8	1788.8	1787.7	1787.4
B-14	444.5	802.8	802.8	802.2	802.0
B-15	385.7	698.2	698.2	697.5	696.9
B-16	636.4	1149.8	1145.1	1144.4	1143.7
B-17	571.8	1021.0	1021.0	1020.4	1020.1
B-18	714.8	1287.3	1287.3	1286.6	1286.4
B-19	625.9	1136.2	1136.2	1135.6	1135.4
B-20	684.4	1247.8	1247.8	1246.9	1246.6
B-21	633.8	1137.9	1137.9	1137.2	1136.8
B-22	570.4	1049.1	1049.1	1048.4	1048.2
T1-1	687.9	1207.0	1204.6	1204.0	1203.7
T1-2	925.9	1638.9	1632.3	1631.8	1631.4
T1-3	929.2	1632.0	1629.3	1628.7	1628.3
T1-4	835.0	1501.9	1486.6	1485.4	1484.7
T1-5	919.6	1602.4	1601.3	1600.9	1600.8
T1-6	804.8	1422.0	1418.9	1417.7	1417.4
T1-7	775.2	1377.9	1373.3	1372.6	1372.0
T1-8	879.0	1555.0	1552.6	1552.1	1551.8
T1-9	807.4	1406.1	1404.9	1404.7	1704.6
T1-10	2059.1	3533.6	3528.9	3527.6	3527.3
T1-11	1775.2	3060.9	3052.7	3051.8	3051.7
T1-12	1805.2	3128.8	3123.1	3122.4	3122.1
T1-13	846.5	1489.0	1487.5	1487.3	1487.0
T1-14	910.9	1587.3	1586.3	1586.1	1585.9
T2-25	772.2	1351.9	1350.7	1350.3	1350.2
T2-26	846.2	1497.2	1494.4	1493.9	1493.8
T2-27	909.4	1573.3	1571.8	1571.4	1571.3
T2-28	772.1	1353.6	1351.6	1351.2	1351.0
T2-29	792.4	1386.7	1384.7	1384.4	1384.2
T2-30	741.7	1316.2	1310.0	1308.8	1308.5
T2-31	799.1	1409.4	1406.9	1406.4	1406.2
T2-32	833.7	1449.9	1448.1	1447.8	1447.6
T2-33	902.2	1588.1	1585.3	1584.7	1584.4

TABLE 4.4. (Con't.) Lab Test Results of Field Cores, Phase I, Group B

Sample ID	Sub. mass (g)	SSD mass (g)	CoreDry™ dry mass (g)	Slow oven dry mass (g)	Fast oven dry mass (g)
T2-34	979.7	1715.2	1713.0	1712.4	1712.1
T2-35	853.4	1497.8	1495.8	1495.2	1495.1
T2-36	824.1	1464.8	1456.7	1455.2	1454.8
T2-37	897.0	1565.8	1562.6	1562.0	1561.7
T2-38	896.9	1584.5	1579.6	1578.9	1578.5
T2-39	864.5	1513.6	1511.1	1510.6	1510.4
T2-40	985.3	1728.8	1727.2	1726.9	1726.9
T2-41	889.7	1563.3	1561.3	1560.9	1560.8
T2-42	890.8	1554.1	1552.4	1552.1	1552.0
T2-43	929.3	1618.5	1617.2	1617.0	1617.0
T2-44	991.9	1753.9	1750.0	1749.3	1749.1
T2-45	935.1	1625.0	1623.4	1623.1	1623.0
T2-46	893.9	1553.4	1552.0	1551.7	1551.7
T2-47	779.5	1368.8	1367.0	1366.8	1366.7
T2-86	1508.1	2640.3	2634.5	2633.7	2633.5
T2-13B	929.0	1622.0	1620.1	1619.9	1619.9
SC-6	1254.2	2196.1	2193.2	2192.9	2192.7
SC-7	1375.8	2392.3	2388.9	2388.8	2388.7
SC-8	1280.4	2263.9	2257.5	2257.1	2256.9
SC-9	1294.9	2260.4	2256.5	2256.2	2256.1
H-1	946.0	1724.0	1713.9	1712.8	1712.3
H-2	720.3	1270.3	1269.0	1268.8	1268.7
H-3	1764.0	3091.8	3085.5	3084.6	3084.3
H-4	690.6	1208.4	1206.8	1206.6	1206.3
H-5	1496.2	2606.2	2603.0	2602.2	2601.7
H-6	1255.4	2231.0	2223.1	2221.8	2221.2
H-7	1112.2	1915.4	1913.5	1913.1	1912.8
H-8	1420.8	2454.6	2453.1	2452.8	2452.3
H-9	1052.5	1808.9	1807.2	1806.9	1806.4
H-10	899.9	1606.0	1603.2	1602.5	1601.9
H-11	1223.8	2180.4	2168.2	2166.7	2166.0
H-12	923.7	1611.0	1607.4	1606.7	1605.5
H-13	1697.7	2962.8	2959.5	2958.8	2958.2
A-12	781.8	1420.1	1409.1	1407.8	1407.3
A-13	587.9	1055.2	1049.7	1048.8	1048.5

TABLE 4.4. (Con't.) Lab Test Results of Field Cores, Phase I, Group B

Sample ID	Sub. mass (g)	SSD mass (g)	CoreDry™ dry mass (g)	Slow oven dry mass (g)	Fast oven dry mass (g)
A-14	777.2	1416.3	1406.2	1404.6	1403.7
A-15	637.9	1149.1	1141.3	1140.1	1139.4
A-16	690.5	1246.7	1241.5	1240.3	1239.9
A-17	554.6	1002.6	999.0	998.2	997.6
A-18	556.3	1008.8	1000.8	999.7	999.2
B-23	619.5	1121.1	1117.9	1117.0	1116.7
B-24	621.2	1121.5	1118.9	1117.8	1117.7
B-25	629.1	1153.1	1146.3	1145.0	1144.8
B-26	331.9	602.0	599.4	598.8	598.6
B-27	828.0	1503.1	1492.6	1490.7	1490.2
B-28	953.0	1705.4	1701.4	1700.1	1699.7
B-29	815.0	1446.6	1444.3	1443.4	1443.2
B-30	1050.5	1882.9	1877.9	1876.4	1876.0
B-31	527.3	954.3	949.7	948.3	947.8
T1-28	839.7	1491.3	1489.2	1488.4	1488.0
T1-29	1021.8	1768.1	1757.3	1754.1	1752.6
T1-30	1948.0	3369.9	3367.0	3360.0	3365.9
T1-31	1439.2	2481.2	2476.9	2475.7	2474.9
T1-32	1535.4	2671.2	2668.5	2667.5	2667.3
T1-33	923.2	1583.3	1581.9	1581.2	1580.7
T1-34	1418.3	2430.8	2428.1	2428.1	2427.1
T1-35	1803.2	3104.9	3102.6	3102.6	3101.2
T2-48	991.0	1831.0	1806.7	1799.5	1797.5
T2-49	761.5	1332.7	1330.6	1329.8	1329.5
T2-50	1751.8	3053.2	3046.0	3044.2	3043.5
T2-51	1647.4	2854.0	2844.7	2841.9	2841.2
T2-52	1683.2	2908.3	2904.3	2903.0	2902.4
T2-53	1436.9	2521.3	2515.7	2514.6	2514.0
T2-54	3192.9	5571.1	5532.0	5527.3	5525.0
T2-55A	916.3	1634.5	1631.7	1630.6	1630.2
T2-55B	1840.0	3168.7	3160.6	3157.3	3154.4
T2-56	1717.5	2982.7	2970.7	2969.1	2968.5
T2-57	2300.6	3987.3	3966.0	3962.0	3958.7
T2-58	1015.6	1873.1	1832.6	1827.3	1824.6
T2-59	3235.3	5595.3	5588.5	5586.2	5584.9

TABLE 4.4. (Con't.) Lab Test Results of Field Cores, Phase I, Group B

Sample ID	Sub. mass (g)	SSD mass (g)	CoreDry™ dry mass (g)	Slow oven dry mass (g)	Fast oven dry mass (g)
T2-60	2060.8	3554.6	3544.5	3542.1	3541.4
T2-61	977.1	1773.2	1765.7	1763.1	1761.6
T2-62	1570.4	2722.0	2718.9	2717.9	2717.6
T2-63	1145.8	1986.8	1983.2	1982.3	1982.1
T2-64	1666.4	2874.4	2870.5	2869.9	2869.8
T2-65	1543.9	2679.0	2671.7	2670.6	2670.4
T2-66	1415.7	2487.0	2442.4	2439.1	2438.2
T2-67	1699.1	2934.3	2929.3	2928.2	2928.1
T2-68	1070.4	1850.9	1846.1	1845.2	1845.0
T2-69	848.4	1531.3	1523.3	1519.5	1517.5

TABLE 4.5. Lab Test Results of Lab Compacted Samples, Phase II, Group A

Sample ID	Mix	CoreReader™ Gmb	T166 Gmb	Slow oven Gmb	CoreDryer™ Gmb	Fast oven Gmb
95 (1)	S3	2.339	2.386	2.388	2.387	2.386
95(6)	S3	2.332	2.372	2.373	2.372	2.373
95(7)	S3	2.324	2.383	2.383	2.383	2.383
95(8)	S3	2.337	2.380	2.381	2.381	2.380
115(3)	S3	2.437	2.469	2.469	2.469	2.467
115(4)	S3	2.447	2.466	2.467	2.466	2.465
115(5)	S3	2.460	2.465	2.466	2.465	2.464
115(7)	S3	2.449	2.470	2.470	2.470	2.470
115(8)	S3	2.447	2.465	2.465	2.465	2.465
95(2)	S4	2.224	2.261	2.262	2.262	2.262
95(3)	S4	2.227	2.261	2.262	2.262	2.261
95(4)	S4	2.229	2.259	2.260	2.260	2.260
95(5)	S4	2.222	2.264	2.265	2.265	2.265
115(1)	S4	2.309	2.328	2.328	2.328	2.328
115(2)	S4	2.305	2.331	2.331	2.331	2.331
115(3)	S4	2.315	2.324	2.325	2.324	2.324
115(4)	S4	2.319	2.330	2.330	2.330	2.330
S(1)	SMA	2.367	2.391	2.392	2.392	2.391
S(2)	SMA	2.279	2.310	2.311	2.310	2.310
S(3)	SMA	2.295	2.354	2.354	2.354	2.354
S(4)	SMA	2.278	2.319	2.319	2.319	2.319
S(5)	SMA	2.313	2.364	2.364	2.364	2.364
S(6)	SMA	2.247	2.301	2.302	2.301	2.301
S(7)	SMA	2.275	2.318	2.319	2.318	2.318
S(8)	SMA	2.253	2.304	2.305	2.305	2.304
S(9)	SMA	2.351	2.378	2.379	2.379	2.378
S(10)	SMA	2.301	2.348	2.348	2.348	2.348
S(11)	SMA	2.281	2.344	2.344	2.344	2.344
S(12)	SMA	2.265	2.316	2.316	2.316	2.316
S(13)	SMA	2.358	2.387	2.387	2.387	2.387

TABLE 4.6. Lab Test Results of Field Cores, Phase II, Group A

Sample ID	Diameter (mm)	CoreReader™ Gmb	Slow oven Gmb	CoreDryer™ Gmb	Fast oven Gmb
A-1	100	2.173	2.205	2.205	2.203
A-2	100	2.214	2.246	2.246	2.244
A-3	100	2.143	2.192	2.192	2.189
A-4	100	2.154	2.203	2.203	2.201
A-5	100	2.140	2.204	2.204	2.202
A-6	100	2.187	2.216	2.216	2.212
A-7	100	2.229	2.255	2.255	2.255
A-8	100	2.167	2.208	2.208	2.206
A-9	100	2.126	2.192	2.192	2.190
B-1	100	2.194	2.238	2.238	2.236
B-2	100	2.216	2.247	2.247	2.246
B-3	100	2.118	2.181	2.179	2.174
B-4	100	2.135	2.194	2.193	2.190
B-5	100	2.166	2.223	2.223	2.222
B-6	100	2.146	2.191	2.190	2.189
B-7	100	2.191	2.234	2.233	2.232
B-8	100	2.157	2.216	2.216	2.214
B-9	100	2.204	2.228	2.228	2.226
B-10	100	2.156	2.188	2.186	2.185
B11	100	2.190	2.222	2.221	2.220
T1-15	150	2.276	2.346	2.346	2.346
T1-16	150	2.228	2.301	2.301	2.300
T1-17	150	2.299	2.331	2.331	2.330
T1-18	150	2.144	2.215	2.216	2.214
T1-19	150	2.236	2.316	2.315	2.315
T1-20	150	2.339	2.376	2.375	2.375
T1-21	150	2.172	2.233	2.230	2.227
T1-22	150	2.246	2.313	2.313	2.313
T1-23	150	2.268	2.329	2.330	2.329
T1-24	150	2.253	2.315	2.315	2.315
T1-25	150	2.205	2.275	2.275	2.273
T1-26	150	2.179	2.299	2.297	2.295
T1-27	150	2.190	2.272	2.272	2.270
T2-1	150	2.307	2.335	2.335	2.335
T2-2	150	2.209	2.291	2.291	2.291

TABLE 4.6. (Con't.) Lab Test Results of Field Cores, Phase II, Group A

Sample ID	Diameter (mm)	CoreReader™ Gmb	Slow oven Gmb	CoreDryer™ Gmb	Fast oven Gmb
T2-3	150	2.231	2.292	2.292	2.292
T2-4	150	2.237	2.301	2.301	2.301
T2-5	150	2.199	2.278	2.277	2.275
T2-6	150	2.076	2.171	2.163	2.154
T2-7	150	2.322	2.371	2.371	2.371
T2-8	150	2.265	2.327	2.327	2.326
T2-9	150	2.246	2.302	2.302	2.301
T2-10	150	2.223	2.298	2.298	2.297
T2-11	150	2.254	2.305	2.305	2.305
T2-12	150	2.226	2.302	2.302	2.302
T2-13	150	2.331	2.369	2.369	2.369
T2-14	150	2.284	2.340	2.340	2.340
T2-15	150	2.262	2.339	2.339	2.339
T2-16	150	2.264	2.330	2.330	2.330
T2-17	150	2.217	2.297	2.297	2.297
T2-18	150	2.300	2.355	2.355	2.355
T2-19	150	2.192	2.265	2.265	2.264
T2-20	150	2.262	2.341	2.341	2.340
T2-21	150	2.261	2.316	2.316	2.316
T2-22	150	2.217	2.278	2.278	2.278
T2-23	150	2.316	2.366	2.366	2.366
T2-24	150	2.220	2.287	2.287	2.286
SC-1	150	2.251	2.339	2.339	2.339
SC-2	150	2.263	2.337	2.337	2.337
SC-3	150	2.197	2.295	2.294	2.294
SC-4	150	2.230	2.332	2.332	2.332
SC-5	150	2.203	2.312	2.312	2.312
B-32	100	2.246	2.257	2.257	2.256
B-33	100	2.204	2.226	2.225	2.223
B-34	100	2.257	2.283	2.283	2.282
B-35	100	2.245	2.261	2.260	2.259
B-36	100	2.235	2.254	2.254	2.253
B-37	100	2.177	2.200	2.198	2.198
B-38	100	2.260	2.293	2.293	2.293
B-39	100	2.202	2.226	2.225	2.225

TABLE 4.6. (Con't.) Lab Test Results of Field Cores, Phase II, Group A

Sample ID	Diameter (mm)	CoreReader™ Gmb	Slow oven Gmb	CoreDryer™ Gmb	Fast oven Gmb
B-40	100	2.235	2.261	2.260	2.260
T1-36	150	2.236	2.287	2.287	2.286
T1-37	150	2.312	2.364	2.364	2.363
T1-38	150	2.332	2.378	2.378	2.378
T1-39	150	2.343	2.385	2.385	2.385
T1-40	150	2.267	2.329	2.326	2.324
T1-41	150	2.352	2.384	2.383	2.383
T1-42	150	2.364	2.395	2.395	2.394
T1-43	150	2.352	2.386	2.385	2.384
T1-44	150	2.313	2.359	2.359	2.358
T2-71	150	2.343	2.373	2.373	2.372
T2-72	150	2.204	2.277	2.277	2.274
T2-73	150	2.160	2.203	2.202	2.200
T2-74	150	2.163	2.190	2.185	0.000
T2-75	150	2.340	2.376	2.376	2.375
T2-76	150	2.261	2.306	2.306	2.305
T2-77	150	2.359	2.379	2.378	2.376
T2-78	150	2.310	2.355	2.355	2.354
T2-79	150	2.348	2.385	2.385	2.385
T2-80	150	2.321	2.351	2.349	2.348
T2-81	150	2.152	2.206	2.203	2.200
T2-82	150	2.254	2.319	2.318	2.317
T2-83	150	2.228	2.242	2.242	2.240
T2-84	150	2.311	2.376	2.376	2.376
T2-85	150	2.253	2.276	2.276	2.275
T2-86	150	2.316	2.323	2.323	2.322
T2-87	150	2.348	2.378	2.378	2.377
T2-88	150	2.216	2.244	2.244	2.244
T2-89	150	2.341	2.367	2.367	2.367
T2-90	150	2.301	2.329	2.329	2.328
T2-91	150	2.290	2.344	2.343	2.342
T2-92	150	2.317	2.347	2.345	2.344
T2-93	150	2.300	2.313	2.312	2.310

TABLE 4.7. Lab Test Results of Lab Compacted Samples, Phase II, Group B

Sample ID	Mix	CoreReader™ Gmb	T166 Gmb	CoreDry™ Gmb	Slow oven Gmb	Fast oven Gmb
95(10)	S3	2.312	2.372	2.373	2.372	2.372
95(11)	S3	2.332	2.378	2.378	2.378	2.378
95(12)	S3	2.311	2.367	2.367	2.367	2.367
95(13)	S3	2.326	2.382	2.383	2.382	2.382
115 (9)	S3	2.469	2.469	2.469	2.469	2.469
115(10)	S3	2.439	2.474	2.474	2.474	2.474
115(11)	S3	2.437	2.474	2.475	2.474	2.474
115(12)	S3	2.458	2.465	2.465	2.465	2.465
115(13)	S3	2.458	2.472	2.472	2.472	2.472
95(6)	S4	2.231	2.263	2.264	2.264	2.263
95(8)	S4	2.232	2.267	2.268	2.267	2.267
95(9)	S4	2.217	2.259	2.259	2.259	2.259
95(10)	S4	2.251	2.267	2.267	2.267	2.267
115(5)	S4	2.303	2.334	2.334	2.334	2.334
115(6)	S4	2.316	2.333	2.333	2.333	2.333
115(7)	S4	2.314	2.328	2.328	2.328	2.328
115(8)	S4	2.314	2.332	2.332	2.332	2.332
S(14)	SMA	2.260	2.302	2.302	2.301	2.301
S(15)	SMA	2.376	2.395	2.395	2.395	2.395
S(16)	SMA	2.294	2.346	2.346	2.345	2.345
S(17)	SMA	2.371	2.395	2.395	2.394	2.394
S(18)	SMA	2.296	2.338	2.339	2.338	2.338
S(19)	SMA	2.371	2.385	2.385	2.385	2.385
S(20)	SMA	2.367	2.389	2.389	2.389	2.388
S(21)	SMA	2.338	2.385	2.385	2.385	2.385
S(22)	SMA	2.363	2.383	2.383	2.382	2.382
S(23)	SMA	2.318	2.352	2.352	2.352	2.352
S(24)	SMA	2.310	2.345	2.345	2.345	2.344
S(25)	SMA	2.346	2.383	2.383	2.383	2.383

TABLE 4.8. Lab Test Results of Field Cores, Phase II, Group B

Sample ID	Diameter (mm)	CoreReader™ Gmb	Core Dryer Gmb	Slow oven Gmb	Fast oven Gmb
A-10	100	2.191	2.240	2.238	2.237
A-11	100	2.185	2.209	2.208	2.207
B-12	100	2.261	2.281	2.280	2.280
B-13	100	2.242	2.277	2.276	2.275
B-14	100	2.186	2.241	2.239	2.238
B-15	100	2.117	2.234	2.232	2.230
B-16	100	2.182	2.230	2.229	2.228
B-17	100	2.225	2.273	2.272	2.271
B-18	100	2.193	2.249	2.247	2.247
B-19	100	2.138	2.227	2.225	2.225
B-20	100	2.148	2.215	2.213	2.213
B-21	100	2.178	2.257	2.256	2.255
B-22	100	2.066	2.192	2.190	2.190
T1-1	150	2.282	2.321	2.319	2.319
T1-2	150	2.213	2.289	2.289	2.288
T1-3	150	2.255	2.318	2.317	2.317
T1-4	150	2.154	2.229	2.227	2.226
T1-5	150	2.275	2.345	2.345	2.344
T1-6	150	2.225	2.299	2.297	2.297
T1-7	150	2.222	2.279	2.277	2.276
T1-8	150	2.260	2.297	2.296	2.296
T1-9	150	2.274	2.347	2.346	2.847
T1-10	150	2.358	2.393	2.392	2.392
T1-11	150	2.254	2.374	2.374	2.374
T1-12	150	2.305	2.360	2.359	2.359
T1-13	150	2.257	2.315	2.315	2.314
T1-14	150	2.279	2.345	2.345	2.345
T2-25	150	2.289	2.330	2.329	2.329
T2-26	150	2.222	2.296	2.295	2.295
T2-27	150	2.313	2.368	2.367	2.367
T2-28	150	2.278	2.324	2.324	2.323
T2-29	150	2.290	2.330	2.329	2.329
T2-30	150	2.189	2.280	2.278	2.278
T2-31	150	2.264	2.305	2.304	2.304
T2-32	150	2.285	2.350	2.350	2.349
T2-33	150	2.270	2.311	2.310	2.310

TABLE 4.8. (Con't.) Lab Test Results of Field Cores, Phase II, Group B

Sample ID	Diameter (mm)	CoreReader^{TM} Gmb	Core Dryer Gmb	Slow oven Gmb	Fast oven Gmb
T2-34	150	2.286	2.329	2.328	2.328
T2-35	150	2.248	2.321	2.320	2.320
T2-36	150	2.214	2.274	2.271	2.271
T2-37	150	2.286	2.336	2.336	2.335
T2-38	150	2.228	2.297	2.296	2.296
T2-39	150	2.283	2.328	2.327	2.327
T2-40	150	2.272	2.323	2.323	2.323
T2-41	150	2.246	2.318	2.317	2.317
T2-42	150	2.295	2.340	2.340	2.340
T2-43	150	2.292	2.346	2.346	2.346
T2-44	150	2.223	2.297	2.296	2.295
T2-45	150	2.302	2.353	2.353	2.353
T2-46	150	2.303	2.353	2.353	2.353
T2-47	150	2.284	2.320	2.319	2.319
T2-86	150	2.265	2.327	2.326	2.326
T2-13B	150	2.290	2.338	2.338	2.338
SC-6	150	2.249	2.328	2.328	2.328
SC-7	150	2.270	2.350	2.350	2.350
SC-8	150	2.196	2.295	2.295	2.295
SC-9	150	2.244	2.337	2.337	2.337
H-1	150	2.181	2.203	2.201	2.201
H-2	150	2.276	2.307	2.307	2.307
H-3	150	2.283	2.324	2.323	2.323
H-4	150	2.339	2.331	2.330	2.330
H-5	150	2.308	2.345	2.344	2.344
H-6	150	2.26	2.279	2.277	2.277
H-7	150	2.354	2.382	2.381	2.381
H-8	150	2.353	2.373	2.372	2.372
H-9	150	2.373	2.389	2.388	2.388
H-10	150	2.244	2.270	2.270	2.269
H-11	150	2.234	2.267	2.265	2.264
H-12	150	2.320	2.339	2.338	2.336
H-13	150	2.311	2.339	2.339	2.338
A-12	100	2.195	2.195	2.206	2.205
A-13	100	2.236	2.236	2.244	2.244

TABLE 4.8. (Con't.) Lab Test Results of Field Cores, Phase II, Group B

Sample ID	Diameter (mm)	CoreReader™ Gmb	Core Dryer Gmb	Slow oven Gmb	Fast oven Gmb
A-14	100	2.183	2.183	2.198	2.196
A-15	100	2.200	2.200	2.230	2.229
A-16	100	2.208	2.208	2.230	2.229
A-17	100	2.209	2.209	2.228	2.227
A-18	100	2.171	2.171	2.209	2.208
B-23	100	2.210	2.210	2.227	2.226
B-24	100	2.218	2.218	2.234	2.234
B-25	100	2.147	2.147	2.185	2.185
B-26	100	2.178	2.178	2.217	2.216
B-27	100	2.186	2.186	2.208	2.207
B-28	100	2.232	2.232	2.260	2.259
B-29	100	2.257	2.257	2.285	2.285
B-30	100	2.244	2.244	2.254	2.254
B-31	100	2.192	2.192	2.221	2.220
T1-28	150	2.250	2.285	2.284	2.284
T1-29	150	2.259	2.355	2.350	2.348
T1-30	150	2.338	2.368	2.363	2.367
T1-31	150	2.337	2.377	2.376	2.375
T1-32	150	2.313	2.349	2.349	2.348
T1-33	150	2.365	2.396	2.395	2.395
T1-34	150	2.342	2.398	2.398	2.397
T1-35	150	2.355	2.383	2.383	2.382
T2-48	150	2.107	2.151	2.142	2.140
T2-49	150	2.322	2.329	2.328	2.328
T2-50	150	2.303	2.341	2.339	2.339
T2-51	150	2.329	2.358	2.355	2.355
T2-52	150	2.314	2.371	2.370	2.369
T2-53	150	2.274	2.320	2.319	2.318
T2-54	150	2.330	2.326	2.324	2.323
T2-55A	150	2.246	2.272	2.270	2.270
T2-55B	150	2.355	2.379	2.376	2.374
T2-56	150	2.317	2.348	2.347	2.346
T2-57	150	2.353	2.351	2.349	2.347
T2-58	150	2.088	2.137	2.131	2.128
T2-59	150	2.365	2.368	2.367	2.366

TABLE 4.8. (Con't.) Lab Test Results of Field Cores, Phase II, Group B

Sample ID	Diameter (mm)	CoreReader™ Gmb	Core Dryer Gmb	Slow oven Gmb	Fast oven Gmb
T2-60	150	2.349	2.373	2.371	2.371
T2-61	150	2.175	2.218	2.215	2.213
T2-62	150	2.315	2.361	2.360	2.360
T2-63	150	2.310	2.358	2.357	2.357
T2-64	150	2.333	2.376	2.376	2.376
T2-65	150	2.317	2.354	2.353	2.353
T2-66	150	2.218	2.280	2.277	2.276
T2-67	150	2.328	2.372	2.371	2.371
T2-68	150	2.310	2.365	2.364	2.364
T2-69	150	2.211	2.231	2.225	2.222

TABLE 4.9. CoreReader™ Gmb Before and After Sawing of Field Cores, Phase III

Sample ID	Dia. (mm)	CRD Gmb (before sawing)	CRD Gmb (after sawing)	Sample ID	Dia. (mm)	CRD Gmb (before sawing)	CRD Gmb (after sawing)
B-32	100	2.243	2.246	A-12	100	2.151	2.195
B-33	100	2.195	2.204	A-13	100	2.217	2.236
B-34	100	2.243	2.257	A-14	100	2.184	2.183
B-35	100	2.255	2.245	A-15	100	2.188	2.200
B-36	100	2.230	2.235	A-16	100	2.189	2.208
B-37	100	2.162	2.177	A-17	100	2.161	2.209
B-38	100	2.275	2.260	A-18	100	2.157	2.171
B-39	100	2.179	2.202	B-23	100	2.199	2.210
B-40	100	2.245	2.235	B-24	100	2.192	2.218
T1-36	150	2.154	2.236	B-25	100	2.142	2.147
T1-37	150	2.236	2.312	B-26	100	2.168	2.178
T1-38	150	2.33	2.332	B-27	100	2.183	2.186
T1-39	150	2.364	2.343	B-28	100	2.257	2.232
T1-40	150	2.268	2.267	B-29	100	2.245	2.257
T1-41	150	2.354	2.352	B-30	100	2.234	2.244
T1-42	150	2.511	2.364	B-31	100	2.180	2.192
T1-43	150	2.373	2.352	T1-28	150	2.220	2.250

TABLE 4.9.(Con't.) CoreReader^{TM} Gmb Before and After Sawing of Field Cores, Phase III

Sample ID	Dia. (mm)	CRD Gmb (before sawing)	CRD Gmb (after sawing)	Sample ID	Dia. (mm)	CRD Gmb (before sawing)	CRD Gmb (after sawing)
T1-44	150	2.367	2.313	T1-29	150	2.148	2.259
T2-71	150	2.321	2.343	T1-30	150	2.335	2.338
T2-72	150	2.185	2.204	T1-31	150	2.318	2.337
T2-73	150	2.137	2.160	T1-32	150	2.298	2.313
T2-74	150	2.128	2.163	T1-33	150	2.387	2.365
T2-75	150	2.318	2.340	T1-34	150	2.550	2.342
T2-76	150	2.241	2.261	T1-35	150	2.396	2.355
T2-77	150	2.483	2.359	T2-48	150	2.070	2.107
T2-78	150	2.300	2.310	T2-49	150	2.180	2.322
T2-79	150	2.313	2.348	T2-50	150	2.303	2.303
T2-80	150	2.280	2.321	T2-51	150	2.339	2.329
T2-81	150	2.146	2.152	T2-52	150	2.284	2.314
T2-82	150	2.206	2.254	T2-53	150	2.258	2.274
T2-83	150	2.154	2.228	T2-54	150	2.300	2.330
T2-84	150	2.376	2.311	T2-55A	150	2.209	2.246
T2-85	150	2.254	2.253	T2-55B	150	2.308	2.355
T2-86	150	2.265	2.316	T2-56	150	2.271	2.317
H-1	150	2.070	2.181	T2-57	150	2.338	2.353
H-2	150	2.170	2.276	T2-58	150	2.049	2.088
H-3	150	2.259	2.283	T2-59	150	2.337	2.365
H-4	150	2.178	2.339	T2-60	150	2.315	2.349
H-5	150	2.302	2.308	T2-61	150	2.139	2.175
H-6	150	2.234	2.26	T2-62	150	2.280	2.315
H-7	150	2.262	2.354	T2-63	150	2.491	2.310
H-8	150	2.337	2.353	T2-64	150	2.312	2.333
H-9	150	2.318	2.373	T2-65	150	2.275	2.317
H-10	150	2.253	2.244	T2-66	150	2.194	2.218
H-11	150	2.195	2.234	T2-67	150	2.312	2.328
H-12	150	2.282	2.320	T2-68	150	2.318	2.310
H-13	150	2.287	2.311	T2-69	150	1.558	2.211

CHAPTER 5

ANALYSIS OF TEST RESULTS

This chapter provides the analysis of the experimental test data. Two different statistical analyses techniques were performed for the evaluation of the CoreDry^{TM} and the CoreReader^{TM} equipment. The statistical analysis consisted of comparison of means of dry mass and Gmb after each drying process. Statistical approaches of comparing means by Analysis of Variance (ANOVA) for more than two groups of data and t-test for two groups were used throughout the analysis.

PHASE I COREDRY^{TM}

Dry mass of the sample was used for the evaluation of the CoreDry^{TM} as Gmb is directly related to dry mass and the statistical output is no different than using Gmb. Gmb is the dry mass divided by a constant, equal to 'SSD mass-Submerged mass', so the distribution of data would be the same.

ANOVA with Duncan's multiple range test, paired t-test and comparisons to the standard precision statements were used as analytical tools for the evaluation of the CoreDry^{TM} apparatus. For analysis purposes, data are grouped into two categories, namely lab compacted samples and field cores.

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ANOVA with Duncan's Test

Lab Compacted Samples

The lab compacted samples have four sets of Gmb and consequently dry masses which are referred to as methods. The dry masses and their notation are as follows:

i) Initial dry mass (Initial dry)

ii) Dry mass after CoreDry (CoreDry^{TM})

iii) Dry mass after slow oven drying (Slow oven)

iv) Dry mass after fast oven drying (Fast oven)

For the evaluation of drying efficiency of CoreDry^{TM} apparatus using lab compacted samples, the dry mass by CoreDry^{TM} is compared with initial dry mass (dry mass after cooling to room temperature), dry mass after slow oven drying and dry mass after fast oven drying.

The S3 and S4 mixes consists of samples with two different heights, one 95 mm and 115 mm. The SMA samples were all 115 mm high. For effective comparisons, samples of approximately equal dry mass are necessary. Therefore, ANOVA with Duncan's multiple range tests are performed for each group for the lab compacted samples, by height.

The results of ANOVA with Duncan's multiple range tests are presented in tables 5.1 and 5.2 for group A samples and in tables 5.3 and 5.4 for group B samples. The ANOVA indicates that there is no statistical difference between initial dry, CoreDry^{TM}, slow oven and fast oven dry mass at a confidence limit of 95% ($\alpha = 0.05$). The means and results from Duncan's multiple range tests confirm the results.

TABLE 5.1. ANOVA Test Result, Group A, Height=95mm (By Height)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	1	459432.68	459432.68	13635.30	<0.0001
Method	2	45.01	22.51	0.67	0.5250
Mix*Method	2	11.50	5.75	0.17	0.8445

Duncan Grouping*	Mean Dry Mass	N	Method
A	3740.4	8	Slow oven
A	3737.8	8	Fast oven
A	3737.2	8	Initial dry

* Means with the same letter are not significantly different.

TABLE 5.2. ANOVA Test Result, Group A, Height=115mm (By Height)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	2	1125034.80	562517.40	9204.86	<0.0001
Method	2	11.49	5.75	0.09	0.9104
Mix*Method	4	8.58	2.15	0.04	0.9976

Duncan Grouping*	Mean Dry Mass	N	Method
A	4753.4	22	Slow oven
A	4752.7	22	Initial dry
A	4752.4	22	Fast oven

* Means with the same letter are not significantly different.

TABLE 5.3. ANOVA Test Result, Group B, Height=95mm (By Height)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	1	439508.53	439508.53	3762.78	<0.0001
Method	2	3.06	1.53	0.01	0.9870
Mix*Method	2	0.05	0.02	0.00	0.9998

Duncan Grouping*	Mean Dry Mass	N	Method
A	3736.9	8	CoreDry^{TM}
A	3736.2	8	Initial dry
A	3736.1	8	Fast oven

* Means with the same letter are not significantly different.

TABLE 5.4. ANOVA Test Result, Group B, Height=115mm (By Height)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	2	1106003.14	553001.57	14682.80	<0.0001
Method	2	1.10	0.55	0.01	0.9855
Mix*Method	4	0.72	0.18	0.00	1

Duncan Grouping*	Mean Dry Mass	N	Method
A	4756.2	21	CoreDry^{TM}
A	4756.0	21	Initial dry
A	4755.7	21	Fast oven

* Means with the same letter are not significantly different.

The following figures, figure 5.1 and 5.2, show the interval plot for the mean dry masses and 95% confidence interval for group A and B lab compacted samples, respectively.

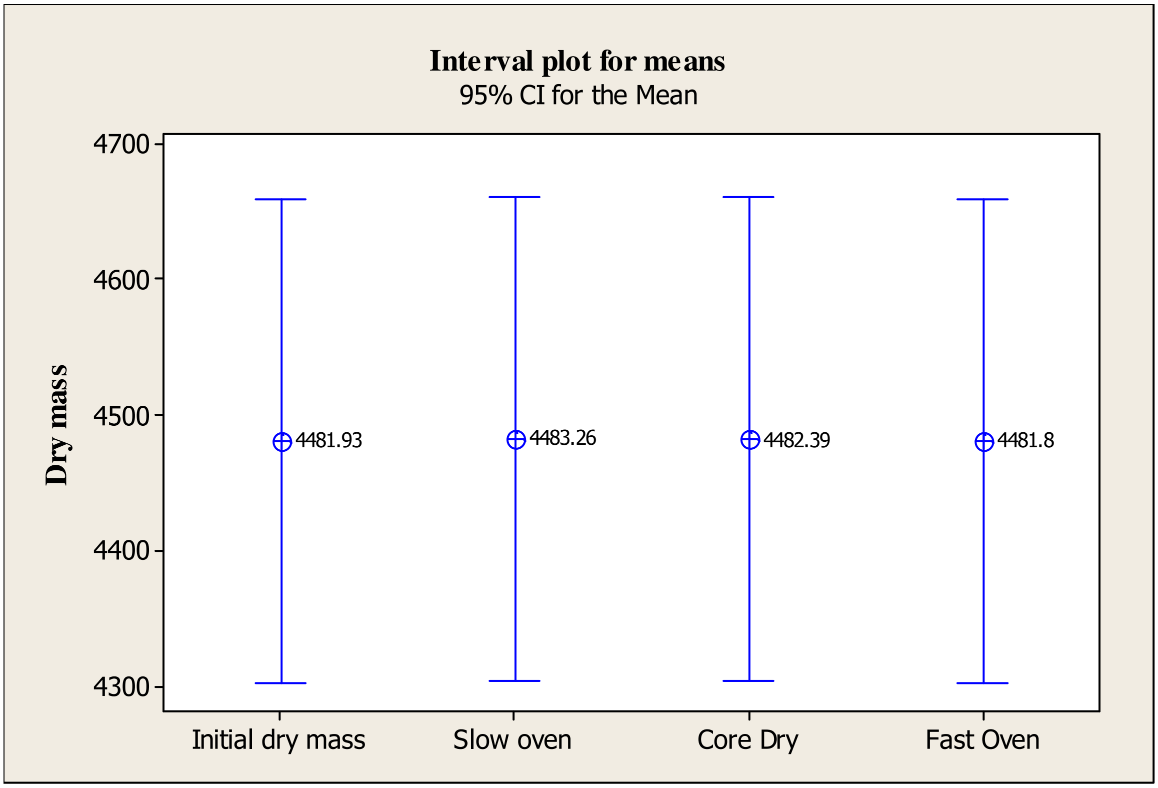

FIGURE 5.1 Interval plot for lab compacted samples (Group A).

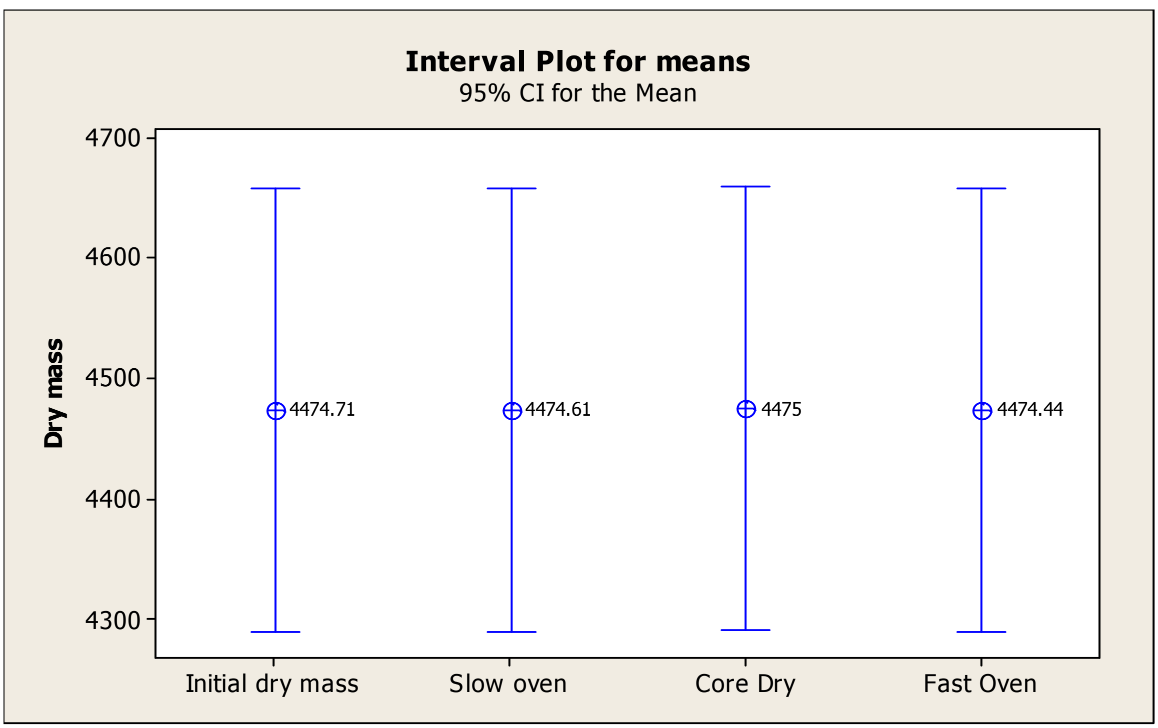

FIGURE 5.2 Interval plots for lab compacted samples (Group B).

The Duncan's multiple range test result presented in tables 5.1 and 5.2 for group A samples, and presented in table 5.3 and 5.4 for group B samples, show that the mean is same for all methods. ANOVA results show that there is no significant interaction of mix type on methods. The mean of initial dry, slow oven, and fast oven dry masses for group A are statistically the same and the mean of initial dry, CoreDry^{TM}, and fast oven dry masses are the same for group B samples. The methods are significantly different by mix which is due to the effect of Gsb on dry mass. The Gsb, and consequently dry mass, can be different for different mixes. The results show that the CoreDry^{TM} method works well for effective drying of lab compacted samples and gives statistically similar results to the oven drying methods of AASHTO T166 and to the initial dry mass.

Field Cores

Field cut cores have only three dry masses; namely slow oven, CoreDry^{TM} and fast oven which are considered as methods for the statistical analysis. Two different sizes of cores were used in the testing, 100 mm and 150 mm and hence, in the analysis. The ANOVA and Duncan's tests were performed by group, and the interaction of diameter on methods was checked. The ANOVA and Duncan's multiple range test results for group A are presented in table 5.5 and the test result for group B are presented in table 5.6. The ANOVA results show the means are same for all methods at a confidence interval of 95 % ($\alpha = 0.05$).

TABLE 5.5. ANOVA Test Result for Field Cores, Group A, (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Diameter	1	52062781.14	52062781.14	101.19	< 0.0001
Method	2	62.28	31.14	0.00	0.9999
Diameter*Method	2	1.95	0.98	0.00	1.0000

Duncan Grouping*	Mean Dry Mass	N	Method
A	1879.06	103	Slow oven
A	1878.56	103	Core Dry
A	1877.77	103	Fast oven

* Means with the same letter are not significantly different.

TABLE 5.6. ANOVA Test Result for Field Cores, Group B, (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Diameter	1	51440952.65	51440952.65	101.19	< 0.0001
Method	2	105.07	75.62	0.00	0.9999
Diameter*Method	2	0.64	0.32	0.00	1.0000

Duncan Grouping*	Mean Dry Mass	N	Method
A	1885.08	116	CoreDry^{TM}
A	1883.96	116	Slow oven
A	1883.51	116	Fast oven

* Means with the same letter are not significantly different.

The interval plots for the mean dry mass and 95% confidence interval for group A and B field core samples are presented in figure 5.3 and 5.4, respectively.

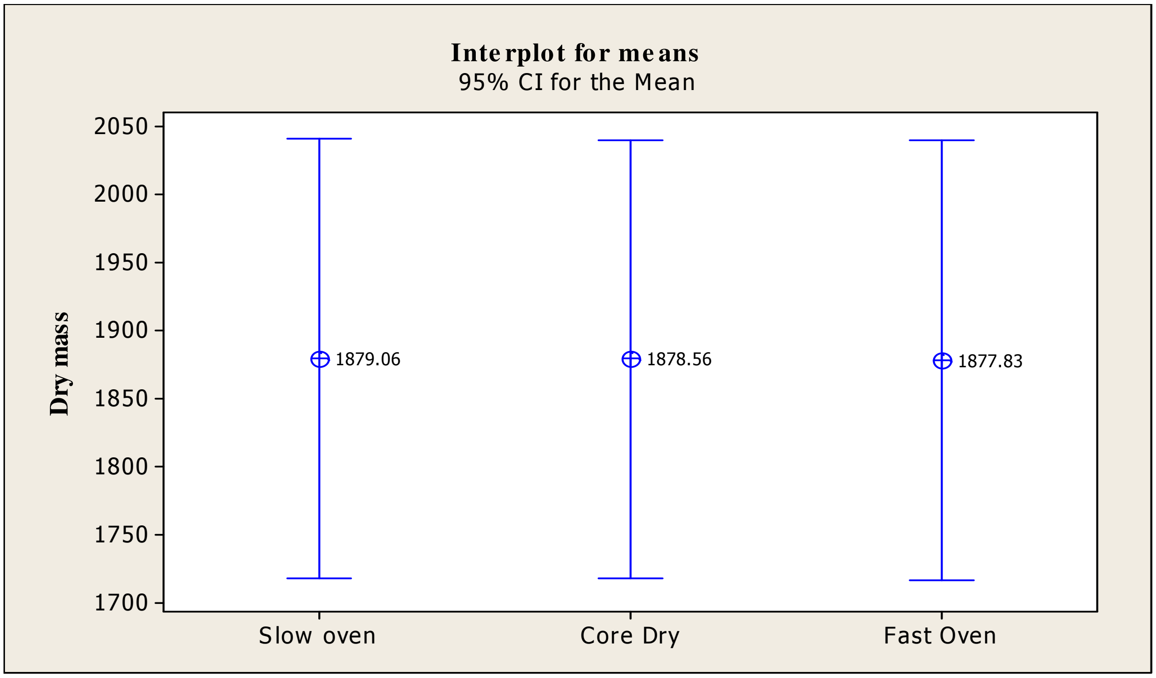

FIGURE 5.3 Interval plot for field cores (Group A).

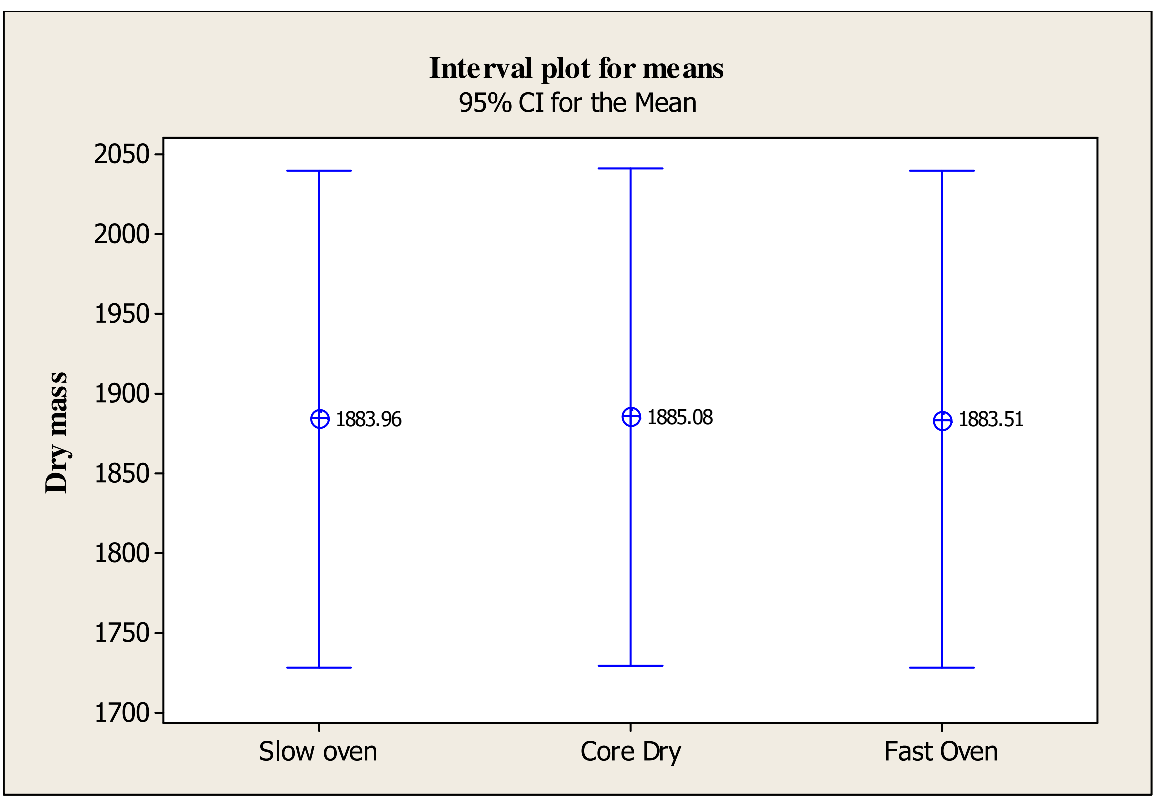

FIGURE 5.4 Interval plot for field cores (Group B).

The ANOVA and Duncan's multiple range test results presented in tables 5.5 and 5.6 show that slow oven, CoreDry™ and fast oven dry mass are statistically similar. The ANOVA results also indicate that there is no significant interaction of diameter on methods. The means are statistically different for the two different diameters, which were expected. Based on the ANOVA test results, CoreDry™ produces similar results to the slow and fast oven drying methods for field cores which have greater water absorption than lab compacted samples.

Paired t-Test

Lab Compacted Samples

The ANOVA test with Duncan's multiple range test showed that there was no statistical difference among the methods i.e. initial dry, CoreDry™, slow oven and fast oven dry mass, and hence the Gmb, for lab compacted samples. When the same set of data was analyzed using a one tail paired t-test for two sample means, a statistical difference at a confidence limit of 95% ($\alpha = 0.05$) was observed. The one-tailed paired t-test was used because the dry mass after a drying method is less than or equal to the dry mass after previous drying. The paired t-test results are presented in table 5.7.

TABLE 5.7. Paired t-test Result for Lab Compacted Samples

	Group	Comparison between	t-statistic	t-critical	P-value	Comments on means
By Height	95 mm, Gr. A	Initial and Slow	-4.39	1.89	1.6E-03	Not same.
		Slow and Core	4.33	1.89	1.7E-03	Not same.
		Slow and Fast	4.31	1.89	1.8E-03	Not same.
	95 mm, Gr. B	Initial and Core	-8.71	1.89	2.6E-05	Not same.
		Core and Slow	4.53	1.89	1.4E-03	Not same.
		Core and Fast	5.24	1.89	6.0E-04	Not same.
	115 mm, Gr. A	Initial and Slow	-2.84	1.86	1.1E-02	Not same.
		Slow and Core	2.24	1.86	2.8E-02	Not same.
		Slow and Fast	2.28	1.86	2.6E-02	Not same.
	115 mm, Gr. B	Initial and Core	-3.21	1.86	6.2E-03	Not same.
		Core and Slow	2.58	1.86	1.6E-02	Not same.
		Core and Fast	2.82	1.86	1.1E-02	Not same.

Note: Initial: Initial dry mass; Core: CoreDry™ mass; Slow: slow oven dry mass; Fast: fast oven dry mass

According to the paired t-test results presented in table 5.7, all methods are statistically different. Hence, the CoreDry™ apparatus does not produce similar dry mass as obtain from slow oven or fast oven drying methods for laboratory compacted samples. Table 5.7 also indicates that slow oven dry mass is statistically different than rest of the methods. The statistical difference between the methods in paired t-test is due to the power of the paired t-test compared to the ANOVA (f-test).

Field Cores

The ANOVA test with Duncan's multiple range tests showed no statistical difference among all of the methods i.e. CoreDry™, slow oven and fast oven dry mass for field core samples. When the same set of data was analyzed using a one tail paired t-test for two sample means, a statistically significant difference at a confidence limit of 95% ($\alpha = 0.05$), was found . The paired t-test results are presented in table 5.8.

TABLE 5.8. Paired t-test Result for Field Core Samples

	Group	Comparison between	t-statistic	t-critical	P-value	Comments on means
By Group	Gr. A	Slow and Core	4.36	1.66	1.5E-05	Not same.
		Slow and Fast	7.31	1.66	3.1E-11	Not same.
	Gr. B	Core and Slow	9.88	1.66	2.4E-17	Not same.
		Core and Fast	10.68	1.66	3.3E-19	Not same.

Note: Core: CoreDry™ mass; Slow: slow oven dry mass; Fast: fast oven dry mass

The statistical difference between the methods was found when compared by paired t-test for field cores. All of the methods are statistically different. Hence, the CoreDry™ apparatus does not produce similar dry mass as obtain from slow oven or fast oven drying methods for field cut core samples.

Practical Significance

Lab Compacted Samples

Sometimes, statistically similar results may have a practical difference and statistically different results may not have any practical difference. To evaluate the practical differences among methods, the difference in means between consecutive methods were calculated and compared with the AASHTO T166 requirement for dry state of mass, which is mass loss less than 0.05 % of total mass. The results are presented in table 5.9 for lab compacted samples. The results show that the difference is less than 0.05 percent. Therefore, no practical difference was found for lab compacted samples. The dry mass obtained from CoreDry™ apparatus can be used for laboratory analysis of HMA samples.

TABLE 5.9. Practical Significance of the Test Result for Lab Compacted Samples

Sample Type	Gr.	Method	Mean dry mass	Comparison between	Mean % difference	Remarks
Lab Compacted	A	Initial	4472.6	Initial Vs Slow	0.031	No difference
		Slow	4474.0	Slow Vs Core	0.020	No difference
		Core	4473.1	Slow Vs Fast	0.034	No difference
		Fast	4472.5			
	B	Initial	4464.3	Initial Vs Core	0.007	No difference
		Core	4464.6	Core Vs Slow	0.009	No difference
		Slow	4464.2	Core Vs Fast	0.006	No difference
		Fast	4464.0			

Note: Initial: Initial dry mass; Core: CoreDry^{TM} mass; Slow: slow oven dry mass; Fast: fast oven dry mass

Field Cores

To evaluate the practical differences among methods for field cores, the same procedure used for lab samples was followed. The mean difference between consecutive methods were calculated and compared with the AASHTO T166 requirements for dry state of mass, which is mass loss less than 0.05 % of total mass, as in case of lab compacted samples. The results are presented in table 5.10.

TABLE 5.10. Practical Significance of the Test Result for Field Cores

Sample Type	Gr.	Method	Mean dry mass	Comparison between	Mean % difference	Remarks
Field Cores	A	Slow	1813.3	Slow Vs Fast	0.050	No difference
		Core	1813.1	Core Vs Fast	0.039	No difference
		Fast	1812.4	Slow Vs Core	0.011	No difference
	B	Core	1758.6	Core Vs Fast	0.045	No difference
		Slow	1757.9	Slow Vs Fast	0.006	No difference
		Fast	1757.8	Core Vs Slow	0.040	No difference

Note: Initial: Initial dry mass; Core: CoreDry^{TM} mass; Slow: slow oven dry mass; Fast: fast oven dry mass

The difference between the methods was equal to or less than 0.05 %. Therefore; there is no practical difference between the slow and fast method and between CoreDry^{TM} and fast method. The CoreDry^{TM} can be used to determine the dry mass for Gmb determination.

PHASE II COREREADER^{TM}

This phase of the analysis is the evaluation of CoreReader^{TM} apparatus. The analysis in this phase includes comparison of the Gmb obtained from CoreReader^{TM} to Gmb obtained by conventional water displacement methods of AASHTO T166. This was accomplished by the statistical comparison of Gmb obtained from CoreReader^{TM} to the Gmb obtained by conventional AASHTO T166 methods and the Gmb obtained from the CoreDry^{TM} dry mass. To analyze the comparisons between the methods, ANOVA with Duncan's multiple range tests and paired t-tests were used throughout the analysis. In addition, if the CoreReader^{TM} Gmb was found different than the Gmb obtained from water displacement method, an attempt will be made to develop a correlation. For the effective analysis and correlation development, lab compacted and field cores are treated separately, similar to phase I analysis.

ANOVA with Duncan's Test

Lab Compacted Samples

For the lab compacted samples, the dry mass used in phase I were used to calculate the Gmb in AASHTO T166 methods. The lab compacted samples have five sets of Gmb. The five categories and their notations for analysis are as follow:

i) AASHTO T166 Gmb(T166)

ii) CoreDry™ Gmb (CoreDry™)

iii) Slow oven Gmb (Slow oven)

iv) Fast oven Gmb (Fast oven)

v) CoreReader™ Gmb (CoreReader™)

In above categories, T166 Gmb is the conventional bulk specific gravity of lab compacted samples calculated using the volume obtained by water displacement method and initial dry mass of sample before submerging in water in accordance to AASHTO T166. Similarly, CoreDry™, Slow oven and Fast oven Gmb are obtained by using the volume by water displacement and dry mass after each respective method.

An ANOVA with Duncan's multiple range test were performed for the whole set of data for each group (Group A and Group B) of lab compacted samples. The results of ANOVA with Duncan's multiple range tests were performed at a confidence limit of 95% ($\alpha = 0.05$). The results for lab compacted samples for group A and group B are presented in tables 5.11 and 5.12, respectively. The results show that CoreReader™ Gmb is statistically different from the other test methods. ANOVA results show there is no interaction of type of mix on methods. The data in this phase need not to be analyzed by height as analysis is performed for Gmb, which normalizes the dry mass data.

TABLE 5.11. ANOVA Test Result for Lab Compacted Samples, Group A (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	2	0.31931	0.15966	97.41	< 0.0001
Method	3	0.02497	0.00832	5.08	0.0025
Mix*Method	6	0.00132	0.00022	0.13	0.9916

Duncan Grouping*	Mean Gmb	N	Method
A	2.356	30	Slow oven
A	2.355	30	Fast oven
A	2.355	30	T166
B	2.320	30	CoreReader™

* Means with the same letter are not significantly different.

TABLE 5.12. ANOVA Test Result for Lab Compacted Samples, Group B (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Mix	2	0.27770	0.13885	77.32	< 0.0001
Method	3	0.02012	0.00671	3.74	0.0135
Mix*Method	6	0.00027	0.00005	0.03	0.9999

Duncan Grouping*	Mean Gmb	N	Method
A	2.367	29	CoreDry™
A	2.366	29	T166
A	2.366	29	Fast oven
B	2.336	29	CoreReader™

* Means with the same letter are not significantly different.

The ANOVA test results and the Duncan's multiple range tests presented in tables 5.11 and 5.12 show that Gmb obtained by CoreReader™ is statistically different than Gmb obtained by water displacement methods. The Gmbs are different for mix type but there is no significant interaction on methods, therefore, it was not necessary to perform the ANOVA by mix type.

Field Cores

Field cores consist of four types of Gmb namely, CoreReader™ Gmb, slow oven Gmb, CoreDry™, and fast oven Gmb. To compare the Gmb by CoreReader™, ANOVA with Duncan's multiple range test was used and the four Gmbs mentioned above were compared. In this case, there is no need to analyze the data by diameter as calculation of Gmb normalizes the data. Therefore, one-way ANOVA with Duncan's multiple range tests at a confidence limit of 95% ($\alpha = 0.05$) was performed for group A and group B samples. The test results are presented in tables 5.13 and 5.14 for group A and B field cores, respectively.

TABLE 5.13. ANOVA Test Result for Field Cores, Group A (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Method	2	0.13106	0.06553	3.13	0.0451

Duncan Grouping*	Mean Gmb	N	Method
A	2.292	103	Slow oven
A	2.269	103	Fast oven
B	2.242	103	CoreReader™

* Means with the same letter are not significantly different.

TABLE 5.14 ANOVA Test Result for Field Cores, Group B (By Group)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	Prob.>F
Method	2	0.14853	0.07427	19.48	<0.001

Duncan Grouping*	Mean Gmb	N	Method
A	2.301	116	CoreDry™
A	2.301	116	Fast oven
B	2.257	116	CoreReader™

* Means with the same letter are not significantly different.

The ANOVA test with Duncan's multiple range test results showed CoreReader™ Gmb is statistically different than other methods for both groups of field core samples. The Gmb obtained from slow oven, CoreDry™ and fast oven drying were found statistically same, which indicates no difference in these methods, as found in the phase I analysis.

Paired t-Test

Lab Compacted Samples

The paired t-test for two sample means between CoreReader™ Gmb and either AASHTO T166 Gmb or fast oven Gmb, in case of lab compacted samples, showed CoreReader™ Gmb is statistically different. The one tail paired t-test at a confidence limit of 95% ($\alpha = 0.05$) for lab compacted samples is presented in table 5.15.

TABLE 5.15. Paired t-test Result for Lab Compacted Samples

	Group	Comparison between	t-statistic	t-critical	P value	Comments on means
By Group	Gr. A	CR and T166	-12.40	1.70	4.1E-13	Not same.
		CR and Fast	-12.28	1.70	2.6E-13	Not same.
	Gr. B	CR and T166	-10.68	1.70	1.1E-11	Not same.
		CR and Fast	-10.66	1.70	1.1E-11	Not same.
By Height	115 mm, Gr. A	CR and T166	-6.32	1.86	1.1E-04	Not same.
		CR and Fast	-6.23	1.86	1.2E-04	Not same.
	115 mm, Gr. B	CR and T166	-4.53	1.86	9.6E-04	Not same.
		CR and Fast	-4.54	1.86	9.6E-04	Not same.
	95 mm, Gr. A	CR and T166	-12.97	1.89	1.9E-06	Not same.
		CR and Fast	-13.55	1.89	1.4E-06	Not same.
	95 mm, Gr. B	CR and T166	-8.1721	1.89	4.0E-05	Not same.
		CR and Fast	-8.2001	1.89	3.9E-05	Not same.

Note: CR: CoreReader^{TM} Gmb; Fast: Fast oven Gmb; T166: AASHTO T166 Gmb.

Field Cores

The same approach for comparison of CoreReader^{TM} Gmb and fast oven Gmb was applied to the field cores. The one tail paired t-test results for field cores at a confidence limit of 95% ($\alpha = 0.05$) are presented in table 5.16. The paired t-test results show that there is a statistical difference between Gmb obtained from CoreReader^{TM} and AASHTO T166.

TABLE 5.16. Paired t-test Result for Field Core Samples

	Group	Comparison between	t-statistic	t-critical	P-value	Comments on means
By Group	Gr. A	CR and Fast	-1.2765	1.6599	0.1023417	Are same
	Gr. B	CR and Fast	-9.3211	1.6582	4.953E-16	Not same.
By Diameter	150 mm, Gr. A	CR and Fast	-19.859	1.666	1.873E-31	Not same.
	150 mm, Gr. B	CR and Fast	-7.6961	1.6628	1.084E-11	Not same.
	100 mm, Gr. A	CR and Fast	-12.481	1.7011	2.933E-13	Not same.
	100 mm, Gr. B	CR and Fast	-7.1918	1.7011	3.963E-08	Not same.

Note: CR: CoreReader^{TM} Gmb; Fast: Fast oven Gmb;

The paired t-test for lab compacted samples showed a statistical difference between CoreReader^{TM} Gmb and the rest of the methods. For field cores, the CoreReader^{TM} Gmb and fast oven Gmb are statistically similar for Group A cores when both 100 and 150 mm diameter samples are analyzed together. When the field cores were tested for paired t-test by breaking into two groups by diameter, CoreReader^{TM} Gmb was found to be different than fast oven Gmb.

Practical Significance

Lab Compacted Samples

Practical significance is as important as statistically similar results. Test results can have no practical difference and show statistical difference. To evaluate the practical differences between AASHTO T166 Gmb and CoreReader^{TM} Gmb, the AASHTO precision guideline was used. According to AASHTO T166 (3), the difference between

Gmb by two consecutive tests should not be greater than 0.02, the acceptable limit for laboratory Gmb determination. In this case, only AASHTO T166 Gmb is used to compare with CoreReader™, as previous section has already shown that AASHTO T166, slow oven, CoreDry™, and fast oven Gmb are similar. Practical significance check is presented in table 5.17 for lab compacted samples. Results show that the difference in Gmb exceeds the acceptable limit for test results and, therefore, the methods produce different results.

TABLE 5.17. Practical Significance of the Test Result for Lab Compacted Samples

Sample Type	Gr.	Method	Mean Gmb	Comparison between	Mean difference	Remarks
Lab Samples	A	AASHTO T166	2.355	AASHTO T166 and CoreReader™	0.035	Are different.
		CoreReader™	2.320			
	B	AASHTO T166	2.367	AASHTO T166 and CoreReader™	0.031	Are different.
		CoreReader™	2.336			

Field Cores

The same approach of evaluating the practical significance of lab compacted samples was applied to the field cores. The mean difference between the CoreReader™ and fast oven Gmb were calculated and compared with the AASHTO T166 precision requirement of a difference of less than 0.02. The results are presented in table 5.18.

TABLE 5.18. Practical Significance of the Test Result for Field Core Samples

Sample Type	Gr.	Method	Mean Gmb	Comparison between	Mean difference	Remarks
Field cores	**A**	CoreReader™ Fast oven	2.241 2.269	CoreReader™ and Fast oven	0.028	Are different.
	B	CoreReader™ Fast oven	2.257 2.305	CoreReader™ and Fast oven	0.048	Are different.

For field cores, the CoreReader™ Gmb produces different results than AASHTO T166 fast oven Gmb. The ANOVA with Duncan's multiple range tests and paired t-test showed CoreReader™ Gmb is different than Gmb obtained from AASHTO T166 methods and CoreDry™ apparatus for both lab compacted and field core samples. The CoreReader™ Gmb is outside the acceptable range of two results listed in AASHTO T166. Thus, the above tests indicate that the CoreReader™ apparatus does not produce the same results as AASHTO T166.

PHASE III

Effect of Parallel Faces on CoreReader™ Gmb

The test procedure for the CoreReader™ says sample ends need to be parallel with smooth edges. To evaluate the effect of parallel faces on CoreReader™ Gmb, field cores with one end uneven or irregular were first tested in CoreReader™ and again with both faces parallel by sawing one side. A less powerful t-test assuming equal variance, which is the same as f-test for two methods, and the more powerful paired t- test for two sample means, were used to evaluate the difference. Table 5.19 shows the comparison using t-test and paired t-test at a confidence limit of 95 % ($\alpha = 0.05$).

TABLE 5.19. t-test Results for Effect of Parallel Faces on CoreReader™ Gmb

Type of test	t-statistic	t-critical	P-value	Comments on means
t-test, assuming equal variances	-1.608	1.661	0.0548	Means are same
Paired t-test, two sample for means	-2.583	1.653	0.0057	Means are not same.

The t-test showed there is no statistical difference between Gmb before and after sawing the cores. The paired t-test, which is a more powerful test than the t-test, showed that there is a significant difference between the two Gmbs. The mean and standard deviation of the CoreReader™ Gmb for cores with one face not smooth (i.e. having higher heights) is 2.249 and 0.1169 whereas for both faces smooth (i.e. having smaller heights) are 2.279 and 0.067. The difference in means value is 0.030, which is greater than the acceptable range of two results of 0.02, as listed in AASHTO T166. In this case the samples with both faces parallel also had a lower standard deviation, 0.067 compared to 0.1169. It appears that the parallel face requirement for CoreReader™ testing is justified.

Figure 5.5 indicates that most of the data are above the line of equality, indicating that having both faces parallel results in slightly higher Gmb values.

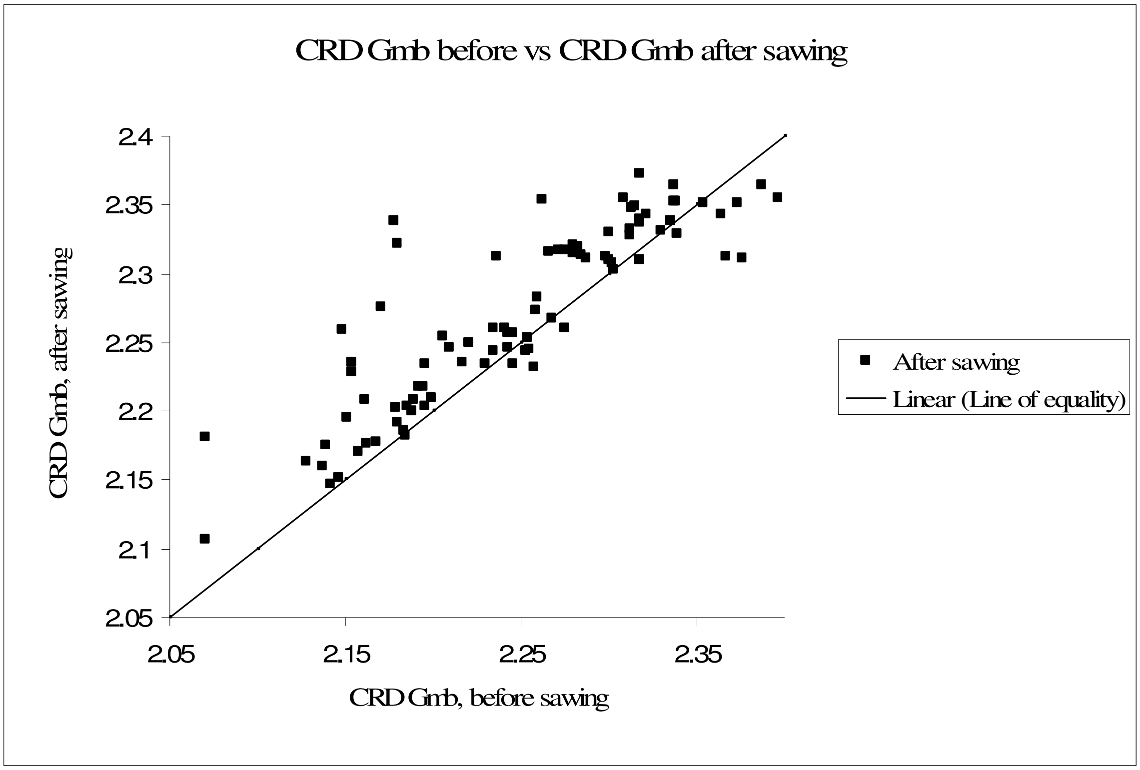

FIGURE 5.5 Before vs. after sawing plot for CoreReader™ Gmb.

CORRELATION BETWEEN COREREADER™ AND AASHTO T166 Gmb

Lab Compacted Samples

The previous statistical analysis showed that CoreReader™ Gmb is statistically different than AASHTO T166 Gmb. However, this does not mean that the CoreReader™ cannot be successfully used to determine the Gmb of HMA samples. Many state DOTs allow the use of nuclear and/or non nuclear density meters to determine the in-place density of HMA pavements if a correlation is established between Gmb from cores of the pavement and gauge results. To develop the correlations between CoreReader™ Gmb and AASHTO T166, Gmb the field cores and lab samples were used. The lab compacted

S3 and S4 mixes were compacted to two VTM contents only, and cannot be used to establish a correlation.

The lab compacted SMA samples contained a wide variation in Gmb, and a meaningful correlation could be developed. The relationship is shown in figure 5.6. The relation has a goodness of fit (R^2) of 0.94 indicating that a good approximation of T166 Gmb can be made. AASHTO T166 Gmb can be approximated using the CoreReader™ Gmb, using the following relationship. T166= 0.7469 * CR + 0.6244

Where, T166= AASHTO T166 Gmb

CR= CoreReader™ Gmb

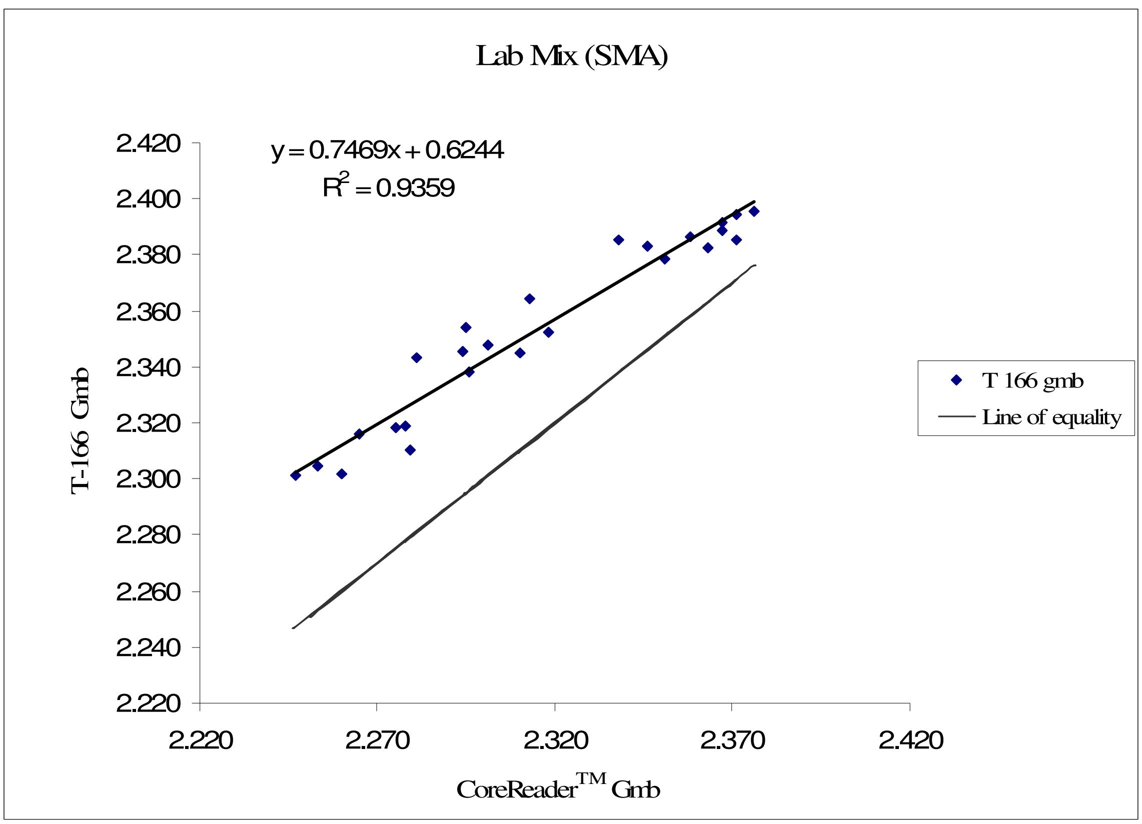

FIGURE 5.6 Correlation of T166 Gmb and CoreReader™ Gmb for SMA.

Field Cores

For field cores, the CoreReader™ Gmb was found to be statistically different from AASHTO T166 Gmb by both the f-test and t-test. A regression plot of CoreReader™ and AASHTO T166 Gmb (fast oven Gmb) for 100 mm and 150 mm samples together, is presented in figure 5.7.

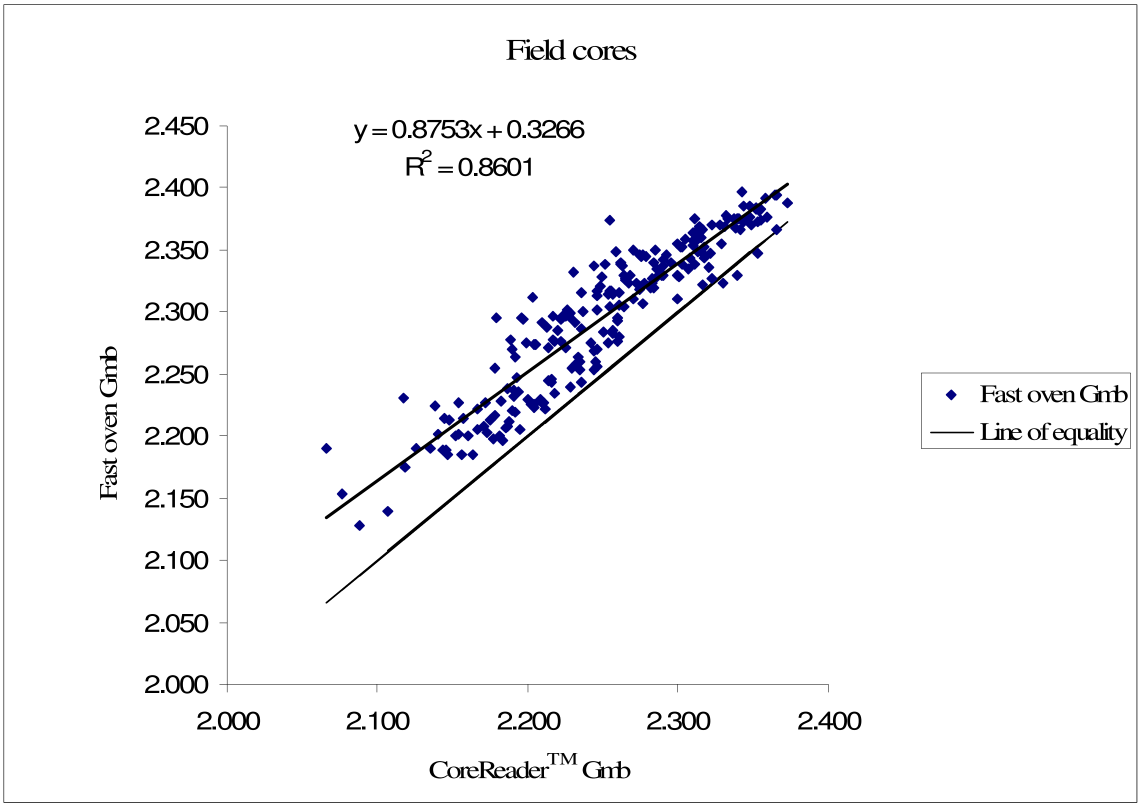

FIGURE 5.7 Correlation of T166 fast oven Gmb and CoreReader™ Gmb for 100 mm and 150 mm field cores.

The value of T166 Gmb (fast oven Gmb) using CoreReader™ Gmb for field cores can be approximated, using the following relationship,

T166 fast oven Gmb = 0.8753 * CR + 0.3226

Where, CR= CoreReader™ Gmb.

The relationship has a goodness of fit (R^2) of 0.86.

CHAPTER 6

CONCLUSIONS AND RECOMMEDDATIONS

CONCLUSION

Based on the test results obtained and analysis of the test data, the following conclusions were made for phase I, phase II and phase III evaluations.

Phase I CoreDry^{TM}

1. The ANOVA test, which is considered a less powerful test than paired t-test, showed that initial dry mass, slow oven dry mass, dry mass after CoreDry^{TM} and fast oven dry mass are statistically similar. ANOVA results also indicated that there is no significant interaction between type of mix and sample diameter on drying methods. This was true for both laboratory compacted and field core samples.
2. Paired t-test analysis showed that the CoreDry^{TM}, slow oven and fast oven dry masses are not statistically similar.
3. Besides the statistical analysis, practical significance of the difference in dry masses was checked according to the AASHTO T166 requirement of a mass loss of less than 0.05 % between the two consecutive drying operations. There was no practical difference found between the slow and fast methods and between the CoreDry^{TM} and fast method for both lab compacted and field core samples.

4. Based on the statistical and practical analysis of the test data, the CoreDry™ can be considered as equivalent to the AASHTO T166 method A and method C, which are slow oven drying method and fast oven drying method, respectively.

Phase II CoreReader™

1. The ANOVA f-test and paired t-test analysis showed that the Gmb obtained by CoreReader™ apparatus is statistically different than Gmb obtained by AASHTO T166 methods at a significance level of 95%.
2. The CoreReader™ Gmb was also statistically different than the Gmb obtained by using the dry mass obtained from the CoreDry™.
3. A practical difference in Gmb greater than 0.020, was also found between the CoreReader™ Gmb and Gmb obtained from AASHTO T166 methods.
4. Based on the statistical and practical analysis, the CoreReader™ apparatus cannot be considered as a direct substitute for the AASHTO T166 methods of Gmb determination. Detail study is required before considering it as an alternative method of Gmb determination.
5. A correlation similar to what is used for field nuclear density devices can be used to calculate AASHTO T166 Gmb using CoreReader™ Gmb for lab compacted and field core samples.

Phase III Effect of Parallel Faces on CoreReader™ Gmb

To check the effect of irregular and uneven faces on CoreReader™ Gmb, paired t-test, and t-test assuming equal variances were used. Paired t-test showed that there is a significant difference between the two Gmbs whereas t-test showed that there is not an effect of unparallel faces on CoreReader™ Gmb. The difference in mean value was out of acceptable limit of 0.020, as listed in ASHTO T166. Hence, there is significant effect of uneven and unparallel faces on CoreReader^{TM} Gmb and the requirement for smooth parallel faces should be followed.

RECOMMENDATIONS

1. The CoreDry^{TM} apparatus can be used for the drying of lab compacted as well as field core samples for the Gmb determination.
2. CoreReader^{TM} apparatus did not produce similar results to AASHTO T166. If desire to use, correlations should be developed similar to those used when using the filed nuclear density devices.
3. It is necessary to saw the field core samples to make its faces smooth and parallel for the Gmb determination by CoreReader^{TM} apparatus.

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Scope and Method of Study: The evaluation of CoreDry^{TM}, and CoreReader^{TM} apparatus was completed based on the test results of laboratory prepared ODOT S3, S4 and SMA mixes and field cores of 100 mm and 150 mm. The CoreDry^{TM} apparatus was evaluated by comparing the dry mass obtained using the CoreDry^{TM} apparatus with dry mass obtained by AASHTO T166 drying methods. The evaluation of CoreReader^{TM} was completed by comparing the Gmb obtained using CoreReader^{TM} apparatus and Gmb obtained by AASHTO T166 procedures. The comparison of means of dry masses and Gmbs was performed by statistical tests such as ANOVA, paired t-test, and t-test.

Findings and Conclusions: The CoreDry^{TM} apparatus can be used for the drying of lab compacted as well as field core samples for the Gmb determination. CoreReader^{TM} apparatus did not produce similar results to AASHTO T166. If desire to use, correlations should be developed similar to those used when using the filed nuclear density devices. It is necessary to saw the field core samples to make its faces smooth and parallel for the Gmb determination by CoreReader^{TM} apparatus.

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