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PCC Properties to Support W/C Determination for Durability

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PCC PROPERTIES TO SUPPORT W/C DETERMINATION FOR DURABILITY

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16. Abstract

The fresh concrete water-cement ratio (w/c) determination tool is urgently needed for use in the QC/QA process at the job site. Various techniques have been used in the past to determine this parameter. However, many of these techniques can be complicated and time consuming. Furthermore, the extensive calibration is often needed to correlate the properties measured by these techniques with w/c. During the course of the present study, the method for the use of the unit weight for the determination of w/c of fresh concrete has been developed and evaluated on both laboratory and field concretes. Additionally, the accuracy of using microwave oven technique for w/c determination reported by previous research was confirmed. Finally, the accuracies of unit weight and microwave oven techniques for the determination of w/c were compared.

The unit weights required for this method have been determined either by using a “zero-air” procedure (ZAP) developed as a part of this study or by using conventional (following AASHTO specifications) methods. The ZAP technique was used to verify the w/c of 58 different laboratory concrete mixes. These verification efforts revealed that the minimum, maximum, standard error, and 95th percentile of the differences (Δw/c) between batched and determined w/c were, respectively, 0.000, 0.042, 0.017, and 0.030. The AASHTO determined unit weight (which also required measurements of the actual air content of concrete) was used to verify the w/c values of additional set of 57 laboratory mixes. When using the AASHTO unit weights (and air contents) the minimum, maximum, standard error, and 95th percentile of Δw/c of were, respectively, 0.000, 0.075, 0.030, and 0.054. In addition, the AASHTO unit weight method was also used to verify the w/c values of 22 different field mixtures. For this case, the differences (Δw/c) between the design and unit weight-calculated values of w/c were in the range ±0.030 for all but one mixture. Finally, direct comparison of the results from the proposed method with the results obtained from the microwave oven method revealed that the former is faster but slightly less accurate. Specifically, when used on five separate concrete samples, the accuracy of the microwave oven method was 0.010, much smaller than previously mentioned values of 0.030 (for the ZAP) and 0.054 (for the AASHTO) unit weight methods.

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EXECUTIVE SUMMARY

Introduction

Concrete, as one of the most widely used construction materials, is very durable and can provide long service life without extensive maintenance. The strength and durability of concrete are primarily a function of its water-cementitious material ratio value (w/c). This ratio is the mass of water divided by the total mass of cementitious material (sum of the masses of Portland cement (or blended cement) and any additional pozzolanic material such as fly ash, slag, silica fume or natural pozzolans).

Although it is a common practice to account for absorption and actual moisture content of aggregates (as well as for the amount of water added to the batch) when reporting the w/c value of fresh concrete during the trial batches, this information is often not tracked during the actual production of field concrete. As a result, the possibility will always exist that the actual w/c of the field mixture will be different from the design (target) w/c value. This difference can occur for three reasons. First, additional water may be purposely added to the mixture prior to the concreting operation to increase the ease of placement and finishing. Second, the water-cement ratio can also change due to the use of aggregates that have absorption values that do not match those used to develop the proportions of the basic mix (the use of aggregates that have lower absorption values will result in a higher w/c value in the batch and vice versa). Finally, the differences in w/c can arise from variability in moisture content of aggregates in the stockpiles.

The use of w/c lower than that specified in the mix design will result in stronger but more brittle concrete, which may also be difficult to place and finish. Similarly, the use of w/c higher than specified will result in concrete that is less strong and less durable. The reason that w/c has such a strong influence on concrete's strength and durability is directly linked to the fact that its value strongly influences the volume and the characteristics of capillary porosity, both of which directly control strength and durability. Since w/c plays such a crucial role in controlling concrete quality, there has always been a need for a tool or procedure that can verify the actual w/c value of concrete immediately prior to placement.

Nowadays, there is no standardized technique for determining w/c in fresh concrete. The three standard test procedures that have been historically used to obtain either water and/or cement content of fresh concrete (both of which are needed for w/c calculations) include the

following: ASTM C 1078 (standard test method for determining the cement content of freshly mixed concrete), ASTM C 1079 (standard test method for determining the water content of freshly mixed concrete), and AASHTO T 318 (standard test method for water content of freshly mixed concrete using microwave oven drying). Since both of the ASTM standards (C 1078 and C 1079) have been discontinued since 1998, the only standard currently available for determining water content in fresh concrete is the AASHTO T 318 (microwave oven) method. Since the modern ready mix plants can typically accurately control the amount of cement in the batch, the knowledge of microwave oven determined water content will allow (after being corrected for the amount of water absorbed by the aggregates) for calculation of w/c.

However, the use of microwave oven measured water content for determining w/c requires the performance of the additional test. Therefore, the focus of the present study was to explore the feasibility of using unit weight (which is already commonly measured as a part of the quality assurance (QA) programs) to determine w/c values of field concretes.

Findings

During the course of the present study, it was found that the unit weight of concrete can be used as a tool for determining w/c by following these three steps:

1. Establish the unit weight-w/c relationship. This was done by changing the amount of water in the basic mix (CMD) composition while keeping the value of air content constant. Consequently, the CMD composition as well as the w/c and unit weight will be altered (i.e., new mixture designs will be created). The unit weights of these new mixture designs, along with their w/c values, were correlated using linear regression analysis.
2. Adjust the measured unit weight. In order to apply the developed unit weight-w/c relationship to determine the w/c values of concrete based on its measured unit weight, corrections may be needed to account for the fact that actual values of air content in the mix and specific gravities of aggregates used in the batch may be different from those used in establishing the w/c-unit weight relationship. The adjustment for the differences in air content specific gravities of aggregates can be performed using equations that have been developed in this study.
3. Determine the actual w/c. This was done by using the adjusted measured unit weight as an input into the previously developed unit weight-w/c relationship.

The proposed method of using the unit weight of concrete for determining w/c has been evaluated on both laboratory and field concretes.

The unit weights for laboratory concretes required for this method have been determined either by using a “zero-air” procedure (ZAP) developed as a part of this study or by using conventional (following AASHTO specifications) methods. The ZAP technique was used to verify the w/c of 58 different laboratory concrete mixes. These verification efforts revealed that the minimum, maximum, standard error, and 95th percentile of the differences (Δw/c) between batched and determined w/c were, respectively, 0.000, 0.042, 0.017, and 0.030. The AASHTO determined unit weight (which also required measurements of the actual air content of concrete) was used to verify the w/c values of an additional set of 57 laboratory mixes. When using the AASHTO unit weights (and air contents) the minimum, maximum, standard error, and 95th percentile of Δw/c of were, respectively, 0.000, 0.075, 0.030, and 0.054.

In the part of the evaluation on field concretes, the AASHTO measured unit weights ware used to determine the w/c values of 22 different field mixtures. For this case, the differences (Δw/c) between the design and unit weight-calculated values of w/c were in the range ±0.030 for all but one mixture.

The direct comparison of the results from the proposed unit weight method with the results obtained from the microwave oven method for determining w/c revealed that the former is faster but less accurate. Specifically, when used on five separate concrete samples, the accuracy of the microwave oven method was 0.010, much smaller than the previously mentioned values of 0.030 for the ZAP and 0.054 for the AASHTO unit weight methods.

Implementation

The method of using the unit weight of concrete for the determination of w/c developed in this study provides a fast and inexpensive tool for quality control. Through the course of laboratory work, the accuracies of this method were found to be 0.030 and 0.054 when were applied to ZAP measured unit weights of non-air-entrained plain concretes and AASHTO measured unit weights of air-entrained ternary concretes.

It is recommended that the implementation part of this study involve further verification of the proposed approach using trial batches because for these batches, the target w/c values, along with the moisture content and specific gravities of aggregates, can be well controlled.

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LIST OF SYMBOLS

Note: The list of symbols given below includes only those symbols which have been developed in the course of the present research. Symbols developed by other researchers and included in this document for reference purposes are listed and explained directly in the corresponding section of the text and are, therefore, not included in this list.

Symbol

a = $\frac{V_a}{V}$ = theoretical (design) fraction of air in the unit volume of basic mix (CMD); expressed in decimals: i.e., $a = 0.065$

a' = measured fraction (expressed as decimal) of air in the unit volume of batched concrete

abs_{CA} = absorption value of coarse aggregate (decimals)

abs_{FA} = absorption value of fine aggregate (decimals)

A = empirical constant in Abram's law for w/c-compressive strength relationship

b = constant in the linear relationship of w/c-unit weight

B = empirical constant in Abram's law for w/c-compressive strength relationship

CA_{batch} = ratio of the weight of dry coarse aggregate in a given volume of concrete to the total weight of the same volume of fresh concrete as per CMD

CA_{sample} = ratio of the weight of dry aggregate extracted from concrete sample to the weight of wet concrete sample

CMD = Concrete Mix Design (basic mix)

f'c = 28 days compressive strength

MC_{CA} = moisture content of coarse aggregate

MC_{FA} = moisture content of fine aggregate

m = slope in the linear w/c-unit weight relationship

n = number of tests

SE = standard error

SG_{CA} = SSD specific gravity of coarse aggregate used in the basic mix design (CMD)

SG'_{CA} = SSD specific gravity of coarse aggregate in actual mix

SG_{ct} = specific gravity of cementitious material

SG_{FA} = SSD specific gravity of fine aggregate used in the basic mix design (CMD)

SG'_{FA} = SSD specific gravity of fine aggregate in actual mix

SG_w = specific gravity of water

UW = unit weight of batch of concrete made with aggregates with specific gravities equal to those used in the basic mix (CMD)

UW' = unit weight of batch of concrete made with aggregates with specific gravities different from those used in the basic mix (CMD)

UW_a = unit weight of concrete with " a " fraction (a%) of air

$UW_{a'}$ = measured unit weight of batched concrete with " a' " fraction (a'%) of air

UW_0 = unit weight of air-free concrete

UW_1 = unit weight of basic mix (CMD) with 6.5% air

UW_2 = adjusted unit weight of batched concrete

V = unit volume of basic mix (CMD)

V' = total volume of altered mix

V_a = volume of air in basic mix (CMD)

V_a' = volume of air in the batched mix

V_{ca} = volume of concrete with fraction of air of a

V_{ct} = volume of cement in basic mix (CMD)

V_{cmt} = volume of cementitious material in basic mix (CMD)

V_{CA} = volume of coarse aggregate in basic mix (CMD)

V_{CA}' = volume of coarse aggregate in the altered batch created by changing the specific gravity value of coarse aggregate of basic mix (CMD)

V_{FA} = volume of fine aggregate in basic mix (CMD)

V_{FA}' = volume of fine aggregate in the altered batch created by changing the specific gravity value of fine aggregate of basic mix (CMD)

V_w = volume of water in basic mix (CMD)

V_w' = volume of water in the altered batch (created by changing the amount of water in the basic mix (CMD))

V_0 = volume of air-free part of one unit volume of concrete

W = the weight of basic mix (CMD)

W' = the weight of altered mix

W_{cont} = weight of unit weight container

W_{ct} = weight of cement in the basic mix (CMD)

W_{cmt} = weight of cementitious materials in the basic mix (CMD)

W_{ct}" = cement content of altered batch created by changing the amount of water in the basic mix (CMD)

W_{fa} = weight of fly ash in the basic mix (CMD)

W_{fa}" = weight of fly ash in the altered batch (created by changing the amount of water in the basic mix (CMD))

W_{sf} = weight of silica fume in the basic mix (CMD)

W_{sf}" = weight of silica fume in the altered batch (created by changing the amount of water in the basic mix (CMD))

W_{CA} = SSD weight of coarse aggregate in the basic mix (CMD)

W_{CA}" = SSD weight of coarse aggregate in the altered batch (created by changing the amount of water in the basic mix (CMD))

$W_{CAactual}$ = weight of coarse aggregate in the mixture in actual moisture condition

W_{CAdry} = weight of coarse aggregate in the mixture in dry condition

W_{CASSD} = weight of coarse aggregate in the mixture in SSD condition

W_{FA} = SSD weight of fine aggregate in the basic mix (CMD)

$W_{FAactual}$ = weight of fine aggregate in the mixture in actual moisture condition

W_{FA}" = SSD weight of fine aggregate in the altered batch (created by changing the amount of water in the basic mix (CMD))

W_{FAdry} = weight of fine aggregate in the mixture in dry condition

W_{FASSD} = weight of fine aggregate in the mixture in SSD condition

W_p = weight of glass plate

W_{sample} = weight of concrete sample

W_w = weight of water in the basic mix

W_w' = weight of total water in the altered batch (created by changing the amount of water in the basic mix (CMD))

W_{wadd} = weight of water added to fully fill up the space in the unit weight container not occupied by the concrete sample

$W_{watercont}$ = weight of water needed to fully fill up the unit weight container

W_{wFA} = the change in the amount of free water in the mixture due to actual moisture condition of fine aggregate with respect to SSD condition

W_{wCA} = the change in the amount of free water in the mixture due to actual moisture condition of coarse aggregate with respect to SSD condition

W_1 = gross weight of the unit weight container completely filled with water and covered with glass plate

W_2 = sum of the weights of unit weight container, concrete sample, and water added to fully fill up the space in unit weight container not occupied by the concrete sample

ρ_w = water density

ΔUW_1 = the value used to adjust the measured unit weight of concrete made from aggregates with specific gravities different from those used in the basic mix

$\Delta w/c$ = the difference between the determined and the batched w/c

ΔW_w = weight of water added to the basic mix (CMD)

ΔV_w = volume of water added to the basic mix (CMD)

Φ = arcus tangent of m (degree)

CHAPTER 1. INTRODUCTION

Concrete, as one of the most widely used construction materials, is very durable and can provide long service life without extensive maintenance. The strength and durability of concrete are primarily functions of its water-cementitious material ratio value (w/cm). This ratio is the mass of water divided by the total mass of cementitious material, which is the sum of the masses of Portland cement (or blended cement) and any additional pozzolanic material such as fly ash, slag, silica fume or natural pozzolans (Neville, 1996).

Although it is a common practice to account for absorption and actual moisture content of aggregates (as well as for the amount of water added to the batch) when reporting the w/c value of fresh concrete during the trial batches, this information is often not tracked during the actual production of field concrete. As a result, the possibility will always exist that the actual w/c of the field mixture will be different from the design (target) w/c value. This difference can occur for three reasons. First, additional water may be purposely added to the mixture prior to the concreting operation to increase the ease of placement and finishing. Second, the water-cement ratio can also change due to the use of aggregates that have absorption values which do not match those used to develop the proportions of the basic mix (the use of aggregates that have lower absorption values will result in a higher w/c value in the batch and vice versa). Finally, the differences in w/c can arise from variability in moisture content of aggregates in the stockpiles.

The use of w/c lower than that specified in mix design will result in stronger but more brittle concrete, which may also be difficult to place and finish. Similarly, the use of w/c higher than specified will result in concrete that is less strong and less durable. The reason that w/c has such a strong influence on concrete's strength and durability is directly linked to the fact that its value strongly influences the volume and the characteristics of capillary porosity, both of which directly control strength and durability. Since w/c plays such a crucial role in controlling concrete quality, there has always been a need for a tool or procedure that can verify the actual w/c value of concrete immediately prior to placement.

Currently, there is no standardized technique for determination of w/c in fresh concrete. The three standard test procedures that have been historically used to obtain either water and/or cement content of fresh concrete (both of which are needed for w/c calculations) include the following: ASTM C 1078, which is the standard test method for determining the cement content of freshly mixed concrete (ASTM, 1992a), ASTM C 1079, which is the standard test method for determining the water content of freshly mixed concrete (ASTM, 1992b), and AASHTO T 318, which is the standard test method for water content of freshly mixed concrete using microwave oven drying (AASHTO, 2002). Since both ASTM standards C 1078 (ASTM, 1992a) and C 1079 (ASTM, 1992b) have been discontinued in 1998, the only standard currently available for determination of water content in fresh concrete is the AASHTO T 318 (microwave oven) method (AASHTO, 2002). Since the modern ready mix plants can typically accurately control the amount of cement in the batch, the knowledge of microwave oven determined water content will allow for calculation of w/c after being corrected for the amount of water absorbed by the aggregates (Nantung, 1998).

However, the use of microwave oven technique requires purchase of the oven itself, as well as determination of the aggregate correction factor (ACF) as further described in Section 2.2.1. Therefore, the focus of the present study is an exploration of the feasibility of using unit weight, which is already commonly measured as a part of the quality assurance (QA) programs, for determination of w/c values of field concretes.

1.1. Problem Statements

As the part of their quality control process (QCP), the Indiana Department of Transportation (INDOT) uses unit weight to control the w/c of structural field concrete at the point of placement. This is done by ensuring that the measured unit weight of fresh concrete does not differ by more than ± 1.0 lb/ft^3 from the predicted value (based on the measured air content) and that it remains above the threshold limit representing the allowable maximum water to cement ratio at the point of placement (ITM 803-08P, 2008). While this practice represents a useful quality assurance (QA) tool by ensuring that the w/c of field concrete is on the target and below the permissible maximum w/c, it does not allow for the determination of actual value of w/c.

In the present study, the application of unit weight as a prospective tool for determination of actual w/c of concrete was explored. This approach was based on the assumption that the unit weight (UW) can be easily measured in the field and that the correlation between the unit weight and w/c can be developed without extensive calibration. Furthermore, an extensive literature search did not reveal any systematic efforts focused on the implementation of fresh concrete unit weight for w/c determination.

1.2. Hypothesis

It is hypothesized that a relationship can be established between the unit weight of fresh concrete (at a given air content) and the water-cement ratio value, and that this relationship can be used as a field-oriented tool for w/c determination.

1.3. Research Objective and Scope

The objective of the current research was to further develop the application of the unit weight of fresh concrete for w/c determination purposes. The laboratory and field verifications of the developed technique were performed. Literature relevant to the influence of w/c on concrete properties and the methods for w/c determination were reviewed extensively. Based on the information found as a result of the literature review, the microwave oven technique was included in the laboratory work to verify its accuracy as reported in the previous study. Finally, a direct comparison of the relative accuracy of the microwave oven technique and the unit weight based technique for w/c determination was performed.

1.4. Organization of the Report

The presentation of the results of this research has been divided into several chapters. Chapter 1 provides a brief summary of the background information, the hypothesis, and the objective and scope of the current study. Chapter 2 summarizes the findings of the literature review on the influence of w/c on concrete properties and examines the existing methods for w/c determination.

Chapter 3 provides a description of the materials used in this study. Chapter 4 describes the development of unit weight technique as a field-oriented tool to determine the w/c value.

Chapters 5 and 6, respectively, report on the results of the laboratory and field verifications of the proposed technique for w/c determination. Chapter 7 presents the results of w/c determination using microwave oven technique and compares this method with the unit weight based technique developed in the course of the present study.

Chapter 8 contains the conclusion of the current study and the recommendation for future research needs.

CHAPTER 2. LITERATURE REVIEW

Water-cement (w/c) ratio determination can be thought of as a testing technique which can be performed either on fresh or on hardened concrete with the objective to obtain the actual w/c value; it is used especially for quality control and quality assurance purposes. Of the many factors influencing strength and concrete durability, water-cement ratio is the most critical. Because of this, a number of techniques have been developed to ensure that the actual w/c of field concrete does not significantly differ from that of the original concrete mix design (CMD) given in the job specifications.

The methods for w/c determination in fresh concrete, along with several criteria regarding their accuracy, simplicity, rapidity and cost have been proposed in some previous research. According to Naik and Ramme (Naik and Ramme, 1989), the ideal method must be accurate (can predict w/c with ±5% error from the actual value), fast (less than 15 minutes), simple to perform, inexpensive, applicable to all types of concretes, and field-worthy. Later, in 1990, NCHRP Project 10-25A titled "Instantaneous Determination of Water-Cement Ratio in Fresh Concrete" focused on developing a method for measuring the w/c value that could form a basis for an acceptance test at the job site (Hime et al., 1990). The proposed requirements for the test method considered in this project were as follows: the result should be obtainable within 2 minutes or less, the accuracy should be within 0.02, the equipment should be relatively inexpensive (under $5,000), and the instrument should be convenient, versatile, and simple. More recently, in 2002, the requirement for the test to give results with a standard error that does not exceed 0.02 was re-confirmed by a panel made up of staff from the Wisconsin department of Transportation (WISDOT) and industry experts. The panel felt that the higher value of error would lead to uncertainty in w/c determination and would not be considered an improvement on the current available acceptance techniques (Dowell and Cramer, 2002).

In addition to the development of techniques for w/c determination in fresh concrete, the studies were also performed to develop the test methods that will allow for w/c determination in hardened concrete. However, several researchers and practitioners observed that the determination of w/c in hardened concrete is not as necessary as the determination of w/c in fresh concrete since it does not allow for control of concrete properties at the time of placement. Neville (1973) stated that it is preferable to determine the composition of fresh concrete and that the test on hardened concrete is unnecessary if the composition of fresh concrete meets the specifications. In 2003, he re-affirmed that statement using stronger terms (Neville, 2003). Mather (1976) suggested that the composition of any concrete batch should be known before the concrete is discharged from the concrete mixer. A similar statement has been made by Williamson (1985). Although the methods to determine w/c in hardened concrete do exist, their use is more appropriate for forensic purposes rather than for quality control or quality assurance purposes.

2.1. Influence of Water-Cement Ratio on Concrete Properties

In this subsection, the influence of w/c on the workability and unit weight of fresh concrete and on the strength and durability of hardened concrete will be reviewed.

The most critical property of fresh concrete with respect to placement is its workability. The workability is defined as the property that determines the ease and homogeneity of fresh concrete for being mixed, placed, consolidated, and finished (ACI 116R-90). For a given fine to coarse aggregates ratio, the higher the w/c, the higher the workability of the concrete (Neville, 1996).

The unit weight of concrete is affected by the cement content, air content, slump, aggregate grading, and specific gravities of the constituents (Popovics, 1964). In 1974, Popovics proposed an expression (Equation 2.1) that correlates the w/c and unit weight of concrete (Popovics, 1974).

$$U = 0.037 \cdot c \cdot \left[1 + SG_{agg} \left(16.85 \cdot (100 - v) \big/ c - w \big/ c - 0.32 \right) + w \big/ c \right] \quad (2.1)$$

Where,

U = unit weight of the fresh concrete (lb/ft^3)

c = cement content (lb/yd^3)

w = water content (lb/yd^3)

SG_{agg} = weighted average specific gravity (dry basis) of the aggregates

v = air content of fresh concrete (%)

In this equation, the specific gravity of cementitious material is assumed to be 3.15 and the specific gravity of aggregate is the weighted average value of both coarse and fine aggregates. This equation was derived by keeping the weight of aggregate constant in a given and constant volume of concrete while changing the amount of water and monitoring the resulting changes in the unit weight.

The relationship between the w/c and compressive strength of concrete was established for the first time by Duff Abrams in 1918 at the Lewis Institute, which is now Illinois Institute of Technology (Mehta and Monteiro, 2006). This relationship is given by Equation 2.2.

$$f'_c = \frac{A}{B^{w/c}} \qquad (2.2)$$

Where,

f'_c = compressive strength of concrete

A = empirical constant

B = empirical constant

Figure 2.1 shows the typical curves illustrating the correlation between w/c and compressive strength as a function of age.

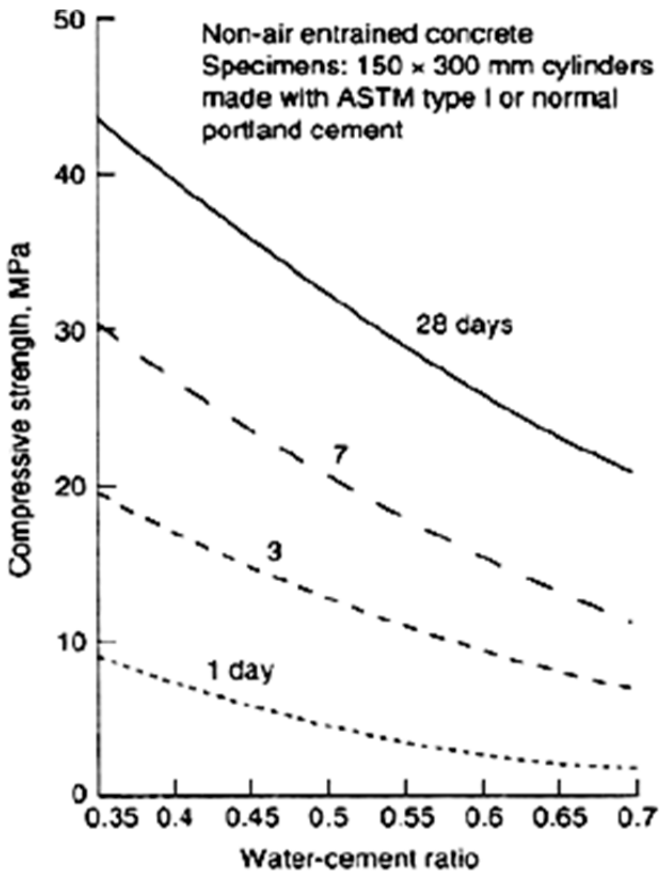


Figure 2.1 Typical w/c-compressive strength at different ages (Mehta and Monteiro, 2006)

Another set of properties which are greatly influenced by the w/c value are concrete transport properties and durability. It is generally accepted that at a certain level of hydration, concrete with a higher w/c value will be more susceptible to freezing and thawing because it contains larger pores and the water that resides in larger pores freezes more easily (Mehta and Monteiro, 2006). In order to ensure adequate freeze-thaw resistance, the concrete should have a relatively low w/c and air entrained (Fig 2.2). The ACI 318-05 document requires that normal weight concrete subject to freezing and thawing in a moist condition should have a maximum water-cement ratio of 0.45.

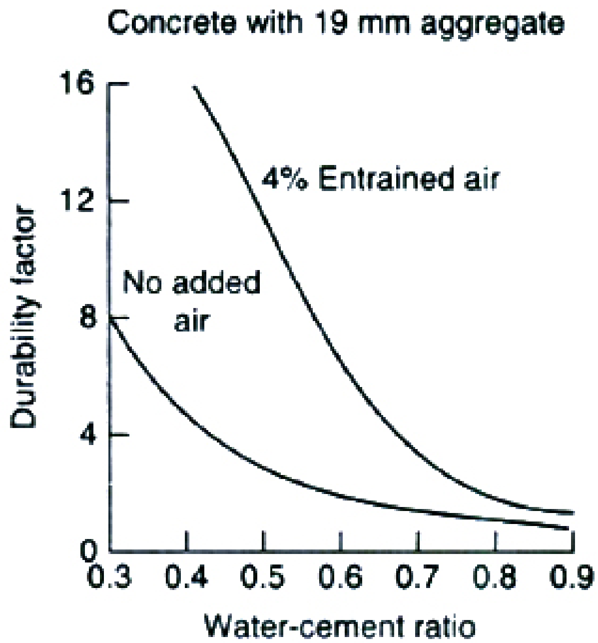


Figure 2.2 Influence of water-cement ratio on durability of concrete to frost action (Mehta and Monteiro, 2006)

Concrete resistivity is influenced by how easily the ions can move between two electrodes separated by a certain length of concrete. Resistivity has been proposed as a tool to access transport properties (Nokken and Hooton, 2006). Within concrete, ions can more easily move through the capillary pores of cement paste, which is more porous when compared to the aggregates. The amount and size of the capillary pores in the cement paste within the concrete are directly proportional to the w/c value. Figure 2.3 illustrates that at any value of w/c, the lower the cement content, the higher the resistivity. This is because concrete with lower cement content contains a lower amount of cement paste. Furthermore, Figure 2.3 also shows that in terms of cement content, the lowering of w/c results in an increased resistivity. Even though Figure 2.3 shows the correlation between w/c and resistivity, it should be realized that this correlation will only be valid for a given set of temperature and the degree of hydration of concrete. The temperature and degree of hydration are two of the three factors influencing resistivity as stated by Nokken and Hooton in 2006. The third factor they mentioned was admixtures.

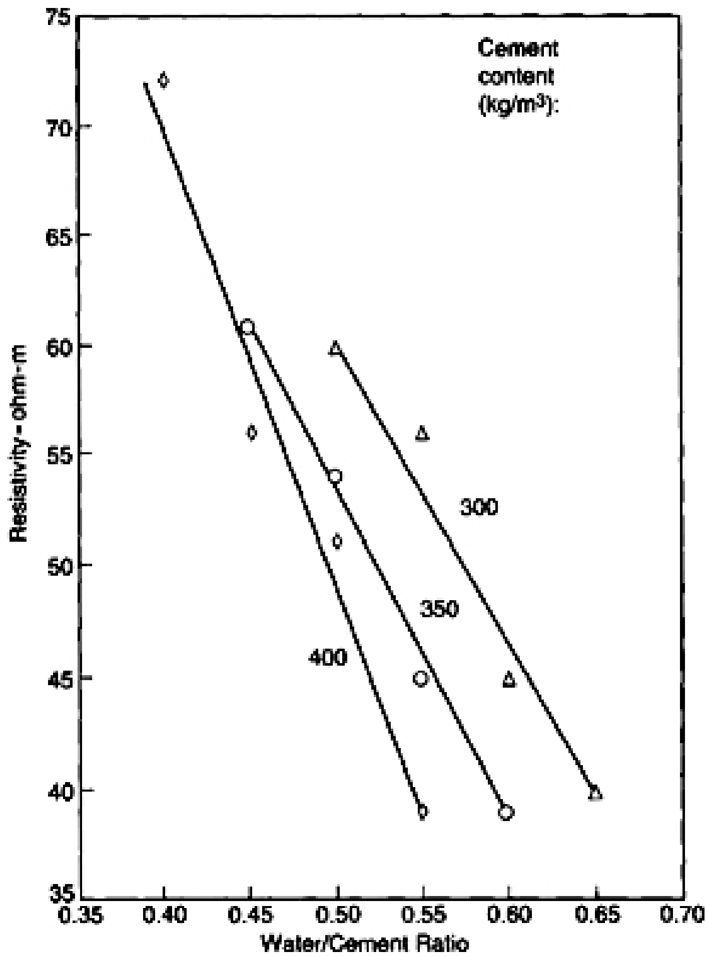


Figure 2.3 Relationship between electrical resistivity and water-cement ratio for concrete with a maximum size of aggregate of 40 mm (1½ in.) made with ordinary (Type I) Portland cement, tested at the age of 28 days (Neville, 1996)

Drying shrinkage of concrete is mostly influenced by the amount of evaporable water within the microstructure. When the amount of aggregates is kept constant, the larger w/c values will result in higher shrinkage, as is shown in Figure 2.4. This occurs because the higher the w/c, the larger the amount of evaporable water.

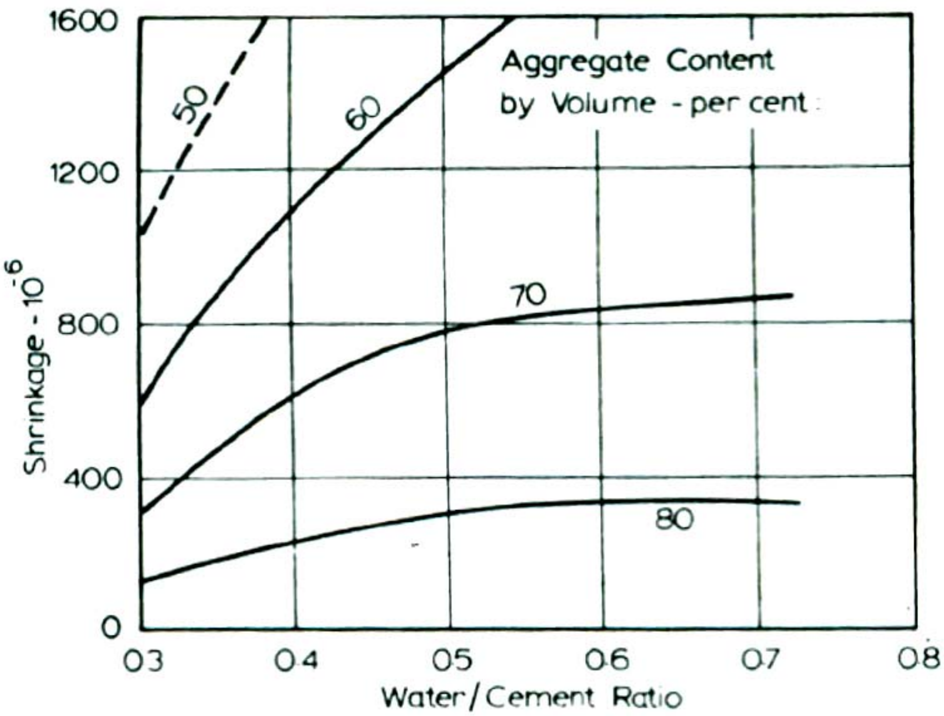


Figure 2.4 Influence of w/c and aggregates content on shrinkage (Neville, 1996)

2.2. Existing Techniques for Water-Cement Ratio Determination

Several techniques for the determination of w/c in both fresh and hardened concrete are available in the literatures and selected ones will be discussed in this section.

2.2.1. *Techniques for Water-Cement Ratio Determination in Fresh Concrete*

According to Ramme (1980), the first reported work on determining the composition of fresh concrete was performed by Griesenauer in 1929. Later, various techniques were developed to ensure the appropriate proportions of concrete while it is in a plastic state. Most of these methods focused on developing a tool for water or cement contents determination.

Hime and Willis (1955) developed a method for cement content determination which employed a heavy liquid (acetylene tetra-bromide solution) to separate fine aggregate and cement. Because acetylene tetra-bromide solution has specific gravity between those of fine aggregate and cement, the aggregate would float in the heavy liquid solution whereas the cement will settle. In this method, the concrete sample of around four to five pounds is washed through a No. 30 mesh (0.0234 in.) wire basket by immersing the wire mesh basket in a container of water. The fine aggregate particles and cement which pass through the basket are then transferred to the pan for drying. Two identical samples of 25 grams each are collected from this dry material and placed in graduate centrifuge tubes. The tubes are next filled with the heavy liquid and rotated in a centrifuge for a prescribed period of time to separate cement and fine aggregate particles. Next, the volumes of cement are determined by reading the mark on the tube. The average of these two determined volumes is used to find the cement content per unit volume using a previously established calibration graph. The typical calibration graph for the Willis-Hime method is shown in Figure 2.5.

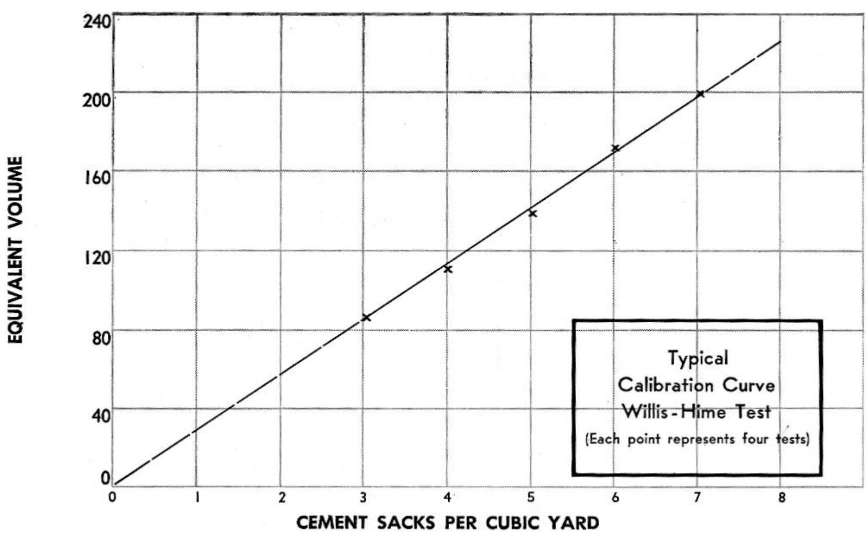


Figure 2.5 Typical calibration curve for Willis-Hime method

Williamson (1985) reintroduced three methods for water and cement content determinations which were originally developed in 1968 by Kelly and Vail 1968) and are sometimes referred to as KV techniques. The techniques reintroduced by Williamson were the third generation of the KV techniques and become known as the USA-CERL Concrete Quality Monitor (CQM), the Rapid Analysis Machine (RAM), and the Toni Flot.

In the CQM method, the cement and water content are related to the calcium and chloride concentrations respectively. Calcium content is obtained by a fluorometric determination, while the chloride content is obtained using a coulometric technique. Based on the evaluation by Head et al. (1983) and Williamson (1985), the first generation of the KV instruments was considered obsolete because the equipment was fragile (especially its flame photometer) and relatively difficult to operate under field conditions. The second generation was a more useful and accurate system that has been used for rapidly analyzing fresh concrete in the field, but it contained an excessive amount of glassware and was cumbersome for the operators. The third generation was developed by utilizing the EDTA titration process to replace the flame photometer for determining w/c, so the procedure became simpler. This third set of methods has been standardized as ASTM 1078 (ASTM, 1992a) and 1079 (ASTM, 1992b), and used to determine, the cement and water content of freshly mixed concrete respectively. By combining the results of these two tests, the water-cement ratio value of concrete could be calculated. However, both of these methods were discontinued in 1998.

RAM is the device used to measure cement contents by employing a wet screening procedure in which cement and aggregates are separated on a 150 µm (No. 100) screen. The separated cement particles are then gathered in a vessel with constant volume and are flocculated using a flocculating agent. The cement content of the original sample can be determined by reference to a previously established calibration graph. That calibration graph is developed by constructing the linear relationship between cement content of the samples and the weights of the constant volume vessel plus cement and water. When the design mix proportions contain particles of aggregates smaller than 150 µm, a correction line must be established because the constant volume vessel will also collect these particles, which increases the actual cement content of the sample. The only admixtures found to affect the calibration were the air entraining agents. Once the sample has been loaded into the instrument, the entire process runs automatically and can be finished in 15 minutes. The Rapid Analysis Machine (RAM) is available commercially and is covered by British Standard 1881, part 128 (BS 1881, 1997).

Flotation is a process that separates the components of dust-like mixtures. This process is widely used in the ore industry. The Toni Flot is the instrument used to separate the cement particles from aggregates by the flotation process. The cement particles are selectively made hydrophobic by using special agents called collectors, which cause them to float. Siliceous aggregates do not float by themselves, but the calcareous will. The calcareous aggregates will float because the collectors also made them hydrophobic. No influence of concrete admixtures, temperature, and age on the amount of cement floated can be detected, except for concrete with ages less than one minute. Below this age, the reaction of cement with water is so vigorous that the adsorption of the collector to the cement surface is disturbed, which results in an amount of cement floated that is less than the amount of concrete at ages above one minute. If the machine is calibrated with the individual cement, every cement type can be floated with an accuracy of at least ± 0.5%.

In 1978, Peterson and Leftwich developed the microwave oven method for the determination of water content in fresh concrete. This method has been standardized as AASHTO T 318 (AASHTO, 2002). This method has been modified several times, and the current version of the AASHTO standard reduced the testing time from 60 minutes to 15 minutes. The testing period of 15 minutes was first proposed by Ramme in 1980.By combining the information on water content obtained using this test with the known cement content information from the batch ticket, the w/c of fresh concrete can easily be determined (Naik and Ramme, 1987). Based on their study of twenty-four w/c determination tests, twenty-one tests resulted in the predicted w/c with less than 5% errors from the target value.

The microwave oven technique was found to be sufficiently reproducible to be used for field control purposes as it was independent of aggregate absorption and concrete consistency (Nagi and Whitting, 1994). Those researchers also found that the technique was applicable to latex-modified and silica-fume concretes. The total test time needed was 16 minutes and the result of water content obtained from two properly conducted tests by the same operator on the same material did not differ by more than ±7.6 lb/yd^3.

It was also found (Nantung, 1998) that neither the workability of the mix, nor the 25 minutes delay in the start of the test (with intermittent agitation every 5 minutes) influenced the amount of water removed from the mix by the microwave oven. When attempting to calculate the w/c of concrete using the water content as determined by the microwave over technique, Nantung (2008) observed that the variability in the amount of coarse aggregate present in the test sample of concrete caused by the relatively small (~1550 g) size of the sample could lead to underestimation of the measured water content. To correct this problem, Nantung (1998) modified the w/c calculation expression (Equation 2.3) previously proposed by the New Hampshire Department of Transportation (NMDOT) by introducing the coarse aggregate correction factor (CF) given in Equation 2.4 developed by the National Ready Mixed Concrete Association (NRMCA) (Hoover et al., 2008).

$$W/C = [(N+1)\times MD] - N\times[\{abs_{CA}\times(1-FA)\} + abs_{FA}\times FA] \qquad (2.3)$$

Where,

N = (total weight of dry aggregates)/(cement weight)

MD = (wet weight of the concrete sample – dry weight of the concrete sample)/(dry weight of the concrete sample)

FA = ratio of the weight of dry fine aggregate in a given volume of concrete to the total weight of dry aggregates of the same volume of fresh concrete

abs_{FA} = absorption value of fine aggregate (decimals)

abs_{CA} = absorption value of coarse aggregate (decimals)

$$CF = \frac{1-(CA_{batch})}{1-(CA_{sample})} \tag{2.4}$$

Where,

CA_{batch} = ratio of the weight of dry coarse aggregate in a given volume of concrete to the total weight of the same volume of fresh concrete

CA_{sample} = ratio of the weight of dry aggregate extracted from concrete sample to the weight of wet concrete sample

This modified expression is given below as Equation 2.5.

$$W/C = [(N+1)\times(MD\times CF)] - N\times[\{ACA\times(1-FA)\} + AFA\times FA] \tag{2.5}$$

If the coarse aggregate contains particles smaller than 4.75 mm, the total amount of coarse aggregate should be adjusted by subtracting the weight of that part of the coarse aggregate that is smaller than 4.75 mm and adding the weight of the fine aggregate (Nantung, 2008).

Minnesota DOT uses a different correction factor to adjust the errors in the amount of total water in the sample obtained from the microwave test that were due to the small sample size. The expression of this correction factor is given below as Equation 2.6.

$$CF' = \frac{1-\left(\%\ \ solid\ \ particles\ \ smaller\ \ than\ \ 4.75mm\ \left(No.4\right)\ \ in\ \ sample\right)}{1-\left(\%\ \ solid\ \ particles\ \ smaller\ \ than\ \ 4.75mm\ \left(No.4\right)\ \ in\ \ mix\ \ design\right)} \quad (2.6)$$

Santos (1999) reported that the standard error in w/c determination using the microwave oven technique was±0.02 for concrete with target w/c of 0.32 and 0.40 and ±0.04 for concrete with target w/c of 0.48 respectively. Dowell and Cramer (2002) reported that the standard error for the microwave test performed in the laboratory and the field were ±0.027 and ±0.037 respectively. Bescher et al. (2003) showed the applicability of the microwave oven technique to determine the w/c of freshly mixed rapid-setting calcium sulfoaluminate concrete. The laboratory results of their experiment showed that the microwave oven method was able to determine w/c with an accuracy of ±0.01. However, after the field verification, the authors suggested that an accuracy of ±0.05 would be more appropriate for the onsite acceptance process.

NRMCA proposed the use of the correlation between w/cm and water content as determined by the microwave oven technique to estimate w/cm at the point of discharge. The results of this test should estimate w/cm in the range of ±0.03 to ±0.05 from the actual value after the coarse aggregate correction factor (CF as is calculated using Equation 2.3) has been applied to the measured total water content.

Naik and Ramme (1989) reintroduced and modified Thaulow’s equation to determine w/c in fresh concrete. This equation was developed using the buoyancy principle (Archimedes’ Law). Equation 2.7 uses Thaulow’s original formula and it is only applicable to plain concrete. Equation 2.8 is the modified version of this formula and it is applicable to concrete containing pozzolanic material.

$$W/C = \frac{W_c}{W'_c}\left\|\left[\frac{\gamma_\alpha - 1}{\gamma_\alpha}\cdot B\right] + \left[\frac{\gamma_{ct} - 1}{\gamma_{ct}}\right]\right\| - \left(1 + B\right) \qquad (2.7)$$

$$W/C = \frac{W_c}{W'_c}\left\|\left[\frac{\gamma_\alpha - 1}{\gamma_\alpha}\cdot B\right] + \left[\frac{\gamma_{ct} - 1}{\gamma_{ct}}\right] + \left[\frac{\gamma_p - 1}{\gamma_p}\cdot C\right]\right\| - \left(1 + B + C\right) \qquad (2.8)$$

Where,

W_c = weight of the fresh concrete test sample in air

W'_c = calculated submerged weight of the fresh concrete test sample

γ_α = average (weighted) specific gravity of aggregates

γ_{ct} = specific gravity of cement

γ_p = specific gravity of pozzolan

B = aggregate-to-cement ratio by weight

C = the pozzolan-to-cement ratio by weight

The Indiana Test Method 803 (ITM 803-08P, 2008) specifies the use of unit weight to control the w/c of concrete as part of the quality control process (QCP) for structural concrete at the point of placement. This is done by ensuring that the difference between the predicted unit weight (UW) of fresh concrete (based on concrete mix design (CMD)) and the measured unit weight of fresh concrete (based on measured air content) is not greater than ± 1.0 lb/ft³ (16 kg/m³). The CMD is the theoretical basic mix design that utilizes the absolute volume approach in determining the quantities of individual components and assumes that aggregates are in the saturated surface dry (SSD) condition. The procedure specified in ITM 803 also ensures that the actual UW of concrete is above the threshold unit weight corresponding to a water-cementitious ratio of 0.420 at the point of placement. The practice recommended in ITM 803 is only used to ensure that the w/c of field concrete is on target and not below the permissible w/cm of 0.42; it does not allow for the determination of the actual w/cm value. In order to determine the actual w/cm, INDOT uses the ITM 403 method (ITM 403-08P, 2008). This method requires the determination of moisture content of the representative sample of fine and coarse aggregate as well as the obtainment of the information on the absorption from CMD and several additional parameters regarding mixture composition from the batch ticket representative of the concrete tested (weight of wet aggregate in the batch, total water added to the batch, weight of cement in the batch and total weight of pozzolans in the batch). All of the above information is then used to calculate the water-cementitious ratio of the mix as shown in Appendix C.

In addition to the direct methods of w/c determination described above, several indirect methods were also attempted by various researchers. Most of those methods involved development of the w/c "probe" and included approaches utilizing such technologies as specific ion electrodes, nuclear gages, microwave sensors and time domain reflectometry (TDR) sensors.

During the course of NCHRP Project 10-25A (Hime et al., 1990), an extensive literature search was made to find the probes that could be used to determine the w/c of fresh concrete. As a result of this literature study, the ion-selective electrode technique was identified as capable of determining the w/c of the fresh concrete. As the heart of the proposed approach was the assumption that the ion-selective electrodes would accurately determine the concentration of water-soluble components of the Portland cement in the pore solution and that these concentrations could be linked to the actual w/c value of the fresh concrete after proper calibration of the equipment. Commercial grade sodium and potassium ion sensitive electrodes were buried in a sample (water + cement) system and the measured ion concentrations were successfully used to determine the w/c after development of suitable calibration curves. However, it was also found that in addition to the w/c value, the concentrations of sodium and potassium ions varied with time and source of cement. In addition, once the system to be measured become more complex, e.g., upon introduction of aggregates or when measurements were performed over a longer period of time, the electrode readings became difficult to reproduce, mostly due to the change in the solubility rates of sodium and potassium ions and the loss of mix water due to the hydration process. Although new prototype electrodes were manufactured in an attempt to resolve these complications, this also failed to produce successful results and the study on the use of specific ion electrodes for w/c determination was formally abandoned.

More recently, a few studies have been conducted on the use of nuclear gage for w/c determination. The actual instrument consists of two separate probes, one for the determination of cement and the other for determination of water.

The test period is short, requiring approximately ten minutes per sample, including the consolidation of concrete into a test bucket. The effects of air content, pozzolans, hold time, coarse aggregate content, and temperature on the response of the gages have been studied by Whitting and Nagi (1999). The laboratory part of their study confirmed that the gages were indeed sensitive to the above factors, and demonstrated the capability of this technique to determine the cement and water content within approximately 10 to 20 lb/yd^3 and 2 to 4 lb/yd^3, respectively. However, two subsequent field investigations showed much larger errors for both sensors. Another study on the application of this method to both laboratory and field concrete has been performed in 2003 by Dowell and Cramer. For laboratory concrete, the discrepancy between the actual value of w/c and the predicted value of w/c based on measurements has been reported to be within ± 0.01 for concrete mixtures containing limestone aggregates and slightly larger for concretes containing igneous aggregates. Higher errors have been reported for the field concrete and were partially attributed to batching and sampling variations.

In another attempt, Mubarak and his co-workers (2001) explored the use of the monopole antenna probe for w/c determination via microwave technology. Based on the initial optimization study, the authors selected the 15 mm long monopole probe operating at the output frequency of 3 GHz. According to the results obtained from this optimization, the dc voltage of the output of the probe can be linearly correlated with w/c value. The reported accuracy of this technique in predicting the actual w/c of mixes with relatively wide ranges of aggregate-cement ratios was ± 0.01.

Time domain reflectometry (TDR) was initially the technique used to check the quality of transmission cables. In civil engineering, the advanced theory of TDR has been developed for moisture monitoring in soils. By adopting some of the theories from soil science to concrete, Yu et al. (2004) evaluated the potential applicability of the TDR technique for determination of water content in fresh concrete. The results of water content measurements were then combined with the information on cement content obtained from the batch ticket to determine the w/c value. The technique was tested on concretes and the reported discrepancies between predicted and target w/c values were found to be 0.1 and 0.4, respectively.

The use of ultrasonic technique for w/c determination was attempted by Popovics and Popovics (1998). The results were not very successful but the authors indicated that the technique can perhaps be improved by using the accelerating admixture and allowing for direct contact of the transducers with the concrete sample.

Hossain et al. (1996) used a turbidimeter to correlate w/c and NTU (nephelometric turbidity units) at a certain time after mixing. Turbidity is a measure of the extent to which light is either absorbed or scattered by the suspended particles in water. The reading from the turbidimeter was influenced by the use of an air entraining agent but this interference could be neutralized by an air detraining agent. The effects of other factors, such as the presence of water reducing admixtures, superplasticizers and fine (passing through 150 μm sieve) particles, were negligible. The measured w/c ratio was predicted to have an accuracy of ± 0.01 in the laboratory for a single test at a 90 percent confidence level.

Finally, although not applied for w/c determination, the infrared technique was successfully used to evaluate the influence of w/c on the analyte band (Melhem, 1999).

2.2.2. *Techniques for Water-Cement Ratio Determination in Hardened Concrete*

Most techniques used to identify w/c in hardened concrete require preparation of reference standards for a range of mixes with specific ingredients and a known curing history. One of these techniques is optical fluorescence microscopy. This method requires vacuum impregnation of concrete using a yellow fluorescent epoxy. The amount of fluorescent dye entering the cement paste depends on the capillary porosity, which is determined by the w/c and the degree of hydration. By placing a special set of filters in the optical path of the microscope, the amount of fluorescent epoxy presented in the cement can be determined by measuring the intensity of the light passing through the sample. Since the amount of epoxy in the sample is a function of capillary porosity (and hence w/c value), this method allows for direct w/c determination after calibration. The optical fluorescence microscope technique is covered by the NT Built 361 standard (NT Build 361, 1999) and has been used as a quality control tool as well as for forensic evaluation of deteriorated concrete (Jakobsen et al., 2000 and 2006).

In addition to the above fluorescence microscope technique, various other methods have been proposed for w/c determination in hardened concrete. These include such techniques as absorption of a water drop on a concrete surface and the resistance of cement paste to scratching (Liu and Khan, 2000). Besides these methods, Philippidis and Aggelis (2003) conducted a series of experiments to determine the w/c values in hardened concrete at a number of ages (starting from two days up to ninety days) using an acousto-ultrasonic approach. Furthermore, Bois et al. (1998) showed the potential of testing the near-field microwave inspection for w/c determination. The proposed approach utilized the reflection properties of an open-ended rectangular waveguide probe which operated at the frequency of 5 GHz and 10 GHz.

Erlin and Campbell (2000) reported the potential of using the Knoop microhardness method (ASTM E 384) and the Rockwell microhardness method (ASTM E 18) for w/c ratio determination. In their trials, the microhardness values from these two methods showed a progressive non-linear change as the water-cement ratio varied. However, the curve obtained from the Rockwell microhardness allowed a better discrimination of the water-cement ratio than the Knoop method because it was more linear and had a greater slope. To obtain a more reliable value for w/c in hardened concrete, Liu and Khan (2000) suggested the use of more than one technique.

Finally, the NRMCA suggested using the relationship of compressive strength vs. w/c at a given amount of air content to estimate the w/c in hardened concrete. While the concrete specimen used for a compressive strength test does not have the air content equal to the value used to develop the relationship of compressive strength vs. w/c, it was recommended that the measured compressive strength should be adjusted by considering that 250 psi in the compression strength value is equivalent to a 1% change in the air content.

2.3. Summary and Conclusion

Several techniques are available in the literature for determination of w/c in both hardened and fresh concrete. A summary of the existing methods published to date are presented in Tables 2.1 and 2.2 containing fresh and hardened concrete, respectively. A similar table was published by Head et al. (1983). The main techniques tried for w/c determination in hardened concrete include fluorescent microscopy, acousto-ultrasonic method, near-field microwave method, and Knoop and Rockwell microhardness. The main techniques for w/c determination in fresh concrete are summarized in more detail below. While some of these techniques allow for the direct determination of w/c, most can be used to determine either the water content or the cement content.

1. The establishment of a correlation between certain characteristics of fresh concrete and w/c. Some of the test methods that belong to this category include ion selective electrode, nuclear gage, microwave sensor, ultrasonic, infrared, and turbidimeter.
2. The use of the buoyancy principle was originally proposed by Thaulow and later modified as shown in Equation 2.8. This equation allows for the determination of w/c of fresh concrete from known values of the specific gravities of all the ingredients, the ratio of aggregate to cement, and the weight of concrete in the air and under the water.
3. The measurement of water content in fresh concrete. Because the amount of cement used for concrete batching can be easily controlled in the modern ready mix plants, this information can be combined with the in-situ determined water content and used to obtain the w/c after being corrected for the amount of water absorbed by the aggregates (Nantung, 1998). Several methods for water content determination have been reported

including the USA-CERL Concrete Quality Monitor (CQM), microwave oven technique, and TDR. The methods that can be used to measure cement content of the batch are the USA-CERL Concrete Quality Monitor (CQM), Rapid Analysis Machine (RAM), nuclear cement content gage, and the Willis-Hime method. The USA-CERL Concrete Quality Monitor (CQM) can be used to measure water and cement content; ASTM C 1078 (ASTM, 1992a) and C 1079 (ASTM, 1992b) were based on these techniques.

Based on the current practice of using unit weight to control the w/c of concrete at the point of placement and considering the w/c-unit weight correlation developed by Popovics (1974), it appears that unit weight of concrete can also be potentially used for w/c determination. Therefore, the focus of the current study is on further development of the unit weight based method for w/c determination.

The w/c-unit weight correlation as expressed by Equation 2.1 was derived by considering the constant volume of concrete in which the weight of aggregates was also kept constant but the unit weight was varied by changing the amount of water (Popovics, 1974). Since the water's volume changes when it is added to concrete in the field, a relationship between the unit weight and w/c that accounts for this volume change will allow for more accurate determination of the actual w/c value. To be reasonably accurate, in addition to volume change, this relationship should also account for the following factors:

1. The use of aggregates with absorption values that are different from those used to develop the mix design.
2. The variability of moisture content of aggregates in the stockpile.
3. The changes in the unit weight related to the volume of air in the mixture.
4. The changes in the unit weight related to the specific gravities of aggregates in the mixture.

Because the w/c-unit weight correlation expressed in Equation 2.1 did not account for the above factors, it was not used in the current study and a new expression which did account for these variables was developed. During the laboratory work, the accuracy of this correlation was verified by creating groups of mixes with artificially altered values of w/c. These artificial alterations were created to represent the four previously mentioned factors that can cause the changes in the w/c and unit weight of field concrete.

Another promising technique for water-cement ratio determination appears to be the use of a microwave oven as previously proposed by Nantung (1998). Laboratory work will be performed during the course of the current study to confirm the accuracy of this technique.

Finally, the results of the w/c determination of the fresh concrete obtained using the unit weight and the microwave oven techniques will be compared.

Table 2.1 Summary of published techniques for fresh concrete w/c determination (Head et al, 1983) modified by the author

			Method intended for								
Method	Reported by	Date of report	Cement Content	Water Content	Water to Cement Ratio	Basis of Method	Advantages of Method	Disadvantages of Method	Result Affected by	The Highest Accuracy Claimed	Time Required for Analysis, min
CERL/KV U.S. Army	Kelly and Vail; P.A. Howdyshell Head et al. Williamson	1968 1974 1983 1985	yes	yes	yes	Mechanical; flocculation	▪ determines both water and cement content ▪ compact equipment suitable for field use ▪ insensitive to aggregate moisture and mix proportions	▪ calibration curve required ▪ fragile equipment ▪ requires AC current ▪ requires water supply	▪ calcareous aggregates: measures all calcium passing sieve No. 50 or 100 ▪ perceptibility of end point reaction	Cement content within about ± 28 lb/yd^3; Water content within about ± 0.24 gal/sack	15
Rapid analysis machine (RAM)	Cement and Concrete Association of Britain Head et al. Williamson	1974 1983 1985	yes	no	no	Mechanical; flocculation	▪ simple test procedure ▪ fully automatic equipment ▪ rugged equipment	▪ calibration curve required ▪ aggregate source and mix proportions should remain constant ▪ unit weights 350 lbs ▪ operated level floor ▪ 110 V AC supply required	▪ Cement particle larger than 0.006 in ▪ Silt smaller than 0.006 in ▪ Entrained air	Cement content ± 17 lb/yd^3 to 35 lb/yd^3	5 to 10
Nuclear water and cement content gage	Federal Highway Administration; Whitting and Nagi; Dowell and Cramer	1973 1999 2003	yes	yes	yes	Nuclear, gamma ray backscatter and absorption	▪ simple test procedure ▪ sample unaltered by test	▪ calibration curve required ▪ aggregate source and mix proportions should remain constant ▪ shipping regulations ▪ license requirements	▪ chemical compositions ▪ calcareous aggregates and other elements with atomic number > 20 ▪ dirty probe ▪ temperature	After calibration, the nuclear gage was able to determine w/cm with the accuracy of ± 0.01	10 to 15
Microwave oven	Peterson and Leftwich; Naik and Ramme; Nagi and Whitting; Nantung; Dowell and Crammer; Bescher et al.	1978 1987 1994 1998 2002 2003	no	yes	yes	Removed of water by heating	▪ simple test procedure	▪ must be tested within 1 hour after mixing ▪ total water content is determined ▪ AC current required	▪ Water lost to evaporation between mixing and start of test ▪ Admixtures that act as an evaporable liquid ▪ Melting of cement in oven ▪ Aggregate absorption	Water to cement ratio value within ± 0.01	± 15 minutes

Table 2.1 (*continued*)

			Method intended for								
Method	Reported by	Date of report	Cement Content	Water Content	Water to Cement Ratio	Basis of Method	Advantages of Method	Disadvantages of Method	Result Affected by	Reported Accuracy	Time Required for Analysis, min
Constant neutralization method	California Department of Transportation	1976	yes	no	no	Mechanical; chemical	▪ little equipment required for test ▪ multiple sample can be tested simultaneously ▪ low cost	▪ calibration curve required ▪ aggregate source and mix proportions should remain constant ▪ operator must maintain a neutral solution by adding acid at 1 minute intervals for 1 hour	▪ excess acid attacking ▪ calcareous aggregates	Cement content ± 24 lb/yd^3	90
Willis- Hime method	Hime and Willis	1955	yes	no	no	Mechanical; heavy liquid separation	▪ simple test procedure ▪ low cost	▪ calibration curve required ▪ cement source should remain constant ▪ lengthy test period (more than 1 hour) ▪ significant operator judgment required	▪ specific surface area of cement ▪ specific gravity of separating media ▪ centrifugal forces acting on the tube ▪ incomplete separation	Average error with type I cement was 13 lb/yd^3 with standard deviation of 20 lb/yd^3 and average error with type III cement was 21 lb/yd^3 with a standard deviation of 27 lb/yd^3	75
Ultrasonic	Popovics and Popovics	1998	no	no	yes	Ultrasonic wave transmission	Not reported	▪ not accurate for fresh concrete	▪ cement type ▪ size and type of aggregate ▪ air content ▪ time and process of hardening	Not reported	Not reported

Table 2.2 Summary of published techniques for hardened concrete water to cement ratio determination

Method	Reported by	Date of report	Basis of Method	Advantages of Method	Disadvantages of Method	Result Affected by	Reported Accuracy	Time Required for Analysis, min
Stereoscopic microscope techniques; thin sections impregnated with blue epoxy	Liu and Khan.	2000	Petrography	▪ economical ▪ easy to implement	▪ concrete maturity must be known ▪ sample preparation is complicated	▪ cement type ▪ impregnation process	Not reported	Not reported
Needle scratching	Liu and Khan.	2000	Concrete hardness	▪ easy to implement ▪ economical	▪ objective judgment ▪ concrete maturity must be known	▪ cement type ▪ needle used ▪ chosen investigated location	Not reported	Not reported
Absorption of water drop	Liu and Khan.	2000	Water absorption	▪ easy to implement ▪ economical	▪ calibration curve required ▪ sample preparation is complicated ▪ concrete maturity must be known	▪ cement type ▪ water purity ▪ the difference between relative humidity of sample and environment ▪ temperature	The correlation coefficient (R^2) of 0.96 of the relationship between absorption time and w/c was obtained	Not reported
Optical fluorescence microscopy; yellow fluorescent epoxy	Jakobsen et al.	2000 2006	Petrography	▪ economical ▪ easy to implement	▪ sample preparation is complicated ▪ concrete maturity must be known	▪ cement type ▪ impregnation process	Expected accuracy is about ± 0.02	Not reported
Microhardness	Erlin and Campbell	2000	Concrete hardness	▪ economical ▪ easy to implement	▪ concrete maturity must be known ▪ reflects the w/c at discrete points of the thin sections	▪ cement type	Not reported	Not reported
An acousto-ultrasonic	Philippidis and Aggelis	2003	Ultrasonic wave transmission	▪ economical ▪ easy to implement	▪ concrete maturity must be known	▪ air content ▪ type and size of aggregate	Not reported	Not reported

CHAPTER 3. MATERIALS AND MIXTURE PROPORTIONING

This chapter contains description of the properties of materials used during this research and information on the mixture proportioning of concretes.

3.1. Materials

This section provides details on the properties and types of materials used for making the concrete specimens.

3.1.1. *Cement*

All concrete mixes were prepared using ASTM C 150 Type I Portland cement manufactured by Buzzi Unicem USA in Greencastle, Indiana. The specific gravity of Portland cement was assumed to be 3.15.

3.1.2. *Aggregates*

Natural siliceous sand was used as fine aggregate in this study. The specific gravity and absorption value of fine aggregate have been obtained following the procedures in AASHTO T 84 (standard method of test for specific gravity and absorption of fine aggregate, (AASHTO, 2004a)) and are shown in Table 3.1. The sieve analysis of fine aggregate provided by the manufacturer satisfied gradation #23 in INDOT specifications as shown in Appendix A (the nominal maximum size of aggregate was 3/8 in.). This fine aggregate was obtained from Vulcan Materials Company (Switchers Plant).

Table 3.1 Absorption and specific gravity values (SSD) of fine aggregate

Aggregate	Absorption %	Specific Gravity (SSD)
Natural Siliceous Sand	1.7%	2.64

Three types of coarse aggregates (dolomite, limestone, and steel slag) were used in this study. The dolomite and limestone aggregates were obtained from Vulcan Materials Company (Monon Plant) and the steel slag aggregate was supplied by Brooks Construction Company, Inc.

(Auburn Plant). The specific gravity and absorption values of coarse aggregates have been obtained by following the procedure in AASHTO T 85, the standard method of testing for specific gravity and absorption of coarse aggregate (AASHTO, 2004b), and results are shown in Tables 3.2. Sieve analysis of coarse aggregates satisfied gradation #8 in INDOT specifications as shown in Appendix A (the nominal maximum size of aggregate was 1 in.). These sieve analysis data for dolomite and steel aggregates were obtained from the manufacturer. The sieve analysis of the limestone was defined by the author following AASHTO T 27 (AASHTO, 2006a).

Table 3.2 Absorption and specific gravity values (SSD) of coarse aggregates

Aggregate	Dolomite	Limestone	Steel Slag
Absorption %	1.3%	1.0%	1.7%
Specific Gravity (SSD)	2.69	2.72	3.57

3.2. <u>Mixture Proportions</u>

Two types of mixture proportions were used during the laboratory part of the study. The first type is called the basic mix design and the second type is called the altered mix design. The basic mix design is also referred to as the concrete mix design (CMD) to reflect the terminology used in INDOT's standard specifications (INDOT, 2008). The CMD have been previously defined in section 2.2.1 of this document. The altered mix represents the field concrete mix with proportions altered from those of the basic mix (CMD).

The mixture proportions of the basic mix are shown in Table 3.3. The fine and coarse aggregates specified for the basic mix are natural siliceous sand and dolomite, respectively. These proportions are similar to the proportion of class C concrete given in Section 700 of INDOT's specifications (INDOT, 2008). However, the amount of fine aggregate in the basic mix was 50% of the total weight of aggregate used, which is 5% higher than allowed in Section 702.05 of INDOT's specifications (INDOT, 2008). The other requirements for INDOT's class C concrete are as follows:

1. The minimum cement content is 658 lbs/yd^3.
2. The maximum water-cement ratio is 0.443.

Table 3.3 Mixture composition of basic mix (CMD)

Target air content =		6.5%	
w/c =		0.400	
Material	**Specific gravity**	**Weight lbs/yd^3**	**Volume ft^3**
Cement	3.15	658	3.36
Fine Aggregate, SSD	2.64 (SG_{FA})	1450 (W_{FA})	8.83
Coarse Aggregate, SSD	2.69 (SG_{CA})	1477 (W_{CA})	8.83
Water	1.00	263	4.23
Air	N/A	0	1.76
Total =		3849 lbs/yd^3 (UW_1)	27 ft^3

The altered mixes were created either by changing the amount of water in the basic mix, by assuming the aggregates were in SSD condition when they were not, by using the coarse aggregate with its specific gravity and absorption values that were different from those specified for basic mix, or a combination of one or more of these factors. A more detailed description of the mechanism used to alter the basic mixture composition listed in Table 3.3 to create concretes with varying values of w/c is provided in Section 5.1.1.2.

CHAPTER 4. ESTABLISHMENT OF THE PROCEDURE TO PREDICT W/C BASED ON THE MEASURED UNIT WEIGHT OF CONCRETE

This chapter provides the procedure of utilizing unit weight of fresh concrete for w/c determination. In order to use the unit weight for w/c determination, a theoretical (or model) relationship linking the unit weight and w/c has to be established first. The process of establishing the unit weight-w/c relationship was performed mathematically by changing the amount of water in the basic mix compositions while keeping the values of air content constant. Once this relationship was established, it was then used to predict water-cement ratio by measuring the unit weight of concrete and using it as an input to the model. The technique to establish this relationship is explained in more detail in Section 4.1.

In the field, the air content and the specific gravities of aggregates used to make concrete are very often different from those used in the development of the theoretical unit weight-w/c relationship. When such a situation occurs, the measured unit weight needs to be adjusted in such a way that the air content of the actual mixture and the specific gravities of aggregates in that mixture are equal to those used in the development of the unit weight-w/c relationship. The adjustment equation that corrects for the differences in air content is derived in Section 4.2. The adjustment equation that corrects for the differences in specific gravities of aggregates is derived in Section 4.3.

In addition to these two issues, the batching tolerances during the production of concrete can also lead to fluctuations in the actual amounts of ingredients in the mixture. Current INDOT specifications limit the batching variability to 1% (by weight) for cement, 2% (by weight) for aggregates, and 1% (by weight) for water with the respect to their target weights stated in concrete mix design (CMD). When the production variability occurs, the unit weight and w/c of the concrete mixture will also change. Because of these changes, there will be a difference between unit weight determined and target w/c. In order to find the 95th percentile of these differences, a Monte Carlo simulation was performed using 5000 trials. The results of this simulation are presented in Section 4.4.

Section 4.5 contains the summary of the steps required for the implementation of unit weight testing for w/c determination. Additionally, this section also addresses the issue of the impact of batching tolerances on the accuracy of w/c prediction using unit weight.

4.1. Development of the Unit Weight and Water-Cement Ratio Relationship

The theoretical correlation between w/c and unit weight was developed by changing the water amount in the basic mix (CMD) while keeping the values of air content constant. The basic mix design used in the current study was that previously shown in Table 3.3.

Figure 4.1 shows the component diagram of the basic mixture (System #1) and the modified component diagram resulting from the addition of extra water. This modified diagram is titled “System #2 (altered mixture)”. All aggregates used in Systems #1 and #2 are assumed to be in saturated surface dry (SSD) condition. The list of symbols used in Figure 4.1 is given in Table 4.1.

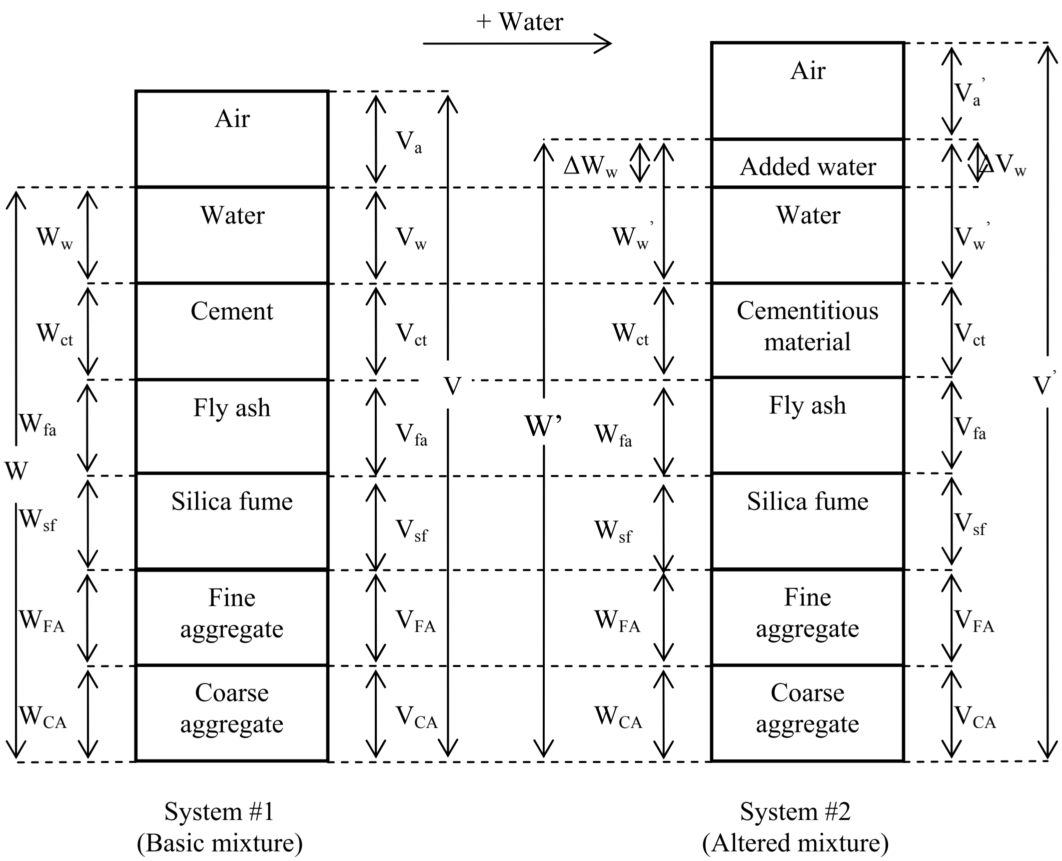


Figure 4.1 Batch component diagram before and after water addition

Table 4.1 List of symbols used in Figure 4.1

Material	System #1 (before water addition)		System #2 (after water addition)	
	Weight notation	Volume notation	Weight notation	Volume notation
Air	-	V_a	-	V_a'
Total water	W_w	V_w	W_w'	V_w'
Cement	W_{ct}	V_{ct}	W_{ct}	V_{ct}
Fly ash	W_{fa}	V_{fa}	W_{fa}	V_{fa}
Silica fume	W_{sf}	V_{sf}	W_{sf}	V_{sf}
Fine aggregate	W_{FA}	V_{FA}	W_{FA}	V_{FA}
Coarse aggregate	W_{CA}	V_{CA}	W_{CA}	V_{CA}
Amount of water added	-		ΔW_W	
Total batch weight	W	V_{fa}	W’	V_{fa}
Total batch volume	W_{sf}	V	W_{sf}	V’
Volume of air	$Va = a \cdot V$		$Va' = a \cdot V'$	
Unit weight	UW_1		UW_2	

Note: $W_{w'} = W_w + \Delta W_w$

The volume of the altered batch can be expressed mathematically by Equations 4.1 and 4.2 shown below.

$$V' = V - V_a + \Delta Vw + V_a' \qquad (4.1)$$

Systems #1 and #2 are designed to have a certain (and constant) air content "*a*" expressed as $a = \frac{V_a}{V} = \frac{V_a'}{V'}$.

$$V' = V - a \cdot V + \Delta Vw + a \cdot V' \qquad (4.2)$$

Since the amount of water added will most likely be recorded in weight rather than in volume, Equation 4.2 can be transformed into Equation 4.3, which can accommodate the weight of water.

$$V' = V \cdot (1-a) + \frac{\Delta W_w}{\rho_w} + a \cdot V' \qquad (4.3)$$

Where,

ΔW_w = weight of water added to the basic mix

ρ_w = water density

Equation 4.3 can be further rearranged to yield the volume of the altered (System #2) batch that contains the same decimal quantity of air, "a", as the basic mix. The individual steps in this rearrangement process are shown as Equations 4.4 and 4.5, with the final form given in Equation 4.6.

$$V' \cdot (1-a) = V \cdot (1-a) + \frac{\Delta W_w}{\rho_w} \qquad (4.4)$$

$$V' = \frac{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}}{(1-a)} \qquad (4.5)$$

$$V' = \frac{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}}{(1-a)} \qquad (4.6)$$

The next step is to obtain the weight of concrete ingredients per unit volume for the altered batch (System #2). In order to do so, the weight of each ingredient in this batch is divided by the volume of the altered batch, " V' " (see Equations 4.7 to 4.12). In these calculations, the original weight of water in the basic (System #1) batch (W_w) was increased by the amount of water added to the System #2 batch (ΔWw). The weight of water, cement, fly ash, silica fume, fine aggregate and coarse aggregate (all per unit volume of concrete) are respectively labeled as W_w", W_{ct}", W_{fa}", W_{sf}", W_{FA}", and W_{CA}". When added, the results of these calculations yield the unit weight of the altered (System #2) batch that contains " a " decimal quantity of air.

$$W_w'' = \frac{W_w'}{V'} = \frac{W_w + \Delta W_w}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \qquad (4.7)$$

$$W_{ct}'' = \frac{W_{ct}}{V'} = \frac{W_{ct}}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \qquad (4.8)$$

$$W_{fa}'' = \frac{W_{fa}}{V'} = \frac{W_{fa}}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \qquad (4.9)$$

$$W_{sf}'' = \frac{W_{sf}}{V'} = \frac{W_{sf}}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \qquad (4.10)$$

$$W_{FA}'' = \frac{W_{FA}}{V'} = \frac{W_{FA}}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \tag{4.11}$$

$$W_{CA}'' = \frac{W_{CA}}{V'} = \frac{W_{CA}}{V \cdot (1-a) + \frac{\Delta W_w}{\rho_w}} \cdot (1-a) \tag{4.12}$$

Even though Equations 4.7 through 4.12 were developed for the specific case in which water was added into the basic batch, all of these equations can also be used for a case in which the amount of water is withdrawn from the basic mixture by making ΔW_w negative instead of positive.

By using the basic mix design (from Table 3.3) and set of Equations 4.7 through 4.12, the compositions of five altered mixtures, each with different w/c values, were calculated and are shown in Table 4.2. The calculations shown in this table were performed assuming that all altered mixtures had constant air content a = 0.065 (or 6.5%). The compositions of the altered mixtures were numerically simulated by adding or subtracting a certain amount of water from the basic mixture. This process resulted in altered mixtures with either lower or higher w/c values when compared to the basic mixture, which had a w/c of 0.400.

The unit weights of the altered mixtures (UW_2) were obtained by adding the weight of individual ingredients calculated by Equations 4.7 through 4.12 as shown below (Equation 4.13):

$$UW_2 = W_w'' + W_{ct}'' + W_{fa}'' + W_{sf}'' + W_{FA}'' + W_{CA}'' \tag{4.13}$$

Table 4.2 Compositions of altered mixtures

Material	Specific gravity	Amount of air (a= 0.065)									
		Change in the amount of water (ΔW_w, lbs) with respect to the basic mix									
		-13		-7		0		7		13	
		w/c of altered mixture									
		0.38		0.389		0.4		0.411		0.42	
		Composition, volumes and unit weights of altered batches									
		Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3
Cement	3.15	663	0.125	661	0.125	658	0.124	655	0.124	653	0.123
Fine agg.	2.64	1462	0.33	1457	0.329	1450	0.327	1444	0.326	1438	0.324
Coarse agg.	2.69	1489	0.33	1484	0.329	1477	0.327	1470	0.326	1465	0.324
Water	1	252	0.15	257	0.153	263	0.157	269	0.16	274	0.163
Air	N/A	0	0.065	0	0.065	0	0.065	0	0.065	0	0.065
Sum		3867	1	3859	1	3849	1	3838	1	3830	1
Unit weight UW, (lbs/yd^3)		3867 (UW_2)		3859 (UW_2)		3849 (UW_1)		3838 (UW_2)		3830 (UW_2)	

To further illustrate these concepts, an example of calculation for mix with w/c of 0.389 is presented below.

$$W_w" = \frac{263+(-7)}{1\cdot(1-0.065)+\frac{(-7)}{62.27\cdot 27}}\cdot(1-0.065) = 257\,{}^{lbs}\!/\!{}_{yd^3}$$

$$V_w" = \frac{W_w"}{SG_w\cdot\rho_w} = \frac{257}{62.27} = 4.13\,ft^3 = 0.153\,yd^3$$

$$W_{ct}" = \frac{658}{1\cdot(1-0.065)+\frac{(-7)}{62.27\cdot 27}}\cdot(1-0.065) = 661\,{}^{lbs}\!/\!{}_{yd^3}$$

$$V_{ct}" = \frac{W_{ct}"}{SG_{ct}\cdot\rho_w} = \frac{661}{3.15\cdot 62.27} = 3.37\,ft^3 = 0.125\,yd^3$$

$$W_{FA}" = \frac{1450}{1\cdot(1-0.065)+\frac{(-7)}{62.27\cdot 27}}\cdot(1-0.065) = 1457\,{}^{lbs}\!/\!{}_{yd^3}$$

$$V_{FA}" = \frac{W_{FA}"}{SG_{FA} \cdot \rho_w} = \frac{1457}{2.64 \cdot 62.27} = 8.87\,ft^3 = 0.329\,yd^3$$

$$W_{CA}" = \frac{1477}{1 \cdot (1 - 0.065) + \frac{(-7)}{62.27 \cdot 27}} \cdot (1 - 0.065) = 1484\, {lbs}/{yd^3}$$

$$V_{CA}" = \frac{W_{CA}'}{SG_{CA} \cdot \rho_w} = \frac{257}{2.69 \cdot 62.27} = 8.87\,ft^3 = 0.329\,yd^3$$

$$V_a" = 0.065 \cdot 27 = 1.76\,ft^3 = 0.065\,yd^3$$

$$UW_{a\%}" = 257 + 661 + 1457 + 1484 = 3859\, {lbs}/{yd^3}$$

$$V" = V_w" + V_{ct}" + V_{FA}" + V_{CA}" + V_a" = 0.153 + 0.125 + 0.329 + 0.329 + 0.065 = 1.000\,yd^3$$

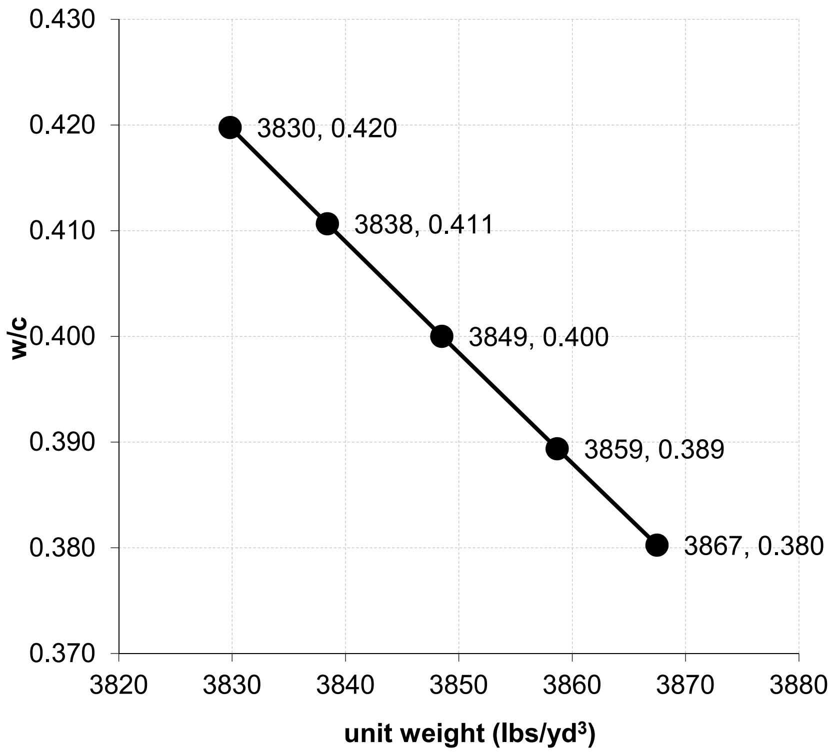


Figure 4.2 Theoretical w/c–unit weight correlation

$$W/C = -0.0010494 \cdot UW_2 + 4.439 \quad (4.14)$$

By utilizing the altered w/c and unit weights data from Table 4.2, the correlation between these two variables was established using linear regression analysis and is presented in Figure 4.2 and as Equation 4.14. The values of slope, intercept, and R^2 for this linear regression correlation were obtained utilizing the Microsoft Excel® library functions LINEST, INTERCEPT, and CORREL (squared), respectively. The copy of the Excel spreadsheet that was used to obtain Equation 4.14 is shown in Appendix B. It is important to note that the values of the slope of the regression line should be reported to seven decimal places and the values of the intercept should be reported to three decimal places. Analysis of the sensitivity of the predicted w/c values to the number of decimals indicated that using fewer decimals than suggested earlier leads to significant reduction in the accuracy of w/c determination. This analysis is shown in Table 4.3.

Table 4.3 Sensitivity of w/c determination to the number of decimals in slope and intercept terms of the regression line

Slope of Equation 4.14	Intercept of Equation 4.14	Parameters used to express the distribution of differences between the actual (based on the unit weight) and target (design) w/c		
		Absolute average of differences	Standard deviation of differences	95th percentile
-0.00104940531506432	4.43873992402826	0.014	0.009	0.030
-0.0010494053150643	4.4387399240283	0.014	0.009	0.030
-0.001049405315064	4.438739924028	0.014	0.009	0.030
-0.00104940531506	4.43873992403	0.014	0.009	0.030
-0.0010494053151	4.438739924	0.014	0.009	0.030
-0.001049405315	4.43873992	0.014	0.009	0.030
-0.00104940532	4.4387399	0.014	0.009	0.030
-0.0010494053	4.43874	0.014	0.009	0.030
-0.001049405	4.43874	0.014	0.009	0.030
-0.00104941	4.4387	0.014	0.009	0.030
-0.0010494	4.439	0.014	0.009	0.030
-0.001049	4.44	0.014	0.009	0.029
-0.00105	4.4	0.044	0.017	0.072
-0.0011	4	0.636	0.017	0.665

4.2. Adjustment of Measured Unit Weight to Account for the Differences between Target and Measured Air Contents

This section contains the derivation of the equation that can be used to adjust the measured unit weight to account for differences between target (used in development of unit weight-w/c relationship) and measured (actual) air contents. The process involves the following steps:

1. Development of the equation for the unit weight of the air-free part of unit volume of concrete with measured air content " a' ".
2. Entrainment of air into this air-free part until the resulting concrete acquires the same fraction of air as that used in the development of the w/c-unit weight relationship.
3. Development of the equation to calculate the unit weight of air-entrained concrete. This equation allows for the conversion of measured unit weight (with the actual air content) to the unit weight of concrete with target air content (the same as that used in development of the w/c-unit weight relationship).

Shown in Figure 4.3 is the component diagram of the unit volume of the concrete sample with measured air content " a' ", where $a' = \frac{V_{air1}}{1}$. The unit weight of this concrete is $UW_{a'}$. The part of this concrete without air is described as airless concrete. The air-free part of this occupies volume V_0 which can be calculated using Equation 4.15.

$$V_0 = (1 - a') \tag{4.15}$$

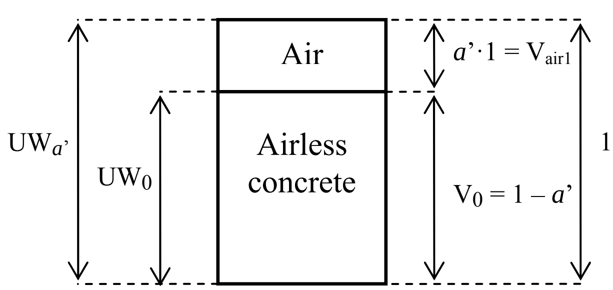


Figure 4.3 Component diagram of concrete containing measured air content of a'

The unit weight of this air-free concrete is designated as UW_0 and can be calculated using Equation 4.16.

$$UW_0 = \frac{UW_{a'}}{V_0} = \frac{UW_{a'}}{(1-a')} \qquad (4.16)$$

Where,

a' = measured fraction of air in the unit volume of concrete

$UW_{a'}$ = measured unit weight of concrete with a' air content

As explained earlier, the second step in the process of unit weight correction involves "infusing" the air free concrete with the same amount of air " a " as that used in the development of theoretical unit weight-w/c relationship.

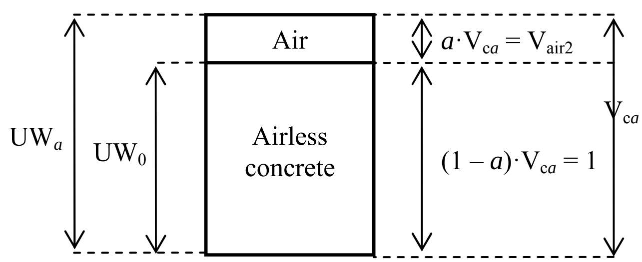


Figure 4.4 Component diagram of concrete containing a % of air content

Figure 4.4 shows the component diagram containing the unit weight of airless concrete equal to UW_0 and the " a " content of air. It should be note that the value of "a" is numerically equal to the air content in the CMD (target) value and can be calculated as $a = \frac{V_{air2}}{V_{ca}}$. Based on Figure 4.4, the volume of "air-infused" concrete can be calculated using Equation 4.17 and its unit weight (UW_a) can be calculated using Equation 4.18.

$$V_{ca} = \frac{1}{(1-a)} \qquad (4.17)$$

$$UW_a = \frac{UW_0}{V_{ca}} = \frac{UW_{a'}}{(1-a')} \times (1-a) \qquad (4.18)$$

Equation 4.18 can therefore be used to adjust the measured unit weight of concrete to allow for difference in CMD and actual air contents " a' ".

4.3. Adjustment of Measured Unit Weight to Account for the Difference between Target and Measured Specific Gravities of Aggregates

In addition to the air content of the actual concrete being different from the target used to develop the unit weight-w/c relationship, the specific gravities of aggregates (SG) used in that concrete can also be different from those used in CMD. When this happens, the measured unit weight which has already been corrected for differences in air content needs to be further corrected to account for SG differences. This correction was developed by changing the target specific gravities of aggregates in the basic mix (CMD), while keeping the values of air content constant.

The first step in the development of the SG correction equation is to examine how the unit weight of the basic mixture changes in response to the changes in the SG. This is accomplished by first illustrating the change in relative volumes of coarse and fine aggregates resulting from changes in their specific gravities. Figure 4.5 represents the basic mixture before SG changes were implemented (System #1) and altered mixture (System #2) after the SG change took place.

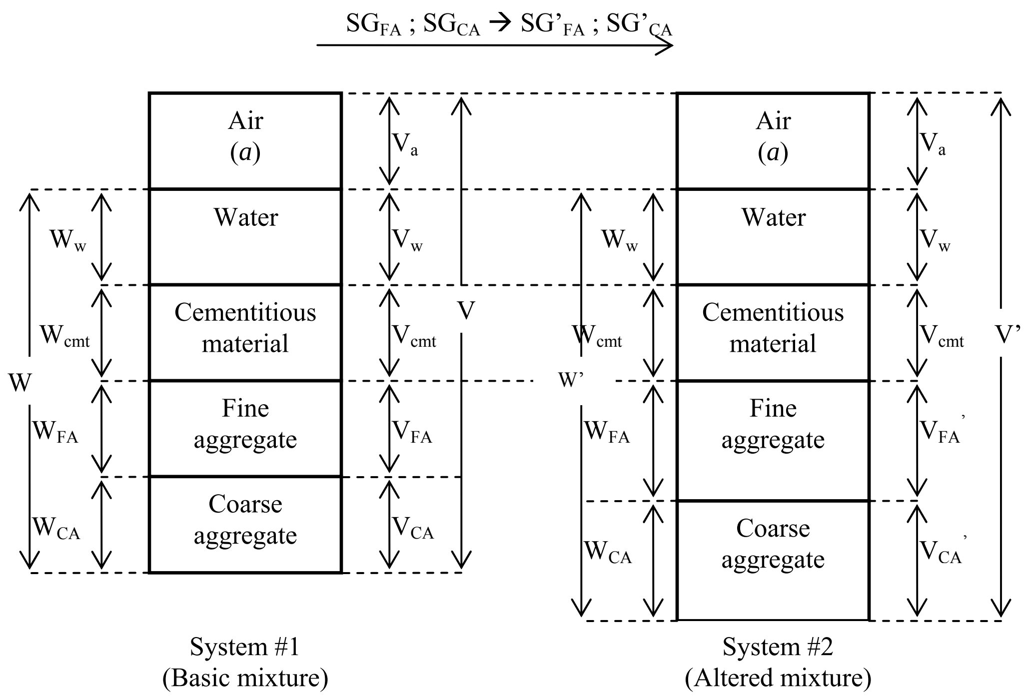


Figure 4.5 Component diagram of basic batch before and after changes in specific gravities of aggregates

While the specific gravities of aggregates in altered mixture (System #2) are different than those in System #1, their weights remain the same as in the basic mixture. This is a direct consequence of the fact that mixtures are batched on a weight basis. In other words, as shown in Equation 4.19, the weight of the original mixture (W) is going to be the same as the weight of the altered mixture (W').

$$W = W' = W_{FA} + W_{CA} + W_{cmt} + W_w \tag{4.19}$$

The total volume of System #1 (V) can be calculated using Equation 4.20. Since, as mentioned earlier, the mixtures are batched on a weight basis, it is desirable to express the volumes of fine and coarse aggregates in Equation 4.20 on a weight basis as well. This has been accomplished by rearranging the terms in Equation 4.20 as shown in Equations 4.21 and 4.22. Similar rearrangement of terms of Equation 4.23 is shown in Equations 4.24 and 4.25.

$$V = V_{FA} + V_{CA} + V_{cmt} + V_W + a \cdot V \tag{4.20}$$

$$V = \frac{V_{FA} + V_{CA} + V_{cmt} + V_W}{(1-a)} \tag{4.21}$$

$$V = \frac{\dfrac{W_{FA}}{SG_{FA} \cdot \rho_w} + \dfrac{W_{CA}}{SG_{CA} \cdot \rho_w} + (V_{cmt} + V_w)}{(1-a)} \tag{4.22}$$

$$V' = V'_{FA} + V'_{CA} + V_{cmt} + V_W + a \cdot V' \tag{4.23}$$

$$V' = \frac{V'_{FA} + V'_{CA} + V_{cmt} + V_W}{(1-a)} \tag{4.24}$$

$$V' = \frac{\dfrac{W_{FA}}{SG'_{FA} \cdot \rho_w} + \dfrac{W_{CA}}{SG'_{CA} \cdot \rho_w} + (V_{cmt} + V_w)}{(1-a)} \tag{4.25}$$

Where,

V = total volume of basic mixture (SG as per CMD)

V' = total volume of altered mixture (SG different than those in CMD)

V_{FA} and V_{CA} = volumes of fine and coarse aggregates, respectively, in System #1

V'_{FA} and V'_{CA} = volumes of fine and coarse aggregates, respectively, in System #1

V_{cmt} = volume of cementitious material in Systems #1 and #2

V_w = volume of water in Systems #1 and #2

SG_{CA} = SSD specific gravity of coarse aggregate in System #1

SG_{FA} = SSD specific gravity of fine aggregate in System #1

SG'_{FA} = SSD specific gravity of fine aggregate in System #2

SG'_{CA} = SSD specific gravity of coarse aggregate in System #2

a = air content of Systems #1 and #2 (is in decimal and equal to the value used for basic mix (Table 3.3))

ρ_w = density of water

Because the total volumes of water and cementitious material (V_{cmt}+V_w) in Equations 4.22 and 4.25 are equal, these two equations can be combined as shown in Equation 4.26.

$$V\cdot(1-a)-\frac{W_{FA}}{SG_{FA}\cdot\rho_w}-\frac{W_{CA}}{SG_{CA}\cdot\rho_w}=V'\cdot(1-a)-\frac{W_{FA}}{SG'_{FA}\cdot\rho_w}-\frac{W_{CA}}{SG'_{CA}\cdot\rho_w} \qquad (4.26)$$

In order to get the equation for the total volume of the modified mixture " V' " needed to determine its unit weight " UW' ", Equation 4.26 is further rearranged into Equation 4.27.

$$V'=\frac{V\cdot(1-a)+\frac{W_{FA}}{\rho_w}\cdot\left(\frac{1}{SG'_{FA}}-\frac{1}{SG_{FA}}\right)+\frac{W_{CA}}{\rho_w}\cdot\left(\frac{1}{SG'_{CA}}-\frac{1}{SG_{CA}}\right)}{(1-a)} \qquad (4.27)$$

The unit weight of System #2 (UW') is obtained by dividing " W' " by " V' ". Because " W' " is equal to " W ", then " UW' " can be expressed using Equation 4.28.

$$UW'=\frac{W'}{V'}=\frac{W\cdot(1-a)}{V\cdot(1-a)+\frac{W_{FA}}{\rho w}\cdot\left(\frac{1}{SG'_{FA}}-\frac{1}{SG_{FA}}\right)+\frac{W_{CA}}{\rho w}\cdot\left(\frac{1}{SG'_{CA}}-\frac{1}{SG_{CA}}\right)} \qquad (4.28)$$

The numerator and denominator of Equation 4.28 are then divided by " V " to obtain the expression of UW' in terms of the unit weight of the basic mixture (UW_1). This is shown in Equation 4.29.

$$UW'=\frac{\frac{W}{V}\cdot(1-a)}{\frac{V\cdot(1-a)+\frac{W_{FA}}{\rho w}\cdot\left(\frac{1}{SG'_{FA}}-\frac{1}{SG_{FA}}\right)+\frac{W_{CA}}{\rho w}\cdot\left(\frac{1}{SG'_{CA}}-\frac{1}{SG_{CA}}\right)}{V}} \qquad (4.29)$$

Assuming that System #1 represents unit volume, the value of " V " is equal to one and Equation 4.29 can be rewritten in the form of Equation 4.30.

$$UW' = \frac{UW_1 \cdot (1-a)}{(1-a) + \frac{W_{FA}}{\rho_w} \cdot \left(\frac{1}{SG'_{FA}} - \frac{1}{SG_{FA}} \right) + \frac{W_{CA}}{\rho_w} \cdot \left(\frac{1}{SG'_{CA}} - \frac{1}{SG_{CA}} \right)} \quad (4.30)$$

The next step in development of the SG correction equation is to analyze how the unit weight-w/c relationship changes as a result of changes in SG. This has been accomplished by developing five series of mixtures (each corresponding to a different w/c) and calculating how the unit weight within each of the series varies with changes in the SG values within each series; five different values of SG were considered. This approach allows for establishment of unique unit weight-w/c relationships; each corresponds to a given value of SG.

The five series of mixtures used in this analysis are the same ones which have been previously developed in Section 4.1 and are presented in Table 4.2. These five series of mixtures were originally developed using SG_{FA}=2.64 and SG_{CA}=2.69. When the specific gravities of aggregates of these five series of mixtures were changed to the randomly selected values as shown in Table 4.4, the values of the unit weights of these five series of mixtures were also altered. These altered unit weights can be calculated using Equation 4.30 and the results are shown in Table 4.4.

Table 4.4 Calculated unit weights of altered mixtures obtained from the basic mix (Table 4.2) by changing the values of SG

Air content	6.50%					
w/c value	**SG of the original mix (Table 4.2)**	**Randomly selected fine aggregate specific gravity**				
		2.55	2.6	2.61	2.75	2.8
	SG_{FA} = 2.64	**Randomly selected coarse aggregate specific gravity**				
	SG_{CA} = 2.69	2.55	2.6	2.79	2.75	2.8
	Unit weight of five series of mixtures, lbs/yd^3	**Unit weights of altered mixtures, lbs/yd^3**				
0.380	3867	3752	3804	3905	3957	4007
0.389	3859	3744	3796	3896	3948	3998
0.400	3849	3734	3786	3885	3937	3986
0.411	3838	3725	3776	3875	3926	3975
0.420	3830	3717	3768	3866	3917	3966

As an example, an application of Equation 4.30 to determine the altered unit weight of a basic mixture by changing the original specific gravity of fine and coarse aggregates to the same values of 2.60 is presented below:

$$UW' = \frac{3849 \cdot (1 - 0.065)}{(1 - 0.065) + \frac{1450}{62.27 \cdot 27} \cdot \left(\frac{1}{2.60} - \frac{1}{2.64} \right) + \frac{1477}{62.27 \cdot 27} \cdot \left(\frac{1}{2.60} - \frac{1}{2.69} \right)}$$

$$UW' = 3786 \,{}^{lbs}\!/_{yd^3}$$

In order to see how the unit weight-w/c relationship changes as a result of changes in the SG of aggregates, the unit weight-w/c relationship for each pair (fine and coarse aggregates) shown in Table 4.4 has been developed using linear regression routines of Microsoft Excel®. The lines representing these relationships are plotted in Figure 4.6, whereas Table 4.5 lists the numerical values of slopes and intercepts for these lines.

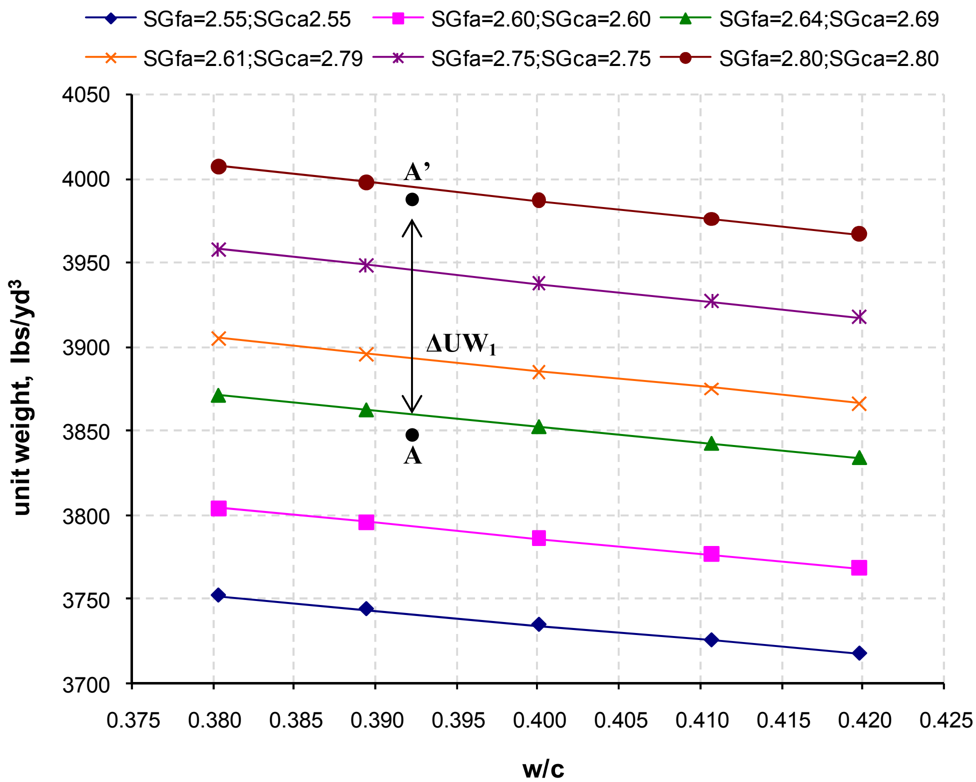


Figure 4.6 Impact of changes in the specific gravities of aggregates on the shift of unit weight-w/c relationships

The general form of these linear relationships is shown as Equation 4.31.

$$UW' = m \cdot {}^{w}\!/_{c} + b \tag{4.31}$$

Where,

UW' = unit weight of fresh concrete (lbs/yd^3)

m = slope

b = intercept

The slope values in degree units were obtained using Equation 4.32.

$$\Phi = \tan^{-1}(m) \tag{4.32}$$

Table 4.5 Parameters of regression equation lines of w/c-unit weight relationship shown in Figure 4.6

Specific gravity of fine aggregate	Specific gravity of coarse aggregate	Slope values of regression lines (m)	Intercept values of regression lines (d)	Degree values of slopes (Φ)
2.55	2.55	-878	4085	-89.93474
2.60	2.60	-912	4150	-89.93718
2.64	2.69	-955	4234	-89.94000
2.61	2.79	-977	4276	-89.94136
2.75	2.75	-1012	4342	-89.94338
2.80	2.80	-1046	4405	-89.94522

It can be seen from Figure 4.6 that the regression lines correlating unit weight and w/c for concretes with different specific gravities of aggregates shifted depending on the values of specific gravities used. The apparent parallelism of the lines shown in Figure 4.6 implies that the observed shift is predominantly driven by SG and practically independent of w/c values. To further confirm this hypothesis, the numerical values of slopes from Table 4.6 were converted to angular (Φ) values using Equation 4.32. It can be seen that the angular values of slope (Φ) listed in Table 4.5 are indeed very similar, thus confirming the negligible effect of w/c. On the other hand, the values of intercepts for individual lines are quite different, thus confirming the dominant role of SG.

Because the specific gravities of aggregates significantly shift the unit weight-w/c equation lines, the measured unit weights of concretes prepared with aggregates of specific gravities different from those used in the development of w/c-unit weight correlation in Section 4.1 need to be reduced by the value of ΔUW_1 (see Figure 4.6). For example, point A' in Figure 4.6 representing the unit weight of concrete with the specific gravity of fine and coarse aggregates of 2.80 (UW') needs to be shifted to position A, which represents the unit weight (UW_1) of concrete with the specific gravities of aggregates that were equal to those used in the development of w/c-unit weight correlation in Section 4.1 (SG_{FA}= 2.64 and SG_{CA} 2.69). The value of this shift (ΔUW_1) is the difference between UW' and UW_1 (UW' is calculated using Equation 4.30) and it can be expressed as shown in Equations 4.33 and 4.34.

$$\Delta UW_1 = UW' - UW_1 \qquad (4.33)$$

$$\Delta UW_1 = UW_1 \cdot \left[\frac{(1-a)}{(1-a) + \frac{W_{FA}}{\rho_w} \cdot \left(\frac{1}{SG'_{FA}} - \frac{1}{SG_{FA}} \right) + \frac{W_{CA}}{\rho_w} \cdot \left(\frac{1}{SG'_{CA}} - \frac{1}{SG_{CA}} \right)} - 1 \right] \quad (4.34)$$

4.4. The Sensitivity of Unit Weight to the Concrete Production Variability

Another factor that can lead to changes in the values of unit weight and w/c is batching variability during concrete production. Based on the input from INDOT (Zander, personal communication, 2008), the allowed batching tolerances are: 1% (by weight) for cement, 2% (by weight) for aggregates, and 1% (by weight) for water. These tolerances, when applied to basic mix proportions in Table 3.3, correspond to the weight differences of ±7 lbs for cement, ±29 lbs for fine aggregate, ±30 lbs for coarse aggregate, and ±3 lbs for water (as shown in Table 4.6).

Table 4.6 Weight variations of basic mix constituent due to production batching tolerances

Constituent	Allowed batching tolerance (%)	Deviation in the weights from basic mix constituents (lbs)
Cement	1%	1% x 658 lbs = 7 lbs
Fine aggregate	2%	2% x 1450 lbs = 29 lbs
Coarse aggregate	2%	2% x 1477 lbs = 30 lbs
Water	1%	1% x 263 lbs = 3 lbs

Since there are a total of four main components of the concrete mixture (cement, water, fine aggregate, and coarse aggregate) and since each of these four components can assume two different (positive and negative) limiting values of batching tolerances, there will be 16 different combinations of these two types of variables that will affect the final mixture proportions and, as a consequence, measured unit weight and associated w/c values. These 16 combinations are shown in Table 4.7.

Table 4.7 List of possible combinations of variables affecting mixture proportions due to batching tolerances combinations

Combination No.			1	2	3	4	5	6	7	8
Constituent	Cement	Batching tolerance (%)	1	1	1	1	1	1	1	1
	Fine aggregate		2	2	2	2	-2	-2	-2	-2
	Coarse aggregate		2	2	-2	-2	2	2	-2	-2
	Water		1	-1	1	-1	1	-1	1	-1
Combination No.			**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Constituent	Cement	Batching tolerance (%)	-1	-1	-1	-1	-1	-1	-1	-1
	Fine aggregate		2	2	2	2	-2	-2	-2	-2
	Coarse aggregate		2	2	-2	-2	2	2	-2	-2
	Water		1	-1	1	-1	1	-1	1	-1

When applied to the basic mix composition from Table 3.3, the combinations shown in Table 4.7 will result in the overall changes in mixture composition as shown in Table 4.8. As an example, combination #9 from Table 4.7 will yield the following adjusted weight of the basic mixture.

Table 4.8 Adjusted weights of basic mix constituents due to the production tolerances

Basic mix constituent			Weight			
Cement			658 lbs			
Fine aggregate			1450 lbs			
Coarse aggregate			1477 lbs			
Water			263 lbs			
Combination No.			**1**	**2**	**3**	**4**
Constituent	Cement	Adjusted weight of constituents (lbs)	665	665	665	665
	Fine aggregate		1479	1479	1479	1479
	Coarse aggregate		1507	1507	1447	1447
	Water		266	261	266	261
Total (lbs)			3916	3911	3857	3852
Combination No.			**5**	**6**	**7**	**8**
Constituent	Cement	Adjusted weight of constituents (lbs)	665	665	665	665
	Fine aggregate		1421	1421	1421	1421
	Coarse aggregate		1507	1507	1447	1447
	Water		266	261	266	261
Total (lbs)			3858	3853	3799	3794
Combination No.			**9**	**10**	**11**	**12**
Constituent	Cement	Adjusted weight of constituents (lbs)	651	651	651	651
	Fine aggregate		1479	1479	1479	1479
	Coarse aggregate		1507	1507	1447	1447
	Water		266	261	266	261
Total (lbs)			3903	3898	3844	3839

Table 4.8 (*continued*)

Combination No.			13	14	15	16
Constituent	Cement	**Adjusted weight of constituents (lbs)**	651	651	651	651
	Fine aggregate		1421	1421	1421	1421
	Coarse aggregate		1507	1507	1447	1447
	Water		266	261	266	261
Total (lbs)			3845	3840	3786	3781

Weight of cement (W_{ct9}) = 658 - 7 = 651 lbs

Weight of fine aggregate (W_{FA9}) = 1450 + 29 = 1479 lbs

Weight of coarse aggregate (W_{CA9}) = 1477 + 30 = 1507 lbs

Weight of water (W_{w9}) = 266 + 3 = 266 lbs

The total weight of all constituents in this adjusted mixture would, therefore, be equal to W_{T9} = $W_{ct9} + W_{FA9} + W_{CA9} + W_{w9}$ = 651 + 1479 + 1507 + 266 = 3903 lbs.

As the weights of the constituents change, the w/c of the basic mix (0.400) also automatically changes. The w/c values resulting from batching tolerances for each of the possible combinations of variables from Table 4.7 are shown in Table 4.9. These resulting w/c values are called production w/c and reflect the change in the w/c due to the change in the amount of water and cement in CMD caused by the production variability. An example of the calculation of the new (after applying the batching tolerances) w/c value for combination #9 is shown below.

$$W\!\!\diagup\!\!C_9 = \frac{W_{w9}}{W_{ct9}} = \frac{266lbs}{651lbs} = 0.408$$

Table 4.9 Production values of w/c resulting from batching tolerances

Combination No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Production w/c	0.400	0.392	0.400	0.392	0.400	0.392	0.400	0.392
Combination No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Production w/c	0.408	0.400	0.408	0.400	0.408	0.400	0.408	0.400

The individual volumes of the adjusted constituents and the total volume of the mix due to each of the possible combinations of production tolerances are shown in Table 4.10.

Table 4.10 Adjusted volumes of basic mix constitutes and their total volumes due to production tolerances

Combination No.			1	2	3	4
Constituent	Cement	Volume of adjusted constituents (yd^3)	0.125	0.125	0.125	0.125
	Fine aggregate		0.334	0.334	0.334	0.334
	Coarse aggregate		0.334	0.334	0.321	0.321
	Water (lbs)		0.158	0.155	0.158	0.155
Total (yd^3)			0.951	0.948	0.938	0.935
Combination No.			**5**	**6**	**7**	**8**
Constituent	Cement	Volume of adjusted constituents (yd^3)	0.125	0.125	0.125	0.125
	Fine aggregate		0.321	0.321	0.321	0.321
	Coarse aggregate		0.334	0.334	0.321	0.321
	Water		0.158	0.155	0.158	0.155
Total (yd^3)			0.938	0.935	0.925	0.922
Combination No.			**9**	**10**	**11**	**12**
Constituent	Cement	Volume of adjusted constituents (yd^3)	0.123	0.123	0.123	0.123
	Fine aggregate		0.334	0.334	0.334	0.334
	Coarse aggregate		0.334	0.334	0.321	0.321
	Water		0.158	0.155	0.158	0.155
Total (yd^3)			0.948	0.945	0.935	0.932
Combination No.			**13**	**14**	**15**	**16**
Constituent	Cement	Volume of adjusted constituents (yd^3)	0.123	0.123	0.123	0.123
	Fine aggregate		0.321	0.321	0.321	0.321
	Coarse aggregate		0.334	0.334	0.321	0.321
	Water		0.158	0.155	0.158	0.155
Total (yd^3)			0.935	0.932	0.922	0.919

Shown below are calculations to obtain the volumes of adjusted constituents and their total volume for combination #9. The adjusted volumes of cement, fine aggregate, coarse aggregate, and water are labeled, as V_{ct9}, V_{FA9}, V_{CA9}, and V_{w9}, respectively. The adjusted total volume of basic mix constituents due to the production tolerances of combination #9 is labeled as V_{T9}.

$$V_{ct9} = \frac{W_{ct9}}{SG_{ct} \cdot \rho_w} = \frac{651 lbs}{3.15 \cdot 62.27 \, {lbs}/{ft^3} \cdot 27 \, {ft^3}/{yd^3}} = 0.123 yd^3$$

$$V_{FA9} = \frac{W_{FA9}}{SG_{CA} \cdot \rho_w} = \frac{1479 lbs}{2.64 \cdot 62.27 \, {lbs}/{ft^3} \cdot 27 \, {ft^3}/{yd^3}} = 0.334 yd^3$$

$$V_{FA9} = \frac{W_{CA9}}{SG_{CA} \cdot \rho_w} = \frac{1507 lbs}{2.69 \cdot 62.27 \, {}^{lbs}\!/_{ft^3} \cdot 27 \, {}^{ft^3}\!/_{yd^3}} = 0.334 yd^3$$

$$V_{W9} = \frac{W_{W9}}{SG_{W} \cdot \rho_w} = \frac{266 lbs}{1.00 \cdot 62.27 \, {}^{lbs}\!/_{ft^3} \cdot 27 \, {}^{ft^3}\!/_{yd^3}} = 0.158 yd^3$$

$$V_{T9} = V_{ct9} + V_{FA9} + V_{CA9} + V_{w9} = 0.123 + 0.334 + 0.334 + 0.158 = 0.948 yd^3$$

Table 4.11 shows the adjusted unit weights due to each of the possible combinations of production variability. Again, the example below shows the calculation for obtaining these adjusted unit weights for combination #9. The adjusted unit weight is labeled as UW_9.

$$UW_9 = \frac{W_{T9}}{V_{T9}} = \frac{3903 lbs}{0.948 yd^3} = 4116 \, {}^{lbs}\!/_{yd^3}$$

Table 4.11 Adjusted values of unit weights due to the production tolerances

Combination No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Unit weight (lbs/ yd^3)	4119	4127	4113	4121	4114	4122	4109	4117
Combination No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Unit weight (lbs/ yd^3)	4116	4124	4110	4118	4111	4119	4105	4114

The unit weights shown in Table 4.11 are those for mixtures with 0% of air content. In order to use these to obtain the determined w/c by utilizing Equation 4.14, these unit weights need to be converted to those with 6.5% air content. The required adjustments can be performed using Equation 4.18. The adjusted unit weights with 6.5% air content and the determined w/c for all possible combinations of production tolerances are shown in Table 4.12. An example below shows the calculation for the unit weight and the w/c values for a mixture with combination #9 of production tolerances and air content of 6.5%.

$$UW_2 = UW_{6.5\%} = \frac{4116 \, lbs/yd^3}{(1-0.00)} \times (1-0.065) = 3848 \, lbs/yd^3$$

$$W/C = -0.0010494 \cdot 3848 \, lbs/yd^3 + 4.439 = 0.401$$

Table 4.12 Adjusted unit weight of concrete with 6.5% of air and determined w/c values resulting from production tolerances

Combination No.	1	2	3	4	5	6	7	8
UW_2 (lbs/ yd^3)	3851	3858	3846	3853	3847	3854	3842	3849
Determined w/c (1)	0.398	0.390	0.403	0.395	0.402	0.394	0.407	0.399
Production w/c from Table 4.9 (2)	0.400	0.392	0.400	0.392	0.400	0.392	0.400	0.392
Δw/c = (1) – (2)	-0.002	-0.002	0.003	0.003	0.002	0.002	0.007	0.007
Combination No.	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
UW_2 (lbs/ yd^3)	3848	3856	3843	3850	3844	3852	3839	3846
Determined w/c (1)	0.401	0.393	0.406	0.398	0.405	0.397	0.411	0.402
Production w/c from Table 4.9 (2)	0.408	0.400	0.408	0.400	0.408	0.400	0.408	0.400
Δw/c = (1) – (2)	-0.007	-0.007	-0.002	-0.002	-0.003	-0.003	0.003	0.002

As can be seen from Table 4.12, the production variability will result in the maximum difference between unit weight determined and production w/c of ±0.007.

In order to find the 95th percentile of the Δw/c from Table 4.12, Monte Carlo simulations (runs) of these Δw/c were performed as a function with randomly changing amounts of ingredients in the mixture.

The value of the deviation of the actual weights of mixture components from the target weights has been established using the RANDBETWEEN function of Microsoft Excel® which returns random values of variables between the specified limits. These limits have been assumed to be equal to batching tolerances; i.e., ±1% for cement, ±2% for aggregates and ±1% for water. Once the random values of allowed weight differences for cement, aggregates and water have been generated for each run, the corresponding Δw/c values were calculated following the same procedure as that used to obtain the Δw/c shown in Table 4.12. The details of the procedures have been previously shown in the example calculations for combination #9. Table 4.13 presents the generated random values of weight differences for cement, aggregates and water, the adjusted weights of concrete ingredients, the unit weight of concrete with 6.5% air (UW_2), the production w/c, the unit weight determined w/c and Δw/c for the first 5 of 5000 runs.

Figure 4.7 shows the results of Δw/c simulations for all 5000 runs. It can be seen from this figure that all of the Δw/c values are in the ±0.007 range. This confirms the previous calculation for the prediction of the maximum Δw/c which showed that its absolute value would not be greater than 0.007 (Table 4.12).

Table 4.13 Results of the first 5 of 5000 runs of Monte Carlo simulation

Trial no.		1	2	3	4	5
Randomly generated weight differences due to production variability	**Cement (±1%)**	0.31%	-0.87%	0.20%	0.82%	-0.42%
	Fine agg. (±2%)	1.11%	1.28%	1.63%	-0.39%	-0.96%
	Coarse agg. (±2%)	-0.22%	1.60%	-0.72%	1.50%	-0.08%
	Water (±1%)	-0.12%	0.59%	-0.99%	-0.34%	0.78%
Adjusted weights of concrete ingredients	**Cement (658 lbs†)**	660	652	659	663	655
	Fine agg. (1450 lbs†)	1466	1469	1474	1445	1436
	Coarse agg. (1477 lbs†)	1474	1501	1466	1499	1476
	Water (263 lbs†)	263	265	261	262	265
Unit weight with.(6.5% air), lbs/yd^3 (UW_2)		3850	3849	3853	3853	3844
Production w/c (1)		0.398	0.406	0.395	0.395	0.405
Unit weight-Determined w/c (2)		0.398	0.400	0.395	0.396	0.405
Δw/c = (1) - (2)		0.000	-0.006	0.000	0.000	0.000

† The weights of cement, fine agg., coarse agg and water used in basic mix (Table 3.3) were, respectively, 658 lbs, 1450 lbs, 1477 lbs and 263 lbs.

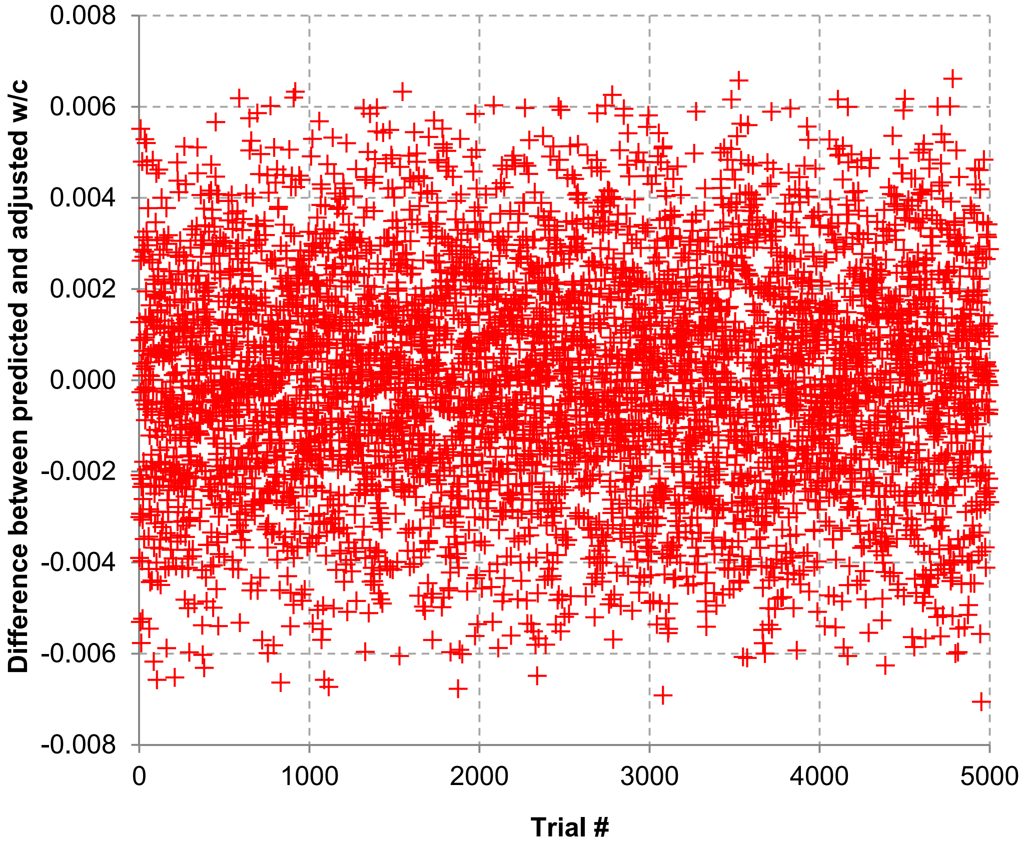


Figure 4.7 Difference between unit weight determined and production w/c (Δw/c) of 5000 runs generated using Monte Carlo simulation

This figure shows that the frequency of the differences between predicted and production w/c values appear to be normally distributed. In order to aid in the analysis of the Monte Carlo simulation results, the Δw/c values of Figure 4.7 have been converted into the histogram shown in Figure 4.8.

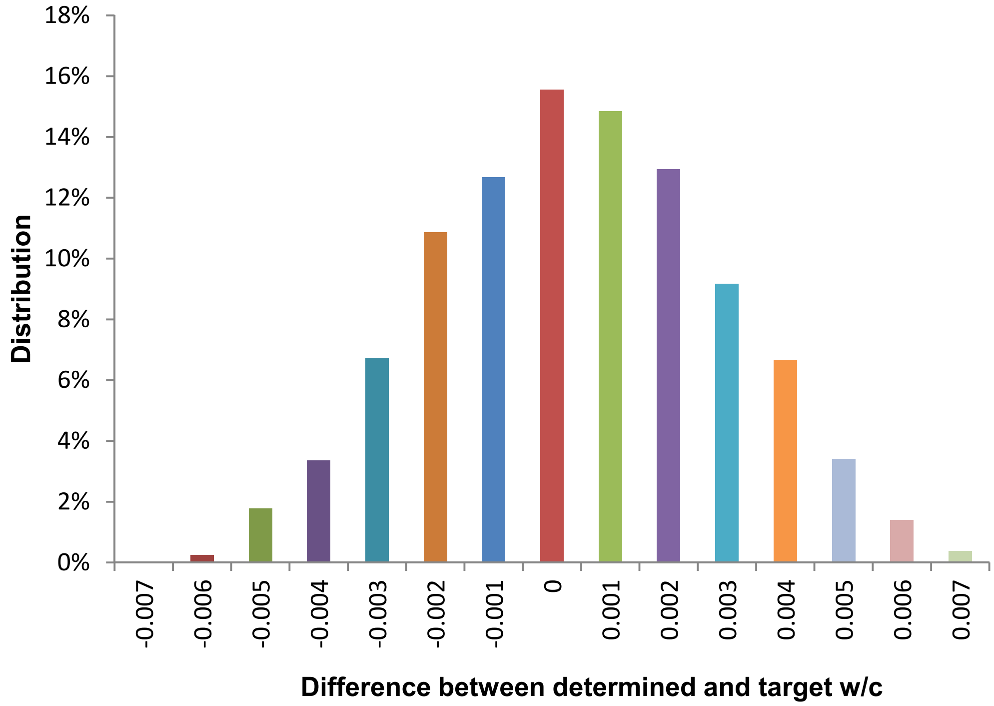


Figure 4.8 Histogram of the differences between unit weight determined and production w/c values (Δw/c) of 5000 runs generated using Monte Carlo simulation

The mean, standard deviation and 95th percentile of the absolute differences between unit weight determined and production w/c of 5000 runs generated using Monte Carlo simulation are 0.002, 0.002 and 0.004, respectively. The standard deviation is calculated using Equation 4.35 and the 95th percentile is calculated by multiplying the standard deviation by 1.645.

$$s = \sqrt{\frac{\sum \left(adjusted \, {}^{w}\!/_{c} - measured \, {}^{w}\!/_{c} \right)^2}{(n-1)}} \tag{4.35}$$

Where,

s = standard deviation

n = number of tests or trials

4.5. Summary

The determination of w/c values using the measured unit weight of concrete can be accomplished using the following three steps:

1. First, the theoretical unit weight-w/c relationship needs to be developed for a series of mixtures having the CMD air content but variable w/c when compared to the basic (CMD) mixture. The procedure for development of this relationship is described in Section 4.1.
2. Next, the measured unit weight of the batched concrete needs to be adjusted to account for potential differences in the air content and specific gravities of aggregates between the CMD (basic) mixture and the batched mixture. In order to perform these adjustments, the measured unit weight ($UW_{a'}$) is first recalculated (using Equation 4.18) to reflect the change in the air content from the measured value to the value used in the basic mixture. This converted unit weight is labeled as UW_a. Afterwards, the converted unit weight is further adjusted for the differences in the specific gravities of aggregates by subtracting the value of ΔUW_1 (calculated using Equation 4.34) from UW_a to obtain UW_2 as shown in Equation 4.36.

   $$UW_2 = UW_a - \Delta UW_1 \tag{4.36}$$

   UW_2 is then the adjusted measured unit weight that reflects the differences between target and measured air contents as well as the potential difference in the specific gravities of aggregates.
3. Finally, the previously calculated UW_2 is used to determine the w/c value by using it as an input to the previously developed (see step 1) unit weight-w/c relationship. This relationship will have the same general form as represented by Equation 4.14.

Based on the input from INDOT (Zander, personal communication, 2008), the allowed weight batched tolerance for cement, aggregates, and water are 1%, 2%, and 1% of the target (CMD) values, respectively. These tolerances theoretically result in the maximum error in predicted w/c of ±0.007 for the basic mix used in the current study. The previously described Monte Carlo simulation using 5000 runs shows that the 95th percentile of this error is within ±0.002 from the value of the production w/c.

CHAPTER 5. LABORATORY VERIFICATION OF THE UNIT WEIGHT METHOD TO DETERMINE W/C VALUE

This chapter presents data on the laboratory verification of the applicability of the unit weight method to determine the w/c of concrete and the discussion of the sensitivity of compressive strength to w/c variations.

The verification process was performed on specimens from two distinctive sets of fresh concretes and one set of hardened concrete specimens as shown schematically in Figure 5.1. The first set of fresh concretes consisted of a total of 60 plain, laboratory-produced mixtures divided into four different groups as described in Section 5.1.1.2. The determination of the unit weight during this part of the laboratory trials was performed using a non-standard procedure that has been developed as a part of this study (see Section 5.1.1.1). This procedure required removal of all air from the sample of fresh concrete before taking the unit weight measurement and is therefore called the "zero-air procedure" (ZAP).

The second set of fresh concretes consisted of an additional 57 mixtures, of which all but three contained supplementary cementitious materials. However, unlike in the case of the first set for which the unit weights were determined using the non-standard ZAP developed during this study, the unit weights and air contents of the second set of mixtures were measured following the AASHTO T 121 (AASHTO, 2005a) and AASHTO T 152 (AASHTO, 2005b) methods, respectively. The details are presented in Section 5.2.2.

A small subset (7 mixtures) of Group I of the original set of 60 mixtures was used to prepare concrete cylinders which were, in turn, used to verify the applicability of the unit weight method to determine the w/c of the hardened concrete (see Section 5.3).

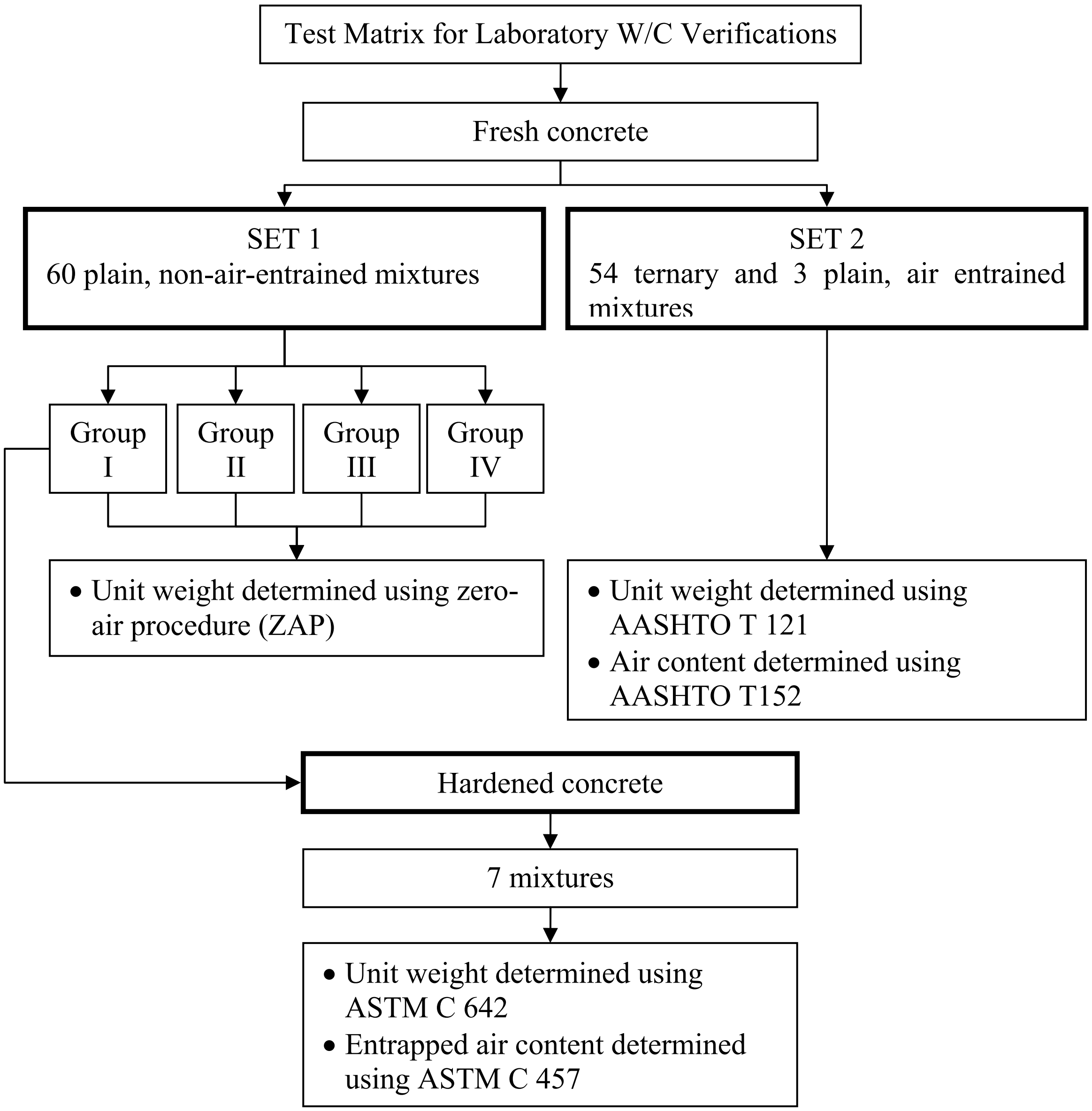


Figure 5.1 Test matrix for laboratory w/c verifications

5.1. <u>Determination of the W/C of the Fresh Concrete</u>

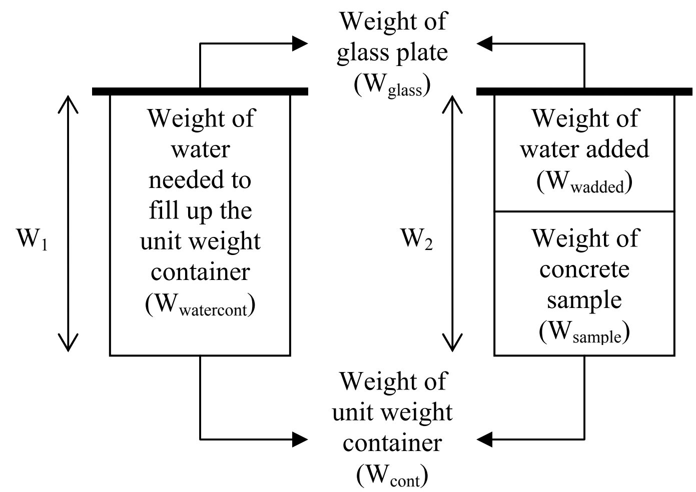
As already mentioned at the beginning of this chapter, the verification of the applicability of the unit weight method for determination of the w/c of fresh concrete involved two sets of mixtures. The unit weights of the first set of 60 mixtures were measured following the zero-air procedure, as presented in Section 5.1.1.1. The unit weights and air contents of the second set of 57 concrete mixtures were measured following the standard AASHTO procedures, as presented in Section 5.2.2.

5.1.1. *Use of Unit Weight Determined by Zero-Air Procedure (ZAP)*

This section presents the results of laboratory verification of the applicability of the proposed unit weight based method for the determination of w/c of fresh concrete values using 60 laboratory-produced mixtures, which were divided into four types (groups). For this set of mixtures, the values of the unit weight were measured following the zero-air procedure described below.

5.1.1.1. Development of the Zero-Air Procedure (ZAP)

As a part of this study, a non-standard procedure for the determination of the unit weight of fresh concrete has been developed. This procedure allows for the determination of the unit weight of fresh concrete by placing an arbitrary amount of concrete and water in the unit weight container and removing all air from the resulting slurry by vigorous stirring. As mentioned in the previous section, this approach has been named ZAP or "zero-air procedure". The main reason for the adoption of this particular technique is that it directly provides the value of the unit weight of concrete without the necessity of determining its air content and associated aggregate correction factor (ACF). The individual steps of the proposed procedure are outlined below and various weights that need to be determined are schematically shown in Figure 5.2.



Note:

$W_1 = W_{cont} + W_{watercont} + W_{glass}$ – total weight of container filled with water

- W_{cont} = weight of unit weight container
- $W_{watercont}$ = weight of water needed to fully fill up the unit weight container
- W_{glass} = weight of glass plate

$W_2 = W_{cont} + W_{sample} + W_{wadded} + W_{glass}$ – total weight of after removal of air

- W_{sample} = initial weight of concrete sample
- W_{wadded} = weight of water added to fully fill up the unoccupied space of unit weight by the concrete sample

Figure 5.2 Schematic of various weights required in the zero-air procedure

1. The empty unit weight container and flat glass plate are weighed and their weights are recorded as W_{cont} and W_{glass}, respectively.
2. The unit weight container is filled up with water, covered with the flat glass plate and the weight of the entire assembly is recorded as W_1. Thus,

   $$W_1 = W_{cont} + W_{watercont} + W_{glass}$$

   Where,

   W_{cont} = weight of empty container

   $W_{watercont}$ = weight of water needed to fully fill up the container

   W_{glass} = weight of the glass plate

   The unit weight container used in this study had a capacity of ~ 0.25 ft^3 and it satisfied the requirements of the AASHTO T 121 method (AASHTO, 2005a).
3. The container is emptied and put back on the scale. The scale is tarred and the unit weight container is filled with concrete up to approximately 80% of its volume; the weight of added concrete is then recorded as W_{sample}.
4. Water is added to the concrete until the container is about 90% full.

5. The concrete/water mixture is then stirred to force the air to rise to the surface.
6. In order to eliminate the foam produced as a result of the stirring process, the surface of the concrete-water mix is sprayed with an anti-foaming agent. In this study, isopropyl alcohol was used.
7. The sample is stirred again in order to make sure that all of the air had been removed. If necessary, the spraying process is repeated until no more bubbles rise to the surface.
8. More water is added to the existing concrete slurry until the container is completely full. Flat glass plate is then placed on the top of the container to make the water's surface completely flat.
9. The full container is then weighed and its weight is recorded as W_2. Thus,

   $$W_2 = W_{cont} + W_{sample} + W_{wadded} + W_{glass}.$$

   Where,

   W_{cont} = weight of empty container

   W_{sample} = weight of concrete sample

   W_{wadded} = weight of total water added

   W_{glass} = weight of flat glass plate
10. The unit weight of the "zero-air" concrete sample ($UW_{zero\text{-}air}$) is calculated using Equation 5.1 shown below. The symbol ρ_w shown in this equation represents the density of water.

$$UW_{zero-air} = \frac{W_{sample} \cdot \rho_w}{\left(W_1 - W_2 + W_{sample}\right)} \qquad (5.1)$$

5.1.1.2. Types of Laboratory Mixtures used in the ZAP

Four types (groups) of laboratory mixtures were prepared for use with the zero-air procedure to verify the w/c values. All of these mixtures were created by altering the basic mixture (with the composition listed in Table 3.3) by one of the mechanisms described below and summarized in Table 5.1. In total, 60 different mixtures were produced, all being plain concrete with no admixtures. It should be noted that although the mixture composition listed in Table 3.3 calls for 167ml/yd^3 of air entraining admixture, the concretes listed in Table 5.1 were actually prepared without the air entrained as the ultimate objective of the proposed method was to determine the unit weight of concrete with no air.

Table 5.1 Summary of the mechanisms of altering the basic mixture proportioning to create mixtures with varying w/c values

Mix code	Methods used to alter basic mix composition					Data of aggregates						
	Varying moisture content		Varying specific gravity and absorption		Varying water amount	Moisture content		Specific gravity		Absorption		Change in the amount of free water, ΔW_w (lbs)
	FA	CA	FA	CA		FA (MC_{FA})	CA (MC_{CA})	FA (SG'_{FA})	CA (SG'_{CA})	FA (abs_{FA})	CA (abs_{CA})	
GROUP I												
A1					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	-13.10
A2					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	-6.60
A3					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	0.00
A4					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	6.40
A5					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	-13.10
A6					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	-13.10
A7					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	0.00
A8					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	0.00
A9					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	13.20
CS1					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	0.00
CS2					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	32.90
CS3					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	65.80
CS4					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	98.70
CS5					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	131.60
CS6					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	197.40
CS7					W	1.75%	1.27%	2.64	2.69	1.7%	1.3%	263.20
GROUP II												
B1	MC	MC				3.80%	1.91%	2.64	2.69	1.7%	1.3%	0.00
B2	MC	MC				3.80%	1.91%	2.64	2.69	1.7%	1.3%	0.00
B3	MC	MC				3.80%	4.20%	2.64	2.69	1.7%	1.3%	0.00
B4	MC	MC				3.80%	1.54%	2.64	2.69	1.7%	1.3%	0.00
B5	MC	MC				3.62%	2.00%	2.64	2.69	1.7%	1.3%	0.00
B6	MC	MC				3.62%	2.00%	2.64	2.69	1.7%	1.3%	0.00
B7	MC	MC				3.62%	2.00%	2.64	2.69	1.7%	1.3%	0.00
B8	MC	MC				3.62%	2.00%	2.64	2.69	1.7%	1.3%	0.00
B9	MC	MC				2.76%	0.07%	2.64	2.69	1.7%	1.3%	0.00
B10	MC	MC				2.76%	0.07%	2.64	2.69	1.7%	1.3%	0.00
B11	MC	MC				2.76%	0.07%	2.64	2.69	1.7%	1.3%	0.00
GROUP III												
D1	MC	MC		SG+A		3.62%	1.25%	2.64	2.72	1.7%	1.0%	0.00
D2	MC	MC		SG+A		3.62%	1.25%	2.64	2.72	1.7%	1.0%	0.00
D3	MC	MC		SG+A		3.33%	0.90%	2.64	2.72	1.7%	1.0%	0.00
D4	MC	MC		SG+A		3.33%	0.90%	2.64	2.72	1.7%	1.0%	0.00
D5	MC	MC		SG+A		3.33%	0.90%	2.64	2.72	1.7%	1.0%	0.00
F1	MC	MC		SG+A		2.87%	1.92%	2.64	3.57	1.7%	1.7%	0.00
F2	MC	MC		SG+A		2.87%	1.92%	2.64	3.57	1.7%	1.7%	0.00
F3	MC	MC		SG+A		2.87%	1.92%	2.64	3.57	1.7%	1.7%	0.00
F4	MC	MC		SG+A		2.87%	1.92%	2.64	3.57	1.7%	1.7%	0.00
F5	MC	MC		SG+A		2.36%	1.24%	2.64	3.57	1.7%	1.7%	0.00
F6	MC	MC		SG+A		2.36%	1.24%	2.64	3.57	1.7%	1.7%	0.00

Table 5.1 (*continued*)

Mix code		Methods used to alter basic mix composition					Data of aggregates						
		Varying moisture content		Varying specific gravity and absorption		Varying water amount	Moisture content		Specific gravity		Absorption		Change in the amount of free water, ΔW_W (lbs)
		FA	CA	FA	CA		FA (MC_{FA})	CA (MC_{CA})	FA (SG'_{FA})	CA (SG'_{CA})	FA (abs_{FA})	CA (abs_{CA})	
R1	R1A R1B R1C	MC	MC		SG+A		2.02%	1.85%	2.64	3.57	1.7%	1.7%	0.00
R2	R2A R2B R2C	MC	MC		SG+A		2.02%	1.85%	2.64	3.57	1.7%	1.7%	0.00
GROUP IV													
C1		MC	MC			W	3.62%	2.00%	2.64	2.69	1.7%	1.3%	-77.77
C2		MC	MC			W	3.62%	2.00%	2.64	2.69	1.7%	1.3%	10.44
C3		MC	MC			W	3.46%	1.74%	2.64	2.69	1.7%	1.3%	-29.16
C4		MC	MC			W	3.46%	1.74%	2.64	2.69	1.7%	1.3%	-20.16
C5		MC	MC			W	3.46%	1.74%	2.64	2.69	1.7%	1.3%	-11.16
C6		MC	MC			W	3.46%	1.74%	2.64	2.69	1.7%	1.3%	-2.16
E1		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	-29.16
E2		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	-20.26
E3		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	-11.16
E4		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	6.84
E5		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	-18.36
E6		MC	MC		SG+A	W	3.56%	1.42%	2.64	2.72	1.7%	1.0%	-9.36
G1		MC	MC		SG+A	W	2.36%	1.24%	2.64	3.57	1.7%	1.7%	6.84
G2		MC	MC		SG+A	W	2.36%	1.24%	2.64	3.57	1.7%	1.7%	6.84
G3		MC	MC		SG+A	W	2.36%	1.24%	2.64	3.57	1.7%	1.7%	-83.17
G4		MC	MC		SG+A	W	2.36%	1.24%	2.64	3.57	1.7%	1.7%	-83.17

Group I (mixtures A1-A9 and CS1-CS7) – This group of mixtures was created by adding or subtracting the predetermined amount of water from the basic mix design (Table 3.3). This group of mixtures was used to represent the field concrete batches in which the design water content was changed due to errors in the batched amount of water or due to addition of extra water during transport, placement or finishing operations.

Group II (mixtures B1-B11) - This group of mixtures was created by assuming that the aggregates used were in SSD condition; however, in reality, they were not. This approach was used to evaluate the capability of the zero-air method to determine the changes in the w/c of field concrete resulting from the variability of the moisture content of aggregates in the stockpile.

Group III (mixtures D1-D5, F1-F6, R1 and R2) - This group of mixtures duplicated mixtures from the second group but was obtained by changing the type of coarse aggregate used to develop the unit weight-w/c relationship. Two types of coarse aggregates (steel slag and limestone) were used, each with different values of specific gravity and absorption, then the coarse aggregate (dolomite) specified for the basic mix design (Table 3.3) was used. These mixtures were used to determine the capability of the zero-air method to determine the influence of changes in the unit weight caused by using an aggregate with a different specific gravity and absorption from those used in the basic mixture (Table 3.3) on the w/c values.

Group IV (mixtures C1-C6, E1-E6 and G1-G4) - This group of mixtures was created by combining the mechanism of w/c alteration used in the previous groups and included a combination of the variables used in the first and second or the first and third groups.

More detailed descriptions of the laboratory preparation of these groups of mixtures are presented below:

Group I (mixtures A1-A9 and CS1-CS7) – Since the composition of these mixtures was based on the aggregate being in the SSD condition, the actual moisture of the stockpiled aggregates was determined prior to batching and the required water amount was adjusted accordingly. Next, in order to create mixtures with values different from that of the basic mix, the batched amount of water was further changed as shown in Table 5.1. As already mentioned, this additional change in the amount of water represented potential batching errors of water additions during transport, placement and finishing operations.

Group II (mixtures B1-B11) – Prior to the batching of this group of mixtures, the moisture contents of the aggregates were measured. Although the measurements showed that the aggregates were not in SSD condition, they were still assumed to be in such a condition. The practical consequence of this assumption was that the weights of the aggregates as batched (in their actual moisture condition) were in fact equal to the weight called for by the mixture design in SSD conditions. In other words, no adjustments were made in the amount of added water to account for the conditions of the aggregates. The measured values of moisture contents and the absorptions are given in Table 5.1. These values are used in Section 5.2.1.5 to calculate the actual w/c of the mixture.

Group III (mixtures D1-D5, F1-F6, R1 and R2) – The process of the batching of this group of mixtures was exactly the same as that used to create mixtures in the second group in that the moisture content of aggregates was different then the SSD values. In addition, the absorption and specific gravity values of coarse aggregates were also different from those specified for the basic mix design (Table 3.3). The measured values of moisture contents and the absorptions are given in Table 5.1. These values are used in Section 5.2.1.5 to calculate the actual w/c of the mixture.

Group IV (mixtures C1-C6, E1-E6 and G1-G4) – The batching process used to prepare mixtures in this group was a combination of the process as used in the first and second or the first and third groups.

In order to assess the repeatability of the zero-air technique when used for the determination of w/c, mixtures with codes R1 and R2 were prepared in triplicate (as shown in Table 5.1).

5.1.1.3. Mixing Procedure

The mixing procedure for all laboratory concrete mixtures followed the Standard Method of Making and Curing Concrete Test Specimen in the Laboratory (ASTM C 192M-06) (ASTM, 2006). However, modifications have been made in terms of placing the ingredients and the mixing sequence as described below. All of the mixtures were mixed using the Lancaster pan mixer with the nominal capacity of ~ 4.0 ft^3. In order to prevent materials loss, all concrete ingredients except for water were put into the pan prior to starting the mixer. Once the ingredients were in the pan, the mixer was started. After 30 seconds, the entire amount of water was added to the pan and the mixing process continued for an additional 7 minutes and 30 seconds.

5.1.1.4. Calculation of Batched W/C

In this section, the batched w/c of the first set of 60 laboratory-produced mixtures is calculated. The batched w/c is the weight of free water in the mixture over the weight of cement. The weights of the free water of the 60 laboratory-produced mixtures were calculated using

Equation 5.13. The weight of cement used in the calculation of the w/c was equal to that specified for the basic mix (Table 3.3). Equation 5.13 was derived as presented below.

The total amount of free water in each of the batched mixtures can be expressed by Equation 5.2:

$$W'_w = W_w + \Delta W_w + W_{wFA} + W_{wCA} \tag{5.2}$$

Where,

W'_w = the amount of free water in each mixture of the first set of concretes

W_w = specified amount of water in the basic mixture

ΔW_w = the amount of water either purposely or accidentally added (+) to the basic mixture, or purposely or accidentally withheld (-) from the basic mixture

W_{wFA} = the change in the amount of free water in the mixture due to actual moisture condition of fine aggregate with respect to SSD condition

W_{wCA} = the change in the amount of free water in the mixture due to actual moisture condition of coarse aggregate with respect to SSD condition

The amount of free water contributed by the aggregates (W_{wFA} and W_{wCA}) will depend on their actual moisture content and absorption. The following paragraph presents the development of the equations that allow for calculation of W_{wFA} and W_{wCA}.

Based on AASHTO T 255 (the standard method of testing for total evaporable moisture content of aggregate by drying (AASHTO, 2004c)), the moisture contents of aggregates can be expressed as shown in Equation 5.3. Using AASHTO T 84 (AASHTO, 2004a) and T 85 (AASHTO, 2004b) the absorptions of aggregates can be expressed as shown in Equation 5.4 (note: these equations will give a decimal values) .

$$MC_{FA/CA} = \frac{\left(W_{FA/CAactual} - W_{FA/CAdry}\right)}{\left(W_{FA/CAdry}\right)} \tag{5.3}$$

$$abs_{FA/CA} = \frac{\left(W_{FA/CASSD} - W_{FA/CAdry}\right)}{\left(W_{FA/CAdry}\right)} \tag{5.4}$$

Where,

$W_{FA/CAactual}$	= weight of fine or coarse aggregate in the mixture in actual moisture condition
$W_{FA/CAdry}$	= weight of fine or coarse aggregate in the mixture in dry condition
$W_{FA/CASSD}$	= weight of fine or coarse aggregate in the mixture in SSD condition
$MC_{FA/CA}$	= moisture content of fine or coarse aggregate
$abs_{FA/CA}$	= absorption value of fine or coarse aggregate

Since the values of parameter $W_{FA/CAdry}$ used in Equations 5.3 and 5.4 are equal, these two equations can be combined in order to develop the relationship between the weight of aggregates in actual and SSD conditions. These relationships are presented as Equation 5.5 and 5.6 for fine and coarse aggregates, respectively.

$$W_{FA_{SSD}} = \frac{\left(1 + abs_{FA}\right)}{\left(1 + MC_{FA}\right)} \cdot W_{FAactual} \tag{5.5}$$

$$W_{CA_{SSD}} = \frac{\left(1 + abs_{CA}\right)}{\left(1 + MC_{CA}\right)} \cdot W_{CAactual} \tag{5.6}$$

Where,

$W_{FAactual}$	= weight of fine aggregate in the mixture in actual moisture condition
$W_{CAactual}$	= weight of coarse aggregate in the mixture in actual moisture condition
W_{FASSD}	= weight of fine aggregate in the mixture in SSD condition
W_{CASSD}	= weight of coarse aggregate in the mixture in SSD condition
MC_{FA}	= moisture content of fine aggregate
MC_{CA}	= moisture content of coarse aggregate
abs_{FA}	= absorption value of fine aggregate (entered as decimal)
abs_{CA}	= absorption value of coarse aggregate (entered as decimal)

The changes in the amount of mix water caused by the use of aggregates with a moisture condition different than SSD are equal to the differences between their actual and SSD weights. These differences are expressed by Equation 5.7 (for fine aggregate) and 5.8 (for coarse aggregate), respectively.

$$W_{wFA} = W_{FAactual} - W_{FASSD} \tag{5.7}$$

$$W_{wCA} = W_{CAactual} - W_{CASSD} \tag{5.8}$$

Where,

W_{wFA} = amount in the amount of mixture water due to actual moisture condition of fine aggregate being different than SSD

W_{wCA} = amount in the amount of mixture water due to actual moisture condition of fine aggregate being different than SSD

Rearrangement of Equations 5.5 and 5.6 in order to obtain expressions for $W_{FAactual}$ and $W_{CAactual}$ will yield Equations 5.9 and 5.10, respectively. Substitution of Equation 5.9 into Equation 5.7 will result in Equation 5.11. Substitution of Equation 5.10 into Equation 5.8 will result in Equation 5.12.

$$W_{FA\,actual} = \frac{(1 + MC_{FA})}{(1 + abs_{FA})} \cdot W_{FASSDl} \tag{5.9}$$

$$W_{CA\,actual} = \frac{(1 + MC_{CA})}{(1 + abs_{CA})} \cdot W_{CASSD} \tag{5.10}$$

$$W_{wFA} = W_{FAactual} \cdot \left[1 - \frac{(1 + abs_{FA})}{(1 + MC_{FA})} \right] \tag{5.11}$$

$$W_{wCA} = W_{CAactual} \cdot \left[1 - \frac{(1 + abs_{CA})}{(1 + MC_{CA})} \right] \quad (5.12)$$

Substitution of Equation 5.11 and 5.12 into Equation 5.2 yields Equation 5.13.

$$W'_w = W_w + \Delta W_w + W_{FAactual} \cdot \left[1 - \frac{(1 + abs_{FA})}{(1 + MC_{FA})} \right] + W_{CAactual} \cdot \left[1 - \frac{(1 + abs_{CA})}{(1 + MC_{CA})} \right] \quad (5.13)$$

Starting with the water content for the basic mix (Table 3.3) and modifying it by utilizing one or more of the parameters provided in Table 5.1 (change in the free water content ΔW_w, absorption and/or moisture content), the total weight of free water in all of the 60 mixtures of the first set of concretes can be calculated using Equation 5.13. Once the total weight of free water is calculated, the batched w/c of all 60 mixtures can be calculated by dividing that weight of free water by the weight of cement specified for the basic mix. Table 5.2 shows the batched w/c of all 60 laboratory-produced mixtures.

Table 5.2 Batched w/c of 60 laboratory-produced mixtures

Mix code	**Batched w/c**	**Mix code**	**Batched w/c**	**Mix code**	**Batched w/c**	**Mix code**	**Batched w/c**
A1	0.380	CS7	0.800	D4	0.432	C2	0.472
A2	0.390	B1	0.458	D5	0.432	C3	0.403
A3	0.400	B2	0.458	F1	0.430	C4	0.416
A4	0.410	B3	0.507	F2	0.430	C5	0.430
A5	0.380	B4	0.450	F3	0.430	C6	0.444
A6	0.380	B5	0.456	F4	0.430	E1	0.404
A7	0.400	B6	0.456	F5	0.404	E2	0.417
A8	0.400	B7	0.456	F6	0.404	E3	0.431
A9	0.420	B8	0.456	R1A	0.410	E4	0.458
CS1	0.400	B9	0.395	R1B	0.410	E5	0.420
CS2	0.450	B10	0.395	R1C	0.410	E6	0.434
CS3	0.500	B11	0.395	R2A	0.410	G1	0.414
CS4	0.550	D1	0.446	R2B	0.410	G2	0.414
CS5	0.600	D2	0.446	R2C	0.410	G3	0.278
CS6	0.700	D3	0.432	C1	0.338	G4	0.278

As an example, the batched w/c of mixture E1 will be calculated. This mixture has been designed by purposely withholding 29.16 lbs of water (see Table 5.1) from the amount specified in the basic mix (263 lbs) and by using aggregates that were not in SSD conditions (MC_{FA} = 3.56% and MC_{CA} = 1.42% as listed in Table 5.1). In addition, the specific gravity value of coarse aggregate and the absorption value of coarse aggregate were also different from those used in the basic mix design. The absorption values of fine and coarse aggregates used in this mixture were 1.7% (abs_{FA}) and 1.0% (abs_{CA}) respectively, as presented in Table 5.1. However, despite the fact that the moisture content of aggregates was higher than that required for SSD condition when making this mixture, the amounts of aggregates used were the same as those listed in Table 3.3. This was done purposely to simulate the situation when batching is performed without proper monitoring of actual moisture condition in the stockpile. As a result, the amounts of aggregates actually batched to prepare this mixture were equal to those in SSD condition specified in the basic mix ($W_{FAactual}$ = W_{FA} = 1450 lbs and $W_{CAactual}$ = W_{CA} = 1477 lbs). The amount of cement used for this mixture was also equal to that specified in the basic mix, 658 lbs. The amount of free water in mixture E1 was then calculated using Equation 5.13 as shown below.

$$W'_w = 263.2 - 29.16 + 1450 \cdot \left[1 - \frac{(1+0.017)}{(1+0.0356)}\right] + 1477 \cdot \left[1 - \frac{(1+0.01)}{(1+0.042)}\right] = 266 \quad lbs$$

Since the actual amount of water used during the batching of mixture E1 (266 lbs) was higher than that listed in Table 3.3 (263 lbs), the resulted w/c value of this mixture was also slightly higher (0.404) than that of the basic mix (0.400).

5.1.1.5. Determination of the Unit Weight of Air Free Concrete

The unit weights of all 60 laboratory-produced mixtures were determined using the zero-air procedure (ZAP) previously described in Section 5.1.1.1. Table 5.3 shows the initial weights of concrete samples (W_{sample}) and total weight of the container filled with concrete after removal of all air (W_2) as well as the ZAP based unit weights ($UW_{zero\text{-}air}$) of concrete samples. The same value of W_1 (25.9 lbs) was used for all the mixtures (this value represents the weights of the unit weight container plus flat glass plate plus water filling the container).

Table 5.3 Initial weights of concrete samples (W_{sample}) and ZAP based unit weight ($UW_{zero\text{-}air}$) of 60 laboratory-produced mixtures

Mix code	Initial Sample weight (W_{sample}) (lbs)	W_2 (lbs)	ZAP Based Unit Weight ($UW_{zero\text{-}air}$) (lbs/yd^3)	Mix code	Initial Sample weight (W_{sample}) (lbs)	W_2 (lbs)	ZAP Based Unit Weight ($UW_{zero\text{-}air}$) (lbs/yd^3)
A1	28.00	42.47	4119	D4	28.00	42.46	4115
A2	28.00	42.48	4122	D5	28.00	42.47	4119
A3	28.00	42.44	4108	F1	28.00	43.37	4471
A4	28.00	42.38	4086	F2	28.00	43.38	4475
A5	28.00	42.52	4137	F3	28.00	43.40	4483
A6	28.00	42.51	4133	F4	33.00	46.54	4489
A7	28.00	42.47	4119	F5	28.00	43.50	4527
A8	28.00	42.45	4111	F6	28.00	43.50	4527
A9	28.00	42.35	4076	R1A	22.00	39.72	4522
CS1	24.00	40.10	4117	R1B	22.00	39.69	4505
CS2	24.00	39.93	4047	R1C	22.00	39.68	4500
CS3	28.00	42.12	3996	R2A	22.00	39.71	4516
CS4	24.00	39.68	3948	R2B	22.00	39.71	4516
CS5	28.00	41.92	3930	R2C	22.00	39.67	4494
CS6	28.00	41.78	3884	C1	28.00	42.59	4162
CS7	29.00	42.31	3873	C2	28.00	42.30	4058
B1	28.00	42.35	4076	C3	28.00	42.40	4094
B2	28.00	42.29	4055	C4	28.00	42.34	4072
B3	28.00	42.26	4044	C5	28.00	42.31	4062
B4	28.00	42.38	4086	C6	28.00	42.30	4058
B5	28.00	42.34	4072	E1	28.00	42.47	4119
B6	28.00	42.34	4072	E2	28.00	42.45	4111
B7	28.00	42.33	4069	E3	28.00	42.46	4115
B8	28.00	42.30	4058	E4	28.00	42.40	4094
B9	21.00	38.39	4149	E5	28.00	42.45	4111
B10	22.00	38.84	4083	E6	28.00	42.42	4101
B11	22.00	38.79	4060	G1	28.00	43.52	4535
D1	28.00	42.45	4111	G2	28.00	43.46	4509
D2	28.00	42.45	4111	G3	22.00	39.90	4624
D3	28.00	42.46	4115	G4	22.00	39.93	4641

As an example, the computation of the ZAP based unit weight of mixture E1 will be presented. The initial weight of the concrete sample for this mixture was 28 lbs and the measured W_2 value was 42.47 lbs. As already mentioned, the value of W_1 used was 25.90 lbs. The weights of the unit weight container, the water inside it, and the flat glass plate, were 7.65 lbs, 15.54 lbs, and 2.71 lbs, respectively. This information is summarized as follows:

W_{sample}= 28.00 lbs.

W_1 = 7.65 lbs. + 15.54 lbs. + 2.71 lbs. = 25.9 lbs

W_2 = 42.47 lbs.

ρ_w = 62.27 lbs/ft^3 (density of water)

By using Equation 5.1, the ZAP based unit weight for mixture E1 can be computed as follows:

$$UW_{zero-air} = \frac{28 \cdot 62.27}{(25.9 - 42.47 + 28)} = 152.54\, {}^{lbs}\!/_{ft^3} = 4119\, {}^{lbs}\!/_{yd^3}$$

The computation above indicates that mixture E1 has the ZAP based unit weight of 4119 lbs/yd^3. Because this value is computed using Equation 5.1 (obtained using zero-air procedure) then this is the unit weight of concrete with a' = 0.000 air content (see Equation 4.18).

5.2.1.6. Determination of Actual (as Produced) W/C Using ZAP Based Unit Weight

The ZAP based unit weights of all 60 laboratory-produced mixtures were used to determine the actual (as produced) values of w/c. This was accomplished by first converting the ZAP based unit weights ($UW_{zero\text{-}air}$) presented in Table 5.2 to the unit weight, representing concrete with a = 0.065 of air. These converted unit weights are labeled as $UW_{6.5\%}$ and were calculated using Equation 4.18. Next, the value of $UW_{6.5\%}$ was further adjusted to account for the differences between the batched specific gravities of aggregates and those used for the basic mix (Table 3.3). This was accomplished by subtracting ΔUW_1 (calculated using Equation 4.34) from $UW_{6.5\%}$. The result of this subtraction is the final adjusted unit weight, UW_2, where UW_2 =

$UW_{6.5\%} - \Delta UW_1$ (as per Equation 4.36). In order to determine actual w/c value, the UW_2 was then used as an input in Equation 4.14.

Table 5.4 summarizes the values of $UW_{6.5\%}$, ΔUW_1, UW_2 and the actual (determined using unit weights) w/c for all 60 laboratory mixtures.

Table 5.4 The $UW_{6.5\%}$, ΔUW_1, UW_2 and actual w/c values for 60 laboratory mixtures

Mix code	Air content adjusted (0%→6.5%) unit weight ($UW_{6.5\%}$), lbs/yd^3	ΔUW_1, lbs/yd^3	Final adjusted unit weight (UW_2) (lbs/yd^3)	Actual w/c
A1	3851	0	3851	0.398
A2	3854	0	3854	0.394
A3	3841	0	3841	0.408
A4	3821	0	3821	0.429
A5	3868	0	3868	0.380
A6	3864	0	3864	0.383
A7	3851	0	3851	0.398
A8	3844	0	3844	0.405
A9	3811	0	3811	0.440
CS1	3850	0	3850	0.399
CS2	3784	0	3784	0.468
CS3	3737	0	3737	0.518
CS4	3692	0	3692	0.565
CS5	3674	0	3674	0.583
CS6	3632	0	3632	0.628
CS7	3552	0	3552	0.711
B1	3811	0	3811	0.440
B2	3791	0	3791	0.460
B3	3781	0	3781	0.470
B4	3821	0	3821	0.429
B5	3808	0	3808	0.443
B6	3808	0	3808	0.443
B7	3804	0	3804	0.446
B8	3795	0	3795	0.457
B9	3834	0	3834	0.415
B10	3840	0	3840	0.409
B11	3836	0	3836	0.413
D1	3844	18	3826	0.423
D2	3844	18	3826	0.423
D3	3848	18	3830	0.420
D4	3848	18	3830	0.420
D5	3851	18	3833	0.416
F1	4180	365	3815	0.435

Table 5.4 (*continued*)

Mix code	Air content adjusted (0%→6.5%) unit weight ($UW_{6.5\%}$), lbs/yd^3	ΔUW_1, lbs/yd^3	Final adjusted unit weight (UW_2) (lbs/yd^3)	Actual w/c
F2	4224	365	3859	0.389
F3	4192	365	3827	0.423
F4	4197	365	3832	0.418
F5	4232	365	3867	0.381
F6	4232	365	3867	0.381
R1A	4228	365	3863	0.385
R1B	4212	365	3847	0.402
R1C	4207	365	3842	0.407
R2A	4223	365	3857	0.391
R2B	4223	365	3857	0.391
R2C	4202	365	3837	0.412
C1	3892	0	3892	0.355
C2	3795	0	3795	0.457
C3	3827	0	3827	0.422
C4	3808	0	3808	0.443
C5	3798	0	3798	0.453
C6	3795	0	3795	0.457
E1	3851	18	3833	0.416
E2	3844	18	3826	0.423
E3	3848	18	3830	0.420
E4	3827	18	3810	0.441
E5	3844	18	3826	0.423
E6	3834	18	3816	0.434
G1	4240	365	3875	0.372
G2	4216	365	3851	0.398
G3	4323	365	3958	0.285
G4	4339	365	3974	0.268

As an example, calculations to obtain the actual (determined using unit weight) w/c value for mixture E1 are provided below. Since the unit weight ($UW_{zero\text{-}air}$) of mixture E1 was obtained using the zero-air procedure, it is the unit weight of concrete with a' = 0.000 air content. The mixture E1 was produced with coarse aggregate with the specific gravity of 2.72 (SG'_{CA}), as indicated in Table 5.1. Since both the specific gravity of coarse aggregate in the "as produced" mixture and the air content of this mixture were different than those specified for the basic mix (2.69 (SG_{CA}) and 6.5%), respectively, the ZAP based unit weight of mixture E1 needs to be adjusted before the w/c calculations can be performed. The adjustment of the ZAP based unit weight is a two-step process. In the first step, the unit weight is adjusted for the differences in the air content in the ZAP (zero-air) and basic (6.5% air) mixtures using Equation 4.18. The actual calculations are shown below and the results are reported in the second column of Table 5.4.

$$UW_{6.5\%} = \frac{UW_{zero-air}}{(1-a')} \times (1-a) = \frac{4119}{(1-0.000)} \cdot (1-0.065) = 3851 \, {}^{lbs}\!/_{yd^3}$$

Afterward, the unit weight obtained in step 1 ($UW_{6.5\%}$) is further adjusted to account for the differences in specific gravity of coarse aggregate between the actual and as produced mixtures. This (step 2) adjustment involves subtracting the values of ΔUW_1 from $UW_{6.5\%}$ values, where ΔUW_1 is calculated as shown below. This subtraction generates the value UW_2, which is the final adjusted unit weight which will be used to calculate the actual w/c. Starting with Equation 4.36, UW_2 is calculated as

$$UW_2 = UW_{6.5\%} - \Delta UW_1 = 3851 \, {}^{lbs}\!/_{yd^3} - 18 \, {}^{lbs}\!/_{yd^3} = 3833 \, {}^{lbs}\!/_{yd^3}$$

The ΔUW_1 is calculated from Equation 4.34 as below using UW_1, W_{FA}, W_{CA}, SG_{FA}, and SG_{CA} values obtained from Table 3.3 and SG'_{FA} and SG'_{CA} values from Table 5.1.

$$\Delta UW_1 = 3849 \cdot \left[\frac{(1-0.065)}{(1-0.065) + \frac{1450}{62.27 \cdot 27} \cdot \left(\frac{1}{2.64} - \frac{1}{2.64} \right) + \frac{1477}{62.27 \cdot 27} \cdot \left(\frac{1}{2.72} - \frac{1}{2.69} \right)} - 1 \right]$$

$$\Delta UW_1 = 18 \, {}^{lbs}\!/_{yd^3}$$

Finally, the actual w/c of mixture E1 is obtained by using the adjusted unit weight (UW_2) as an input into Equation 4.14 as shown below:

$$W\!/_C = -0.0010494 \cdot 3833 + 4.439 = 0.416$$

As the result, the actual w/c of mixture E1 determined by the ZAP based unit weight is 0.416.

Table 5.5 summarizes both the batched and the actual w/c values and also lists the differences between them for all 60 of the laboratory-produced mixtures. These differences were calculated by subtracting the actual w/c from the batched values.

Table 5.5 Differences between batched and actual w/c values for set one of laboratory mixtures

Mix code	Batched w/c	Actual w/c	$\Delta_{w/c}$	Mix code	Batched w/c	Actual w/c	$\Delta_{w/c}$	Mix code	Batched w/c	Actual w/c	$\Delta_{w/c}$
A1	0.380	0.398	-0.018	B5	0.456	0.443	+0.013	R1C	0.410	0.407	+0.003
A2	0.390	0.394	-0.004	B6	0.456	0.443	+0.013	R2A	0.410	0.391	+0.019
A3	0.400	0.408	-0.008	B7	0.456	0.446	+0.010	R2B	0.410	0.391	+0.019
A4	0.410	0.429	-0.019	B8	0.456	0.457	-0.001	R2C	0.410	0.412	-0.002
A5	0.380	0.380	0.000	B9	0.395	0.415	-0.020	C1	0.338	0.355	-0.017
A6	0.380	0.383	-0.003	B10	0.395	0.409	-0.014	C2	0.472	0.457	+0.015
A7	0.400	0.398	+0.002	B11	0.395	0.413	-0.018	C3	0.403	0.422	-0.019
A8	0.400	0.405	-0.005	D1	0.446	0.423	+0.023	C4	0.416	0.443	-0.027
A9	0.420	0.440	-0.020	D2	0.446	0.423	+0.023	C5	0.430	0.453	-0.023
CS1	0.400	0.399	+0.001	D3	0.432	0.420	+0.012	C6	0.444	0.457	-0.013
CS2	0.450	0.468	-0.018	D4	0.432	0.420	+0.012	E1	0.404	0.416	-0.012
CS3	0.500	0.518	-0.018	D5	0.432	0.416	+0.016	E2	0.417	0.423	-0.006
CS4	0.550	0.565	-0.015	F1	0.430	0.435	-0.005	E3	0.431	0.420	+0.011
CS5	0.600	0.583	+0.017	F2	0.430	0.389	+0.041	E4	0.458	0.441	+0.017
CS6	0.700	0.628	+0.072	F3	0.430	0.423	+0.007	E5	0.420	0.423	-0.003
CS7	0.800	0.711	+0.089	F4	0.430	0.418	+0.012	E6	0.434	0.434	0.000
B1	0.458	0.440	+0.018	F5	0.404	0.381	+0.023	G1	0.414	0.372	+0.042
B2	0.458	0.460	-0.002	F6	0.404	0.381	+0.023	G2	0.414	0.398	+0.016
B3	0.507	0.470	+0.037	R1A	0.410	0.385	+0.025	G3	0.278	0.285	-0.007
B4	0.450	0.429	+0.021	R1B	0.410	0.402	+0.008	G4	0.278	0.268	+0.010

The differences between the batched and actual w/c for mixtures with the codes CS6 and CS7 were significant most likely because those mixtures had high initial w/c values (0.700 and 0.800, respectively). As a result, it was difficult to obtain a representative test sample as these mixtures partially segregated in the mixer.

5.2.2. *Use of Unit Weight Determined by AASHTO Procedures*

The set of concretes used in this part of the study consisted of 57 laboratory prepared, air-entrained mixtures of which 54 were ternary (cement + fly ash + silica fume) and 3 were plain mixtures. Table 5.7 shows the design compositions of these mixtures, each having the nominal entrained air content of 6.5%. They have the batched w/c of 0.410, except mixtures number 26, 36, and 49 which have the batched w/c of 0.430. The specific gravities of materials used for these mixtures are shown in Table 5.6. The specific gravity of coarse aggregate used for mixtures number 24, 25, 27, 28, 33, 35, 36, 41, 42, and 44 to 57 was 2.64 instead of 2.65.

Table 5.6 Specific gravities of materials used for 57 laboratory-produced mixtures

Material	Cement	Fly ash	Silica fume	Fine aggregate	Coarse aggregate	Water
Specific Gravity	3.15	2.59	2.20	2.66	2.65	1.00

Table 5.7 Summary of composition of 57 laboratory-produced mixtures designed to contain 6.5% of entrained air

Mixture number	**Materials**					
	Cement	**Fly ash**	**Silica fume**	**Fine aggregate**	**Coarse aggregate**	**Water**
1 to 2	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
3	390 lbs/yd^3	107 lbs/yd^3	38lbs/yd^3	1243 lbs/yd^3	1858 lbs/yd^3	219 lbs/yd^3
4 to 5	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1776 lbs/yd^3	246 lbs/yd^3
6 to 7	390 lbs/yd^3	186 lbs/yd^3	44lbs/yd^3	1171 lbs/yd^3	1750 lbs/yd^3	254 lbs/yd^3
8 to 10	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
11 to 12	390 lbs/yd^3	107 lbs/yd^3	38lbs/yd^3	1243 lbs/yd^3	1858 lbs/yd^3	219 lbs/yd^3
13	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1776 lbs/yd^3	246 lbs/yd^3
14	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1750 lbs/yd^3	254 lbs/yd^3
15 to 16	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
17	390 lbs/yd^3	107 lbs/yd^3	38lbs/yd^3	1243 lbs/yd^3	1858 lbs/yd^3	219 lbs/yd^3
18	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1776 lbs/yd^3	246 lbs/yd^3
19	390 lbs/yd^3	186 lbs/yd^3	44lbs/yd^3	1171 lbs/yd^3	1750 lbs/yd^3	254 lbs/yd^3
20 to 25	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1776 lbs/yd^3	246 lbs/yd^3

Table 5.7 (*continued*)

Mixture Number	Materials					
	Cement	Fly ash	Silica fume	Fine aggregate	Coarse aggregate	Water
26	658 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3	1233 lbs/yd^3	1629 lbs/yd^3	283 lbs/yd^3
27 to 28	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3
29	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
30 to 31	390 lbs/yd^3	107 lbs/yd^3	38lbs/yd^3	1243 lbs/yd^3	1858 lbs/yd^3	219 lbs/yd^3
32	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1776 lbs/yd^3	246 lbs/yd^3
33	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1774 lbs/yd^3	246 lbs/yd^3
34	390 lbs/yd^3	186 lbs/yd^3	44lbs/yd^3	1171 lbs/yd^3	1750 lbs/yd^3	254 lbs/yd^3
35	390 lbs/yd^3	186 lbs/yd^3	44lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3
36	658 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3	1233 lbs/yd^3	1627 lbs/yd^3	283 lbs/yd^3
37 to 38	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
39 to 40	390 lbs/yd^3	107 lbs/yd^3	38 lbs/yd^3	1243 lbs/yd^3	1858 lbs/yd^3	219 lbs/yd^3
41	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1774 lbs/yd^3	246 lbs/yd^3
42	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3
43	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1878 lbs/yd^3	213 lbs/yd^3
44	390 lbs/yd^3	107 lbs/yd^3	38 lbs/yd^3	1243 lbs/yd^3	1856 lbs/yd^3	219 lbs/yd^3
45	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1774 lbs/yd^3	246 lbs/yd^3
46	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3
47	390 lbs/yd^3	107 lbs/yd^3	38 lbs/yd^3	1243 lbs/yd^3	1856 lbs/yd^3	219 lbs/yd^3
48	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3
49	658 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3	1233 lbs/yd^3	1627 lbs/yd^3	283 lbs/yd^3
50 to 51	390 lbs/yd^3	104 lbs/yd^3	26 lbs/yd^3	1257 lbs/yd^3	1876 lbs/yd^3	213 lbs/yd^3
52 to 53	390 lbs/yd^3	107 lbs/yd^3	38 lbs/yd^3	1243 lbs/yd^3	1856 lbs/yd^3	219 lbs/yd^3
54 to 55	390 lbs/yd^3	180 lbs/yd^3	30 lbs/yd^3	1189 lbs/yd^3	1774 lbs/yd^3	246 lbs/yd^3
56 to 57	390 lbs/yd^3	186 lbs/yd^3	44 lbs/yd^3	1171 lbs/yd^3	1748 lbs/yd^3	254 lbs/yd^3

The unit weights and air contents of these mixtures were measured following the procedures of AASHTO (T 121 and T 152, respectively). Once determined, these parameters were subsequently used for determination of the actual w/c. Table 5.8 shows the measured unit weights and air contents, batched w/c and the actual w/c as well as the values of Δw/c (differences between the batched and actual w/c).

Table 5.8 Measured unit weights (AASHTO T 121), air contents (AASHTO T 152), batched w/c, actual w/c and Δw/c of the 57 laboratory produced mixtures

Mixture Number	AASHTO T 121 Measured Unit Weight (lbs/yd^3)	AASHTO T 152 Measured Air Content (%)	Batched w/c	Actual w/c	Δw/c
1	3918	5.9	0.410	0.377	+0.033
2	3893	6.5	0.410	0.376	+0.034
3	3845	6.9	0.410	0.402	+0.008
4	3883	5.0	0.410	0.398	+0.012
5	3834	6.2	0.410	0.397	+0.013
6	3742	7.9	0.410	0.405	+0.005
7	3802	6.4	0.410	0.407	+0.003
8	3869	6.9	0.410	0.386	+0.024
9	3866	6.6	0.410	0.406	+0.004
10	3850	6.8	0.410	0.417	-0.007
11	3861	6.6	0.410	0.397	+0.013
12	3818	7.0	0.410	0.432	-0.022
13	3791	7.1	0.410	0.405	+0.005
14	3812	6.5	0.410	0.390	+0.020
15	3912	5.9	0.410	0.384	+0.026
16	3872	6.5	0.410	0.404	+0.006
17	3848	6.7	0.410	0.409	+0.000
18	3850	6.0	0.410	0.388	+0.022
19	3818	6.5	0.410	0.384	+0.026
20	3845	6.3	0.410	0.380	+0.030
21	3839	6.1	0.410	0.396	+0.014
22	3883	5.3	0.410	0.384	+0.026
23	3904	4.2	0.410	0.410	+0.000
24	3926	4.1	0.410	0.388	+0.022
25	3969	3.4	0.410	0.372	+0.038
26	3764	6.8	0.430	0.459	-0.029
27	3796	6.0	0.410	0.429	-0.019
28	3775	6.0	0.410	0.454	-0.044
29	3823	7.3	0.410	0.425	-0.015
30	3829	5.8	0.410	0.481	-0.071
31	3839	6.7	0.410	0.420	-0.010
32	3796	7.0	0.410	0.403	+0.007
33	3818	6.5	0.410	0.400	+0.010
34	3818	6.2	0.410	0.398	+0.012
35	3839	5.9	0.410	0.385	+0.025
36	3764	6.7	0.430	0.461	-0.032
37	3804	8.0	0.410	0.412	-0.002
38	3856	6.9	0.410	0.404	+0.006
39	3893	6.4	0.410	0.366	+0.044
40	3861	6.6	0.410	0.397	+0.013
41	3775	6.7	0.410	0.441	-0.031
42	3775	6.1	0.410	0.449	-0.039
43	3875	6.8	0.410	0.384	+0.026

Table 5.8 (*continued*)

Mixture Number	AASHTO T 121 Measured Unit Weight (lbs/yd^3)	AASHTO T 152 Measured Air Content (%)	Batched w/c	Actual w/c	Δw/c
44	3829	7.1	0.410	0.405	+0.005
45	3775	6.7	0.410	0.441	-0.031
46	3710	7.2	0.410	0.473	-0.063
47	3883	6.0	0.410	0.399	+0.011
48	3721	7.0	0.410	0.470	-0.060
49	3742	6.7	0.430	0.485	-0.055
50	3861	6.0	0.410	0.443	-0.033
51	3893	5.6	0.410	0.422	-0.012
52	3818	6.7	0.410	0.445	-0.035
53	3775	7.0	0.410	0.485	-0.075
54	3818	5.9	0.410	0.428	-0.018
55	3796	6.0	0.410	0.449	-0.039
56	3775	6.0	0.410	0.454	-0.044
57	3753	6.5	0.410	0.455	-0.045

As an example, the procedure to determine the actual w/c of mixture number 1 (from Table 5.8) using AASHTO determined unit weight will be described. Since the composition of each of the mixtures from set 2 was different then the composition of mixtures used in set 1, a unique unit weight-w/c relationship needed to be first established for each of the mixtures. The data for the development of this relationship for mixture number 1 were taken from Table 5.6 and are summarized in Table 5.9.

Table 5.9 Basic composition of mixtures number 1

Target air content =		6.5%	
w/c =		0.410	
Material	**Specific gravity**	**Weight lbs/yd^3**	**Volume ft^3**
Cement	3.15	390	1.988
Fly ash	2.59	104	0.645
Silica fume	2.20	26	0.190
Fine aggregate, SSD	2.656 (SG_{FA})	1256.5 (SG_{FA})	7.597
Coarse aggregate, SSD	2.646 (SG_{FA})	1877.7 (SG_{FA})	11.396
Water	1.00	213.2	3.424
Air	N/A	0	1.76
Total =		3867.4 lbs/yd^3	27 ft^3

By changing the amount of water in the basic composition of mixture number 1 (Table 5.4) while keeping the value of air content constant, the weight of all concrete ingredients as well as the w/c and unit weight of concrete 1 will be altered (i.e., new mixture designs will be created). These new compositions, along with the new values of w/c and unit weight, are listed in Table 5.10. The incremental changes in the amount of water (ΔW_w) used to create new mixtures were -13, -7, 0, +7 and +13 lbs with respect to the basic amount of 213.2 lbs of water. The resulting weights of concrete ingredients (cement W_{ct}”, fly ash W_{fa}”, silica fume W_{sf}”, fine W_{FA}” and coarse W_{CA}” aggregates and water W_w”) per yd^3 of concrete with a = 0.065 air are calculated using Equations 4.8 through 4.13. The values of w/c of altered mixtures represent the weight of water over the weight of total cementitious materials (W_{ct}” + W_{fa}” + W_{sf}”). The unit weights of 1 cubic yard of the altered mixtures were obtained by adding up the weights of all concrete ingredients (W_{ct}” + W_{fa}” + W_{sf}” + W_{FA}” + W_{CA}” + W_w”).

Table 5.10 Calculated compositions of altered batches of mixture number 1

Material	Specific gravity	Amount of air (a= 0.065)									
		Change in the amount of water (ΔW_w, lbs) with respect to the basic mix									
		-13		-7		0		7		13	
		w/c of altered mixture									
		0.385		0.397		0.410		0.424		0.435	
		Composition, volumes and unit weights of altered batches									
		Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3
Cement	3.15	393	0.074	392	0.074	390	0.074	388	0.073	387	0.073
Fly ash	2.59	105	0.024	104	0.024	104	0.024	104	0.024	103	0.024
Silica fume	2.20	26	0.007	26	0.007	26	0.007	26	0.007	26	0.007
Fine agg.	2.656	1267	0.284	1262	0.283	1257	0.281	1251	0.280	1246	0.279
Coarse agg.	2.646	1893	0.426	1886	0.424	1878	0.422	1869	0.420	1862	0.419
Water	1.00	202	0.120	207	0.123	213	0.127	219	0.130	224	0.133
Air	N/A	0	0.065	0	0.065	0	0.065	0	0.065	0	0.065
Sum		3887	1	3878	1	3867	1	3857	1	3849	1
Unit weight UW, (lbs/yd^3)		3887 (UW_2)		3878 (UW_2)		3867 (UW_1)		3857 (UW_2)		3824 (UW_2)	

By utilizing the altered w/c and unit weights data from Table 5.10, the correlation between these two variables was established using linear regression analysis. The resulting linear relationship is represented by Equation 5.14:

$$W/C = -0.0013172 \cdot UW_2 + 5.505 \quad (5.14)$$

The next step in the process of determination of the actual w/c of mixture number 1 was the correction for the differences in the air content of this mixture (5.9% as shown in Table 5.8) and the design air content (6.5%). In the case of this mixture, the specific gravities of aggregates as batched and as specified for basic mix were the same; hence, the value of $UW_{6.5\%}$ did not require further adjustment to account for the differences between the batched specific gravities of aggregates (Table 5.7) and those used in the basic mix design (Table 5.9). As a result, ΔUW_1 is equal to zero and UW_2 is equal to $UW_{6.5\%}$. The calculation of $UW_{6.5\%}$ for mixture number 1 is shown below. This correction was accomplished using Equation 4.18.

$$UW_2 = UW_{6.5\%} = \frac{3918 \, {ft^3}/{yd^3}}{(1-0.059)} \cdot (1-0.065) = 3893 \, {lbs}/{yd^3}$$

Finally, the actual w/c was determined using the adjusted (UW_2) as an input into Equation 5.14 as shown below:

$$W/C = -0.0013172 \cdot 3898 + 5.505 = 0.377$$

As can be seen, the resulting actual w/c of mixture number 1 determined by using AASHTO measured unit weight is 0.377, which is 0.033 lower than the w/c based on the batched weights.

5.2. Determination of W/C of Hardened Concrete

The verification of applicability of the unit weight method for determination of the w/c of hardened concrete was performed using the cylinders made from a small subset (7 mixtures with codes CS1 to CS7) of Group I of the original set of 60 mixtures (see Figure 5.1). The general approach of using unit weight for w/c determination utilized in this part of the study was the same as that previously described in Section 5.1. However, the actual values of unit weights and air contents were determined using hardened rather than fresh specimens of concrete. The SSD unit weights of concrete were measured following AASHTO T 642 (AASHTO, 2006b) whereas the air contents were determined using the ASTM C 457 method (ASTM, 2008). Once determined, the measured unit weights were adjusted using Equation 4.18 to the level corresponding to 6.5% of air ($UW_{6.5\%}$). It should be noted that $UW_{6.5\%}$ did not require further adjustment to account for the difference between the batched specific gravities of aggregates and those used for the basic mix because in the case of this mixture, the specific gravities of aggregates as batched and as specified for basic mix were the same. Finally, the adjusted measured unit weights ($UW_2 = UW_{6.5\%}$) were used as inputs into Equation 4.14 for determination of actual w/c.

Table 5.11 summarizes the values of measured unit weights, air contents, unit weights adjusted to the level with 6.5% air content, batched and actual w/c as well as Δw/c (the differences between batched and actual w/c). The value of each AASHTO T 642 unit weight presented in Table 5.11 is the average of the measurement of four concrete cylinders. The value of each ASTM C 457 air content presented in Table 5.11 is based on the modified point count measurements of air content performed on rectangular specimen with an area of ~17.5 in^2 prepared by polishing one half of a longitudinally cut cylinder.

Table 5.11 Unit weights, air contents and w/c values of hardened concrete

Mixture code	CS1	CS2	CS3	CS4	CS5	CS6	CS7
AASHTO T 642 Measured unit weight, lbs/yd^3	4058	4015	3988	3953	3969	3924	3873
AASHTO T 457 Measured air content	1.4%	1.1%	1.5%	0.6%	0.8%	0.4%	0.1%
Unit weight with 6.5% air, lbs/yd^3 ($UW_2 = UW_{6.5\%}$)	3846	3794	3784	3717	3741	3683	3625
Batched w/c	0.4	0.45	0.5	0.55	0.6	0.7	0.8
Actual w/c	0.402	0.457	0.468	0.538	0.513	0.574	0.635
Δw/c = w/c batched – w/c actual	-0.002	-0.007	+0.032	+0.012	+0.087	+0.126	+0.165

5.3. Sensitivity of Compressive Strength to W/C Variations

In order to evaluate how the observed differences in w/c values resulting from the use of unit weight methods described earlier influence concrete strength, the w/c-compressive strength relationship was established based on Abram's Law (Equation 5.15). In Equation 5.15, the symbols A and B represent the constants and *f'c* represents the compressive strength.

$$f'c = \frac{A}{B^{w/c}} \qquad (5.15)$$

The linear form of Equation 5.15 is presented in Equation 5.16 as:

$$\log\left(f'c\right) = \log\left(A\right) - \frac{w}{c}\log\left(B\right) \qquad (5.16)$$

The specimens used to develop the w/c-compressive strength relationship were prepared mixtures with codes CS2 to CS7 shown in Table 5.1. Two 4x8 in. cylinders were prepared from each mixture. The specimens were standard cured in a moist room for 28 days and were then tested following the AASHTO T 22 method (AASHTO, 2007). The results of the compressive strength test are shown in Table 5.12.

Table 5.12 28 days compressive strength results for concretes with different w/c values

W/C	Compressive strength, psi		Averaged compressive strength (f'c), psi	log(f'c)
	Specimen 1	Specimen 2		
0.45	7500	7450	7480	3.873902
0.50	6520	6760	6640	3.822168
0.55	5920	5490	5710	3.756636
0.60	5310	5820	5570	3.745855
0.70	4610	4770	4690	3.671173
0.80	3620	3680	3650	3.562293

In order to determine constants A and B for the Abram's equation, the log values of the compressive strength from Table 5.12 are plotted in Figure 5.3 as a function of the w/c.

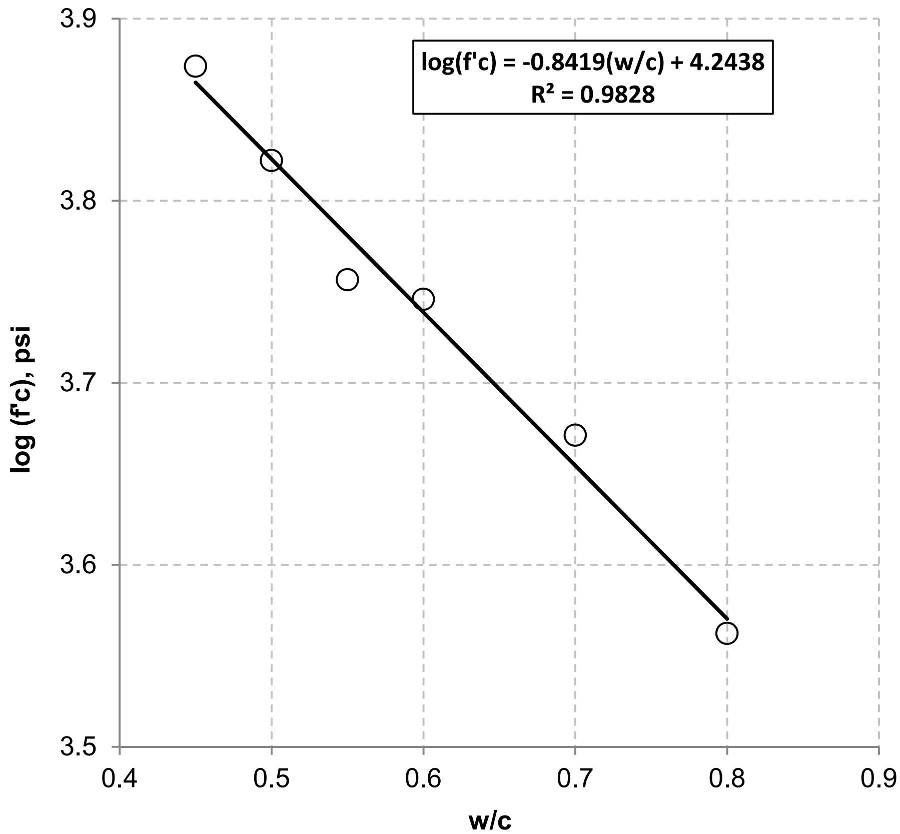


Figure 5.3 The plot of log(f'c) versus w/c values for (4x8 in.) concrete cylinders moist-cured for 28 days

The regression analysis of the data shown in Figure 5.3 resulted in the following linear relationship (with the $R^2 = 0.9828$):

$$\log(f'c) = -0.8419 \cdot (w/c) + 4.2438$$

After substituting the numerical coefficients from the above relationship for the variables in Equation 5.16, the values of A and B coefficients can be calculated as shown below.

$$\log(A) = 4.2438$$

$$\log(B) = 0.8419$$

$$A = 17526.694$$

$$B = 6.950$$

Using the above calculated values of A and B as inputs in Equation 5.15, the final form of Abram's relationship for these mixtures can be obtained as shown in Equation 5.17. These results are also plotted in Figure 5.4.

$$f'c, psi = \frac{17526.694}{6.950^{w/c}} \tag{5.17}$$

The predicted values of compressive strength calculated using Equation 5.17 for specimens corresponding to those in Table 5.12 are presented in Table 5.13.

Table 5.13 Predicted compressive strengths using Equation 5.16

W/C	The average of compressive strength (f'c), psi	Predicted f'c
0.45	7480	7325
0.50	6640	6648
0.55	5710	6034
0.60	5570	5476
0.70	4690	4511
0.80	3650	3716

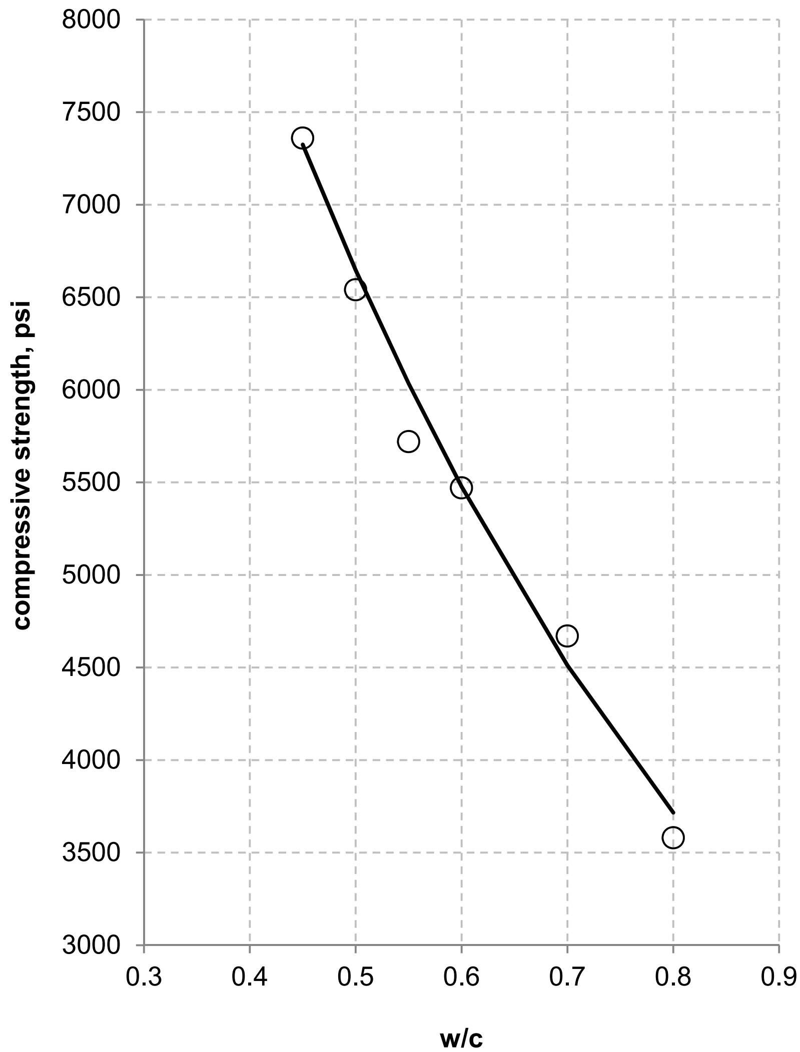


Figure 5.4 The W/C-compressive strength correlation for concrete cylinder (4x8 in.) moist-cured for 28 days

5.4. Summary

Two distinctive sets of mixtures were used for laboratory verification of applicability of the unit weight method for w/c determination. The unit weights of the first set of mixtures were measured following the "zero air" procedure that was developed as a part of this study. The differences (Δw/c) between the laboratory batched and actual w/c values for this group of mixtures are plotted in Figure 5.5. It can be seen from this figure that most of differences between batched and actual w/c are in the range of ± 0.025 or about 6% of the batched value (in fact only four data points are outside this range). It should be noted that because of the differences in obtaining a representative sample, the results for mixtures CS6 and CS7 were excluded from the data set.

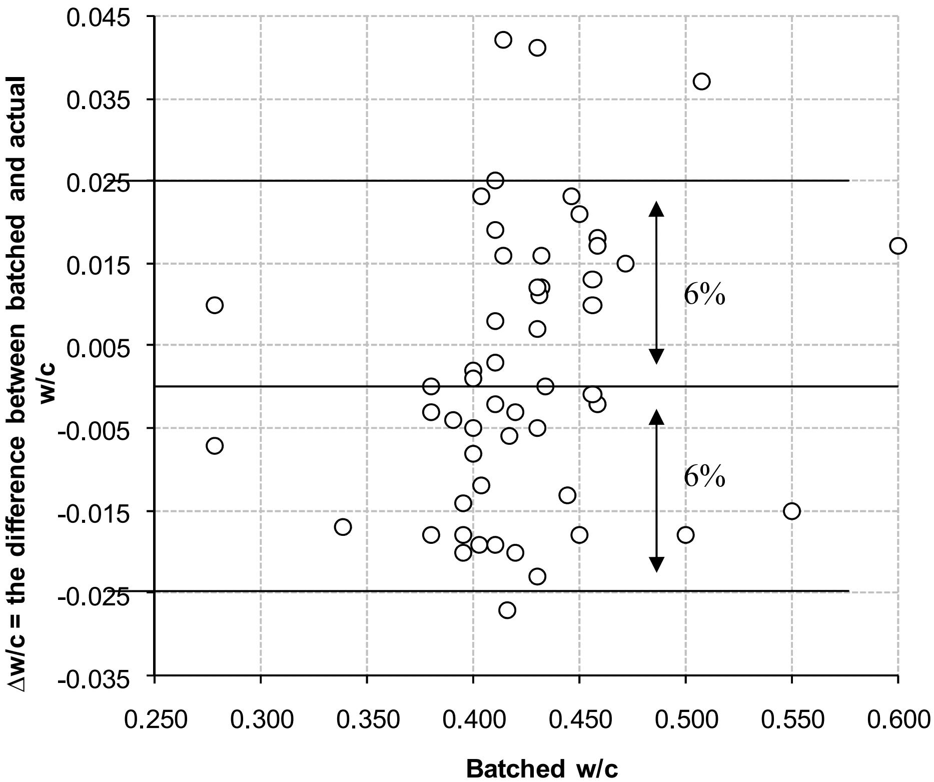


Figure 5.5 The differences between batched and actual w/c (determined using ZAP based unit weight) values for the set of 58 different mixtures

The unit weight and air content of the second group of mixtures were determined following the procedures of AASHTO T 121 (AASHTO, 2005a) and T 152 (AASHTO, 2005b), respectively. The differences (Δw/c) between the batched and the measured (actual) w/c values for this group of mixtures are presented in Figure 5.6. It can be seen that in 8 out of 57 cases, the value of the differences between batched and actual w/c is outside of the range of -0.040 to +0.040 with 7 out of 8 values being located on the negative side of the -0.04 line. It is also interesting to note that the AASHTO mixture overestimated the w/c of the only 3 plots analyzed in the second set of concretes.

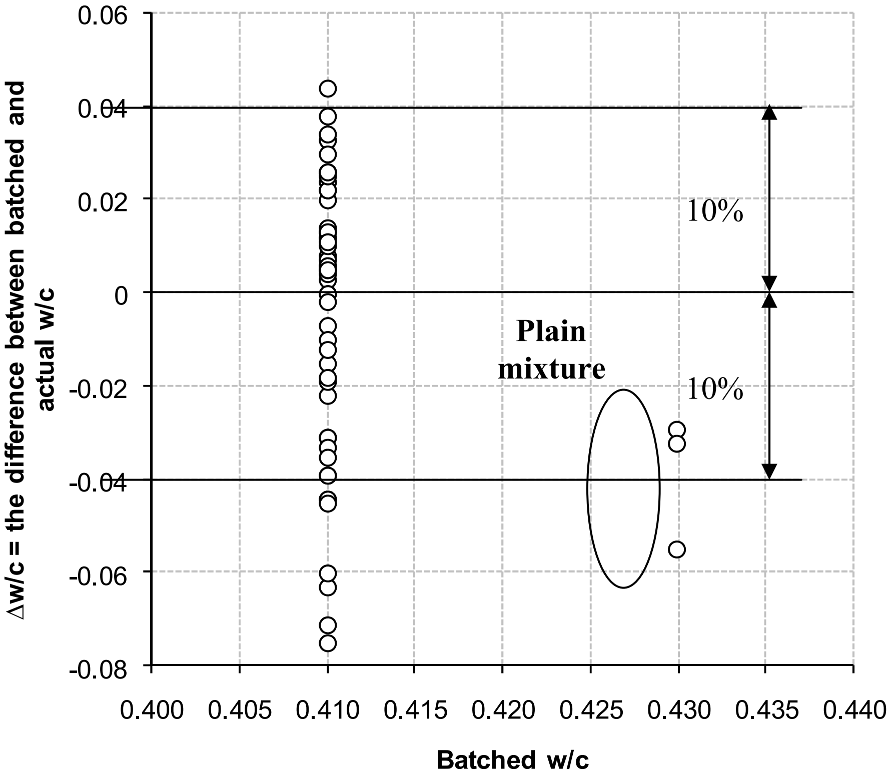


Figure 5.6 The differences (Δw/c) between the batched and actual (determined using AASHTO measured unit weight) w/c values for the second set of 57 mixtures

Table 5.14 summarizes the absolute minimum and absolute maximum values, absolute average values, standard error values, standard deviation values and 95th percentile of the absolute Δw/c for both the first and the second set of mixtures. The standard error is calculated using Equation 5.17 (Dowell and Cramer, 2002). The average, standard deviation (the square root of variance (σ^2)), and 95th percentile were obtained using an integrated distribution fitting tool in Matlab® (see details in Appendix D).

$$SE = \sqrt{\frac{\sum\left(batched\ {}^{w}\!/_{c} - actual\ {}^{w}\!/_{c}\right)^2}{n}} \tag{5.17}$$

Where,

SE = standard error

n = number of tests

Table 5.14 Minimum and maximum values, absolute average, standard error, standard deviation and 95th percentile of Δw/c obtained during laboratory verification

Method used to measure unit weight and air content	Absolute minimum of Δw/c	Absolute maximum of Δw/c	Absolute average of Δw/c	Standard error of Δw/c	Standard deviation of Δw/c	95th percentile of Δw/c
Zero air procedure (ZAP)	0.000	0.042	0.014	0.017	0.009	0.030
AASHTO T 121 and T 152	0.000	0.075	0.024	0.030	0.018	0.054

Note: The results presented in Table 5.14 for "zero-air" procedure do not include data from mixtures CS6 and CS7 as these mixtures were difficult to sample due to their high w/c values and tendencies to segregate.

In addition to the verification of the applicability of the unit weight method for the determination of the w/c of fresh concrete, the verification of the applicability of this method for the determination of the actual w/c of hardened concrete was also verified. This verification was performed using the cylinders made from a small subset (7 mixtures, CS1 until CS7) of Group I of the original set of 60 mixtures. The unit weights and air contents tests for these specimens were performed following the AASHTO T 642 (AASHTO, 2006b) and ASTM C 457 (ASTM, 2008) method, respectively.

Although this may seemingly imply that the ZAP approach is more accurate, such conclusion would not be appropriate as each unit weight determination method was applied to a different set of concretes. While the ZAP was used with plain, non-air-entrained mixtures, the AASHTO method was used with mixtures which were all air-entrained and which all except three contained supplementary cementitious materials.

Table 5.15 shows the batched and measured (actual) w/c values as well as Δw/c for these specimens. Based on the measured values of Δw/c listed in the table, it seems that the use of the unit weight method for determination of the w/c of hardened concrete is not very accurate for mixtures with high batched w/c values (0.600 and higher). However, this method seems to work reasonably well for mixtures with low (less than 0.600) values of w/c. For these cases, the percent differences ranged from 14 to 20 and the observed accuracy ranged from -0.002 to +0.032.

Table 5.15 Batched and actual w/c as well as Δw/c for seven hardened concrete specimens

Mixture code	CS1	CS2	CS3	CS4	CS5	CS6	CS7
Batched w/c	0.4	0.45	0.5	0.55	0.6	0.7	0.8
Measured (actual) w/c	0.402	0.457	0.468	0.538	0.513	0.574	0.635
Δw/c	-0.002	-0.007	+0.032	+0.012	+0.087	+0.126	+0.165
Δw/c as % of the batched w/c	0.5%	1.5%	6.4%	2.0%	14.5%	18.0%	20.6%

The w/c-compressive strength relationship was established in Section 5.3 and is presented in Equation 5.17. By using this equation and knowing the 95th percentile of Δw/c obtained from the unit weight method for fresh concrete, the range of 28 days compressive strengths can be approximated. As an example, when the ZAP based unit weight indicates the actual w/c of 0.420, the value of batched w/c is in the range of 0.390 to 0.450 (0.042 ± 0.030). Using Equation 5.17 to estimate the differences in w/c values, the 0.390 to 0.450 w/c range corresponds to the 28 days compressive strength range of 7325 to 8228 psi. The compressive strength of 7325 psi is 439 psi (or about 6%) lower than the f'c of concrete with w/c of 0.420, which is 7764 psi.

Unfortunately, similar analyses were not performed for the second set of mixtures (tested using AASHTO methods) since Equation 5.17 was developed for plain, air free mixtures and is therefore not applicable to mixtures which are air entrained and contain supplementary cementitious materials.

CHAPTER 6. VERIFICATION OF THE APPLICABILITY OF AASHTO BASED UNIT WEIGHT METHOD TO DETERMINE W/C VALUE OF FRESH FIELD CONCRETES

This chapter presents data on the verification of the applicability of the AASHTO-based unit weight method to determine the w/c of fresh field concrete using two groups of concretes. The first group included concretes from 22 different INDOT projects. For each of the concretes, the following data has been collected and made available for the analysis:

a. design mixture composition (CMD)
b. unit weights and air contents (determined using AASHTO procedure)
c. w/c values calculated using ITM-403 procedure
d. 28 days compressive strengths

In addition, for this group of mixtures the data also included the batched specific gravities of fine and coarse aggregates used in the field concretes. The second group included 89 concrete mixtures from an I-94 project in Northern Indiana. The data for this set of concretes was collected by the contractor and included the following:

a. design mixture composition (CMD)
b. unit weights and air contents (determined using AASHTO procedure)
c. estimated values of w/c (estimated based on visual observation of the degree of wetness)
d. flexural strength

The measured unit weight and air content values were combined with the CMD data and used to determine the actual w/c values for both group of mixtures using the unit weight method. Once determined, these w/c values were plotted against the corresponding strength data for concretes in each of these two groups in order to determine if reasonable trends can be observed.

6.1. Use of the Data from 22 INDOT Mixtures

This section presents the results of the verification of the applicability of the unit weight method for the determination of the w/c of fresh concrete using the data gathered for 22 of INDOT's mixtures. These data were obtained from the trial batch demonstrations of various QC/QA superstructure concretes. The analysis of these data is divided into two subsections. Section 6.1.1 describes the process of determination of the actual values of w/c whereas Section 6.1.2 presents the relationship between the 28 days compressive strength and the determined actual w/c.

6.1.1. *Determination of Actual W/C Values for the Group of 22 INDOT Mixtures*

The determination of the actual w/c values for the group of 22 INDOT mixtures was performed following the unit weight method described in Chapter 4 which can be summarized as follows:

1. In the first step, the unit weight-w/c relationship was established using the CMD composition as the base.

2. Next, the measured unit weight was adjusted to account for possible differences in specific gravities of aggregates and air contents between the batched and CMD compositions.
3. Finally, the actual w/c was determined by using the value of adjusted measured unit weight as an input into the unit weight-w/c relationship developed in the first step.

A more detailed summary and the results of these three steps of the procedures for the determination of actual w/c of 22 INDOT mixtures are provided in Sections 6.1.1.1 through 6.1.1.3. Section 6.1.1.3 also includes the analysis of the differences between the batched w/c and actual w/c (determined using the unit weight method) as well as the differences between batched and ITM-403-calculated w/c. In Section 6.1.1.4, an example of the calculation of the results of these three steps is provided by describing the determination of the actual w/c of one of the 22 INDOT mixtures using the unit weight method.

6.1.1.1. Establishment of the Unit Weight-W/C Relationships

The unit weight-w/c relationships for 22 of INDOT's mixtures were established following the method presented in Section 4.1. The data required to establish unit weight-w/c relationships included the weights and specific gravities of concrete ingredients as well as the air content data specified for the basic mixture (CMD). These data are shown in Tables 6.1 (weights of concrete ingredients) and 6.2 (specific gravities of the materials). All 22 mixtures have been designed at a constant air content of 6.5%. The final versions of the unit weight-w/c relationships established for these 22 mixtures are summarized in Table 6.3.

Table 6.1 The CMD weights of concrete ingredients for the group of 22 INDOT mixtures

Project No.	Material				
	Cement	Fly ash	Fine aggregate	Coarse aggregate	Water
1	659 lbs/yd^3	0 lbs/yd^3	1145 lbs/yd^3	1769 lbs/yd^3	267 lbs/yd^3
2	650 lbs/yd^3	100 lbs/yd^3	1144 lbs/yd^3	1674 lbs/yd^3	280 lbs/yd^3
3	659 lbs/yd^3	0 lbs/yd^3	1136 lbs/yd^3	1808 lbs/yd^3	260 lbs/yd^3
4	659 lbs/yd^3	0 lbs/yd^3	1136 lbs/yd^3	1808 lbs/yd^3	260 lbs/yd^3
5	659 lbs/yd^3	0 lbs/yd^3	1136 lbs/yd^3	1808 lbs/yd^3	260 lbs/yd^3
6	532 lbs/yd^3	100 lbs/yd^3	1176 lbs/yd^3	1769 lbs/yd^3	253 lbs/yd^3
7	658 lbs/yd^3	0 lbs/yd^3	1174 lbs/yd^3	1723 lbs/yd^3	263 lbs/yd^3
8	659 lbs/yd^3	0 lbs/yd^3	1129 lbs/yd^3	1808 lbs/yd^3	257 lbs/yd^3
9	533 lbs/yd^3	91 lbs/yd^3	1198 lbs/yd^3	1755 lbs/yd^3	259 lbs/yd^3
10	607 lbs/yd^3	0 lbs/yd^3	1231 lbs/yd^3	1804 lbs/yd^3	239 lbs/yd^3
11	539 lbs/yd^3	76 lbs/yd^3	1204 lbs/yd^3	1804 lbs/yd^3	246 lbs/yd^3
12	659 lbs/yd^3	0 lbs/yd^3	1148 lbs/yd^3	1778 lbs/yd^3	257 lbs/yd^3
13	615 lbs/yd^3	0 lbs/yd^3	1210 lbs/yd^3	1812 lbs/yd^3	246 lbs/yd^3
14	659 lbs/yd^3	0 lbs/yd^3	1148 lbs/yd^3	1778 lbs/yd^3	257 lbs/yd^3
15	659 lbs/yd^3	0 lbs/yd^3	1148 lbs/yd^3	1762 lbs/yd^3	264 lbs/yd^3
16	659 lbs/yd^3	0 lbs/yd^3	1234 lbs/yd^3	1674 lbs/yd^3	254 lbs/yd^3
17	659 lbs/yd^3	0 lbs/yd^3	1234 lbs/yd^3	1674 lbs/yd^3	254 lbs/yd^3
18	600 lbs/yd^3	100 lbs/yd^3	1136 lbs/yd^3	1730 lbs/yd^3	277 lbs/yd^3
19	659 lbs/yd^3	0 lbs/yd^3	1162 lbs/yd^3	1794 lbs/yd^3	250 lbs/yd^3
20	658 lbs/yd^3	0 lbs/yd^3	1309 lbs/yd^3	1652 lbs/yd^3	254 lbs/yd^3
21	658 lbs/yd^3	0 lbs/yd^3	1309 lbs/yd^3	1652 lbs/yd^3	254 lbs/yd^3
22	506 lbs/yd^3	185 lbs/yd^3	1082 lbs/yd^3	1759 lbs/yd^3	276 lbs/yd^3

Table 6.2 The CMD specific gravities of materials used in the 22 INDOT mixtures

Project No.	Specific Gravity of Materials				
	Cement	Fly ash	Fine aggregate	Coarse aggregate	Water
1	3.15	N/A	2.61	2.69	1
2	3.15	2.62	2.68	2.70	1
3	3.15	N/A	2.64	2.69	1
4	3.15	N/A	2.64	2.69	1
5	3.15	N/A	2.64	2.69	1
6	3.15	2.72	2.64	2.65	1
7	3.15	N/A	2.67	2.61	1
8	3.15	N/A	2.62	2.68	1
9	3.15	2.65	2.63	2.68	1
10	3.15	N/A	2.63	2.68	1
11	3.15	2.60	2.68	2.67	1
12	3.15	N/A	2.60	2.68	1
13	3.15	N/A	2.68	2.67	1
14	3.15	N/A	2.60	2.68	1
15	3.15	N/A	2.61	2.67	1
16	3.15	N/A	2.65	2.60	1
17	3.15	N/A	2.65	2.60	1
18	3.15	2.59	2.67	2.71	1
19	3.15	N/A	2.61	2.69	1
20	3.15	N/A	2.68	2.66	1
21	3.15	N/A	2.68	2.66	1
22	3.15	2.91	2.66	2.65	1

Table 6.3 The unit weight-w/c relationships for the group of 22 INDOT mixtures

Project No.	Developed unit weight-w/c relationship	Project No.	Developed unit weight-w/c relationship
1	$W/C = -0.0010588\ UW_2 + 4.473$	12	$W/C = -0.0010580\ UW_2 + 4.457$
2	$W/C = -0.0010484\ UW_2 + 3.917$	13	$W/C = -0.0011137\ UW_2 + 4.726$
3	$W/C = -0.0010484\ UW_2 + 4.447$	14	$W/C = -0.0010580\ UW_2 + 4.457$
4	$W/C = -0.0010484\ UW_2 + 4.447$	15	$W/C = -0.0010626\ UW_2 + 4.474$
5	$W/C = -0.0017671\ UW_2 + 4.447$	16	$W/C = -0.0010684\ UW_2 + 4.469$
6	$W/C = -0.0011056\ UW_2 + 4.620$	17	$W/C = -0.0010684\ UW_2 + 4.469$
7	$W/C = -0.0010633\ UW_2 + 4.459$	18	$W/C = -0.0009890\ UW_2 + 4.197$
8	$W/C = -0.0010532\ UW_2 + 4.450$	19	$W/C = -0.0010475\ UW_2 + 4.431$
9	$W/C = -0.0011218\ UW_2 + 4.720$	20	$W/C = -0.0010382\ UW_2 + 4.407$
10	$W/C = -0.0011304\ UW_2 + 4.782$	21	$W/C = -0.0010382\ UW_2 + 4.407$
11	$W/C = -0.0011202\ UW_2 + 4.736$	22	$W/C = -0.0010245\ UW_2 + 4.303$

6.1.1.2. Adjustment of the Measured Unit Weight

The adjustment of the measured unit weight can be accomplished using a two-step process. The first step involves the conversion of each measured unit weight (UW_a) of the 22 INDOT mixtures to the unit weight representing concrete with a = 0.065 air. This converted unit weight is labeled as $UW_{6.5\%}$ and was calculated using Equation 4.18. In the second step, the values of $UW_{6.5\%}$ were further adjusted to account for the differences between the batched specific gravities of aggregates and those specified for the basic mix (CMD). This was accomplished by subtracting ΔUW_1 (calculated using Equation 4.34) from $UW_{6.5\%}$. The result of this subtraction is the final adjusted unit weight, UW_2, where $UW_2 = UW_{6.5\%} - \Delta UW_1$ (as per Equation 4.36). This adjusted value can, in turn, be used to determine the w/c value of fresh concrete using a previously established w/c-unit weight relationship for the basic mix.

The measured unit weights and air contents for the group of 22 INDOT mixtures are shown in Table 6.4. The field measurements of unit weight and air content were performed by three different parties (INDOT, a contractor and a third party) except for mixtures from projects number 11, 12 and 13. For these mixtures, the measurements were performed by INDOT and a contractor only. Table 6.5 shows the target (CMD) and the batched specific gravity values for aggregates used in field mixtures. It can be seen that the maximum differences between the target (CMD) and batched specific gravity values were 0.03 for fine aggregate (project No. 19) and 0.07 for coarse aggregate (projects No. 16 and 17). Table 6.6 summarizes the values of $UW_{6.5\%}$, ΔUW_1 and UW_2 for all 22 INDOT mixtures.

Table 6.4 Measured unit weights and air contents for the group of 22 INDOT mixtures

Project No.	AASHTO T 121 Measured unit weight			AASHTO T 152 Measured air content		
	Contractor Rep.	**INDOT Rep.**	**Third Party**	**Contractor Rep.**	**INDOT Rep.**	**Third Party**
1	3789 lbs/yd^3	3791 lbs/yd^3	3791 lbs/yd^3	8.7%	8.0%	8.1%
2	3831 lbs/yd^3	3834 lbs/yd^3	3834 lbs/yd^3	6.7%	6.3%	6.2%
3	3810 lbs/yd^3	3766 lbs/yd^3	3807 lbs/yd^3	7.3%	8.9%	8.4%
4	3965 lbs/yd^3	3931 lbs/yd^3	3945 lbs/yd^3	4.3%	5.0%	4.8%
5	3715 lbs/yd^3	3694 lbs/yd^3	3704 lbs/yd^3	8.7%	10.0%	10.1%
6	3861 lbs/yd^3	3910 lbs/yd^3	3834 lbs/yd^3	6.8%	6.8%	7.3%
7	3826 lbs/yd^3	3861 lbs/yd^3	3861 lbs/yd^3	7.2%	6.9%	6.5%
8	3817 lbs/yd^3	3819 lbs/yd^3	3835 lbs/yd^3	7.2%	7.7%	7.4%

Table 6.4 (*continued*)

Project No.	AASHTO T 121 Measured unit weight			AASHTO T 152 Measured air content		
	Contractor Rep.	INDOT Rep.	Third Party	Contractor Rep.	INDOT Rep.	Third Party
9	3873 lbs/yd^3	3884 lbs/yd^3	3877 lbs/yd^3	7.2%	7.3%	6.9%
10	3801 lbs/yd^3	3787 lbs/yd^3	3827 lbs/yd^3	8.2%	8.9%	8.1%
11	3787 lbs/yd^3	3762 lbs/yd^3	N/A	8.5%	8.9%	N/A
12	3875 lbs/yd^3	3885 lbs/yd^3	N/A	6.3%	5.9%	N/A
13	3796 lbs/yd^3	3814 lbs/yd^3	N/A	8.4%	8.1%	N/A
14	3836 lbs/yd^3	3859 lbs/yd^3	3861 lbs/yd^3	6.6%	6.5%	6.5%
15	3776 lbs/yd^3	3784 lbs/yd^3	3782 lbs/yd^3	7.5%	7.8%	8.0%
16	3865 lbs/yd^3	3905 lbs/yd^3	3853 lbs/yd^3	5.8%	5.6%	5.8%
17	3841 lbs/yd^3	3872 lbs/yd^3	3850 lbs/yd^3	6.4%	5.8%	6.0%
18	3812 lbs/yd^3	3839 lbs/yd^3	3818 lbs/yd^3	7.4%	6.7%	7.0%
19	3762 lbs/yd^3	3775 lbs/yd^3	3818 lbs/yd^3	9.4%	9.4%	8.6%
20	3923 lbs/yd^3	3926 lbs/yd^3	3934 lbs/yd^3	5.4%	5.7%	5.1%
21	3896 lbs/yd^3	3885 lbs/yd^3	3888 lbs/yd^3	5.8%	6.3%	5.6%
22	3786 lbs/yd^3	3835 lbs/yd^3	3841 lbs/yd^3	7.1%	7.3%	5.8%

Table 6.5 Summary of the CMD specified and batched values of specific gravities of fine and coarse aggregates for the group of 22 INDOT mixtures

Project No.	SSD Specific Gravity			
	CMD values		As Batched values	
	Fine aggregate (SG_{FA})	Coarse aggregate (SG_{CA})	Fine aggregate (SG'_{FA})	Coarse aggregate (SG'_{CA})
1	2.61	2.69	2.62	2.71
2	2.68	2.70	2.68	2.70
3	2.64	2.69	2.63	2.71
4	2.64	2.69	2.63	2.71
5	2.64	2.69	2.63	2.71
6	2.64	2.65	2.64	2.67
7	2.67	2.61	2.66	2.65
8	2.62	2.68	2.62	2.66
9	2.63	2.68	2.63	2.68
10	2.63	2.68	2.63	2.68
11	2.68	2.67	2.68	2.67
12	2.60	2.68	2.60	2.68
13	2.68	2.67	2.68	2.67
14	2.60	2.68	2.60	2.68
15	2.61	2.67	2.61	2.67
16	2.65	2.60	2.65	2.67

Table 6.5 (*continued*)

Project No.	SSD Specific Gravity			
	CMD values		As Batched values	
	Fine aggregate (SG_{FA})	Coarse aggregate (SG_{CA})	Fine aggregate (SG'_{FA})	Coarse aggregate (SG'_{CA})
17	2.65	2.60	2.65	2.67
18	2.67	2.71	2.66	2.75
19	2.61	2.69	2.64	2.70
20	2.68	2.66	2.68	2.66
21	2.68	2.66	2.68	2.66
22	2.66	2.65	2.66	2.65

Table 6.6 The $UW_{6.5\%}$, ΔUW_1 and UW_2 values for 22 INDOT mixtures

Project No.	Air content adjusted unit weight ($UW_{6.5\%}$)			Project No.	Air content adjusted unit weight ($UW_{6.5\%}$)		
	Contractor Rep.	INDOT Rep.	Third Party		Contractor Rep.	INDOT Rep.	Third Party
1	3880 lbs/yd^3	3853 lbs/yd^3	3857 lbs/yd^3	12	3867 lbs/yd^3	3860 lbs/yd^3	N/A
2	3840 lbs/yd^3	3826 lbs/yd^3	3822 lbs/yd^3	13	3875 lbs/yd^3	3881 lbs/yd^3	N/A
3	3843 lbs/yd^3	3866 lbs/yd^3	3886 lbs/yd^3	14	3840 lbs/yd^3	3859 lbs/yd^3	3861 lbs/yd^3
4	3874 lbs/yd^3	3868 lbs/yd^3	3875 lbs/yd^3	15	3816 lbs/yd^3	3837 lbs/yd^3	3844 lbs/yd^3
5	3804 lbs/yd^3	3837 lbs/yd^3	3852 lbs/yd^3	16	3836 lbs/yd^3	3868 lbs/yd^3	3824 lbs/yd^3
6	3874 lbs/yd^3	3922 lbs/yd^3	3867 lbs/yd^3	17	3837 lbs/yd^3	3843 lbs/yd^3	3829 lbs/yd^3
7	3855 lbs/yd^3	3878 lbs/yd^3	3861 lbs/yd^3	18	3850 lbs/yd^3	3848 lbs/yd^3	3839 lbs/yd^3
8	3847 lbs/yd^3	3869 lbs/yd^3	3873 lbs/yd^3	19	3882 lbs/yd^3	3896 lbs/yd^3	3906 lbs/yd^3
9	3902 lbs/yd^3	3917 lbs/yd^3	3893 lbs/yd^3	20	3877 lbs/yd^3	3892 lbs/yd^3	3876 lbs/yd^3
10	3871 lbs/yd^3	3887 lbs/yd^3	3893 lbs/yd^3	21	3867 lbs/yd^3	3877 lbs/yd^3	3851 lbs/yd^3
11	3870 lbs/yd^3	3861 lbs/yd^3	N/A	22	3810 lbs/yd^3	3868 lbs/yd^3	3813 lbs/yd^3

Project No.	ΔUW_1			Project No.	ΔUW_1		
	Contractor Rep.	INDOT Rep.	Third Party		Contractor Rep.	INDOT Rep.	Third Party
1	7 lbs/yd^3	7 lbs/yd^3	7 lbs/yd^3	12	0 lbs/yd^3	0 lbs/yd^3	N/A
2	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3	13	0 lbs/yd^3	0 lbs/yd^3	N/A
3	3 lbs/yd^3	3 lbs/yd^3	3 lbs/yd^3	14	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3
4	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3	15	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3
5	3 lbs/yd^3	3 lbs/yd^3	3 lbs/yd^3	16	23 lbs/yd^3	23 lbs/yd^3	23 lbs/yd^3
6	13 lbs/yd^3	13 lbs/yd^3	13 lbs/yd^3	17	23 lbs/yd^3	23 lbs/yd^3	23 lbs/yd^3
7	22 lbs/yd^3	22 lbs/yd^3	22 lbs/yd^3	18	24 lbs/yd^3	24 lbs/yd^3	24 lbs/yd^3
8	-7 lbs/yd^3	-7 lbs/yd^3	-7 lbs/yd^3	19	11 lbs/yd^3	11 lbs/yd^3	11 lbs/yd^3
9	-2 lbs/yd^3	-2 lbs/yd^3	-2 lbs/yd^3	20	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3
10	-2 lbs/yd^3	-2 lbs/yd^3	-2 lbs/yd^3	21	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3
11	0 lbs/yd^3	0 lbs/yd^3	N/A	22	0 lbs/yd^3	0 lbs/yd^3	0 lbs/yd^3

Table 6.6 (*continued*)

Project No.	Final adjusted measured unit weight (UW_2)			Project No.	Final adjusted measured unit weight (UW_2)		
	Contractor Rep.	INDOT Rep.	Third Party		Contractor Rep.	INDOT Rep.	Third Party
1	3873 lbs/yd^3	3846 lbs/yd^3	3850 lbs/yd^3	12	3867 lbs/yd^3	3860 lbs/yd^3	N/A
2	3840 lbs/yd^3	3826 lbs/yd^3	3822 lbs/yd^3	13	3875 lbs/yd^3	3881 lbs/yd^3	N/A
3	3840 lbs/yd^3	3863 lbs/yd^3	3883 lbs/yd^3	14	3840 lbs/yd^3	3859 lbs/yd^3	3861 lbs/yd^3
4	3874 lbs/yd^3	3868 lbs/yd^3	3875 lbs/yd^3	15	3816 lbs/yd^3	3837 lbs/yd^3	3844 lbs/yd^3
5	3801 lbs/yd^3	3834 lbs/yd^3	3849 lbs/yd^3	16	3813 lbs/yd^3	3845 lbs/yd^3	3801 lbs/yd^3
6	3861 lbs/yd^3	3909 lbs/yd^3	3854 lbs/yd^3	17	3814 lbs/yd^3	3820 lbs/yd^3	3806 lbs/yd^3
7	3833 lbs/yd^3	3856 lbs/yd^3	3839 lbs/yd^3	18	3826 lbs/yd^3	3824 lbs/yd^3	3815 lbs/yd^3
8	3854 lbs/yd^3	3876 lbs/yd^3	3880 lbs/yd^3	19	3871 lbs/yd^3	3885 lbs/yd^3	3895 lbs/yd^3
9	3904 lbs/yd^3	3919 lbs/yd^3	3895 lbs/yd^3	20	3877 lbs/yd^3	3892 lbs/yd^3	3876 lbs/yd^3
10	3873 lbs/yd^3	3889 lbs/yd^3	3895 lbs/yd^3	21	3867 lbs/yd^3	3877 lbs/yd^3	3851 lbs/yd^3
11	3870 lbs/yd^3	3861 lbs/yd^3	N/A	22	3810 lbs/yd^3	3868 lbs/yd^3	3813 lbs/yd^3

6.1.1.3. Determination of W/C

The process of determination of the actual w/c of 22 INDOT mixtures using the unit weight method involves the use of final adjusted measured unit weights presented in Section 6.1.1.2 (UW_2 in Table 6.6) as inputs into the unit weight-w/c relationships shown in Table 6.3, Section 6.1.1.1. For the groups of 22 INDOT mixtures studied, three actual w/c values for each mixture were determined using the unit weight and air content data measured by INDOT, a contractor and a third party, with the exception of the mixtures from projects number 11, 12 and 13. For those three projects, only two actual w/c values for each mixture were determined; one value was determined using the unit weight and air content data measured by INDOT and the second using values determined by the contractor.

Table 6.7 summarizes both the actual (as determined using unit weight measured by INDOT, a contractor and a third party) and batched w/c values, and also lists the differences between them for all 22 INDOT mixtures. The differences between batched w/c and actual w/c determined using the unit weights measured by a contractor, INDOT and a third party are symbolized by Δw/cCont, Δw/cINDOT and Δw/cTp, respectively. The plots of these differences are shown in Figure 6.1.

Table 6.7 Actual and batched w/c values and their differences

Project No.	Determined actual w/c based on measured unit weights from:			Batched w/c (4)	Δw/cCont (4)-(1)	Δw/cINDOT (4)-(2)	Δw/cTp (4)-(3)
	Cont. (1)	INDOT (2)	Third Party (3)				
1	0.374	0.403	0.399	0.405	0.031	0.002	0.006
2	0.381	0.394	0.398	0.373	-0.008	-0.021	-0.025
3	0.421	0.397	0.376	0.395	-0.026	-0.002	0.019
4	0.386	0.391	0.384	0.395	0.009	0.004	0.011
5	0.462	0.427	0.412	0.395	-0.067	-0.032	-0.017
6	0.367	0.313	0.374	0.400	0.033	0.087	0.026
7	0.383	0.359	0.377	0.400	0.017	0.041	0.023
8	0.391	0.367	0.363	0.390	-0.001	0.023	0.027
9	0.340	0.323	0.350	0.415	0.075	0.092	0.065
10	0.406	0.388	0.381	0.394	-0.012	0.006	0.013
11	0.401	0.411	N/A	0.400	-0.001	-0.011	N/A
12	0.366	0.373	N/A	0.390	0.024	0.017	N/A
13	0.411	0.404	N/A	0.400	-0.011	-0.004	N/A
14	0.394	0.374	0.372	0.390	-0.004	0.016	0.018
15	0.419	0.397	0.390	0.401	-0.018	0.004	0.011
16	0.395	0.361	0.407	0.385	-0.010	0.024	-0.022
17	0.394	0.388	0.402	0.385	-0.009	-0.003	-0.017
18	0.410	0.408	0.419	0.396	-0.012	-0.014	-0.023
19	0.375	0.361	0.350	0.379	0.004	0.018	0.029
20	0.381	0.366	0.383	0.386	0.005	0.020	0.003
21	0.392	0.382	0.409	0.386	-0.006	0.004	-0.023
22	0.400	0.341	0.397	0.399	-0.001	0.058	0.002

In general, the differences between the INDOT's and the third party data appear to be smaller than between any of the other combination of results (see also Figure 6.1). In addition, the data from these two groups appear to show the same trends. This suggest that the contractor's data was somewhat biased, perhaps due to lack of calibration of the air meter or due to inconsistencies in performing the test.

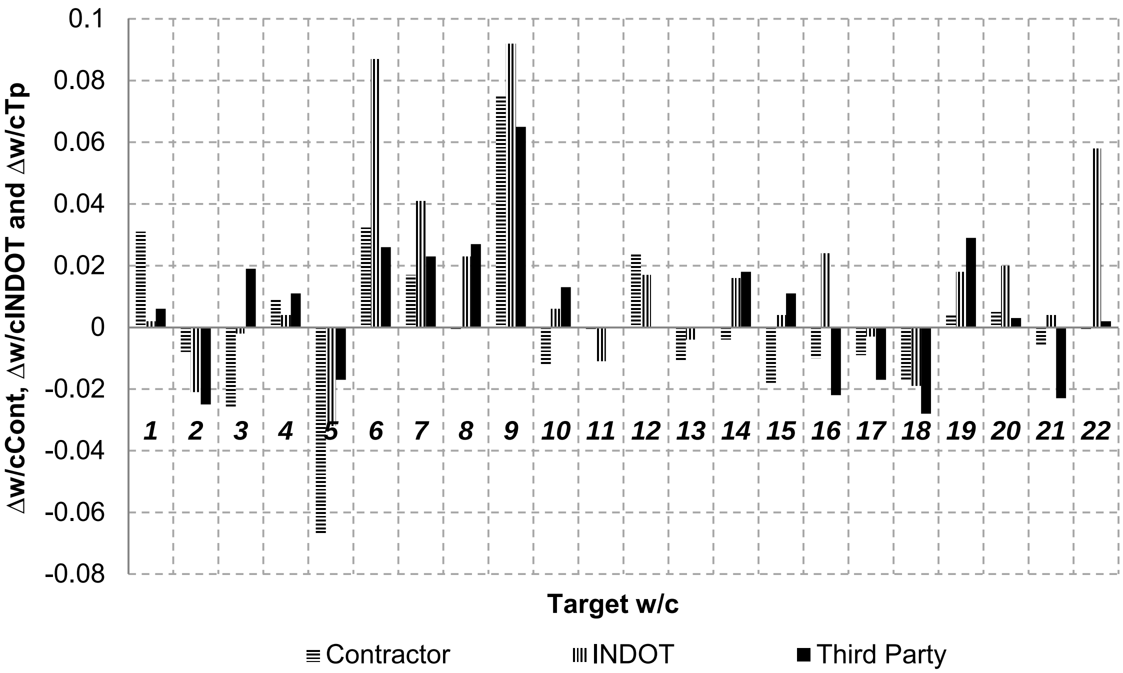


Figure 6.1 Plots of the values of Δw/cCont, Δw/cINDOT and Δw/cTp against the number of projects

Since the w/c differences (Δw/c) shown in Figure 6.1 were calculated using measurements obtained from the same mixture by three different and independent operators, it was assumed that if one of these differences was significantly higher or lower than the remaining two, it would be considered an outlier and thus eliminated from further analysis. Typically, it was relatively easy to make the decision as to which of the values shown in Figure 6.1 should be eliminated. However, in one case (mixture #9), all three values were eliminated as their differences from the batched w/c were much higher compared to the other mixtures. In general, the differences between the INDOT's and the third party data appear to be

Figure 6.2 shows the plots of the differences between actual (as determined using the unit weight method) w/c for individual projects after the outliers have been eliminated. As can be seen, all but two values of the differences are within the range of ±0.030 and none of differences are outside the range of ±0.040.

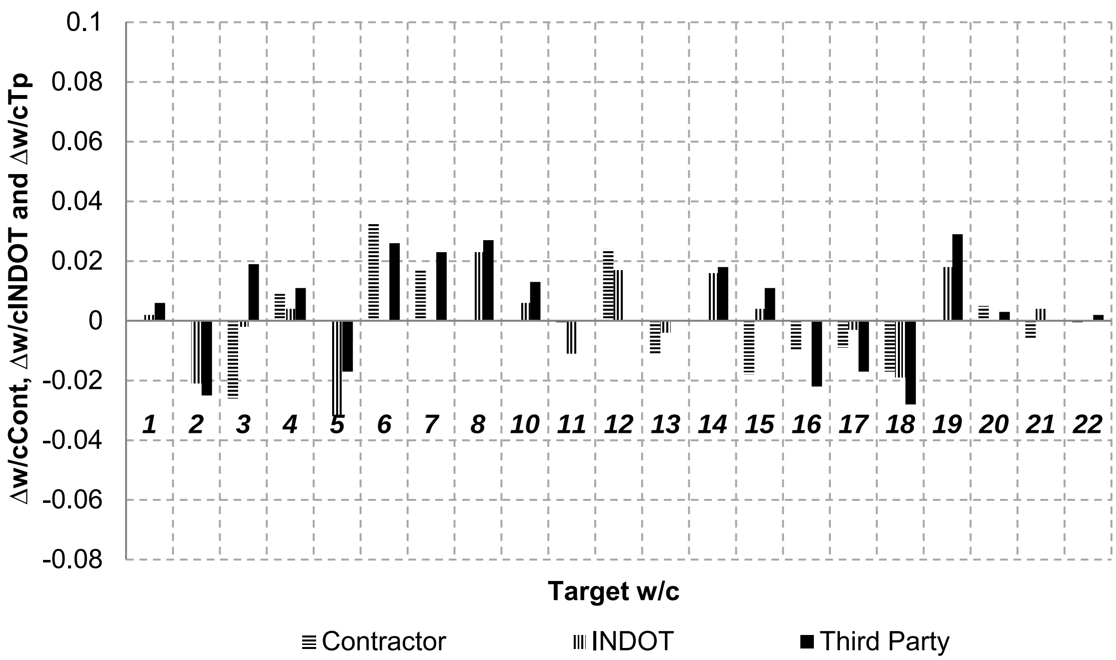


Figure 6.2 Plots of the differences between determined (without those that are assumed to be outliers) and batched w/c against the number of projects

The final value of the determined w/c for each mixture was calculated as an average of the w/c values obtained from the unit weight measurements by the three operators (without the outliers) and is shown in Table 6.8 as w/c (1). In addition, Table 6.5 also shows the ITM-403-calculated w/c and batched w/c for each of the 22 INDOT mixtures. The ITM-403-calculated w/c was obtained following INDOT's Test Methods (ITM 403-08P, 2008) which are summarized in the next paragraph. Finally, Table 6.8 also shows the values of Δw/c1 and Δw/c2 which represents the differences between the batched and final determined w/c values (Δw/c1) and the differences between the batched and ITM-403-calculated w/c values (Δw/c2), respectively.

The ITM 403 (ITM 403-08P, 2008) test method allows for determination of the water-cementitious ratio of a representative batch of concrete to ensure compliance with the specifications. The procedure involves determination of the total free water in a concrete mixture and dividing it by the total weight of cement (or cementitious material) obtained from the batch ticket. The total free water of a concrete mixture is the actual amount of water added after being corrected for the amount of water either expelled or absorbed by the aggregates as the result of using aggregates that were not in the saturated surface dry (SSD) condition. The typical worksheet for the computation of ITM-403-calculated w/c is included in Appendix C.

Table 6.8 The actual, the ITM-403-calculated and batched w/c plus the values of Δw/c1 and Δw/c2 for 22 INDOT mixtures

Project No.	Actual w/c determined based on measured unit weights from:			Final determined w/c [avg.(A+B+C)] (1)	ITM-403-calculated w/c (2)	Batched w/c (3)	Δw/c1 (3)-(1)	Δw/c2 (3)-(2)
	Cont. (A)	INDOT (B)	Third Party (C)					
1	0.374 (outlier)	0.403	0.399	0.401	0.408	0.405	0.004	-0.003
2	0.381(outlier)	0.394	0.398	0.396	0.384	0.373	-0.023	-0.011
3	0.421	0.397	0.376	0.398	0.400	0.395	-0.003	-0.005
4	0.386	0.391	0.384	0.387	0.401	0.395	0.008	-0.006
5	0.462 (outlier)	0.427	0.412	0.420	0.401	0.395	-0.025	-0.006
6	0.367	0.313 (outlier)	0.374	0.371	0.397	0.400	0.030	0.003
7	0.383	0.359 (outlier)	0.377	0.380	0.385	0.400	0.020	0.015
8	0.391 (outlier)	0.367	0.363	0.365	0.382	0.390	0.025	0.008
9	0.340 (outlier)	0.323 (outlier)	0.350 (outlier)	N/A	0.393	0.415	N/A	0.022
10	0.406 (outlier)	0.388	0.381	0.385	0.395	0.394	0.010	-0.001
11	0.401	0.411	N/A	0.406	0.404	0.400	-0.006	-0.004
12	0.366	0.373	N/A	0.370	0.374	0.390	0.021	0.016
13	0.411	0.404	N/A	0.408	0.413	0.400	-0.007	-0.013
14	0.394 (outlier)	0.374	0.372	0.373	0.390	0.390	0.017	0.000
15	0.419	0.397	0.390	0.402	0.415	0.401	-0.001	-0.014
16	0.395	0.361 (outlier)	0.407	0.401	0.387	0.385	-0.016	-0.002
17	0.394	0.388	0.402	0.395	0.381	0.385	-0.010	0.004
18	0.408	0.410	0.419	0.412	0.407	0.396	-0.016	-0.011
19	0.375 (outlier)	0.361	0.350	0.356	0.389	0.379	0.024	-0.010
20	0.381	0.366 (outlier)	0.383	0.382	0.388	0.386	0.004	-0.002
21	0.392	0.382	0.409 (outlier)	0.387	0.383	0.386	-0.001	0.003
22	0.400	0.341 (outlier)	0.397	0.399	0.398	0.399	0.001	0.001

Figure 6.3 shows the final determined w/c (based on field measured unit weights) and ITM-403-calculated w/c plotted against the batched w/c. It can be observed that the width of the range of differences between batched and final determined w/c (Δw/c1) is greater than the width of the range of differences between batched and ITM-403-calculated w/c (Δw/c2). Figure 6.4 shows the plots of these differences (Δw/c1 and Δw/c2) against the batched w/c. It can be observed that the overall width of the Δw/c1 band is about ±0.030 whereas the width of the Δw/c2 is about ±0.020. The narrower band observed for Δw/c2 may be related to the fact that determination of this value depends only on the accuracies of the measurements of weights,

moisture contents and absorptions of aggregates as well as weights of cement and water added. On the other hand, Δw/c1 depends on the accuracy of determination of w/c using the accuracy of the unit weight which, in turn, involves the accuracy of the measurements of specific gravity and of the weight of each concrete ingredient and measurement of the air content.

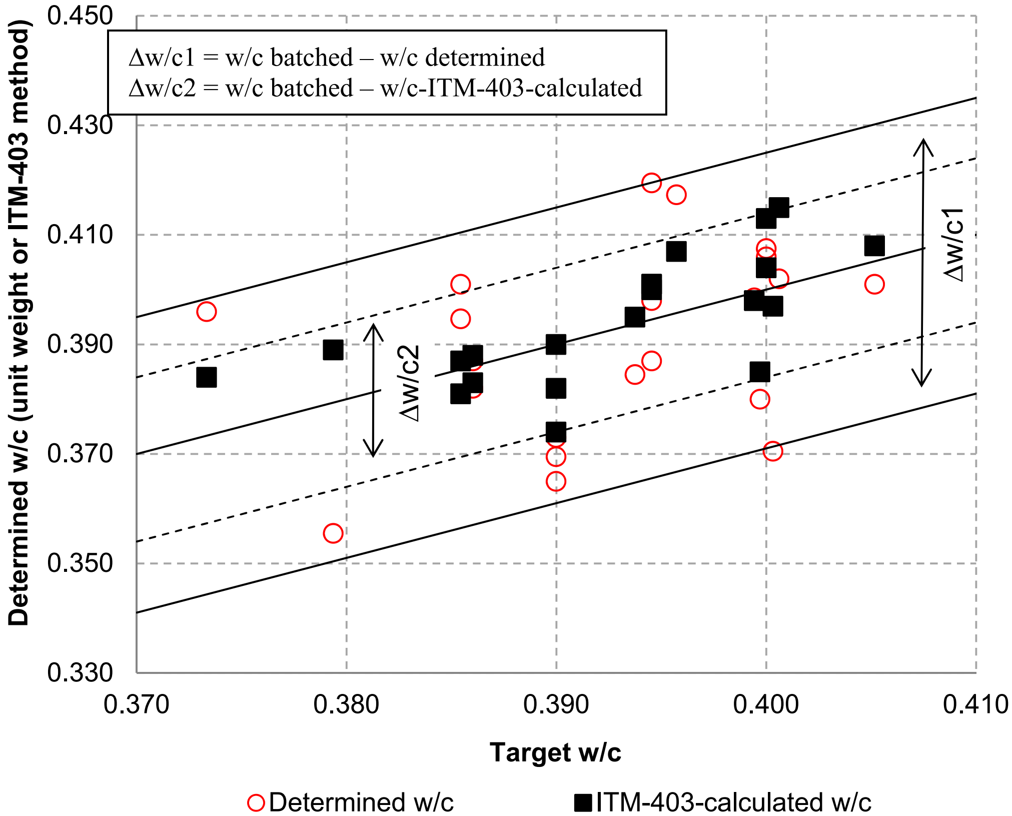


Figure 6.3 Final determined and ITM-403-calculated w/c vs. batched w/c

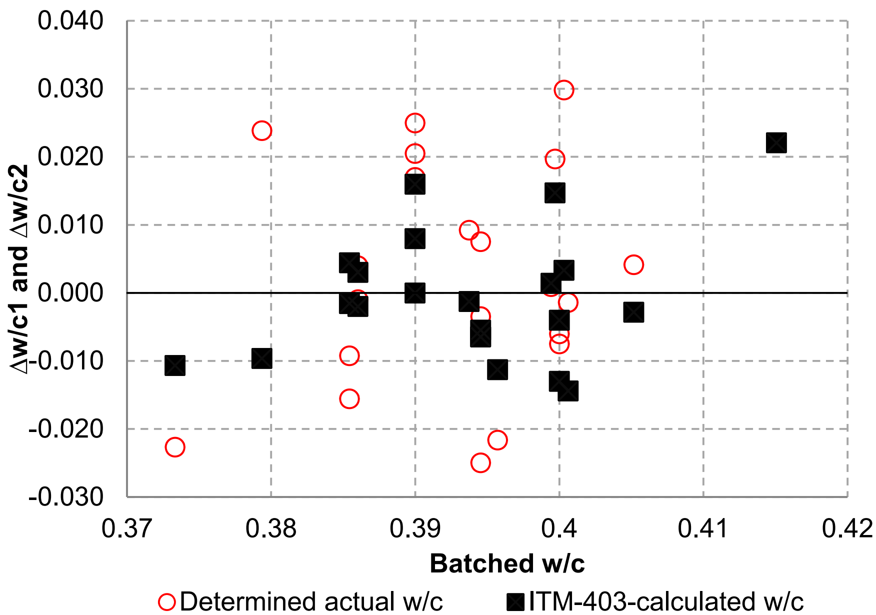


Figure 6.4 Differences of determined (Δw/c1) and ITM-403-calculated (Δw/c2) w/c from batched w/c

6.1.1.4. Calculation of the Determined W/C Value

In order to provide a more specific explanation of the procedure for calculation of the determined w/c values, a numerical example is presented for the mixture from project #18.

The final determined w/c of the mixture from project number 18 was obtained by first establishing the unit weight-w/c relationship. The data for the development of this relationship were taken from Tables 6.1 and 6.2 and are summarized in Table 6.9.

Table 6.9 Basic composition of mixture for project number 18

Target air content =		6.5%	
w/c =		0.396	
Material	**Specific gravity**	**Weight lbs/yd^3**	**Volume ft^3**
Cement	3.15	600	3.06
Fly ash	2.59	100	0.62
Fine aggregate, SSD	2.67 (SG_{FA})	1136 (W_{FA})	6.84
Coarse aggregate, SSD	2.71 (SG_{CA})	1730 (W_{CA})	10.27
Water	1.00	277	4.45
Air	N/A	0	1.76
Total =		3843 lbs/yd^3 (UW_1)	27 ft^3

As the first step, the basic proportions of the mixture listed in Table 6.9 were altered by changing the original weight of water (277 lbs/yd^3) by an arbitrarily selected amount (ΔW_w) as listed in Table 6.10. In total, four different values of ΔW_w were selected (-13 lbs, -7 lbs, +7 lbs, +13 lbs), thus resulting in four new mixture designs (compositions). These new compositions, along with the corresponding new values of w/c and unit weights, are also listed in Table 6.10. The weights of concrete ingredients in these newly designed mixtures (cement-W_{ct}", fly ash-W_{fa}", fine aggregate-W_{FA}" and coarse aggregate-W_{CA}" and water-W_w") per yd^3 of concrete where a = 0.065 air were calculated using Equations 4.8 through 4.13. The values of the w/c of altered mixtures represent the weight of water over the weight of total cementitious materials (W_{ct}" + W_{fa}"). The unit weights of 1 cubic yard of the altered mixtures were obtained by adding up the weights of all concrete ingredients (W_{ct}" + W_{fa}" + W_{FA}" + W_{CA}" + W_w").

Table 6.10 Compositions of altered batches of project number 18

Material	Specific gravity	**Amount of air (a= 6.5 %)**									
		Change in the amount of water (ΔW_w, lbs)									
		-13		-7		0		7		13	
		w/c of altered batch									
		0.377		0.386		0.396		0.406		0.414	
		Composition volumes and unit weights of altered batches									
		Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3
Cement	3.15	605	0.114	603	0.114	600	0.113	597	0.113	595	0.112
Fly ash	2.59	101	0.023	100	0.023	100	0.023	100	0.023	99	0.023
Fine agg.	2.57	1145	0.265	1141	0.264	1136	0.263	1131	0.262	1127	0.261
Coarse agg.	2.71	1744	0.383	1738	0.381	1730	0.380	1722	0.378	1716	0.377
Water	1.00	266	0.159	271	0.161	277	0.165	283	0.168	288	0.171
Air	N/A	0	0.065	0	0.065	0	0.065	0	0.065	0	0.065
Sum		3862	1	3853	1	3843	1	3833	1	3824	1
Unit weight UW, (lbs/yd^3)		3862 (UW_2)		3853 (UW_2)		3843 (UW_1)		3833 (UW_2)		3824 (UW_2)	

By utilizing the w/c and unit weight data from Table 6.10, the relationship between these two variables was established using linear regression analysis (see Equation 6.1).

$$W/C = -0.0009890 \cdot UW_2 + 4.197 \quad (6.1)$$

The next step in the process of calculating the determined w/c of the mixture for project number 18 was the correction of unit weights shown in Table 6.4 (as measured by a contractor, INDOT and a third party) for the differences in the measured air content of this mixture and the design air content (6.5%). These corrected unit weights are labeled as $UW_{6.5\%}$ (see Table 6.6) and were calculated using Equation 4.18. Afterward, the values of $UW_{6.5\%}$ were further adjusted to account for the differences between the specific gravities of batched aggregates (2.66 for fine aggregate and 2.75 for coarse aggregate as shown in Table 6.5) and those specified in CMD for project number 18 (see Table 6.9). This correction was accomplished by subtracting ΔUW_1 (calculated using Equation 4.34) from $UW_{6.5\%}$. The result of this subtraction was the final adjusted unit weight, UW_2 (see Table 6.11) where $UW_2 = UW_{6.5\%} - \Delta UW_1$ (as per Equation 4.36). Finally, using these UW_2 values as inputs for Equation 6.1, the determined w/c values were calculated (see the last column of Table 6.11).

Table 6.11 Determined water-cement ratio of project number 18

Representative	Air content adjusted unit weight ($UW_{6.5\%}$)	ΔUW_1	Adjusted unit weight (UW_2)	Determined w/c value
Contractor	3850 lbs/yd^3	19 lbs/yd^3	3831 lbs/yd^3	w/c = -0.0009890•3831 + 4.197 = 0.408
INDOT	3848 lbs/yd^3	19 lbs/yd^3	3829 lbs/yd^3	w/c = -0.0009890•3829 + 4.197 = 0.410
Third party	3839 lbs/yd^3	19lbs/yd^3	3820 lbs/yd^3	w/c = -0.0009890•3820 + 4.197 = 0.419

The following section presents a numerical example of the previously described adjustments and calculation of the determined w/c value steps:

1. Correction of measured unit weight to account for the air content differences (performed using Equation 4.18).

$$UW_{6.5\%} = \frac{3839\, {}^{lbs}\!/\!{}_{yd^3}}{(1-0.067)} \cdot (1-0.065) = 3848\, {}^{lbs}\!/\!{}_{yd^3}$$

2. Calculation of ΔUW_1 to adjust the value of $UW_{6.5\%}$ for the possible differences in specific gravities of aggregates (performed using Equation 4.34). The values of SG_{FA}, SG_{CA}, W_{FA}, W_{CA}, *a* and UW_1 were obtained from Table 6.9 (CMD for mix #18). The values of SG'_{FA} and SG'_{CA} were obtained from Table 6.5.

$$\Delta UW_1 = 3848 \cdot \left[\frac{(1-0.065)}{(1-0.065) + \frac{1136}{62.27 \cdot 27} \cdot \left(\frac{1}{2.66} - \frac{1}{2.67} \right) + \frac{1730}{62.27 \cdot 27} \cdot \left(\frac{1}{2.75} - \frac{1}{2.71} \right)} - 1 \right]$$

$$\Delta UW_1 = 19\, {}^{lbs}\!/\!{}_{yd^3}$$

3. Calculation of the final adjusted measured unit weight (UW_2) using Equation 4.36.

$$UW_2 = UW_{6.5\%} - \Delta UW1 = 3848\, {}^{lbs}\!/\!{}_{yd^3} - 19\, {}^{lbs}\!/\!{}_{yd^3} = 3829\, {}^{lbs}\!/\!{}_{yd^3}$$

This value of UW_2 was then used as an input in Equation 6.1 to calculate the value of determined w/c based on unit weight provided by the contractor. The result of this calculation yields the value of w/c = 0.410 (see Table 6.11). The other two values of w/c (using, data from INDOT and a third party, respectively) were calculated in a similar manner. After the calculation of all three values of w/c, the values were averaged to yield the final determined w/c = 0.412= average of (0.410+0.408+0.419). Although the quality of these three sets of data is likely not the same, since all of them carry a certain error the process of averaging will likely result in greater randomization of these errors.

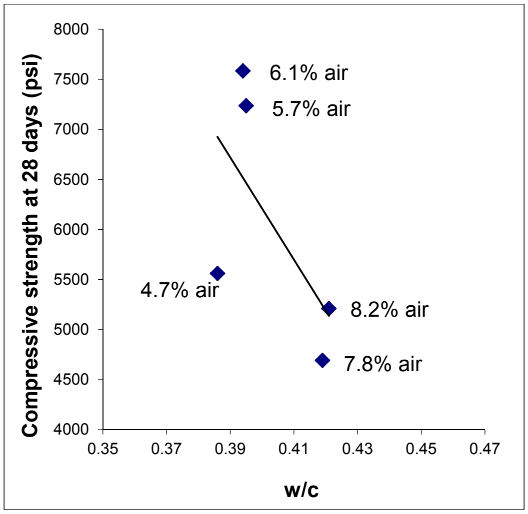
6.1.2. *Plot of 28 Days Compressive Strength against W/C of INDOT's Mixtures*

For projects number 1, 3, 4, 5, 8, 14, 15, 16, and 17, the values of determined w/c, the final determined w/c, the ITM-403-calculated w/c, and the batched w/c were plotted against the 28 days compressive strengths in order to evaluate if reasonable trends exist between these parameters. These projects were chosen because they have similar compositions. The determined actual w/c, final determined actual w/c, ITM-403-calculated w/c, batched w/c, average of AASHTO T 152 measured air contents and 28 days compressive strengths for these projects are presented in Table 6.12.

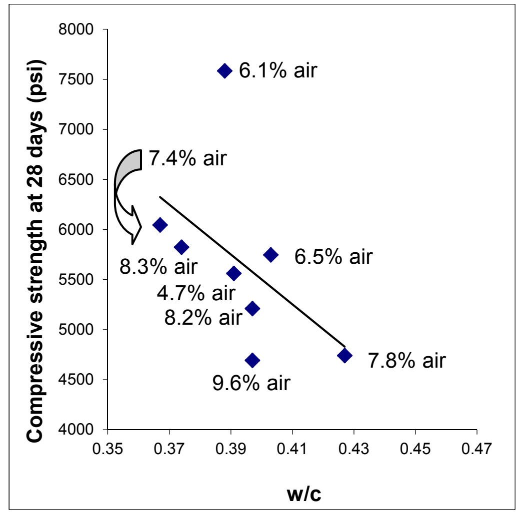
Table 6.12 The values of w/c, average of AASHTO T 152 measured air contents and 28 days compressive strengths for projects number 1, 3, 4, 5, 8, 14, 15, 16, and 17

Project No.	Determined w/c			Final determined w/c	ITM-403-calculated w/c	Δ'w/c	Average of AASHTO T 152 measured air contents	28 days compressive strength (psi)
	Contractor Rep.	INDOT Rep.	Third Party					
1	0.374 (outlier)	0.403	0.399	0.392	0.408	-0.016	8.3%	5746
3	0.421	0.397	0.376	0.398	0.400	-0.002	8.2%	5210
4	0.386	0.391	0.384	0.387	0.401	-0.014	4.7%	5561
5	0.462 (outlier)	0.427	0.412	0.434	0.401	0.033	9.6%	4740
8	0.391 (outlier)	0.367	0.363	0.374	0.382	-0.008	7.4%	6045
14	0.394 (outlier)	0.374	0.372	0.380	0.390	0.010	6.5%	5823
15	0.419	0.397	0.390 (outlier)	0.402	0.415	-0.013	7.8%	4692
16	0.395	0.361	0.407	0.388	0.387	0.001	5.7%	7236
17	0.394	0.388	0.402	0.395	0.381	0.014	6.1%	7585

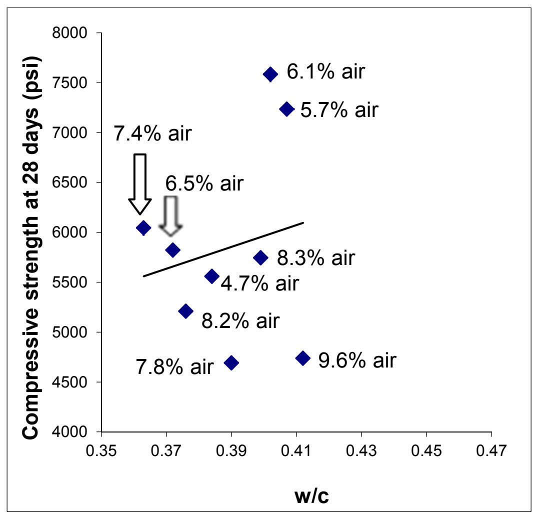
The values of determined w/c (based on unit weight measured by a contractor, INDOT and a third party) are plotted against the 28 days compressive strength in Figure 6.5. It should be noted that the determined w/c values selected as outliers are not included in these plots. This figure shows that the 28 days compressive strengths decrease as the determined w/c based on the unit weights measured by a contractor (Figure 6.5a) and INDOT (Figure 6.5b) increase, and the 28 days compressive strengths increase as the determined w/c based on the unit weight measured by a third party (Figure 6.5c) increases. However, the plots of determined w/c against 28 days compressive strengths do not show clear trends, as can be observed in Figure 6.5.



(a)



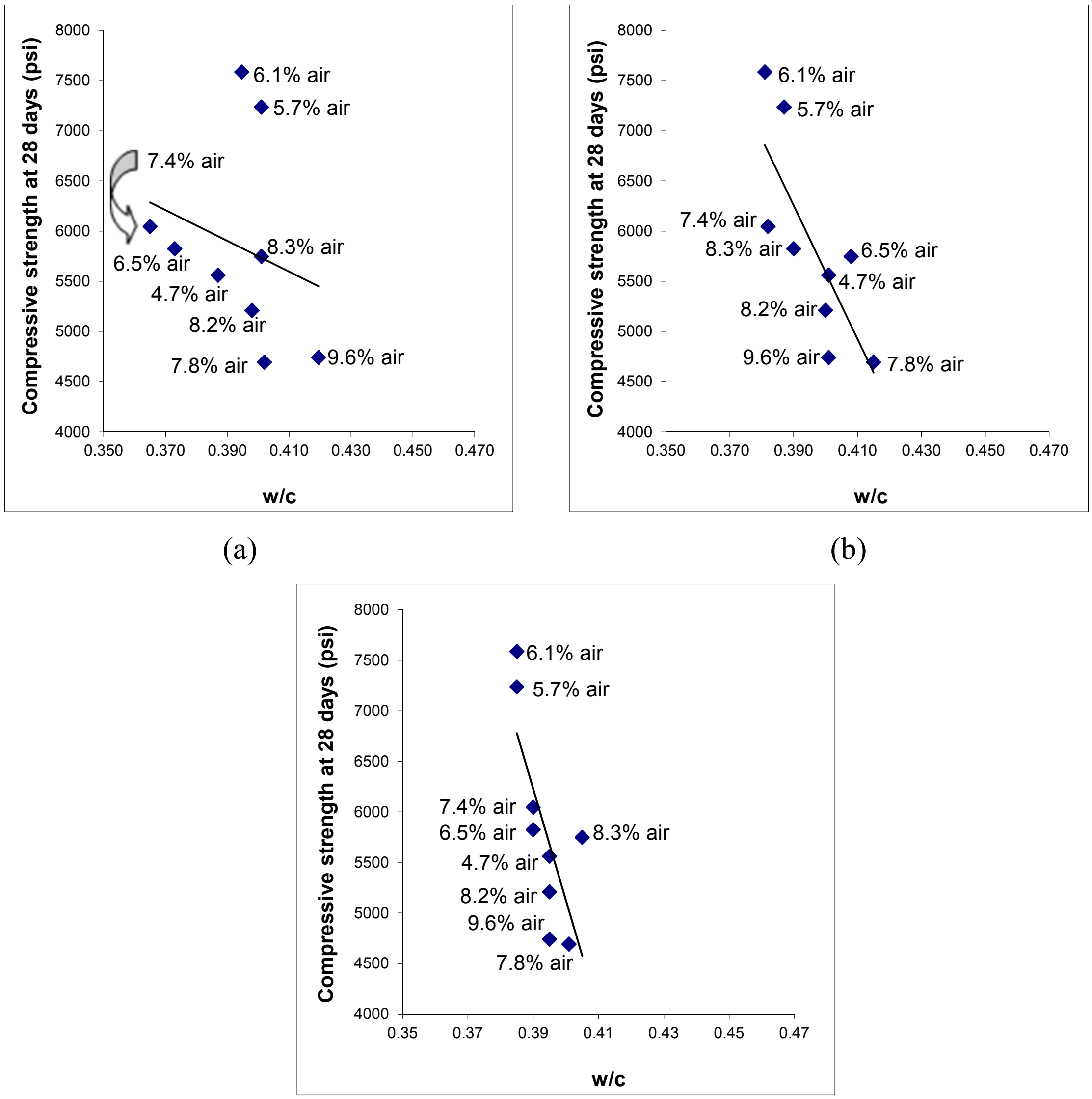
(b)



(c)

Figure 6.5 Plots of 28 days compressive strength against determined w/c based on unit weight and air content measured by (a) contractor, (b) INDOT, and (c) third party

Figure 6.6 shows the plot between: a. Final determined w/c and 28 days compressive strengths, b. ITM-403-calculated w/c and 28 days compressive strengths and c. batched w/c and 28 days compressive strengths. This figure shows that the 28 days compressive strengths decrease as final determined, ITM-403-calculated and batched w/c increase. However, the plots of final determined, ITM-403-calculated, and batched w/c against 28 days compressive strengths as shown in Figure 6.6 show better trends compared to the plots of determined w/c against 28 days compressive strength.



(a) (b)

(c)

Figure 6.6 The plot of (a) Final determined w/c- 28 days compressive strength, (b) ITM-403-calculated w/c-28 days compressive strength and (c) batched w/c-28 days compressive strength

6.2. Use of the Data from Group of Concretes from the I-94 Project

This section presents the results of field verification of the applicability of the proposed unit weight method for the determination of the w/c of fresh concrete using the data gathered for the concretes used in the I-94 project. This section is divided into two subsections. Section 6.2.1 describes the determination of the actual w/c for the group of concretes used in the I-94 project. Section 6.2.2 shows the analysis of the plot of flexural strengths against determined actual w/c.

6.2.1. *Determination of Actual W/C for the Group of 22 Concretes Used on the I-94 Project*

The determination of the actual w/c values for the group of concretes used in the I-94 project was performed following the unit weight method, the same method used for the determination of the w/c of 22 INDOT concretes. The procedures are as follows:

1. Establishment of the unit weight-w/c relationship based on the specification of the basic mixture (CMD). The CMD of the group of concretes used in the I-94 project is shown in Table 6.13 and the unit weight-w/c relationship of this group of concretes is expressed by Equation 6.2.

Table 6.13 Basic composition of mixture used in the I-94 project

Target air content =		6.50%	
w/c =		0.4	
Material	**Specific gravity**	**Weight lbs/yd^3**	**Volume ft^3**
Cement	3.15	440	2.24
Fly ash	1.91	71	0.60
Fine Aggregate, SSD	2.56 (SG_{FA})	1345 (W_{FA})	8.44
Coarse Aggregate, SSD	2.76 (SG_{CA})	1849 (W_{CA})	10.76
Water	1	204	3.28
Air	N/A	0	1.76
Total =		3909 lbs/yd^3	27 ft^3

$$W/C = -0.0013128 \cdot UW_2 + 5.529 \tag{6.2}$$

2. Adjustment of the measured unit weight to account for differences between the specific gravities of aggregates and air content as batched and those specified in the basic mixture (CMD). Table 6.14 shows the values of measured unit weights (UW_a), measured air contents (a) and $UW_{6.5\%}$ of the group of concretes used in the I-94 project.

Table 6.14 Measured unit weights and air contents and final adjusted unit weights of concretes used in the I-94 project

Conc. No.	INDOT			Contractor		
	AASHTO T 121 Measured air content lbs/yd^3	AASHTO T 152 Measured air content %	Final adjusted unit weight (UW_2) lbs/yd^3	AASHTO T 121 Measured air content, lbs/yd^3	AASHTO T 152 Measured air content, %	Final adjusted unit weight (UW_2) lbs/yd^3
1	3991	6.00%	3970	3971	5.80%	3942
2	3997	5.70%	3963	3978	5.60%	3940
3	3869	6.70%	3878	3897	6.60%	3901
4	3922	7.20%	3951	3874	7.20%	3903
5	3984	5.90%	3959	3949	5.80%	3919
6	3929	7.00%	3950	3887	7.00%	3908
7	3965	6.40%	3961	3943	6.10%	3926
8	3953	6.50%	3953	3938	6.30%	3929
9	3934	6.70%	3942	3914	6.70%	3922
10	3949	6.50%	3949	3933	6.10%	3916
11	3951	6.50%	3951	3930	6.20%	3918
12	3990	6.10%	3973	3961	5.70%	3927
13	3965	6.50%	3965	3927	6.20%	3914
14	3967	6.20%	3955	3953	6.00%	3932
15	3972	6.40%	3968	3935	6.40%	3931
16	3946	6.70%	3954	3920	6.60%	3924
17	3955	6.50%	3955	3930	6.80%	3943
18	3941	6.70%	3949	3906	7.10%	3932
19	3952	6.50%	3952	3951	6.20%	3938
20	3936	6.90%	3953	3928	6.80%	3941
21	3991	6.30%	3983	3945	6.20%	3932
22	3881	6.90%	3898	3937	7.00%	3958
23	3891	7.10%	3916	3903	7.20%	3932
24	3894	6.50%	3894	3938	6.50%	3938
25	3885	7.00%	3906	3918	7.30%	3952
26	3927	6.20%	3914	3964	6.20%	3952
27	3938	5.90%	3913	3961	6.20%	3948
28	3907	6.10%	3890	3940	6.20%	3928
29	3931	6.10%	3914	3973	6.20%	3960
30	3902	6.30%	3894	3939	6.60%	3943
31	3943	5.70%	3909	3978	5.90%	3952
32	3924	6.10%	3908	3923	6.40%	3919
33	3909	6.70%	3917	3903	6.90%	3920
34	3934	6.10%	3917	3927	6.30%	3918
35	3929	6.20%	3916	3936	6.20%	3924
36	3915	6.20%	3902	3914	6.70%	3922
37	3897	6.50%	3897	3908	6.50%	3908
38	3927	6.50%	3927	3901	6.80%	3913
39	3910	6.70%	3918	3920	6.60%	3924
40	3946	6.30%	3937	3934	6.30%	3926
41	3967	5.60%	3929	3963	5.60%	3925
42	3931	6.50%	3931	3928	6.40%	3924
43	3924	6.60%	3928	3905	6.70%	3914
44	3939	6.30%	3930	3933	6.20%	3920

Table 6.14 *(continued)*

Conc. No.	INDOT			Contractor		
	AASHTO T 121 Measured air content lbs/yd^3	AASHTO T 152 Measured air content %	Final adjusted unit weight (UW_2) lbs/yd^3	AASHTO T 121 Measured air content lbs/yd^3	AASHTO T 152 Measured air content %	Final adjusted unit weight (UW_2) lbs/yd^3
45	3933	6.40%	3929	3914	6.50%	3914
46	3924	6.20%	3912	3905	6.60%	3909
47	3946	6.30%	3937	3927	6.30%	3918
48	3941	6.70%	3949	3936	6.40%	3932
49	3947	6.20%	3934	3946	6.10%	3929
50	3928	7.00%	3949	3902	7.20%	3931
51	3931	6.70%	3940	3924	6.60%	3929
52	3947	6.40%	3943	3948	6.30%	3940
53	3940	6.50%	3940	3938	6.50%	3938
54	3936	6.50%	3936	3924	6.60%	3929
55	3935	6.30%	3927	3921	6.40%	3917
56	3914	7.00%	3935	3893	6.90%	3910
57	3946	6.40%	3942	3927	6.40%	3923
58	3914	7.30%	3947	3896	7.00%	3917
59	3912	7.10%	3938	3903	7.20%	3932
60	3951	6.20%	3938	3950	6.00%	3929
61	3915	7.40%	3953	3886	7.40%	3924
62	3898	7.00%	3919	3911	6.80%	3924
63	3982	5.70%	3948	3981	5.40%	3934
64	3954	6.00%	3933	3954	6.00%	3933
65	3865	8.00%	3928	3845	8.10%	3912
66	3918	7.00%	3939	3922	7.00%	3943
67	3961	6.00%	3940	3970	5.90%	3945
68	3946	6.50%	3946	3935	6.70%	3944
69	3928	7.00%	3949	3935	6.70%	3944
70	3937	6.50%	3937	3934	6.60%	3938
71	3953	6.20%	3940	3970	6.10%	3953
72	3925	7.00%	3947	3924	7.00%	3946
73	3922	7.00%	3943	3948	7.00%	3970
74	3986	5.40%	3940	4008	5.20%	3953
75	3946	7.10%	3971	3956	7.00%	3977
76	3961	6.50%	3961	3946	7.00%	3967
77	3968	6.50%	3968	3963	6.50%	3963
78	3929	7.50%	3972	3900	7.80%	3955
79	3941	6.80%	3954	3939	6.90%	3956
80	3975	6.10%	3958	3975	6.20%	3962
81	3996	5.90%	3970	3989	6.00%	3968
82	3948	6.40%	3944	3944	6.50%	3944
83	3954	6.50%	3954	3956	6.50%	3956
84	3955	6.30%	3947	3960	6.20%	3948
85	3921	6.90%	3938	3902	7.00%	3923
86	3912	7.40%	3950	3921	7.40%	3959
87	3990	5.90%	3964	3978	6.00%	3957
88	3935	7.10%	3960	3924	7.30%	3958
89	3870	7.50%	3912	3861	8.00%	3924

3. Determination of actual w/c by using the value of the average of INDOT's and a contractor's final adjusted measured unit weights (UW_2) as an input into the unit weight-w/c relationship developed in the first step (Equation 6.2). Table 6.15 shows the values of the averages of final adjusted unit weight (UW_2, taken from Table 6.14), batched w/c, determined actual w/c, approximated w/c (visually determined based on the degree of wetness of concretes) and Δw/c of the group of mixtures used in the I-94 project. It can be seen that the intervals of Δw/c are between -0.023 to +0.088.

Table 6.15 Average of final adjusted measured unit weights (UW_2), batched w/c, determined actual w/c, approximated w/c and Δw/c of concretes used for the I-94 project

Concrete No.	Batched w/c	Average of final adjusted measured unit weight (UW_2) lbs/yd^3	Determined actual w/c	Visually approximated w/c	Δw/c
1	0.400	3956	0.336	0.43	0.064
2	0.400	3951	0.342	N/A	0.058
3	0.400	3889	0.423	N/A	-0.023
4	0.400	3927	0.374	N/A	0.026
5	0.400	3939	0.358	N/A	0.042
6	0.400	3929	0.371	N/A	0.029
7	0.400	3943	0.353	N/A	0.047
8	0.400	3941	0.355	N/A	0.045
9	0.400	3932	0.367	N/A	0.033
10	0.400	3933	0.366	0.4	0.034
11	0.400	3934	0.364	N/A	0.036
12	0.400	3950	0.344	N/A	0.056
13	0.400	3940	0.357	N/A	0.043
14	0.400	3943	0.352	N/A	0.048
15	0.400	3949	0.345	N/A	0.055
16	0.400	3939	0.358	0.38	0.042
17	0.400	3949	0.345	N/A	0.055
18	0.400	3941	0.356	N/A	0.044
19	0.400	3945	0.350	N/A	0.050
20	0.400	3947	0.348	N/A	0.052
21	0.400	3957	0.334	0.39	0.066
22	0.400	3928	0.373	0.42	0.027
23	0.400	3924	0.378	0.42	0.022
24	0.400	3916	0.388	0.43	0.012
25	0.400	3929	0.371	0.44	0.029
26	0.400	3933	0.366	0.45	0.034

Table 6.15 (*continued*)

Concrete No.	**Batched w/c**	**Average of final adjusted measured unit weight (UW_2) lbs/yd^3**	**Determined actual w/c**	**Visually approximated w/c**	**Δw/c**
27	0.400	3930	0.370	0.42	0.030
28	0.400	3909	0.398	0.41	0.002
29	0.400	3937	0.361	0.41	0.039
30	0.400	3918	0.385	0.41	0.015
31	0.400	3931	0.369	0.42	0.031
32	0.400	3913	0.392	0.42	0.008
33	0.400	3919	0.385	0.43	0.015
34	0.400	3918	0.386	0.4	0.014
35	0.400	3920	0.383	0.42	0.017
36	0.400	3912	0.393	0.43	0.007
37	0.400	3902	0.406	0.44	-0.006
38	0.400	3920	0.383	0.44	0.017
39	0.400	3921	0.382	0.42	0.018
40	0.400	3931	0.368	0.41	0.032
41	0.400	3927	0.374	0.4	0.026
42	0.400	3928	0.373	0.4	0.027
43	0.400	3921	0.382	0.41	0.018
44	0.400	3925	0.376	0.41	0.024
45	0.400	3921	0.382	0.42	0.018
46	0.400	3911	0.395	0.41	0.005
47	0.400	3928	0.373	0.42	0.027
48	0.400	3941	0.356	0.41	0.044
49	0.400	3932	0.368	0.4	0.032
50	0.400	3940	0.357	0.41	0.043
51	0.400	3934	0.364	0.4	0.036
52	0.400	3941	0.355	0.41	0.045
53	0.400	3939	0.359	N/A	0.041
54	0.400	3932	0.367	0.41	0.033
55	0.400	3922	0.381	0.4	0.019
56	0.400	3922	0.380	0.41	0.020
57	0.400	3932	0.367	0.4	0.033
58	0.400	3932	0.367	0.4	0.033
59	0.400	3935	0.363	0.4	0.037
60	0.400	3933	0.366	0.41	0.034
61	0.400	3938	0.359	0.39	0.041
62	0.400	3921	0.381	0.42	0.019
63	0.400	3941	0.355	0.4	0.045
64	0.400	3933	0.366	0.42	0.034
65	0.400	3920	0.383	0.43	0.017

Table 6.15 (*continued*)

Concrete No.	Batched w/c	Average of final adjusted measured unit weight (UW_2)	Determined actual w/c	Visually approximated w/c	Δw/c
66	0.400	3941	0.355	0.41	0.045
67	0.400	3942	0.354	0.43	0.046
68	0.400	3945	0.351	0.4	0.049
69	0.400	3946	0.349	0.41	0.051
70	0.400	3938	0.360	0.4	0.040
71	0.400	3947	0.348	0.41	0.052
72	0.400	3946	0.349	0.42	0.051
73	0.400	3956	0.335	0.4	0.065
74	0.400	3947	0.348	N/A	0.052
75	0.400	3974	0.312	0.42	0.088
76	0.400	3964	0.325	N/A	0.075
77	0.400	3965	0.324	0.42	0.076
78	0.400	3963	0.326	0.43	0.074
79	0.400	3955	0.338	0.43	0.062
80	0.400	3960	0.330	N/A	0.070
81	0.400	3969	0.319	0.41	0.081
82	0.400	3944	0.352	N/A	0.048
83	0.400	3955	0.337	0.41	0.063
84	0.400	3947	0.347	N/A	0.053
85	0.400	3930	0.370	0.38	0.030
86	0.400	3955	0.338	0.37	0.062
87	0.400	3961	0.330	N/A	0.070
88	0.400	3959	0.331	N/A	0.069
89	0.400	3918	0.386	N/A	0.014

6.2.2. Plot of Flexural Strength Against W/C for Concretes Used on the I-94 Project

As already mentioned at the beginning of this chapter, the data obtained for the group of concretes used in the I-94 project included flexural strengths. Two values of flexural strengths were obtained for each concrete (one was measured by INDOT and another one by a contractor). Table 6.16 shows the measured flexural strengths along with the values of batched w/c, determined w/c and visually estimated w/c for the group of concretes used in the I-94 project.

Table 6.16 Batched determined actual and visually approximated w/c values and flexural strengths of concretes used in the I-94 project

Concrete No.	Batched w/c	Determined actual w/c	Visually approximated w/c	Measured flexural strength		Average of measured flexural strength psi
				INDOT psi	Contractor psi	
1	0.400	0.336	0.43	694	694	694
2	0.400	0.342	N/A	695	710	703
3	0.400	0.423	N/A	620	657	639
4	0.400	0.374	N/A	616	653	635
5	0.400	0.358	N/A	737	692	714
6	0.400	0.371	N/A	701	680	691
7	0.400	0.353	N/A	701	713	707
8	0.400	0.355	N/A	665	647	656
9	0.400	0.367	N/A	620	657	638
10	0.400	0.366	0.4	688	666	677
11	0.400	0.365	N/A	659	681	670
12	0.400	0.344	N/A	722	722	722
13	0.400	0.358	N/A	738	685	711
14	0.400	0.352	N/A	703	678	691
15	0.400	0.345	N/A	612	681	646
16	0.400	0.358	0.38	626	615	620
17	0.400	0.345	N/A	618	561	589
18	0.400	0.356	N/A	631	585	608
19	0.400	0.35	N/A	679	666	672
20	0.400	0.348	N/A	634	652	643
21	0.400	0.334	0.39	693	632	663
22	0.400	0.373	0.42	646	621	633
23	0.400	0.378	0.42	664	642	653
24	0.400	0.388	0.43	604	636	620
25	0.400	0.371	0.44	587	573	580
26	0.400	0.366	0.45	612	684	648
27	0.400	0.370	0.42	588	619	604
28	0.400	0.398	0.41	611	587	599
29	0.400	0.361	0.41	671	652	661
30	0.400	0.385	0.41	619	632	626
31	0.400	0.369	0.42	667	649	658
32	0.400	0.392	0.42	636	621	628
33	0.400	0.385	0.43	597	575	586
34	0.400	0.386	0.4	632	671	652
35	0.400	0.383	0.42	630	610	620
36	0.400	0.393	0.43	595	587	591
37	0.400	0.406	0.44	576	606	591
38	0.400	0.383	0.44	582	606	594
39	0.400	0.382	0.42	603	638	621
40	0.400	0.368	0.41	615	656	635
41	0.400	0.374	0.4	682	683	682
42	0.400	0.373	0.4	669	669	669
43	0.400	0.382	0.41	626	587	607
44	0.400	0.376	0.41	631	599	615

Table 6.16 (*continued*)

Concrete No.	Batched w/c	Determined actual w/c	Visually approximated w/c	Measured flexural strength		Average of measured flexural strength psi
				INDOT psi	Contractor psi	
45	0.400	0.382	0.42	646	637	642
46	0.400	0.395	0.41	635	664	649
47	0.400	0.373	0.42	666	658	662
48	0.400	0.356	0.41	683	656	669
49	0.400	0.368	0.4	630	656	643
50	0.400	0.357	0.41	659	675	667
51	0.400	0.364	0.4	661	684	672
52	0.400	0.355	0.41	634	617	626
53	0.400	0.359	N/A	720	678	699
54	0.400	0.367	0.41	666	637	651
55	0.400	0.381	0.4	724	687	706
56	0.400	0.380	0.41	645	594	619
57	0.400	0.367	0.4	662	711	687
58	0.400	0.367	0.4	670	654	662
59	0.400	0.363	0.4	712	661	686
60	0.400	0.366	0.41	703	694	699
61	0.400	0.359	0.39	705	656	681
62	0.400	0.381	0.42	554	559	557
63	0.400	0.355	0.4	720	722	721
64	0.400	0.366	0.42	729	650	690
65	0.400	0.383	0.43	605	610	607
66	0.400	0.355	0.41	711	669	690
67	0.400	0.354	0.43	639	677	658
68	0.400	0.351	0.4	670	654	662
69	0.400	0.349	0.41	682	678	680
70	0.400	0.360	0.4	684	656	670
71	0.400	0.348	0.41	637	646	642
72	0.400	0.349	0.42	659	625	642
73	0.400	0.335	0.4	645	637	641
74	0.400	0.348	N/A	697	673	685
75	0.400	0.312	0.42	710	727	718
76	0.400	0.325	N/A	691	722	706
77	0.400	0.324	0.42	693	703	698
78	0.400	0.326	0.43	705	667	686
79	0.400	0.338	0.43	699	691	695
80	0.400	0.330	N/A	698	699	698
81	0.400	0.319	0.41	731	690	710
82	0.400	0.352	N/A	697	708	702
83	0.400	0.337	0.41	760	674	717
84	0.400	0.347	N/A	729	664	696
85	0.400	0.370	0.38	696	713	705
86	0.400	0.338	0.37	634	682	658
87	0.400	0.330	N/A	692	733	713
88	0.400	0.331	N/A	753	740	747
89	0.400	0.386	N/A	711	706	708

Figure 6.7 is the plot of flexural strength values versus visually estimated w/c values. These plots show the significant decrement of flexural strength with the slight increment of w/c.

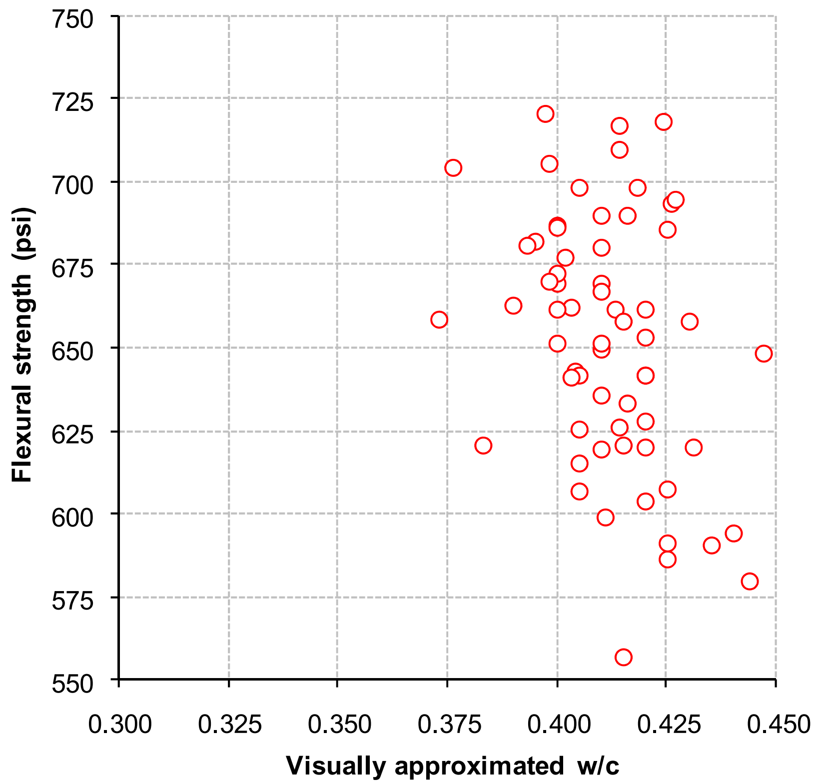


Figure 6.7 The plot of visually approximated w/c-flexural strength of concrete used in the I-94 project

This phenomenon is rather odd. When the plots of unit weight determined w/c versus flexural strength and plots of visually approximated w/c versus flexural strength are put together as shown in Figure 6.8, it shows that the former plots ($R^2 = 0.3334$) indicate the trend better than the latter plots ($R^2 = 0.1258$).

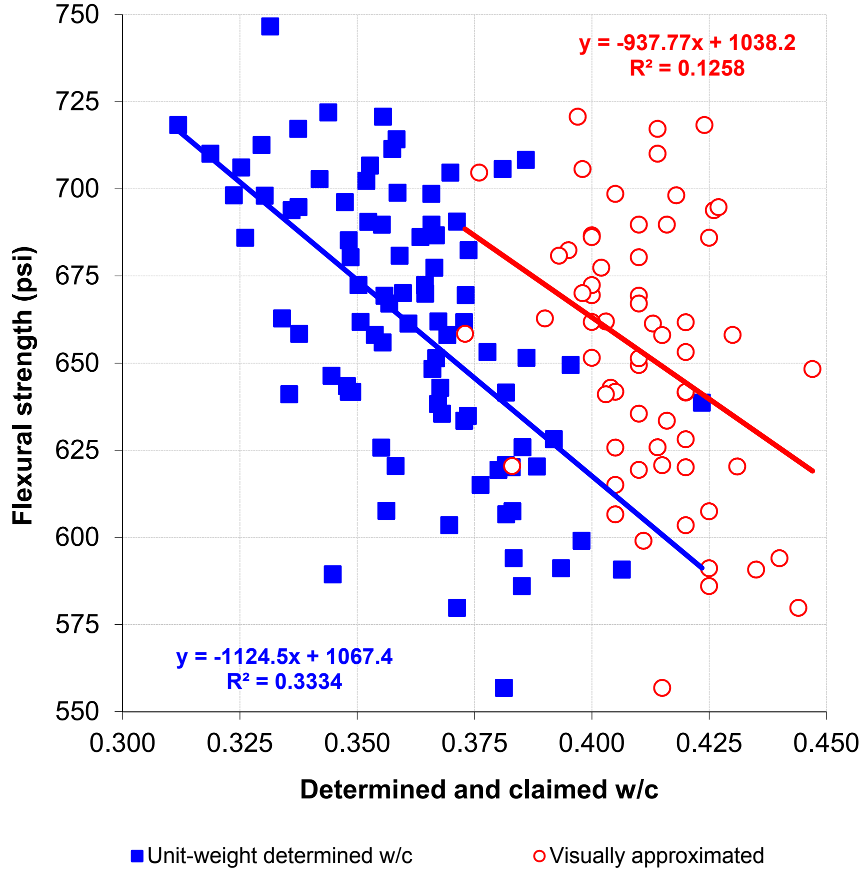


Figure 6.8 The plot of w/c-flexural strength of concrete used in the I-94 project

6.3. Summary

Two distinctive groups of field concretes have been used to check the applicability of the unit weight method for the determination of the w/c of fresh concrete. The first group included mixtures used by INDOT on 22 different projects in Indiana. The data obtained for the first group included the CMD information, the AASHTO T 121 measured unit weights, the AASHTO T 152 measured air contents, the ITM-403-calculated w/c and the 28 days compressive strengths values. The field measurements of unit weight and air content were performed by three different parties (INDOT, a contractor and a third party) except for three of the mixtures. For those three mixtures, the measurements were performed by INDOT and a contractor only. In addition, for this group of mixtures the data also included the batched specific gravities of fine and coarse aggregates used in the field concretes.

The data of the measured unit weights and air contents together with CMD data were used to determine the actual w/c values of 22 INDOT mixtures utilizing the unit weight method. The final actual w/c for each of the mixtures was the average of actual w/c values previously determined using the unit weights measured by INDOT, a contractor and a third party (or by INDOT and a contractor for the three mixtures mentioned earlier). The analysis of the differences between batched and final determined actual w/c (Δw/c1) shows that these values are in the interval of ±0.030. This interval is wider than the interval of the differences between batched and ITM-403-calculated w/c (Δw/c2), which is ±0.020 (only one value was slightly outside of this range).

The plot of 28 days compressive strength against final determined actual w/c for several mixtures that have similar compositions shows that 28 days compressive strength tends to decrease as final determined actual w/c increases. However, the trend is not very clear.

The second group included 89 concretes used for the I-94 project in northern Indiana. The data obtained for the second group included the CMD information, the measured unit weights and air contents, visually approximated w/c (visually determined based on the degree of wetness of concrete) and the flexural strength values. The field measurements of unit weight and air content as well as flexural strengths were performed by INDOT and a contractor. Data of the measured unit weights and air contents together with CMD data were used to find the actual w/c values of all concrete in the second group utilizing the unit weight method. It was also observed that most of the determined actual w/c values were lower than batched w/c and most of the visually approximated w/c values were higher than batched w/c. The differences between batched and determined actual w/c are in the interval of -0.023 and +0.088. The plot of flexural strengths against final determined actual w/c shows that flexural strengths tend to decrease as final determined actual w/c values increase. While the trend is not very clear, it is better than the observed trend of the plot between flexural strengths and visually approximated w/c.

CHAPTER 7. MICROWAVE OVEN MEASURED WATER CONTENT OF FRESH CONCRETE FOR DETERMINATION OF W/C

Several past studies on the use of microwave oven technique for determination of the total water content of fresh concrete also reported on the alleged accuracy of this method to determine the w/c of the mixture (assuming that the cement content of the tested concrete is also known). Based on the study by Dowell and Cramer (2002), the reported accuracy of this method for w/c determination was ~0.027. Nantung (1998) reported the accuracy to be better than 0.010. Similar accuracy (~0.010) was also reported by Bescher et al. (2003). The NRMCA's report written by Hover et al. (2008) reports the accuracy of using this method to be in the range of ~0.030 to ~0.050.

In the current study, the microwave oven method has been used to determine the w/c of five concrete samples. These five concrete samples were all obtained from non-air-entrained plain mixtures, which were created by changing the amount of water in the basic mix (Table 3.3).

The procedures used to dry the wet concrete samples in the current study followed the AASHTO T 318 method (AASHTO, 2002). Once the sample was dried, Equation 7.2 as proposed by Nantung (1998) was used to determine the actual w/c of concrete samples. This equation calculates the w/c of fresh concrete using CMD weights of concrete ingredients, the weight of a wet concrete sample, and the weight of a dry concrete sample as well as the amount of dry coarse aggregate particles in the concrete sample retained on the #4 sieve. This last information needs to be obtained in order to allow for adjustment of the determined w/c value to account for the fraction of the coarse aggregate that is smaller than the #4 sieve.

7.1. Composition of Concretes as Batched

As already mentioned, the determination of w/c using microwave oven (AASHTO T318) measured water content of fresh concrete involved five non air-entrained plain mixtures, which were created by changing the amount of water in the basic mix (Table 3.3). The compositions of these five mixtures are shown in Table 7.1 where the mixture with code MMO40 represents the basic mix.

Table 7.1 Composition of mixtures used for the determination of w/c using microwave oven measured water content of fresh concrete

<table>
<tr><th rowspan="7">Materials</th><th rowspan="7">Composition of basic mixture</th><th colspan="5">Mixture code</th></tr>
<tr><td>MMO38</td><td>MMO40</td><td>MMO42</td><td>MMO44</td><td>MMO46</td></tr>
<tr><th colspan="5">Change in the amount of water with respect to the basic mixture</th></tr>
<tr><td>-13 lbs</td><td>0 lbs</td><td>+13 lbs</td><td>+26 lbs</td><td>+40 lbs</td></tr>
<tr><th colspan="5">Batched w/c</th></tr>
<tr><td>0.380</td><td>0.400</td><td>0.420</td><td>0.440</td><td>0.460</td></tr>
<tr><th colspan="5">Weights of ingredients of mixture</th></tr>
<tr><td>Cement</td><td>658 lbs</td><td>658 lbs</td><td>658 lbs</td><td>658 lbs</td><td>658 lbs</td><td>658 lbs</td></tr>
<tr><td>Fine aggregate, SSD</td><td>1450 lbs</td><td>1450 lbs</td><td>1450 lbs</td><td>1450 lbs</td><td>1450 lbs</td><td>1450 lbs</td></tr>
<tr><td>Coarse aggregate, SSD</td><td>1477 lbs</td><td>1477 lbs</td><td>1477 lbs</td><td>1477 lbs</td><td>1477 lbs</td><td>1477 lbs</td></tr>
<tr><td>Water</td><td>263 lbs</td><td>250 lbs</td><td>263 lbs</td><td>276 lbs</td><td>290 lbs</td><td>303 lbs</td></tr>
<tr><td colspan="2">Total weights</td><td>3835 lbs</td><td>3848 lbs</td><td>3861 lbs</td><td>3875 lbs</td><td>3888 lbs</td></tr>
</table>

The concretes were prepared in small batches by first mixing cement, water and sand in a mortar mixer followed by adding coarse aggregate to the mortar and continuing mixing by hand. This procedure was adopted in order to replicate a previous study by Nantung (2008). The total weight of ingredients needed to prepare mixtures with codes MMO38, MMO40, MMO42, MMO44 and MMO46 were 1546.4 g, 1551.6 g, 1557.0 g, 1562.3 g and 1567.6 g, respectively. The actual compositions of these concretes are given in Table 7.2. The weights of individual ingredients were calculated from the overall proportions given in Table 7.1 by multiplying the previously mentioned total batch weight by the ratio of weight of given ingredients in 1 cu yd by the unit weight of the mixture. As an example, calculation of the weight of cement required to batch mixture MMO40 is shown below:

$$\text{Weight of cement} = \frac{658\ \text{lbs}}{3835\ \text{lbs}} \times 1546.4\ \text{g} = 265.3\ \text{g}$$

Table 7.2 Composition of concretes made for the determination of w/c using microwave oven measured water content of fresh concrete

Materials	**Concrete code**				
	MMO38	MMO40	MMO42	MMO44	MMO46
	Batched w/c				
	0.380	0.400	0.420	0.440	0.460
	Total weight of concretes				
	1546.4 g	1551.6 g	1557.0 g	1562.3 g	1567.6 g
	Weights of ingredients of concretes				
Cement	265.3 g	265.3 g	265.3 g	265.3 g	265.3 g
Fine aggregate, SSD	574.7 g	574.7 g	574.7 g	574.7 g	574.7 g
Coarse aggregate, SSD	588.0 g	588.0 g	588.0 g	588.0 g	588.0 g
Free water	100.8 g	106.1 g	111.4 g	116.8 g	122.0 g

The fine and the coarse aggregate used in these five mixtures consisted of natural siliceous sand and dolomite, respectively. The properties of these aggregates are shown in Tables 3.1 and 3.2. The absorption values of fine and coarse aggregates were 1.7% and 1.3%, respectively.

7.2. Procedure of Laboratory Testing

In this section, the test procedure used to measure the water content of five concrete samples is described in more detail. The steps involved in this process are as follows:

1. About 2500 g of coarse aggregate (2514 g) was sampled from the stockpile and dried constant mass. The dried aggregate then was sieved through No. 4 (4.75 mm). For this particular sample, 426 g of 2514 g (or 15%) of coarse aggregate particles were smaller than the opening size of sieve #4. After being sieved, the particles of coarse aggregate which were larger and smaller than the opening size of sieve #4 were mixed again.
2. Five concretes with the concrete composition presented in Table 7.2 were batched using the aggregate bland provided in step 1.
3. The samples of five wet concretes were taken from the batches to test in the microwave oven. The weights of these wet concrete samples are shown in Table 7.3.

Table 7.3 Weights of wet concrete samples

Concrete code	MMO38	MMO40	MMO42	MMO44	MMO46
Weight of wet concrete sample	1531.0 g	1530.6 g	1529.8 g	1537.4 g	1538.0 g

4. These wet concrete samples were then dried in the microwave oven following the AASHTO T 318 method. The 1200 Watts microwave oven shown in Figure 7.1 was used to dry the concrete. The times needed to dry each wet concrete sample were recorded. After drying, each sample of concrete was wet sieved (using #4) in order to obtain the weights of particles of coarse aggregate in the sample that were larger than 4.75 mm. After wet sieving, the particles of wet coarse aggregate which were retained on sieve #4 were dried using the microwave oven for 5 minutes and weighed. They were then returned to the microwave oven for an additional 2 minutes to ensure that the change in the weight was not greater than 1 g. The weights of wet concrete samples, weights of coarse aggregate particles in the sample (particles retained on sieve #4), and the time needed to dry the concrete samples are shown in Table 7.4.

Table 7.4 Weights of dry concrete samples, weights of dry coarse aggregate in the sample retained on sieve #4 and time needed for drying the sample

Concrete code	MMO38	MMO40	MMO42	MMO44	MMO46
Weight of dry concrete sample	1413.5 g	1408.7 g	1402.5 g	1404.9 g	1401.2 g
Weight of dry coarse aggregate in the sample retained on sieve #4	495.2 g	490.3 g	506.0 g	493.0 g	503.1 g
Time needed (minutes)	20	20	20	20	20

Figure 7.1 Menumaster commercial microwave oven (model number of FS11EVP) used in the study

7.3. Determination of Actual W/C

The water-cement ratios of five concrete samples were calculated using Equation 2.5 previously proposed by Nantung (1998). Equation 7.1 presents the transformed version of Equation 2.5 which directly incorporates Equation 2.4 used to calculate the aggregate production (% retained on sieve #4) correction factor CF.

$$W/C = \left[(N+1)\times\left(MD\times\frac{1-CA_{batch}}{1-CA_{sample}}\right)\right]-N\times\left[\{ACA\times(1-FA)\}+AFA\times FA\right] \quad (7.1)$$

Where,

N = (total weight of dry aggregates in CMD)/(CMD weight of cement)

MD = (wet weight of concrete sample – dry weight of concrete sample)/(dry weight of concrete sample)

FA = ratio of the weight of dry fine aggregate to the total weight of dry aggregates as specified in CMD

abs_{FA} = CMD absorption value of fine aggregate (decimal)

abs_{CA} = CMD absorption value of coarse aggregate (decimal)

CA_{batch} = ratio of the CMD weight of dry coarse aggregate to the CMD total weight of fresh concrete

CA_{sample} = ratio of the weight of dry coarse aggregate (retained on sieve #4) extracted from concrete sample to the weight of wet concrete sample

As previously mentioned, the composition of mixtures with code MMO40 was used as the CMD for all five concrete samples. This was done in order to simulate the possible field scenario where the w/c of CMD may be changed either by deliberate water addition or by improper accounting for the moisture content of aggregates. Table 7.5 summarizes the composition of mixtures with code MMO40 and includes both the SSD and dry weights of the aggregates. The weights of dry aggregates were calculated using Equation 7.2.

Table 7.5 Composition of Mixtures with Code MMO40

Material	Weights
Cement	658 lbs
Fine aggregate, SSD	1450 lbs
Coarse aggregate, SSD	1477 lbs
Free water	263 lbs
Weight of total ingredients	
3848 lbs	
Weight of fine aggregate, dry	
1425 lbs	
Weight of coarse aggregate, dry	
1458 lbs	

$$W_{FA/CAdry} = \frac{W_{FA/CASSD}}{1 + Abs_{FA/CA}} \tag{7.2}$$

Where,

$W_{FA/CAdry}$ = weight of fine (or coarse) aggregate in the mixture in dry condition

$W_{FA/CASSD}$ = weight of fine (or coarse) aggregate in the mixture in SSD condition

$Abs_{FA/CA}$ = absorption value of fine (or coarse) aggregate

Table 7.6 shows all calculated variables required for the calculation of the w/c using Equation 7.1 as well as the determined w/c, batched w/c and Δw/c of all five concrete samples.

Table 7.6 Values of variables in Equation 7.1, batched w/c, determined w/c and Δw/c for all five concrete samples

Mixture code	MMO38	MMO40	MMO42	MMO44	MMO46
N	4.3823	4.3823	4.3823	4.3823	4.3823
MD	0.0831	0.0865	0.0908	0.0943	0.0976
FA	0.4942	0.4942	0.4942	0.4942	0.4942
Abs_{CA}	1.27%	1.27%	1.27%	1.27%	1.27%
Abs_{FA}	1.75%	1.75%	1.75%	1.75%	1.75%
CA_{batch}	0.6210	0.6210	0.6210	0.6210	0.6210
CA_{sample}	0.6766	0.6797	0.6692	0.6793	0.6729
Batched w/c	0.380	0.400	0.420	0.440	0.460
Determined w/c	0.345	0.359	0.387	0.398	0.419
Δw/c	0.035	0.040	0.033	0.042	0.041

The numerical example of calculation performed for mixtures with code MMO38 is given below.

$$N = \frac{(1425lbs + 1458lbs)}{658lbs} = 4.3823$$

$$MD = \frac{(1531.0g - 1413.5g)}{1413.5g} = 0.0831$$

$$FA = \frac{1425lbs}{(1425lbs + 1458lbs)} = 0.4942$$

$$CA_{batch} = 1 - \frac{1458lbs}{3848lbs} = 0.6210$$

$$CA_{sample} = 1 - \frac{495.2g}{1531.0g} = 6766$$

The (w/c) is then calculated using Equation 7.1 as shown below:

$$W/C = \left[(4.3823+1)\times\left(0.0831\times\frac{1-0.6778}{1-0.6766}\right)\right] - 4.3823\times\left[\{1.27\%\times(1-0.4942)\}+1.75\%\times 0.4942\right]$$

$$W/C = 0.345$$

$$\Delta W/C = 0.380 - 0.345 = 0.035$$

The results of Δw/c shown in Table 7.6 seem to confirm the accuracy of ±0.03 to ±0.05 previously reported by NRMCA. Through personal communication with T. Nantung (2008), it was found that these levels of accuracy could be further improved if the amount of CMD coarse aggregate that passes the #4 sieve is assigned to the fine aggregate fraction.

Since the composition of mixtures with code MMO40 has been used as the basic mix (CMD) for the determination of all actual w/c values of concrete samples, then the amount of aggregates in this mixture will need to be properly adjusted.

The percentage of dry coarse aggregate particles that pass sieve #4 was previously determined to be about 15 % (see step #1 in Section 7.1). That 15 % corresponds to 219 lbs of aggregate. Table 7.7 presents "adjusted" amounts of dry aggregates particles in mixture MMO40 before and after modification.

Table 7.7 Composition of dry aggregates in mixtures with Code MMO40 before and after modification

Material	Before	After
Fine aggregate, dry	1425 lbs	1425 lbs + 219 lbs = 1644 lbs
Coarse aggregate, dry	1458 lbs	1458 lbs – 219 lbs = 1240 lbs

Using the "after" values from Table 7.7 as a substitute for the amounts of aggregates in the basic mix listed in Table 7.5, the w/c values of five concrete samples were re-evaluated using Equation 7.1. These re-evaluated values of w/c are listed in Table 7.8 and represent the actual w/c after the corrections. The equivalent value of w/c before the correction was listed in Table 7.6 under the heading "determined w/c".

Table 7.8 Summary of variables used in Equation 7.1, values of batched w/c, re-evaluated w/c and Δw/c

Mixture code	MMO38	MMO40	MMO42	MMO44	MMO46
N	4.3823	4.3823	4.3823	4.3823	4.3823
MD	0.0831	0.0831	0.0831	0.0831	0.0831
FA	0.4942	0.4942	0.4942	0.4942	0.4942
Abs_{CA}	1.27%	1.27%	1.27%	1.27%	1.27%
Abs_{FA}	1.75%	1.75%	1.75%	1.75%	1.75%
CA_{batch}	0.6778	0.6778	0.6778	0.6778	0.6778
CA_{sample}	0.6766	0.6797	0.6692	0.6793	0.6729
Batched w/c	0.380	0.400	0.420	0.440	0.460
Re-evaluated w/c	0.381	0.397	0.427	0.439	0.462
Δw/c	-0.001	0.003	-0.007	0.001	-0.002

Shown below, is a numerical example of calculations for mixture MMO38.

$$N = \frac{(1425lbs + 1458lbs)}{658lbs} = 4.3823$$

$$MD = \frac{(1531.0 - 1413.5)}{1413.5} = 0.0831$$

$$FA = \frac{1425lbs}{(1425lbs + 1458lbs)} = 0.4942$$

$$CA_{batch} = 1 - \frac{1240lbs}{3848lbs} = 0.6778$$

$$CA_{sample} = 1 - \frac{495.2g}{1531.0g} = 6766$$

The w/c was calculated using Equation 7.1 as shown below:

$$W/C = \left[(4.3823+1)\times\left(0.0831\times\frac{1-0.6778}{1-0.6766}\right)\right] - 4.3823\times\left[\{1.27\%\times(1-0.4942)\}+1.75\%\times0.4942\right]$$

$$W/C = 0.381$$

$$\Delta W/C = 0.380 - 0.381 = -0.001$$

Assuming the values of Δw/c from Table 7.6 and 7.8, it can be seen that the proposed modification significantly improves the accuracy of the microwave oven method for w/c determination. While absolute values of uncorrected Δw/c ranged from 0.033 to 0.042 (Table 7.6), the absolute values of corrected Δw/c ranged from 0.001 to 0.007 (Table 7.8).

7.4. Summary

Five different concretes were prepared to assess the applicability of the microwave oven technique to determine the w/c of fresh concrete and to verify the previously reported accuracy of the method. The results entirely confirmed the previously reported accuracy of ±0.030 to ±0.050 (NRMCA) with the corrected absolute values of Δw/c in the range of 0.001 to 0.007. However, this increased level of accuracy was only obtained after making corrections for the amount of coarse aggregate passing sieve #4.

CHAPTER 8. SUMMARY AND CONCLUSIONS

This final chapter contains the summary of the current study, discussion of advantages and disadvantages of using unit weight for the determination of w/c, the main conclusion drawn and the recommendations for the future research.

8.1. Summary

Several techniques for the determination of w/c in both fresh and hardened concrete are available in literature. At this time, there is one standard test method for w/c determination in hardened concrete (NORDTEST Standard NT Build 361). However, no standard test method for the determination of w/c in fresh concrete exists.

Historically, the w/c of fresh concrete was assessed from the water and cement content values determined using such standards as ASTM C 1078, which is the standard test method for determining the cement content of freshly mixed concrete (ASTM, 1992a); AASHTO T 318, which is the standard test method for determining the water content of freshly mixed concrete using microwave oven drying (AASHTO, 2002); or ASTM C 1079, which is the standard test method for determining the water content of freshly mixed concrete (ASTM, 1992b). Since the ASTM C 1078 (ASTM, 1992a) and ASTM C 1079 (ASTM, 1992b) test methods were discontinued in 1998, the only method currently available for water content determination is AASHTO T 318 (AASHTO, 2002). As the cement content can typically be well controlled in the modern ready mix plants, this information can be combined with the microwave oven determined water content after being corrected for the amount of water absorbed by the aggregates, and used to obtain the w/c (Nantung, 1998).

During the course of the present study, an attempt was made to use the unit weight of concrete as a tool for w/c determination. The unit weight of concrete is easy to measure and the theoretical relationship between this property and w/c can be easily developed. The procedure to determine the w/c values based on the measured unit weight of concrete can be performed using the following three steps:

1. Establishment of unit weight-w/c relationship for the basic mix following the procedure in Section 4.1.
2. Adjustment of the measured unit weight. In order to apply the developed unit weight-w/c relationship to predict the w/c values of concrete based on its measured unit weight, corrections may be needed to account for the fact that actual values of air content in the mix and specific gravities of aggregates used in the batch may be different from those used in the establishment of the w/c-unit weight relationship. The adjustment for the differences in air content can be performed using Equation 4.18. The adjustment for the differences in specific gravities of aggregates can be performed using Equation 4.34. The values of unit weight calculated using Equation 4.18 (UWa) should be combined with the changes in unit weight calculated using Equation 4.34 (ΔUW_1) to yield the "corrected"

value of unit weight (UW_2) for use in the prediction of w/c using the previously established unit weight-w/c relationship. This can be accomplished using Equation 4.36.

3. Determination of the w/c by inserting the value of UW_2 into the previously (step #1) developed unit weight-w/c relationship.

It should be noted that the use of Equations 4.18, 4.34, and 4.36 enables one to measure the unit weight of any concrete, irrespective of its actual air content and the specific gravities of the aggregates used in production). Once measured, this unit weight can be converted to an equivalent "corrected" unit weight that reflects the air content and the specific gravities of aggregates used to derive the unit weight-w/c relationship following the procedure in Section 4.1. Equation 4.14 represents the unit weight-w/c relationship for the basic mix used in the current study.

The evaluations of the use of unit weight for w/c determination have been performed using data from both laboratory and field concretes. During the laboratory verification, the accuracy of using unit weight to predict the w/c value was verified by preparing four groups of concretes (a total of 60 mixtures). The four groups of laboratory concretes were as follows:

1. The first group of concretes was created by adding or subtracting the predetermined amount of water from the basic mix with a target w/c value of 0.400. This group of concretes was meant to represent the field concrete batch in which the target water amount changed as a result of batching errors or unreported water additions.
2. The second group of concretes was prepared by assuming that the aggregates used to prepare the batch were in SSD condition while, in reality, they were not. This approach was used to evaluate the capability of the unit weight-w/c relationship which was developed by changing the amount of water in the basic mix to predict the changes in the w/c of field concrete resulting from the variability of the moisture content of aggregates in the stockpile.
3. The third group of concretes duplicated mixtures from the second group but was made by changing the type of original coarse aggregate used to develop the w/c-unit weight correlation to the one with different values of specific gravity and absorption. Two types of coarse aggregates with values of specific gravities and absorption different from those used in the basic mix design (Table 3.3) were used. These aggregates include steel slag

(with SG'$_{CA}$ of 3.57 and absorption of 1.7%) and limestone (with SG'$_{CA}$ of 2.72 and absorption of 1.0%). The tests on the mixtures in this group were performed to determine the capability of the developed unit weight-w/c relationship to predict the alteration of w/c caused by using the aggregates with absorption values that were different from those used for the basic mix design.

4. The fourth group of concretes was created by combining the w/c altering variables used in the previous three groups.

During the "field verification" part of the study, the data from two groups of field concretes were obtained. The data in the first group were obtained from 22 field concretes used by INDOT on several projects in Indiana. The data in the second group were obtained from 94 sublots of field concretes used on an I-94 project. The data obtained for the first group included the batch ticket information, the measured unit weights, measured air contents and the 28 days compressive strengths. The data obtained for the second group included the batch ticket information, the measured unit weights, the measured air contents and the flexural strengths. The unit weights and air contents from both groups were measured following the procedures in AASHTO T 121 (AASHTO, 2005a) and T 152 (AASHTO, 2005b), respectively. The unit weights and air contents data were used determine the w/c values for both groups of concretes.

Additionally, the tests for the determination of the w/c of five mixtures using the microwave oven technique were included in the laboratory work. The results confirmed the accuracy of w/c determination to be in a range of ±0.03 to ±0.05 as previously reported by NRMCA (Hoover et al., 2008). However, in order to achieve this accuracy, correction was required that accounted for the amount of coarse aggregate particles smaller than the #4 sieve.

8.2. Advantages and Disadvantages of Using Unit Weight to Determine W/C

The advantages of using unit weight for the determination of w/c are:

1. The result can be obtained in ±10 minutes when the unit weight and air content are measured following the zero-air procedure (ZAP) that has been developed as a part of the present study. If the measurements of the unit weight and air contents are already performed at the given job site as part of the QC/QA procedure, no additional effort will be required in order to implement the proposed approach.

2. The unit weight and air content are easy to measure. Since the equipment to perform these tests is readily available, no additional expenses will be incurred.
3. The proposed method can be used on the job site and does not require transportation of concrete to a laboratory.
4. Generally, this technique is applicable to any type of concrete.

The disadvantages of using unit weight for the determination of w/c are as follows:

1. The sensitivity of unit weight to the values of specific gravities of aggregates used requires verification of specific gravities prior to predicting w/c. This specific gravity verification process can be time consuming and thus negatively impact the implementation of unit weight as a technique for w/c determination.

8.3. Conclusions

During the course of the present study, a technique to implement the unit weight for the determination of w/c has been developed and evaluated. The evaluations have been performed for both laboratory and field verifications. Additionally, the accuracy of using the microwave oven technique for w/c determination reported by previous research was confirmed. Finally, the accuracies of using unit weight and microwave oven technique for the determination of w/c were compared.

Based on the results of laboratory and field verifications, the following conclusions can be drawn:

1. For any given (design) constant air content, a theoretical relationship can be established based on the absolute volume principles between the unit weight and w/c values of concrete.
2. After measuring the unit weight of field concrete and adjusting it for the field values of air content and specific gravities of aggregates, the previously established unit weight-w/c relationship can be used to predict the actual value of the w/c.
3. The accuracies of using unit weight for w/c determination were expressed in the terms of standard error and 95th percentile. The laboratory verification using 58 mixtures (two mixtures made at the highest values of 0.7 and 0.8 w/c were excluded due to the

segregation) revealed that the values of the standard error and 95th percentile of Δw/c (the difference between predicted and target w/c) were 0.017 and 0.030, respectively.

4. The laboratory verification using the additional data from 57 mixtures, for which the unit weights and air contents were measured following the procedures in AASHTO T 121 (AASHTO, 2005a) and T 152 (AASHTO, 2005b) revealed the standard error and 95th percentile of Δw/c to be 0.030 and 0.054, respectively. Of these 57 mixtures, three were plain concretes and the rest contained fly ash and silica fume. The plain concretes have a w/c of 0.430 and the ternary concretes have w/c of 0.410.
5. Using INDOT's values for allowable batching tolerances (1% for weight of cement, 2% for weights of aggregates and 1% for weight of water), the proposed method results in ± 0.007 error in the predicted w/c value. These tolerances are also in the industry standard (ASTM C94).
6. Once established, the predicted value of w/c can be applied to forecast expected changes in the strength values of concrete. As an example, the correlation between w/c and 28 days compressive strength (Equation 5.15) was developed for the class of concrete used in the current study. The measurement of a unit weight of concrete with a nominal w/c value of 0.420 indicated that the actual w/c was in the range of 0.390 to 0.450. That range of w/c corresponds to the 28 days compressive strength values ranging from 7325 to 8228 psi (calculated using Equation 5.17).
7. As has been stated in the Chapter 2, INDOT currently uses unit weight to control the w/c of concrete at the point of placement (ITM 803-08P, 2008). This is done by ensuring that the measured unit weight of fresh concrete does not differ by more than ± 1.0 lb/ft^3 from the predicted value based on the measured air content. This practice is only limited to providing a certainty that the w/c of field concrete is on the target and below the permissible maximum w/c; it does not allow for the determination of w/c. The unit weight variation of ± 1.0 lb/ft^3 (± 27 lb/yd^3) corresponds to the variation in w/c of ± 0.028. The value of ± 0.028 was obtained by calculating the change in w/c that corresponds to the change in the unit weight of ± 1.0 lb/ft^3 using Equation 4.14.
8. The w/c values of 22 field concrete mixtures from various projects in Indiana were predicted by using their unit weights and air contents data. This prediction showed that:

a) Twenty one values of differences between final determined actual w/c and batched w/c were within the interval of ±0.030.
b) The 28 days compressive strengths values of number of concretes that have similar composition decreased as the determined w/c increased.

9. The w/c values of the concretes used in the I-94 project were predicted using their unit weight and air content. The flexural strength of these concretes decreased as the predicted w/c increased. However, the observed differences between the determined and CMD w/c values were high, ranging from -0.023 to +0.088.
10. Compared to the microwave oven technique, the use of unit weight to predict w/c is much faster but the accuracy of this method is lower. The comparisons between using microwave oven and implementing fresh concrete unit weight and air content to determine w/c are presented in Table 8.1.

Table 8.1 Comparisons between using microwave oven and implementing fresh concrete unit weight and air content to determine w/c

Method	**Unit weight technique**	**Microwave oven technique**
Time needed	Less than 10 minutes.	Can take up to 30 minutes.
Accuracy	- The 95th percentile of Δw/c is 0.030, when the unit weight and air content are measured using the procedure proposed in the current study. - The 95th percentile of Δw/c is 0.054, when the unit weight and air content are measured using the procedures of AASHTO T 121 (AASHTO, 2005a) and T 152 (AASHTO, 2005b), respectively.	Better than 0.01 (using proposed modification) otherwise ~0.04.
Advantages	- Applicable to any type of concretes. - Easy to perform. - Only needs the basic equipment.	- The procedure is already standardized.
Disadvantages	- Sensitive to the specific gravities of constituents. -	- Safety issue (fire hazard). - Relatively time consuming. - Cost of the equipment (i.e., oven, power source) - Portability requirement

8.4. Recommendations for Future Research

It is recommended that the implementation part of this study involves further verification of the proposed approach using trial batches where the target w/c values along with the moisture content and specific gravities of aggregates can be well controlled.

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APPENDICES

Appendix A – Materials

Table A.1 SSD specific gravity of fine aggregate

Fine Aggregate				
Sample Number	**Weight of Water + Pycnometer g**	**SSD Weight g**	**Weight of Pycnometer + water + SSD g**	**SSD SG**
1	604.9	516.1	925.4	2.64
2	651.7	512.2	969.8	2.64
3	660.5	527.2	987.6	2.63
Average SSD Specific Gravity				2.64

Table A.2 Absorption of fine aggregate

Fine Aggregate			
Sample Number	**SSD Weight g**	**dry Weight g**	**SSD Absorption**
1	516.1	507.2	1.8%
2	512.2	503.6	1.7%
3	527.2	518.0	1.8%
Average Absorption			1.7%

Table A.3 SSD specific gravity of limestone coarse aggregate

Coarse Aggregate			
Sample Number	**Buoyant Weight g**	**SSD Weight g**	**SSD SG**
1	2495.2	3941.2	2.73
2	2465.2	3898.9	2.72
3	2452.1	3877.0	2.72
Average SSD Specific Gravity			2.72

Table A.4 Absorption of limestone coarse aggregate

Coarse Aggregate			
Sample Number	**SSD Weight g**	**dry Weight g**	**SSD Absorption**
1	3792.4	3748.5	1.2%
2	3922.0	3885.0	1.0%
3	3849.4	3813.4	0.9%
Average Absorption			1.0%

Table A.5 SSD specific gravity of dolomite coarse aggregate

Coarse Aggregate			
Sample Number	**Buoyant Weight g**	**SSD Weight g**	**SSD SG**
1	2499.4	3984.1	2.68
2	2447.2	3898.1	2.68
3	2378.2	3787.5	2.69
Average SSD Specific Gravity			2.69

Table A.6 Absorption of dolomite coarse aggregate

Coarse Aggregate			
Sample Number	**SSD Weight g**	**dry Weight g**	**SSD Absorption**
1	3984.1	3933.8	1.3%
2	3898.1	3850.7	1.2%
3	3787.5	3738.4	1.3%
Average Absorption			1.3%

Table A.7 SSD specific gravity of steel slag coarse aggregate

Coarse Aggregate			
Sample Number	**Buoyant Weight g**	**SSD Weight g**	**SSD SG**
1	2206.8	3063.4	3.58
2	2205.6	3064.2	3.57
3	2204.8	3063.7	3.57
Average SSD Specific Gravity			3.57

Table A.8 Absorption of steel slag coarse aggregate

Coarse Aggregate			
Sample Number	SSD Weight g	dry Weight g	SSD Absorption
1	3063.4	3013.9	1.6%
2	3064.2	3014.0	1.7%
3	3063.7	3013.9	1.7%
Average Absorption			1.7%

07-3

BUZZI UNICEM USA

PO Box 482-Greencastle, IN 46135-(765) 653-9766

This is to certify that Type I meets ASTM C-150 Specifications for Portland Cement.

Chemical Data		Physical Data	
ASTM C114		ASTM C185	
Silicon Dioxide (SiO_2)	20.22	Air Entrained (%)	8.5
Aluminum Oxide (Al_2O_3)	5.96	ASTM C204	
Ferric Oxide (Fe_2O_3)	2.28	Fineness (cm^2/gm)	3680
Calcium Oxide (CaO)	64.43	ASTM C151	
Magnesium Oxide (MgO)	1.12	Autoclave Expansion (%)	0.047
Sulfur Trioxide (SO_3)	3.37	Compressive Strength, PSI	
Loss on Ignition	1.03	ASTM C109 Mortar Cubes	
Sodium Oxide	0.12	1-Day	2420
Potassium Oxide	0.85	3-Day	3900
Insoluble Residue	0.41	7-Day	4670
Total Alkali as Na_2O	0.68	28-Day	5810
POTENTIAL COMPOUND COMPOSITION		ASTM C191	
		Setting Time:	
Tricalcium Silicate (C_3S)	56	Vicat	
Dicalcium Silicate (C_2S)	16	Initial, Min.	105
Tricalcium Aluminate (C_3A)	12	Final, Min.	210
Tricalcium Aluminoferrite(C_4AF)	7		

Silo	Bill of Lading	Tons	Date	Silo	Bill of Lading	Tons	Date
							03/15/2007

STATE OF INDIANA)
COUNTY OF PUTNAM)

Before me the undersigned, a Notary Public for Putnam County, State of Indiana personally appeared John J. Wachal and acknowledged the execution of the foregoing instrument this 15th day of March 2007.

To:

John J. Wachal

Philip A. Clodfelter, Notary Public
My commission expires May 8, 2008.

John J. Wachal
Quality Manager

Figure A.1 Cement chemistry

Table A.9 INDOT's specification for fine aggregate gradation

SIZES (PERCENT PASSING)						
Sieve Sizes	23	24	15	16	PP	S&I
3/8 in. (9.5 mm)	100	100				100
No. 4 (4.75 mm)	95-100	95-100			100	
No. 6 (3.35 mm)			100			
No. 8 (2.36 mm)	80-100	70-100	90-100		85-95	
No. 16 (1.18 mm)	50-85	40-80				
No. 30 (600 μm)	25-60	20-60	50-75	100	50-65	
No. 50 (300 μm)	5-30	7-40	15-40		15-25	0-30
No. 80 (180 μm)				95-100		
No. 100 (150 μm)	0-10	1-20	0-10		0-10	
No. 200 (75 μm)	0-3	0-6	0-3	65-100		0-7

Table A.10 Sieve analysis of fine aggregate (provided by the manufacture)

Sieve	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Passing Percentage, %	100.0	99.9	94.2	66.1	38.9	13.8	4.6	2.3

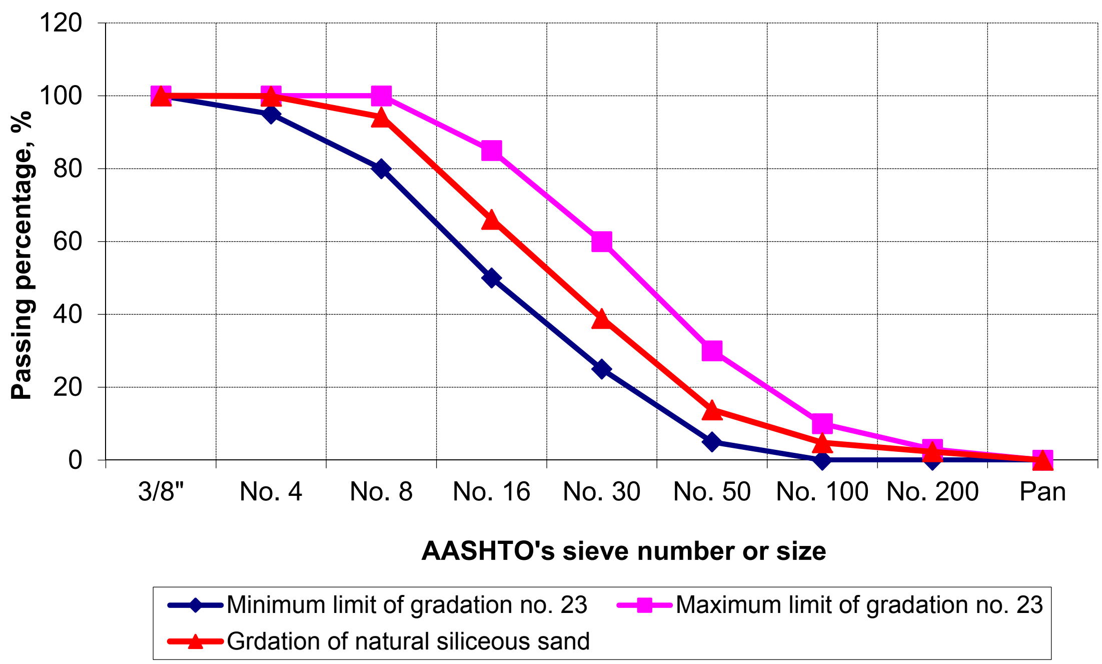

Figure A.2 Gradation curves of fine aggregate

Table A.11 INDOT's specification for coarse aggregate gradation

Sieve Sizes	COARSE AGGREGATE SIZES (PERCENT PASSING)									
	COARSE GRADED								DENSE GRADED	
	2	5	8	9	11	12	43(1)	91	53(1)	73(1)
4 in. (100 mm)										
3 1/2 in. (90 mm)										
2 1/2 in. (63 mm)	100									
2 in. (50 mm)	80-100									
1 1/2 in. (37.5 mm)		100					101		100	
1 in. (25 mm)	0-25	85-98	100				70-90	100	80-100	100
3/4 in. (19 mm)	0-10	60-85	75-95	100			50-70		70-90	90-100
1/2 in. (12.5 mm)	0-7	30-60	40-70	60-85	100	100	35-50		55-80	60-90
3/8 in. (9.5 mm)		15-45	20-50	30-60	75-95	95-100				
No. 4 (4.75 mm)		0-15	0-15	0-15	10-30	50-80	20-40		35-60	35-60
No. 8 (2.36 mm)		0-10	0-10	0-10	0-10	0-35	15-35		25-50	
No. 30 (600 µm)						0-4	5-20		12-30	30-Dec
No. 200 (75 µm)(2)							0-0.6		5.0-10.0(4)	5.0-12.0
Decant (PCC)(3)		0-1.5	0-1.5	0-1.5	0-1.5	0-1.5		0-1.5		
Decant (Non-PCC)	0-2.5	0-2.5	0-3.0	0-2.5	0-2.5	0-2.0		0-2.5		

Notes:
1. The liquid limit shall not exceed 25 (35 if slag) and the plasticity index shall not exceed 5. The liquid limit shall be determined in accordance with AASHTO T 89 and the plasticity index in accordance with AASHTO T 90.
2. Includes the total amount passing the No. 200 (75 µm) sieve as determined by AASHTO T 11 and T 27.
3. Decant may be 0-2.5 for stone and slag.
4. When slag is used for separation layers as defined in 302.01, the total amount passing the No. 200 (75 µm) sieve shall be 10.0 to 12.0.

2-07
Dolomite
Black/Gold, Lab

Vulcan
Materials Company

Basic Quality Statistical Summary Report

Plant	341-Monon
Product	573-Indiana #8 Stone "AP"
Specification	Indiana #8 Stone "AP" Spec

Sieve/Test	Tests	Average	St Dev	Target	Specification
1 1/2" (37.5mm)		100.0			
1" (25mm)		100.0			100-100
3/4" (19mm)		91.8			75-95
5/8" (16mm)		80.7			
1/2" (12.5mm)		50.5			38.7-55.9
3/8" (9.5mm)		26.3			20-50
1/4" (6.3mm)		14.1			
#4 (4.75mm)		7.3			0-15
#8 (2.36mm)		3.3			0-10
#16 (1.18mm)		2.7			
#200 (75um)		2.03			
PAN (0um)		0.00			

Figure A.3 Gradation of dolomite coarse aggregate

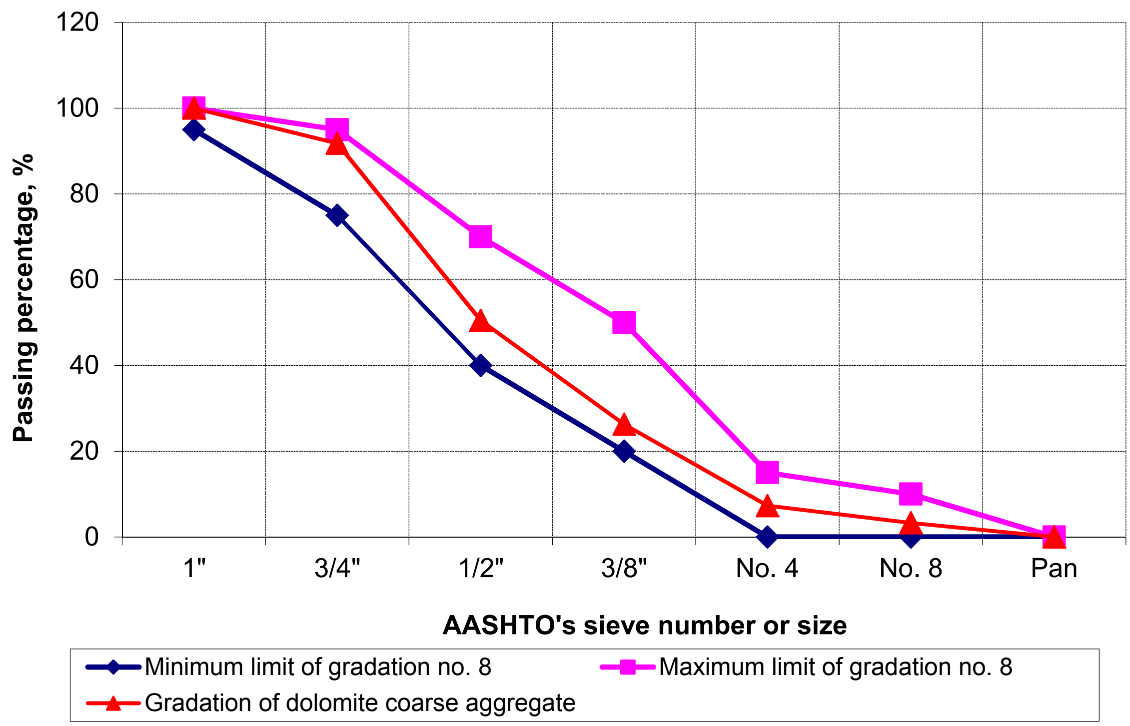

Figure A.4 Gradation curves of dolomite coarse aggregate

Table A.12 Sieve analysis of limestone coarse aggregate

Coarse aggregate	Limestone		
Sieve	**Weight of aggregate retained (lbs)**	**% retained**	**% passing**
1"	0	0	100
3/4"	1.8	7.3	92.7
1/2"	7.4	37.6	62.4
3/8"	4.4	55.5	44.5
No. 4	8.1	88.6	11.4
No. 8	1.6	95.1	4.9
Pan	1.2	100	0

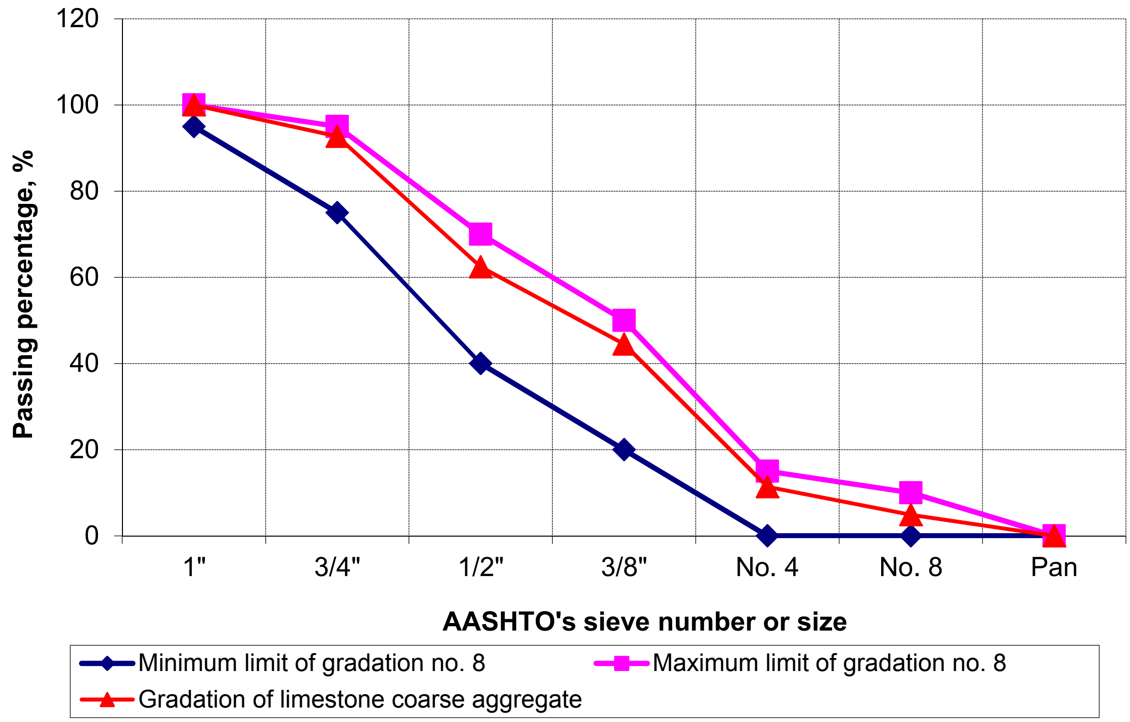

Figure A.5 Gradation curves of limestone coarse aggregate

Table A.13 Sieve analysis of steel slag coarse aggregate (provided by the manufacture)

Sieve	1"	3/4"	1/2"	3/8"	No. 4	No. 8	Pan
Passing Percentage, %	100	90.6	52.1	28.3	6.4	3.5	0

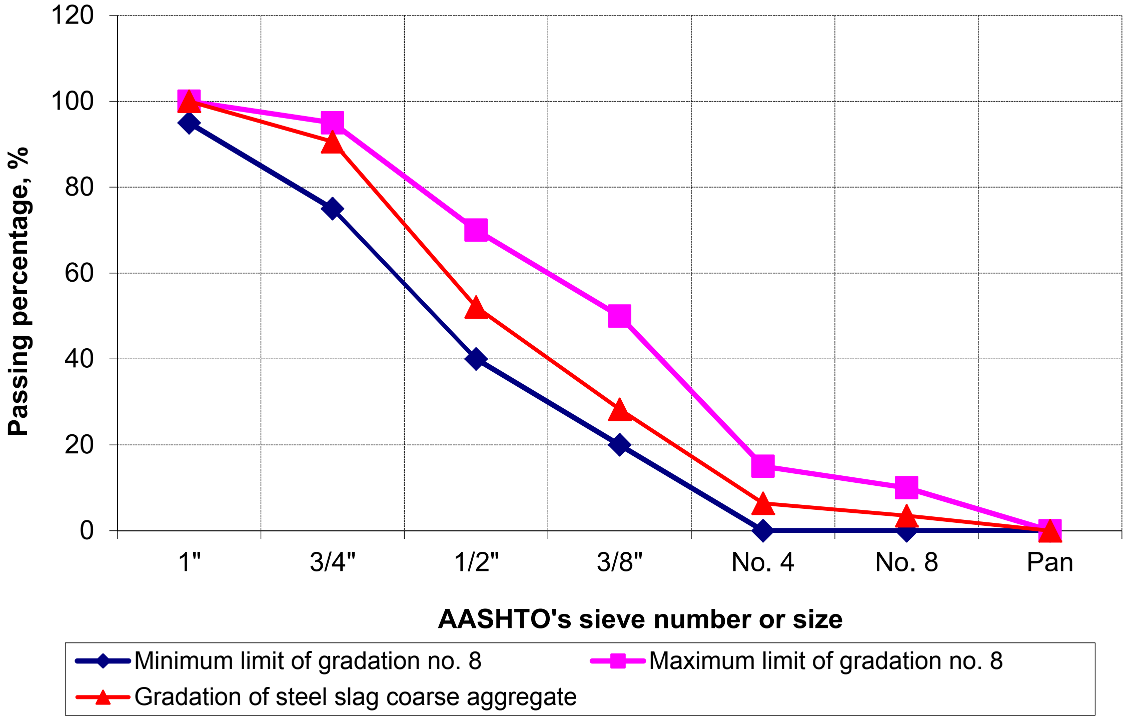

Figure A.6 Gradation curves of steel slag coarse aggregate

Appendix B – Spreadsheet for the Prediction W/C based on Measured Unit Weight

Unit Weight Based Technique for Verification of W/C of Field Concrete

Basic mix design			
	w/c =	0.40	
Material	Specific gravity	Weigt lbs/yd^3	Volume yd^3
Cement	3.15	658	0.12
Fly ash	0.00	0	0.00
Slag	0.00	0	0.00
Fine aggregate	2.64	1450	0.33
Coarse aggregate	2.69	1477	0.33
Water	1.00	263	0.16
Air	N/A	0	0.07
	Total =	3848.5 lbs/yd^3	1.00 yd^3

Amount of air content being used in w/c-unit weight correlation = 6.50%

Material	Change in the amount of water(ΔWw, lbs)									
	-13		-7		0		7		13	
	w/c of altered batch									
	0.380		0.389		0.400		0.411		0.420	
	Composition volumes and unit weights of altered batches									
	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3	Weight lbs	Volume yd^3
Cement	663	0.13	661	0.12	658	0.12	655	0.12	653	0.12
Fly ash	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Slag	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
Fine aggregate	1462	0.33	1457	0.33	1450	0.33	1444	0.33	1438	0.32
Coarse aggregate	1489	0.33	1484	0.33	1477	0.33	1470	0.33	1465	0.32
Water	252	0.15	257	0.15	263	0.16	269	0.16	274	0.16
Air	0	0.07	0	0.07	0	0.07	0	0.07	0	0.07
Sum	3867	1.00	3859	1.00	3849	1.00	3838	1.00	3830	1.00
Unit weight UW' (lbs/yd^3)	3867		3859		3849		3838		3830	

w/c = -0.0010494 UW + 4.439 R^2 = 1.000

Measured unit weight = 3029 lbs/yd^3

Measured air content = 26.5%

Unit weight with 6.5% air content = 3851 lbs/yd^3

Actual specific gravity of fine aggregate (SSD) = 2.64

Actual specific gravity of coarse aggregate (SSD) = 2.72

Unit weight with the SG of aggregates equal to those for the basic mix with 6.5% air = 3833 lbs/yd^3

Actual w/c = 0.416

Figure B.1 Spreadsheet of unit weight based technique for verification of w/c of field concrete

Appendix C – Typical Worksheet for the Computation of ITM-403-Calculated W/C

Row	Procedure	Method	Col.1	Col.2
			C.A.	F.A.
A	Weight (mass) original sample & pan, lbm (kg)	Weight	1784	1152
B	Weight (mass) dry sample & pan, lbm (kg)	Weight	1731	1110
C	Weight (mass) of water in sample, lbm (kg)	A-B	53	42
D	Weight (mass) of pan, lbm (kg)	Weigh	0	0
E	Weight)mass) of dry sample, lbm (kg)	B-D	1731	1110
F	Percent moisture (%)	(C/E)100	3.06	3.78
G	Percent absorption (%)	CMD	1.5	1.05
H	Weight (mass) wet aggregate in batch, lbm (kg)	Batch ticket	1784	1152
I	Weight (mass) dry aggregate in batch, lbm (kg)	H/(1.0+F/100)	1731	1110
J	Weight (mass) water in aggregate in batch, lbm (kg)	H-I	53	42
K	Weight (mass) water absorption in batch, lbm (kg)	I(G/100)	26	12
L	Total weight (mass) water in aggregate, lbm (kg)	J1+J2	95	
M	Total weight (mass) water absorbed, lbm (kg)	K1+K2	38	
N	Total water added to the batch, lbm (kg)	Batch ticket	227	
O	Total free water in the batch, lbm (kg)	N+L-M	284	
P	Weight (mass) Portland cement in batch, lbm (kg)	Batch ticket	599	
Q	Total weight (mass) pozzolans in batch, lbm (kg)	Batch ticket	98	
R	Total weight (mass) cementitious in batch, lbm (kg)	P+Q	697	
S	Water-cementitious ratio	O/R	0.407	

Appendix D – Determination of Average, Variance and 95th Percentile of ΔW/C using Integrated Distribution Fitting Tool in Matlab®

The average, variance and 95th percentile of Δw/c was determined using integrated distribution fitting tool in Matlab®. In this appendix, the example to determine average, variance and 95th percentile of Δw/c of group (first group) of mixtures that was used in the laboratory verification and the unit weight of the individual mixture was measured using zero air procedure is presented.

The steps used are as below (see the figure provided after each step for the illustration of the step):

1. Open *Blank M-File* (***File* → *New* → *Blank M-File***).

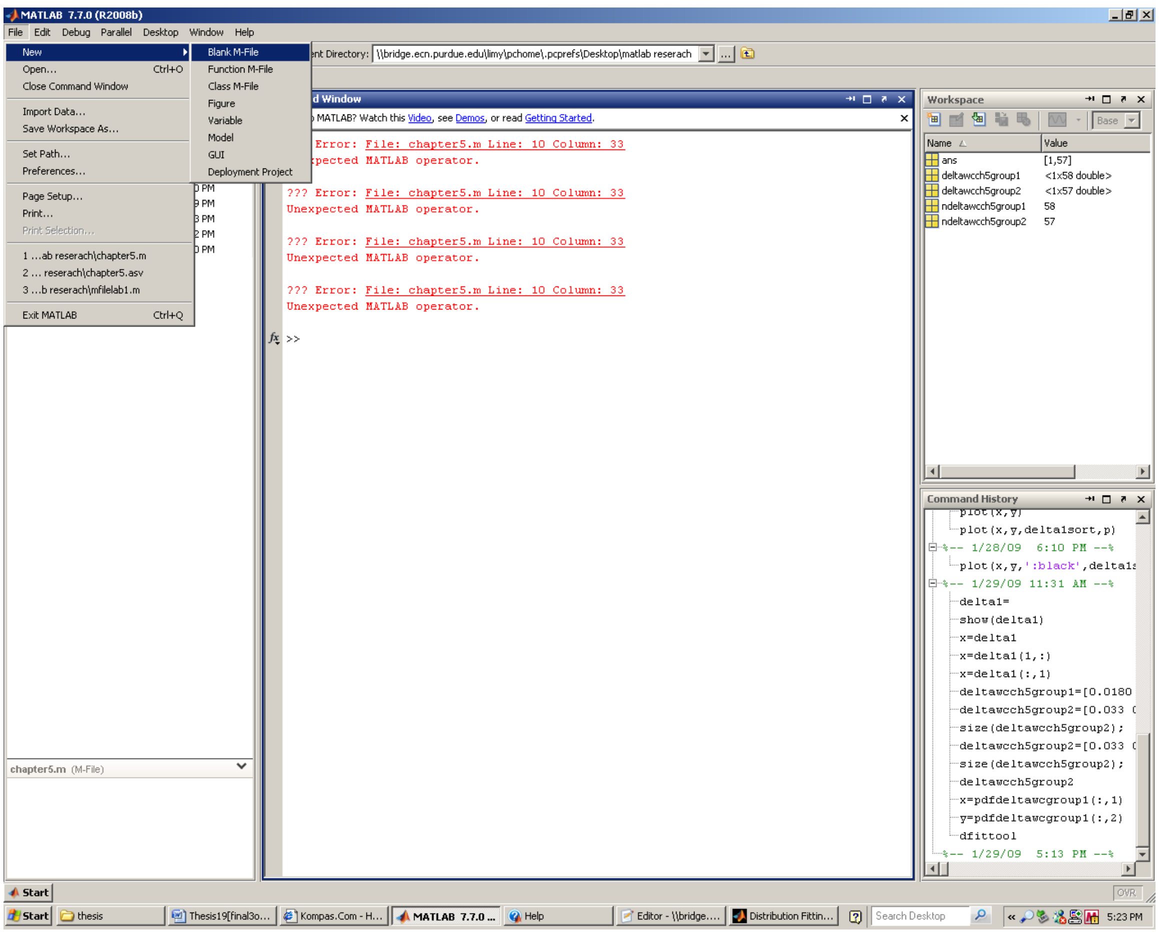

Figure D.1 Illustration to open *Blank M-File*

2. Write matrix (`deltawcch5group1`) Δw/c of first group of mixtures in *M-File*.

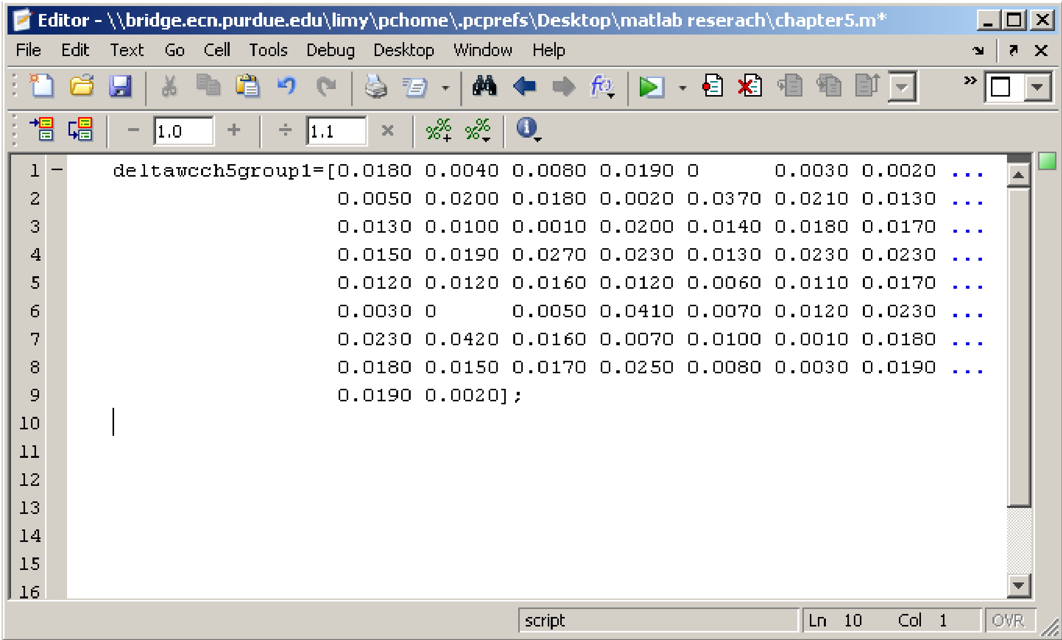

Figure D.2 Illustration to write matrix Δw/c of first group of mixtures in *M-File*

3. Open *distribution fitting tool window* by typing code `dfittool` in *M-File*. Then click *run button*.

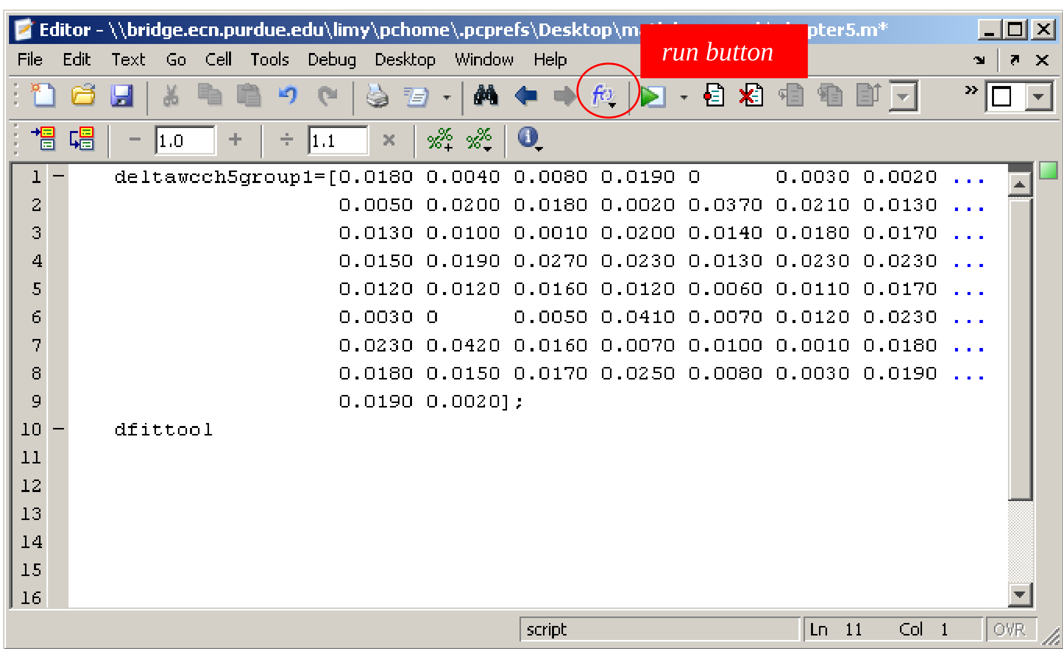

Figure D.3 Illustration to write code `dfittool` in *M-File*

4. Open the *data window* by clicking *data tab* in *distribution fitting tool window*.

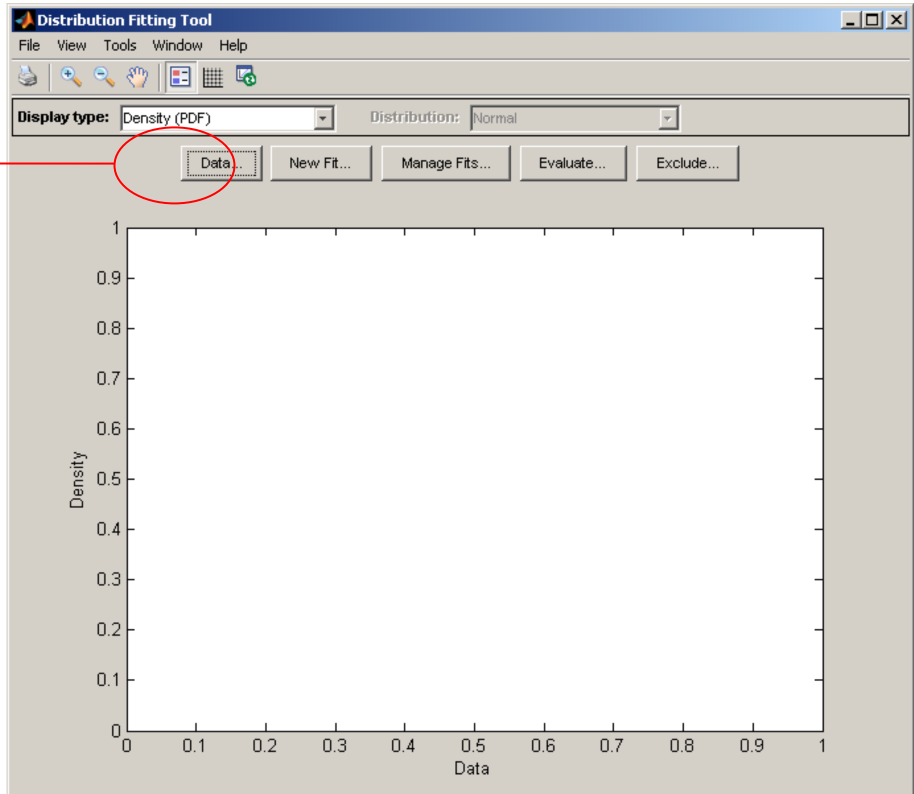

Figure D.4 *Distribution fitting tool window* and the illustration to open *data window*

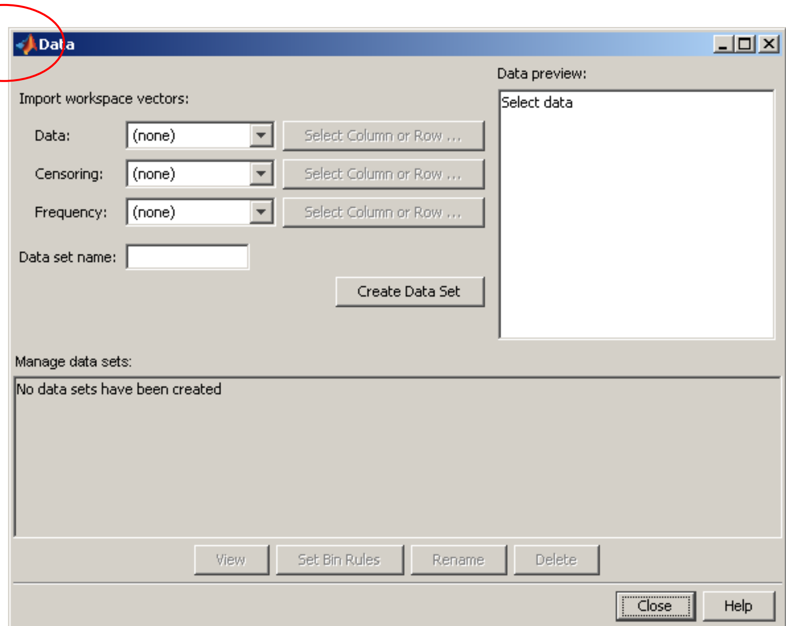

Figure D.5 *Data window*

5. Create data set of)Δw/c of first group of mixtures by choosing “deltawcch5group1” in the selection of *data pull-down menu*. Click *create data set tab* and *close tab*, successively.

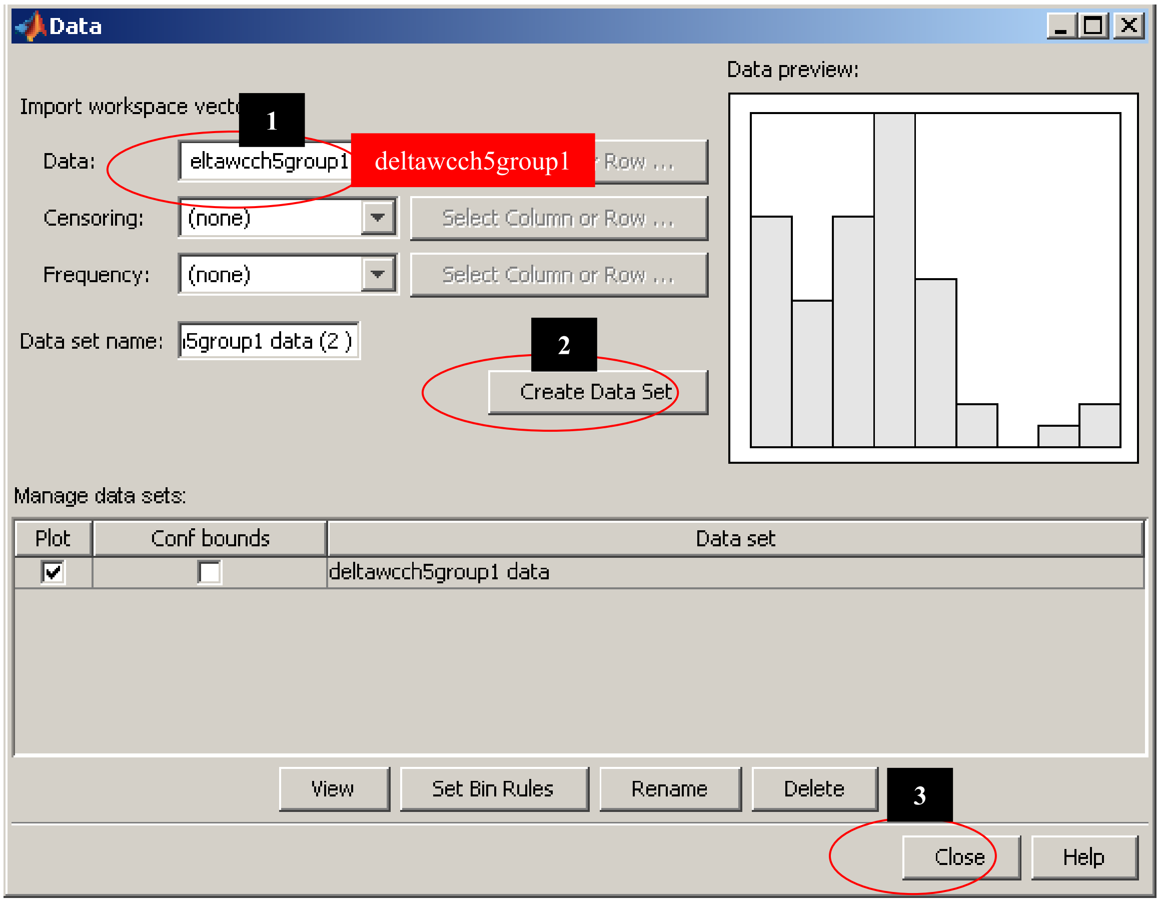

Figure D.6 Illustration to create data set

6. Open *edit fit window* by clicking *new fit tab* in *distribution fitting tool window*. In *edit fit window*, choose “normal” in the selection list of *distribution pull-down menu*. Click *apply tab* (after clicking this tab, the average and variance of Δw/c of first group of mixtures can be obtained from the *results panel*) of and *close tab*, successively.

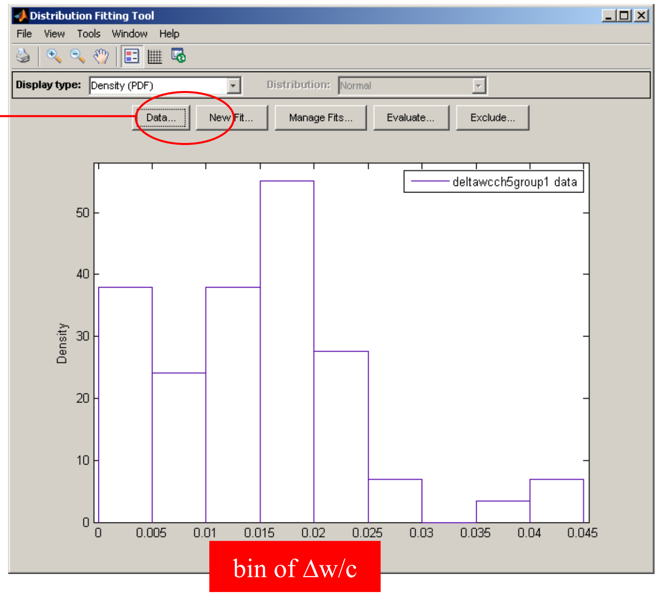

Figure D.7 Illustration of the way to open *edit fit window* and the histogram of Δw/c of first group of mixtures

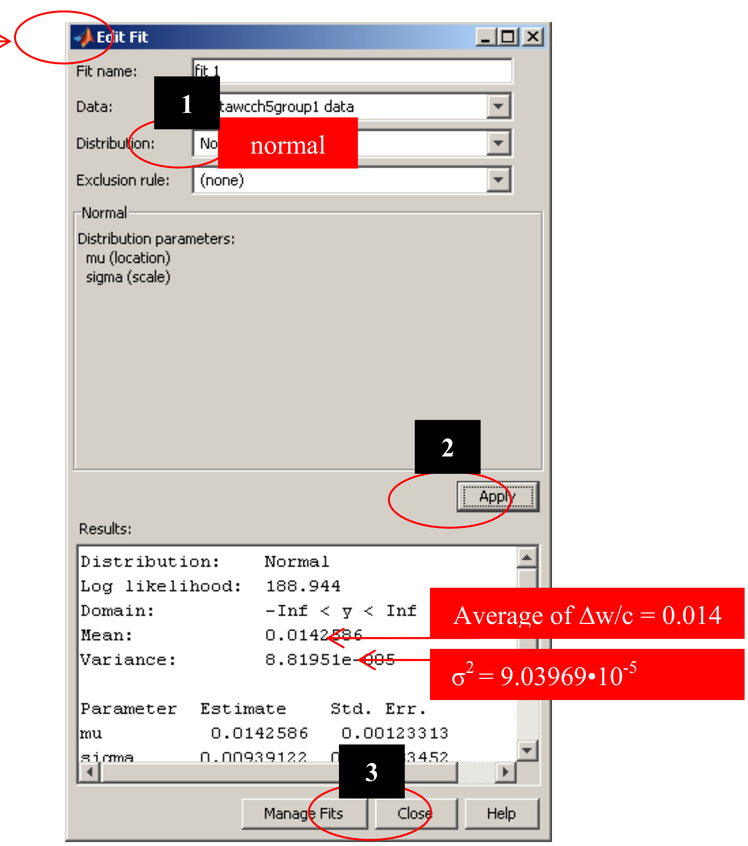

Figure D.8 Illustration to choose "normal" in the selection list of *distribution pull-down menu* and to obtain average and variance of Δw/c

7. In order to see whether it is plausible or not to use the normal probability distribution function (pdf) to represent the pdf of Δw/c, the normal cumulative distribution function (cdf) is compared to cdf of Δw/c. It is done by choosing "cumulative probability (CDF)" in the selection list of *display-type pull-down menu* in *distribution fitting tool window*.

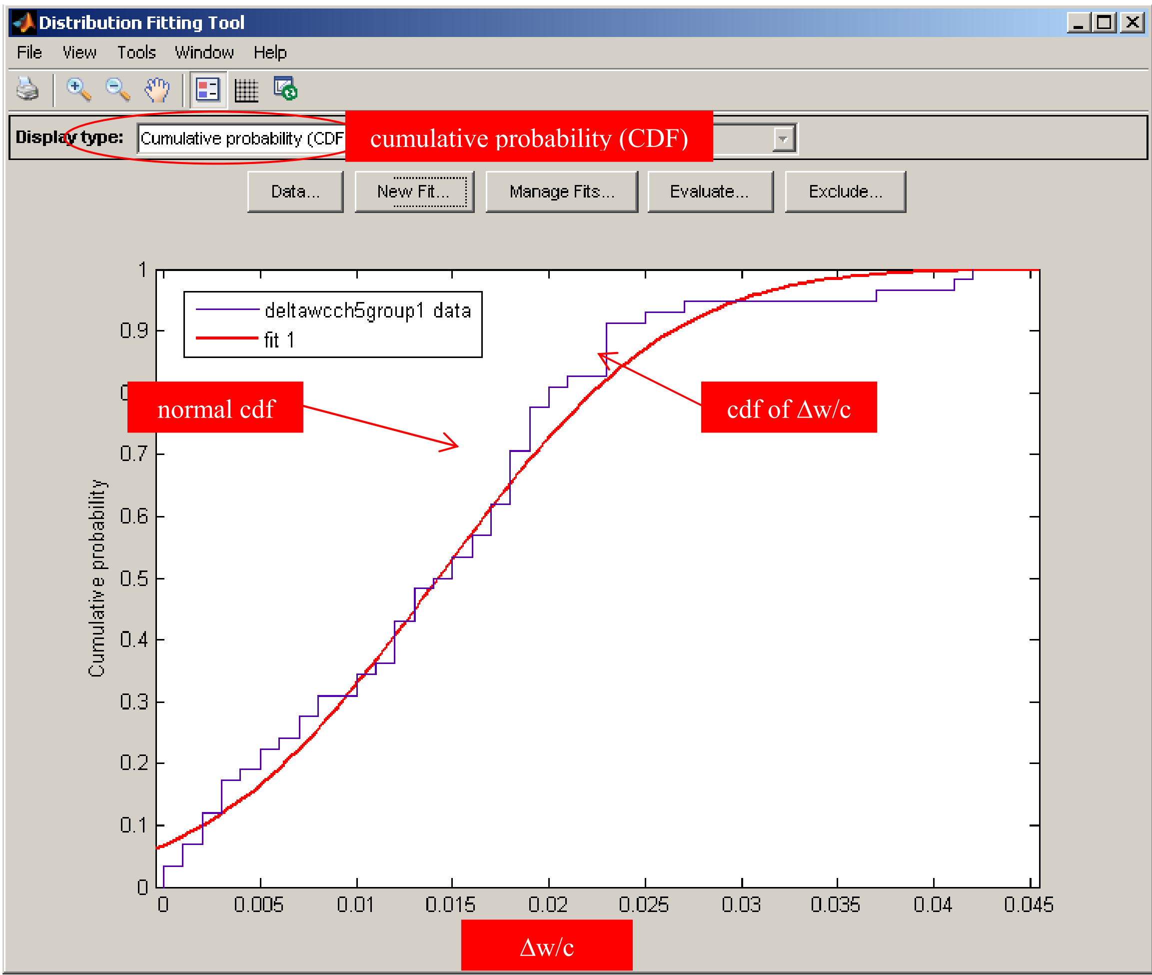

Figure D.9 Comparison of normal cumulative distribution function and cdf of Δw/c

It can be seen from Figure D.9 that the normal cdf fits well the cdf of Δw/c, which in turn concludes that the normal pdf can represent pdf of Δw/c.

8. In order to find the 95th percentile of Δw/c, open *evaluate window* by clicking *evaluate tab* in *distribution fitting tool window*. In *evaluate window*, choose "cumulative probability (CDF)" in the selection list of *function pull-down menu*. Put the code "0:0.001:0.045" (minimum : interval : maximum of Δw/c as variable x) to fill *At x = panel*. Click apply tab and find the cumulative probability value (*F(x)*) that is larger than or equal and is as close as to 0.95. The corresponding 95th percentile of this selected cumulative probability value is assumed to be 95th percentile of Δw/c.

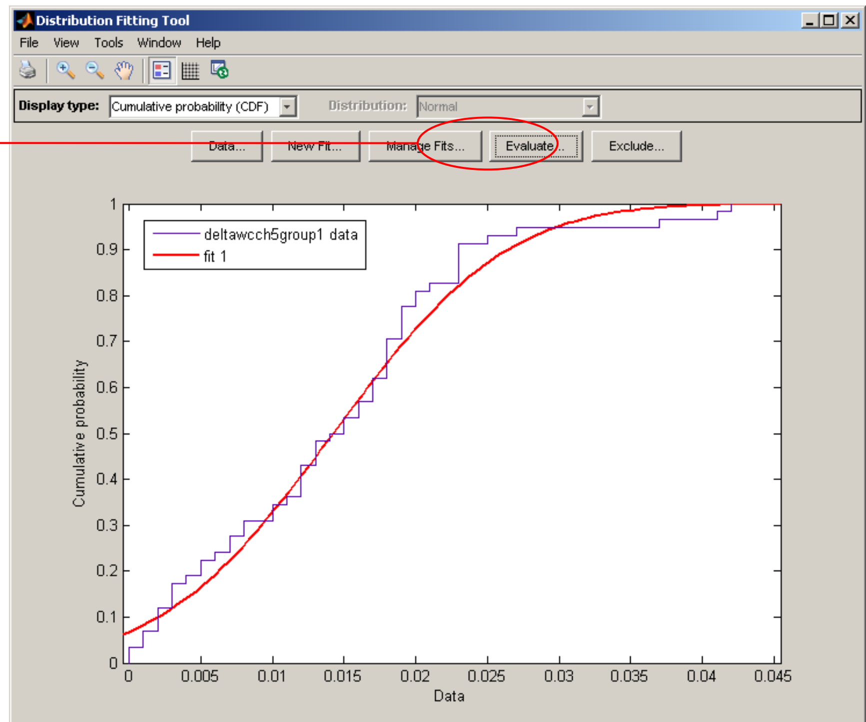

Figure D.10 Illustration to open *evaluate window*

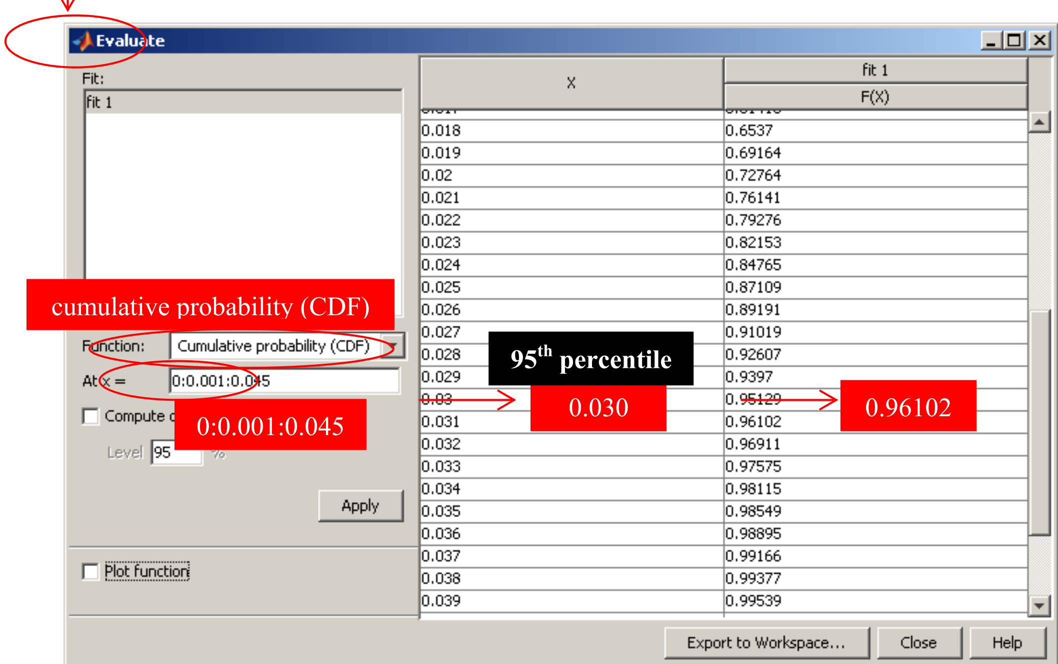

Figure D.11 Illustration to obtain 95th percentile of Δw/c

The average, variance and 95th percentile of Δw/c of group (second group) of mixtures that were used for laboratory verification and the unit weight of individual mixture was measured following AASHTO procedures were obtained using the same procedure explained above. Figure D.12 illustrates *edit fit window* showing the average and variance.

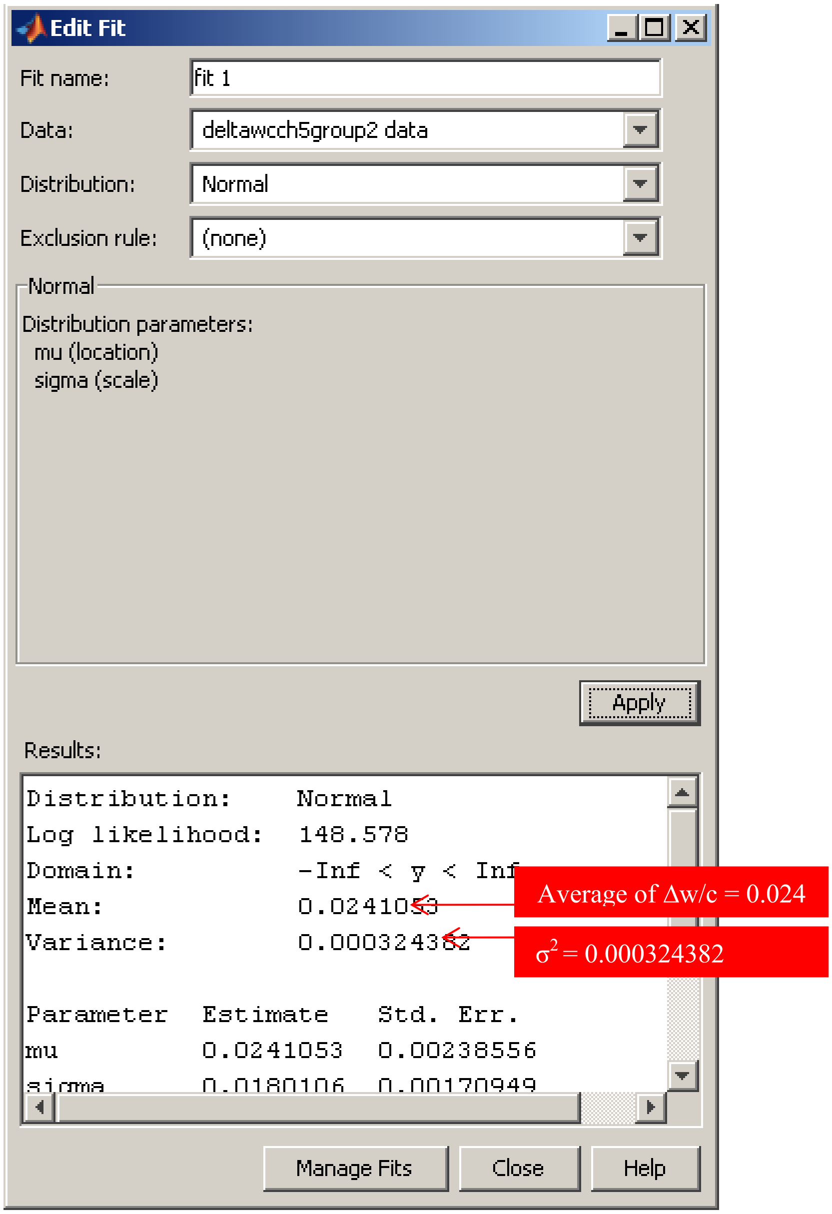

Figure D.12 Illustration to obtain average and variance of Δw/c of second group of mixtures

Figure D.13 illustrates the comparison between the normal cumulative distribution function (cdf) and cdf of Δw/c. It can be seen from this figure that the normal cumulative distribution graph fits well the cumulative distribution graph of Δw/c of second group of mixtures, which in turn concludes that the normal probability distribution function can represent the probability distribution function of Δw/c of second group of mixtures. Figure D.14 illustrates the *evaluate window* showing the assumed 95th percentile.

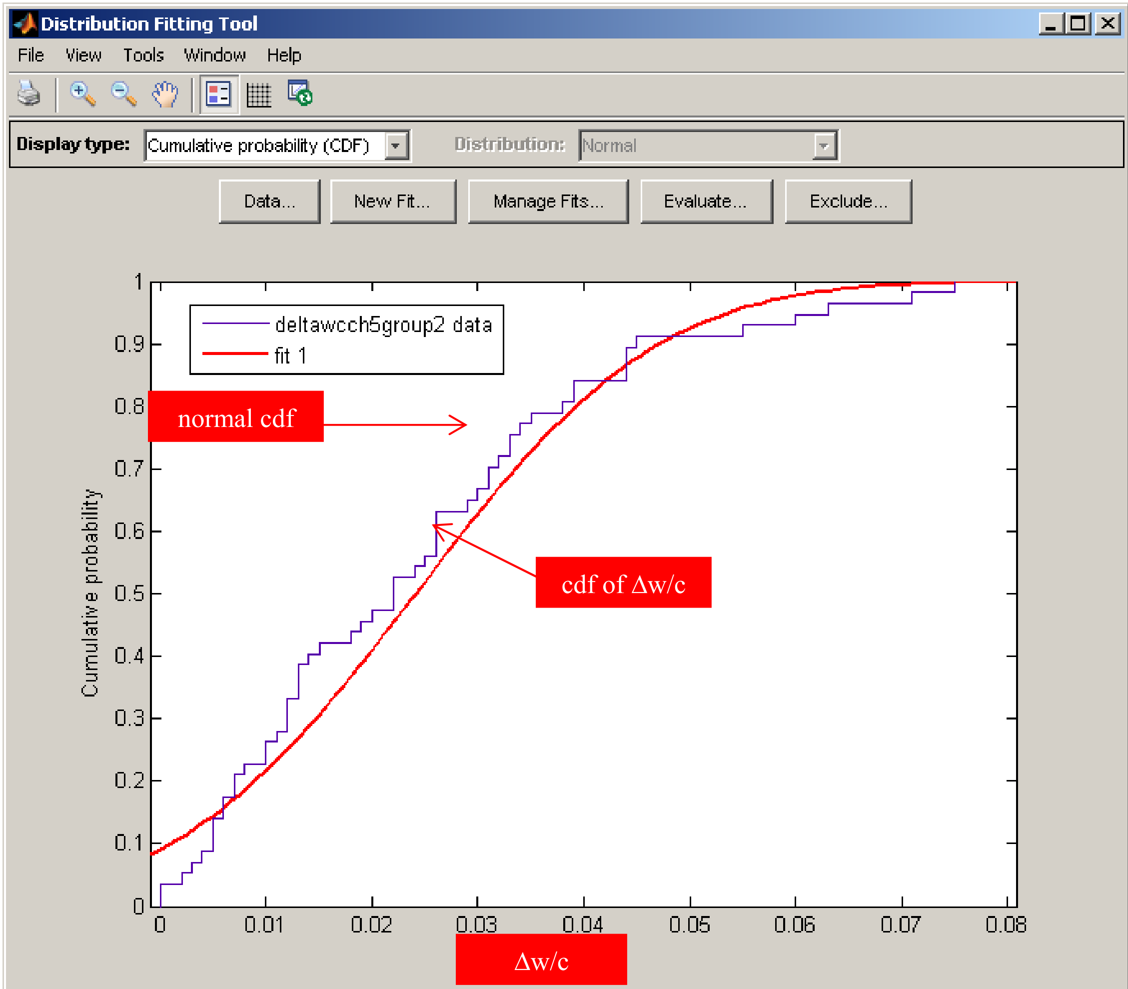

Figure D.13 Comparison of normal cumulative distribution function and cdf of Δw/c of second group of mixtures

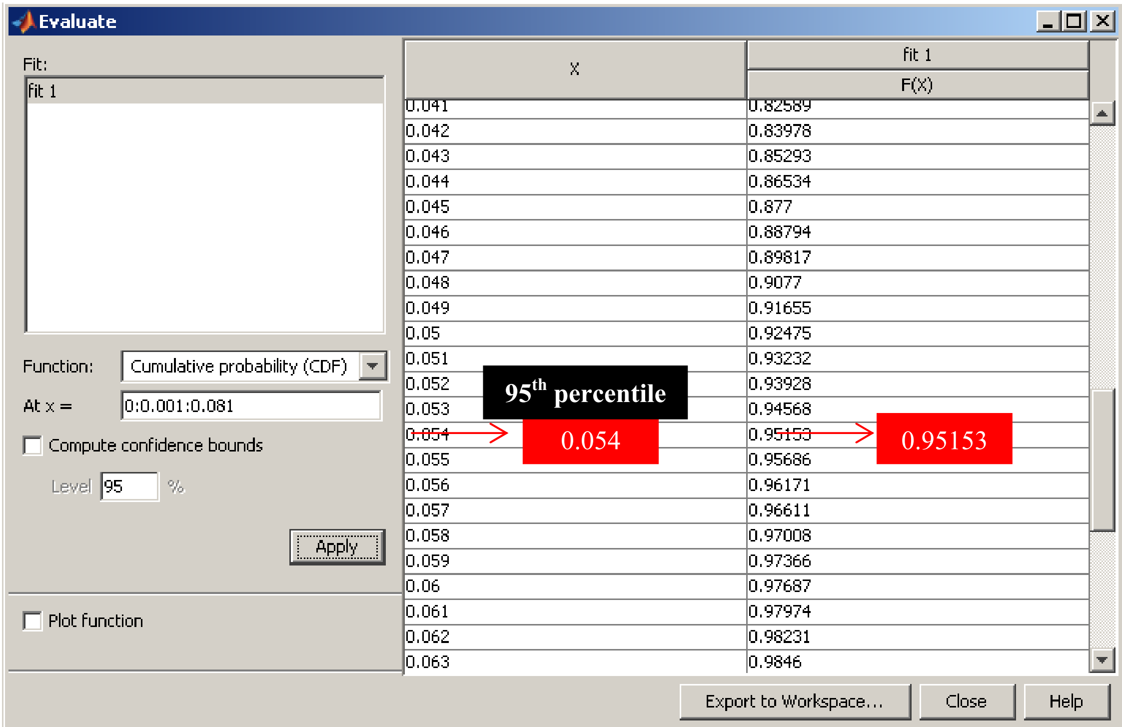

Figure D.14 Illustration to obtain 95th percentile of Δw/c of second group of mixtures