3 MIX DESIGN & PROPORTIONING

CHAPTER THREE: MIX DESIGN

MIX DESIGN

The concrete mix design (CMD) for QC/QA superstructure concrete must produce a workable concrete mixture having properties that will not exceed the maximum and/or minimum values defined in the special provision. Workability in concrete defines its capacity to be placed, consolidated, and finished without harmful segregation or bleeding. Workability is affected by aggregate gradation, particle shape, proportioning of aggregate, amount and qualities of cementitious materials, presence of entrained air, amount and quality of high range water reducer, and consistency of mixture.

Consistency of the concrete mixture is its relative mobility and is measured in terms of slump. The higher the slump the more mobile the concrete, affecting the ease with which the concrete will flow during placement. Consistency is not synonymous with workability. Two different mix designs may have the same slump; however, their workability may be different.

Selection of target parameters by the contractor for any mix design must consider the influence of the following:

1. material availability and economics
2. variability of each material throughout period of usage
3. control capability of production plant
4. ambient conditions expected at the time(s) of concrete placement
5. logistics of concrete production, delivery, and placement
6. variability in testing concrete properties
7. generation of heat in large structural elements and differential in thermal gradient (i.e. 2 - 3 ft thick and cement content above 600 lb/yd^3)

The qualities of the cementitious paste provide a primary influence on the properties of concrete. Proper selection of the cementitious content and water/cementitious ratio is dependent on the experience of the concrete producer and becomes a very important first step in preparing a design. For workable concrete, a higher water cementitious ratio is typically required when aggregate becomes more angular and rough textured. The presence of air, certain pozzolans, and aggregate proportioning will work to lower the water cementitious ratio; however the most significant reduction in water demand comes through the use of a high range water reducing chemical admixture.

Water/cementitious ratio is determined from the net, per unit, quantity of water and total cementitious materials (by weight). The net water content excludes water that is absorbed by the aggregates. For a given set of materials and conditions, as water/cementitious ratio increases, strength and unit weight will decrease. Compressive strength is a concrete parameter used in combination with unit weight and air content to evaluate the durability of the superstructure concrete's exposure to freeze / thaw action, and exposure to deicing salts. It is important to note that the designer of the bridge structure does not recognize the benefit of increased compressive strength. The slab still relies on a minimum design compressive strength (f'c) of 4000 psi at 28-days.

Proportioning of aggregates is defined by the volume of fine aggregate to the volume of coarse aggregate, as a percent. The lower percentage of fine to total aggregate provides an increase in compressive strength at the expense of workability. The gradation, particle shape and texture of the coarse aggregate along with fineness modulus of the fine aggregate will determine how low the fine to total aggregate percentage can be for a given workability requirement.

MIXING PROPORTIONING

Once the cement content, pozzolan content, water/cementitious ratio, and fine to total aggregate percentage are defined for the concrete's intended use in the superstructure, proportioning of the mix in terms of design batch weights can begin. Specific gravities must be accurately defined for each material being utilized in order to proportion the mix properly by the absolute volume method. Cement is typically accepted as having a specific gravity of 3.15. Pozzolans will typically vary between 2.22 and 2.77 depending on the type of pozzolan (fly ash, GGBFS, silica fume) and its source. Pozzolan suppliers should readily be able to provide current values for their material. Approximate specific gravities are identified for each source on the Department's Approved/Prequalified Materials list; however, they should not be considered the most current.

Bulk specific gravity, in the saturated surface dry condition, must be used to proportion the fine and coarse aggregate. Accurate testing of one or more samples of fine and coarse aggregate must be accomplished by the

Contractor as part of any proportioning for a mix design. It is of great benefit to identify the geologic ledges from which a crushed stone coarse aggregate is produced. Subsequent shifts in benching at the aggregate source may cause significant shifts in bulk specific gravity and absorption. These are important aggregate properties to monitor as part of concrete quality control.

Proportioning concrete by the absolute volume method involves calculating the volume of each ingredient and its contribution to making one yd^3 or 27 ft^3 of concrete. Volumes are subsequently converted to design weights, which then become the basis for actual production of concrete from the plant. For cementitious materials and water, the weight to volume conversion is accomplished by dividing the weight (lbs) by the specific gravity of the material and again dividing by the density of water (62.27 lbs/ft^3 at 73.4 °F). Converting from volume to weight is accomplished simply by taking the known volume (ft^3) of the ingredient and multiplying by the specific gravity of the ingredient and again multiplying by the density of water (62.27 lbs/ft^3 at 73.4 °F). Volume to weight conversions for aggregates are accomplished by the same series of computations; however, bulk specific gravity (SSD) must be used. The target air content is established at 6.5% by the special provision, which converts to a volume of 1.76 ft^3 within a cubic yard of concrete.

Instructions for Page 1 of Mix Design & Proportioning Worksheets

A worksheet entitled "Mix Design & Proportioning QC/QA Superstructure Concrete" has been developed and is included in Appendix D, under tab 11 of this manual. Use of this form by the Contractor and Department will provide an easy means to proportion a mix by the absolute volume method and validate compliance, thereby helping to eliminate delays due to errors and/or oversight of the specification requirements.

An example of proportioning a mix design through use of this form is detailed in Table 3.1. The contractor establishes the initial parameters for a mix design and serves as the starting point for subsequent proportioning calculations.

The initial step in proportioning the mix design is to calculate the water content per cubic yard of concrete. This is accomplished by multiplying the total cementitious content by the water/cementitious ratio. It should be noted that space was intentionally provided on the form to allow room for computations.

Example: 658 x 0.395 = 260 lbs water content

There is now sufficient information to begin entering known weights, volumes, and specific gravities into the second table. Table 3.2 illustrates the results for the example problem.

Initial Parameters for yd^3 Concrete	
Target Cement Content, lbs	**658**
Target Pozzolan Content, lbs	**0**
Target Silica Fume Content, lbs	**0**
Target Water / Cementitious Ratio, by wt.	**0.395**
Target Cement / Pozzolan Ratio, by wt.	**Infinity**
Target % Silica Fume	**0.0**
100 FA / FA+CA, Target, % by volume	**41.7**
FA Bulk Sp. Gr. (SSD)	**2.632**
FA Absorption, %	**2.00**
CA Bulk Sp. Gr. (SSD)	**2.711**
CA Absorption, %	**1.40**

Table 3.1

Material	Size, Type or Class	Source	Design Batch Weights lbs	Specific Gravity	Absolute Volume ft^3
Cement	Type I		**658**	3.150	**3.35**
Pozzolan	-------	----------------------------	--------	--------	--------
Silica Fume	--------	----------------------------	--------	--------	--------
FA	#23 NS			**2.632**	
CA	#8 CS			**2.711**	
Water	potable		**260**	1.000	**4.18**
Air	entrained	see table below	**0**	-NA-	**1.76**
∑	-NA-	-NA-		-NA-	27.00

Table 3.2

The volume of total aggregates is now calculated by subtracting the volumes of other known ingredients (i.e. cement, pozzolan, silica fume, water, and air) from 27.00 cubic feet of concrete.

Example: 27.00 - (3.35 + 4.18 + 1.76) = 17.71 ft^3 total aggregates

The percentage of fine to total aggregate is divided by 100 to produce the decimal equivalent, and then multiplied by the total aggregate volume to determine the volume of fine aggregate only.

Example: 17.71 ft^3 x 0.417 = 7.39 ft^3 fine aggregate

The corresponding volume of coarse aggregate is determined by subtracting the known volume of fine aggregate from the known volume of total aggregate.

Example: 17.71 ft^3 - 7.39 ft^3 = 10.32 ft^3 coarse aggregate

These calculated values are now inserted in the appropriate cells of the table as shown in Table 3.3 by the values in boldface print.

Material	Size, Type or Class	Source	Design Batch Weights lbs	Specific Gravity	Absolute Volume ft^3
Cement	Type I		658	3.150	3.35
Pozzolan	-------	---------------------------	--------	--------	--------
Silica Fume	--------	---------------------------	--------	--------	--------
FA	#23 NS			2.632	**7.39**
CA	#8 CS			2.711	**10.32**
Water	potable		260	1.000	4.18
Air	entrained	see table below	0	-NA-	1.76
Σ	-NA-	-NA-		-NA-	27.00

Table 3.3

The volumes of fine and coarse aggregate are each converted to the design batch weight (lbs) based on saturated surface dry condition. The design batch weights are added to obtain the total weight of ingredients required to make 27.00 ft^3 of concrete at 6.5% target air content. Table 3.4 illustrates tabulation of the example problem.

Material	Size, Type or Class	Source	Design Batch Weights lbs	Specific Gravity	Absolute Volume ft^3
Cement	Type I		658	3.150	3.35
Pozzolan	-------	----------------------------	--------	--------	--------
Silica Fume	--------	----------------------------	--------	--------	--------
FA	#23 NS		**1211**	2.632	7.39
CA	#8 CS		**1742**	2.711	10.32
Water	potable		260	1.000	4.18
Air	entrained	see table below	0	-NA-	1.76
Σ	-NA-	-NA-	**3871**	-NA-	27.00

Table 3.4

It should be noted that the volumes and weights of any water present in the admixtures are typically not included in the mix proportioning or in the water content determinations.

LINEAR EQUATION OF UNIT WEIGHT vs. AIR CONTENT

It is known that the unit weight of plastic concrete is inversely proportional to air content. That is to say, as air content increases unit weight decreases. This relationship becomes a very useful tool when evaluating plastic concrete. Unit weight and air content are properties of plastic concrete that can be easily and quickly measured in the field. A unit weight measurement, at a known air content, that deviates excessively from the linear relationship provides information as to the possible deficiencies in the mix and potential effects on properties such as workability, durability, and strength.

The linear equation to predict unit weight based on a given air content is presented below in directional form:

$$UW = m\,(Air) + b$$

Where: **m** is the slope of line (also known as "rise/run")
Air is the plastic concrete air content (independent variable, x-coordinate or abscissa of point)
b is the y-intercept
UW is the plastic concrete unit weight (dependent variable, y-coordinate, or ordinate of point)

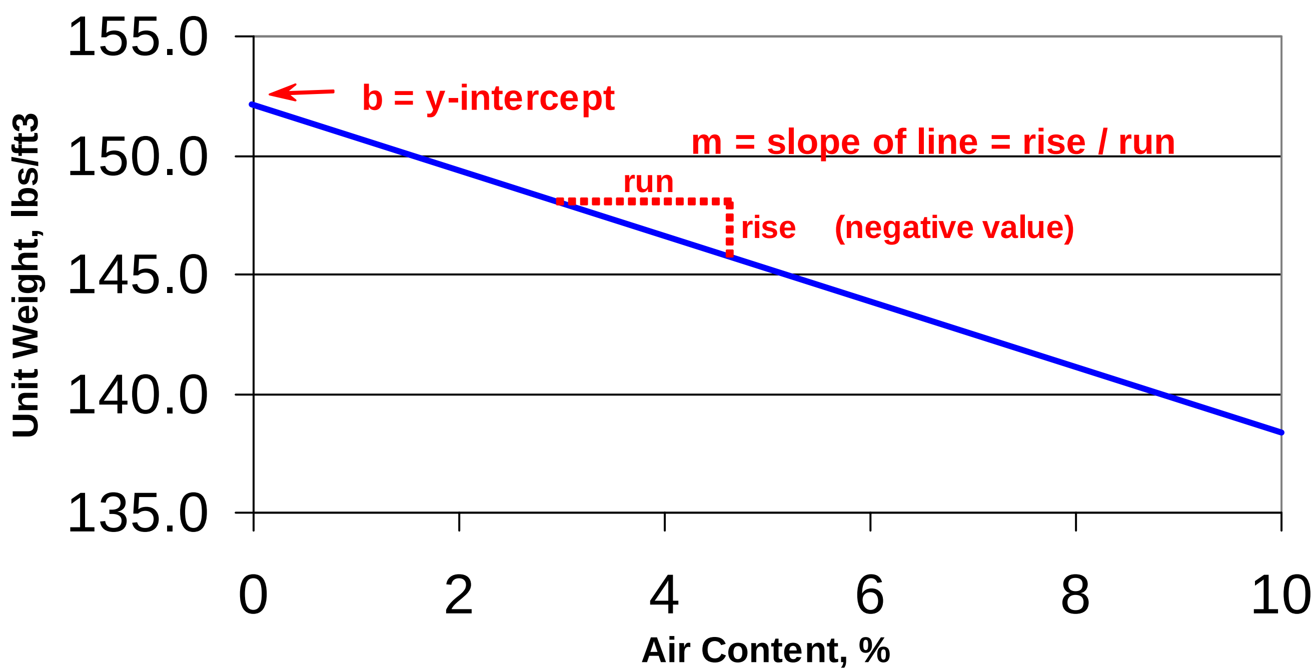

Figure 3.1

If all points (Air, UW) associated with the solution set of this linear equation were plotted on a graph, there would be a straight line as illustrated by Figure 3.1. This linear relationship can be determined for any concrete mix design.

Instructions for Page 2 of Mix Design & Proportioning Worksheets

If at least two points (Air, UW) are known to be a solution to the equation, algebra can be utilized to solve for the two unknown variables (i.e. slope and y-intercept). The form in Appendix D (under tab 11) entitled "WORKSHEET FOR CMD LINEAR EQUATION" provides the format in which two points can be defined and the equation determined

The Cartesian coordinates (Air,UW) of one solution point is already available from the mix design. We can define this as Point 2 with coordinates (x_2, y_2). The value of x_2 is the target air content of the mix design (i.e. $x_2 = 6.5$ %). The value of y_2 is the unit weight of the concrete stated in the mix design. This is determined by obtaining the summation of the design batch weights and dividing by the summation of design absolute volumes which will always be 27.00 ft^3. The following example calculations for the worksheet are based on the mix design and proportioning values presented earlier in this chapter.

Example: $x_2 = 6.5$ %

$y_2 = \sum$ Design Batch Weights $\div$ 27.00 ft^3

$y_2 = 3871$ lbs $\div$ 27.00 ft^3

$y_2 = 143.4$ lbs/ft^3 (rounded to the first decimal place)

A plot of the coordinates for Point 2 ($x_2 = 6.5$, $y_2 = 143.4$) is illustrated in Figure 3.2. It is important to note that the unit weight for Point 2 is calculated to the nearest 0.1 lbs/ft^3.

Point 1, representing the y-intercept having coordinates (x_1, y_1), must now be determined. This is accomplished by theoretically removing all the entrapped and entrained air from the mixture and calculating the concrete unit weight. The value of x_1 is 0.0 % air content. The value of y_1 is determined by again obtaining the summation of the design batch weights and divide by the summation of design absolute volumes except for entrapped or entrained air. This volume will always be 27.00 ft^3 – 1.76 ft^3 = 25.24 ft^3. The following example illustrates how the worksheet calculates the coordinates for Point 1.

Example: $x_1 = 0.0$ %

$y_1 = \sum$ Design Batch Weights $\div$ 25.24 ft^3

$y_2 = 3871$ lbs $\div$ 25.24 ft^3

$y_2 = 153.4$ lbs/ft^3 (rounded to the first decimal place)

The Cartesian coordinates of Point 1, ($x_1 = 0.0$, $y_1 = 153.4$), is graphed along with Point 2 in Figure 3.3, to illustrate the example. Again note that the unit weight is calculated to the nearest 0.1 lbs/ft^3.

It is important to remember that as air is removed from concrete the individual weights of cementitious materials, fine aggregate, coarse aggregate, and water no longer represent amounts relative to 1.000 yd^3 of concrete. Concrete without the 6.5% target air content (1.76 ft^3) would only yield 0.9348 yd^3 of concrete. The actual cement and water contents per 1.000 yd^3 concrete would increase as a result of the under yielding. If air content increases over the 6.5 % target, the actual cement and water contents per 1.000 yd^3 would be less as a result of the over yielding. However, in either case the water cementitious ratio and fine to total aggregate ratio remain unchanged.

From the x and y coordinates of Points 1 & 2, there is now enough information to solve for the variables of slope and y-intercept in the linear equation. The worksheet calculation for slope, also known as "rise / run", is exemplified as follows:

Example:
slope = $m = (y_2 - y_1) / (x_2 - x_1)$
$m = (143.4 - 153.4) / (6.5 - 0.0)$
$m = (^{-}10.0) / (6.5)$
$m = {}^{-}1.54$ (negative value, rounded to second decimal place)

It is important to note that slope will always be negative since unit weight is inversely proportional to air content.

The y-intercept value (b) is simply the ordinate of Point 1, which has already been determined. In the example problem, the worksheet would show the solution b as follows:

Example:
y-intercept = $b = y_1$
$b = 153.4$ lbs/ft^3

The calculated and rounded values for slope and y-intercept can now be inserted in the linear equation for the variables m and b, respectively. The linear equation can now be written for the concrete mix design. The numbers from the example result in the following:

Example:
Predicted Unit Weight = m (Air) + b
Predicted Unit Weight = $^{-}1.54$(Air) + 153.4

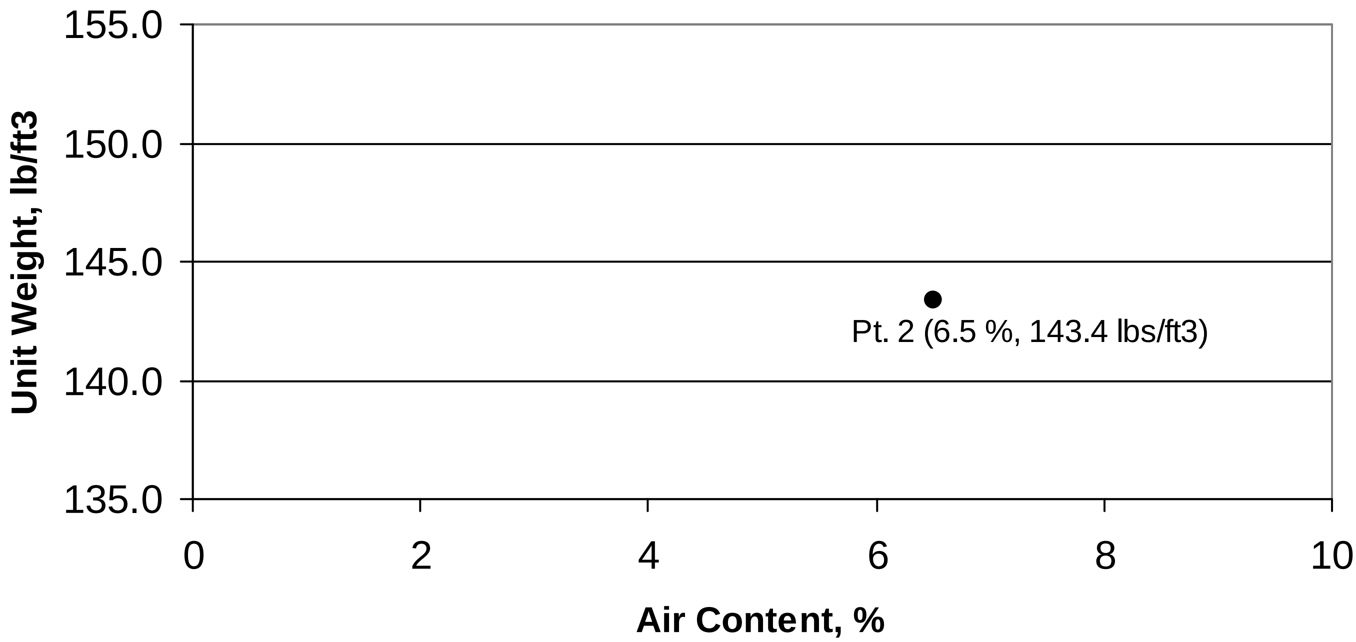

Figure 3.2

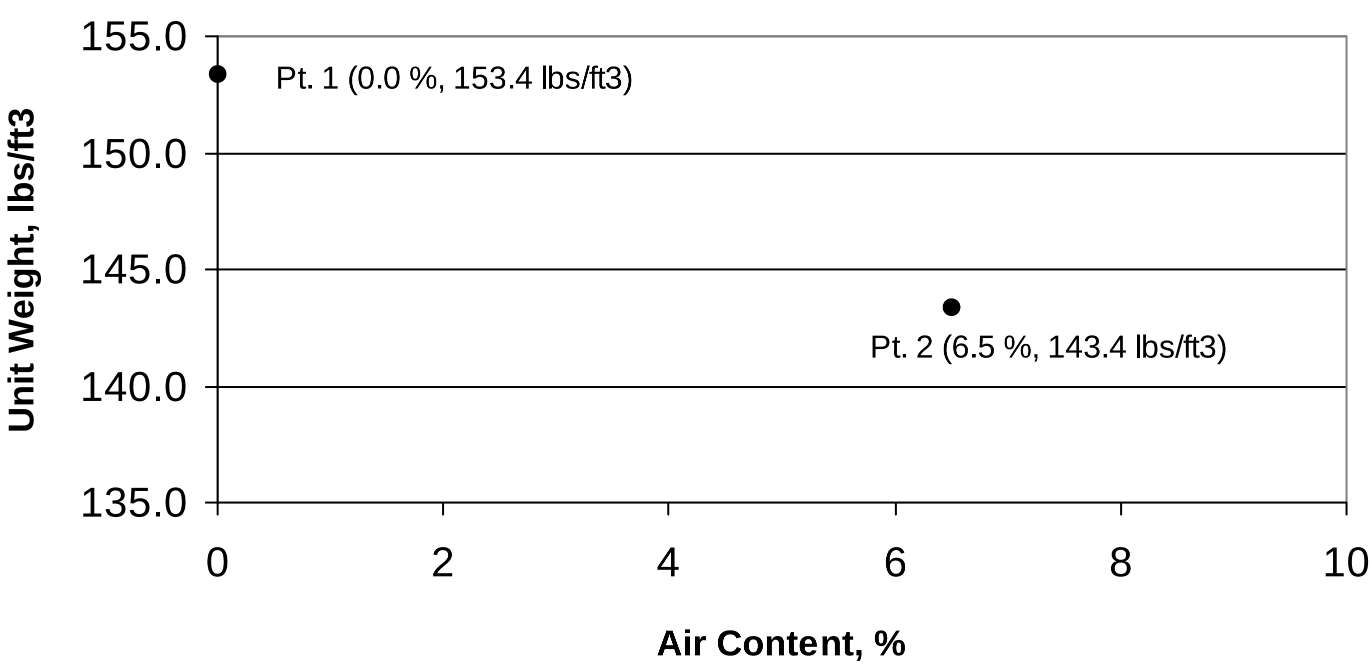

Figure 3.3

THRESHOLD FOR MAXIMUM ALLOWABLE WATER / CEMENTITIOUS RATIO

Just as concrete unit weight is affected by changes in air content, it is also affected by the amount of water that is available to react with cementitious materials. As the amount of water increases the water/cementitious ratio also increases, producing concrete of inferior quality. This serves to lower the concrete unit weight at any given air content. Since the maximum allowable water/cementitious ratio for QC/QA superstructure concrete is 0.420, a threshold line or limit can be determined. This threshold line would be parallel to the linear equation for the mix design (i.e. same slope); however, the unit weight would be lower (i.e. lower y-intercept). The threshold limit has relevancy to results from quality control as well as Acceptance sampling and testing. Should the measured unit weight at any given air content be at or lower than the threshold, it could indicate that the maximum allowable water cementitious ratio was exceeded. It is important to understand that quality control works to center production about the linear equation for the mix design. Concrete production that has shifted toward the threshold line is considered very serious and requires corrective action to re-center it about the linear equation for the CMD.

There are several ways in which additional water could enter a concrete mix. The methodology presented in this chapter assumes that the increase in water/cementitious ratio is due soley to excessive batch water. This provides a simple and accurate determination of the threshold limit equation. The methodology begins with the linear equation already established for the mix design. By establishing a single point below the linear equation, representing concrete with excessive water, the equation for threshold limit can be determined. The easiest point to select is at the y-intercept, where the concrete has no entrapped nor entrained air. This point is defined as Point 3, having coordinates (x_3, y_3). The line for the threshold equation should be parallel to the linear equation for the mix design, which results in the same slope. Knowing the slope and y-intercept the threshold limit equation can then be written.

Instructions for Page 3 of Mix Design & Proportioning Worksheets

A worksheet is provided in Appendix D (under tab 11), which follows the methodology stated previously to generate the threshold limit equation representing the maximum allowable water/cementitious ratio. The instructions for completion of this worksheet are as follows. The first step is to determine the amount of excess water to increase the water cementitious ratio to 0.420. Using the total amount of cementitious materials targeted for the mix design and multiplying it by 0.420 the resultant gives the maximum allowable water content. The example mix design within this chapter is used to provide the following sample calculations:

Example: 658 lbs cementitious x 0.420 = 276 lbs water

This weight of water is entered under the weight subheading for Theoretical Batch Weights and Volumes without entrained or entrapped air, as illustrated in Table 3.9. The remaining mix design weights for cement, pozzolan, fine aggregate, and coarse aggregate are transferred over from the mix proportioning sheet completed previously.

Material	**Theoretical Batch Weights & Volumes w/o air**		
	Weight lbs	**Specific Gravity**	**Volume ft^3**
Cement	**658**	3.150	
Pozzolan	**--------**	**--------**	**--------**
Silica Fume	**--------**	**--------**	**--------**
FA	**1211**		
CA	**1742**		
Water	**276**	1.000	
Air Content	**0**	-NA-	0.00
$\sum$		-NA-	

Table 3.9

The specific gravities for each ingredient are entered in the table and used to calculate the corresponding absolute volumes. It should be noted that each ingredient has the same value as the mix design proportioning except the weight and volume of water has increased; and the volume of air has decreased to 0.00 ft^3. The summations of the weight and volume columns are then determined and recorded in the table. Table 3.10 illustrates that portion of the worksheet completed thus far for the example problem. The next step in the worksheet is to numerically define the coordinates of Point 3. The following calculations are based on the example numbers presented in Table 3.10.

Example: x_3 = 0.0 % air content

$y_3 = \sum$Theoretical Batch Wts. ÷ $\sum$Theoretical Batch Vol.

y_3 = 3887 lbs. ÷ 25.49 ft^3

y_3 = 152.5 lbs/ft^3

The y-intercept of the threshold limit equation is simply equal to y_3, which is the Unit Weight calculated in the worksheet. Since the lines are parallel, the slope of the threshold equation is the same as the value calculated for the mix design linear equation. The solution to the Threshold Limit Equation is now straight forward.

Example: y-intercept = Unit Weight = 152.5 lbs/ft^3 (rounded to 0.1 lb/ft^3)

slope = m = -1.54

Example: Threshold UW = -1.54 (Air) + 152.5 lbs/ft^3

Figure 3.4 is a graphical representation of the example CMD linear equation and its corresponding threshold limit equation.

Material	**Theoretical Batch Weights & Volumes w/o air**		
	Weight lbs	**Specific Gravity**	**Volume ft^3**
Cement	658	3.150	3.35
Pozzolan	--------	--------	--------
Silica Fume	--------	--------	--------
FA	1211	2.632	7.39
CA	1742	2.711	10.32
Water	276	1.000	4.43
Air Content	0	-NA-	0.00
$\sum$	3887	-NA-	25.49

Table 3.10

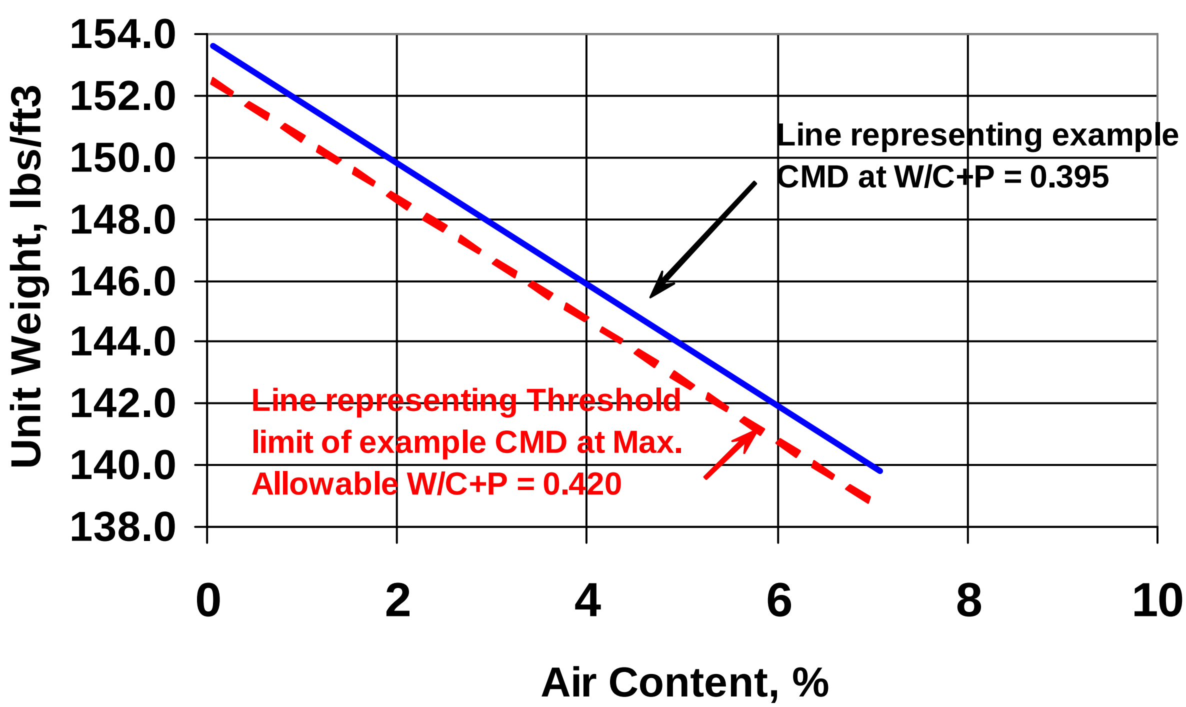

Figure 3.4

DEPARTMENT CONCURRENCE OF MIX DESIGN

It is the responsibility of the Department's Project Engineer / Project Supervisor (PE/PS) to conduct a complete and thorough review of every mix design and proportioning for QC/QA Superstructure Concrete. There is a substantial amount of work that is based on the targets established by the CMD, not the least of which is the linear equation for the threshold limit that represents the maximum allowable water/cementitious ratio. This threshold limit is of critical importance in determining whether additional cylinders are to be cast as part of an acceptance sample for testing per AASHTO T 277 and subsequent action, which may involve a failed material investigation.

The first step in proper review of a CMD is to verify that the materials are from current approved sources. The list of Approved and/or Prequalified Materials is to be used to verify approved sources of cement, fly ash, GGBFS, silica fume, chemical admixtures and air entraining agents. The fine and coarse aggregate ingredients of the concrete mix must be materials from an approved Certified Aggregate Producer. The gradation and quality requirement for the aggregates must also be verified, particularly if stay-in-place metal deck forms are used to facilitate construction of the deck. If AP Quality coarse aggregate is required in the superstructure, the PE/PS will substantiate the quality status. This would include the nature of the mining operations that produce aggregates of the desired quality (e.g. individual ledges or ledge combinations within the working bench of the aggregate source). The PE/PS should contact the District Materials & Tests Engineer or the District Geologist for confirmation.

In addition to the aggregates gradations the PE/PS must verify the bulk specific gravity (SSD) and absorption for the fine and coarse aggregate as being reasonable for the source. If the Contractor's value for absorption differs by more than the multilabortory precision defined within the appropriate test method, the discrepancy will be investigated. These values are defined in the AASHTO test method and summarized in Table 3.15.

Property	**Range for FA**	**Range for CA**
Bulk Sp. Gr. (dry)	0.066	0.038
Bulk Sp. Gr. (SSD)	0.056	0.032
Absorption, %	0.66	0.41

Table 3.15

The bulk specific gravity and absorption for aggregates are measured by the Department as part of the annual "Summary of Production Quality Results", and periodic Point-Of-Use samples. This data provides the correct basis for comparison of absorption and specific gravity. Figures 3.5 and 3.6 are graphs of bulk specific gravity (ssd) vs. absorption for a fine and coarse aggregate and are presented as examples of what historical data might look like for specific products at an aggregate source.

Usually sources will demonstrate a trend of bulk specific gravity (SSD) being inversely proportional to absorption; however, such may not always be the case. Figure 3.6 represents data from the INDOT Summary of Production Quality Results for a specific source of #8 coarse aggregate. The AP quality stone comes from ledges 1803, 1804, 19, & 20 processed as one working bench. These four ledges have thicknesses of 7.9 ft, 8.9 ft, 5.9 ft, and 12.1 ft, respectively. Since these ledges range in absorption from 2 % to 4 %, the consistency of bulk specific gravity and absorption depends on the aggregate source's ability to process the bench in a uniform manner. The District Geologist is the best source for obtaining historical data from "Summary of Production Quality Results" and "Point-of-Use" samples obtained from the aggregate source. They will assist the PE/PS in the proper review of contractor test results for aggregates.

It is important to understand that INDOT historical records for bulk specific gravity (dry or SSD) from coarse aggregate sources are based on procedure 8.1 of AASHTO T 85. The Contractor must therefore test the coarse aggregate according to the same procedure even though the result is typically not appropriate for concrete mix design. If the mix design is submitted with enough advance notice, it becomes preferable for the Department to obtain a Point-Of-Use sample of the coarse aggregate and test for bulk specific gravity (SSD) by procedure 8.2 of AASHTO T 85, which is appropriate for concrete mix design. Splitting a sample between the Contractor and the Department to compare test results would be even better.

The air entraining and chemical admixtures that are approved for use are as stated in the special provision and the Approved/Prequalified Materials List referenced therein. It is important to recognize the limitations of Type F admixtures or HRWR Admixture Systems. These chemical admixtures have no retarding capability and would not be appropriate for superstructure concrete that is placed in conditions where concrete and ambient temperatures are above 65°F, and where dead load deflections are of concern.

After verifying the materials as being approved for the concrete, the initial parameters for the Mix Design must be checked against the specification requirements. The remainder of the PE/PS check involves checking the math for proportioning, and the linear equations for the CMD and threshold limit. Use of the forms and worksheets by the contractor will provide the quickest and most complete review by the Department and therefore help eliminate unnecessary delays by recognizing problems early on.

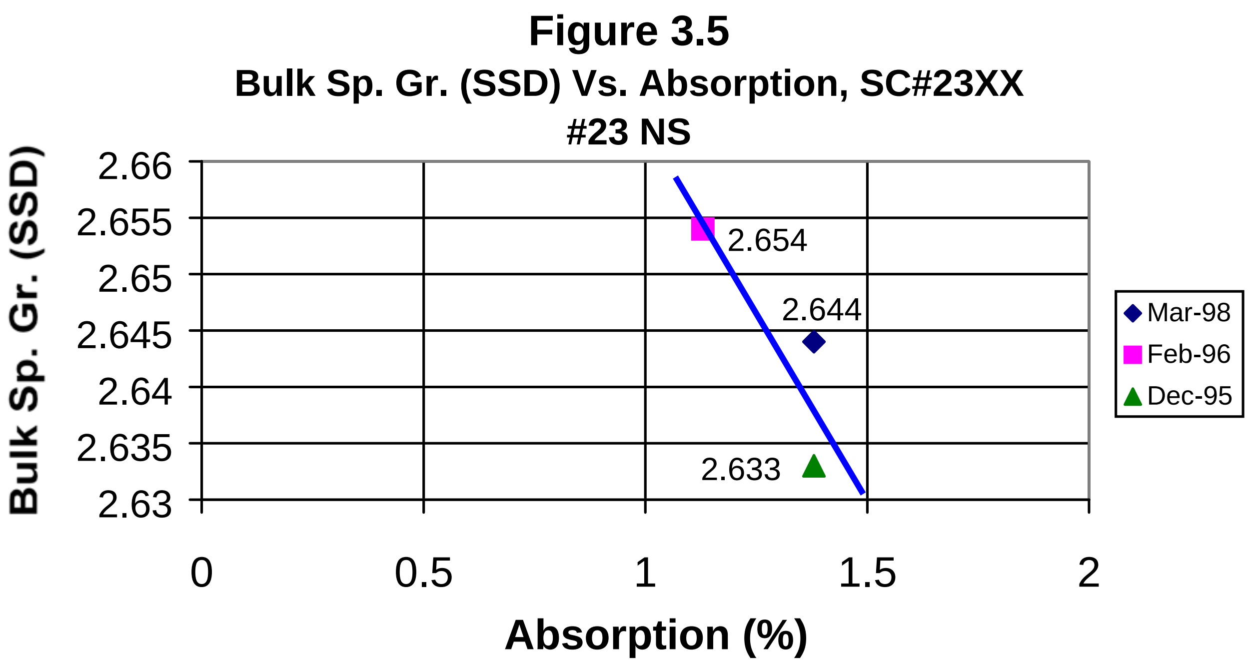
Figure 3.5
Bulk Sp. Gr. (SSD) Vs. Absorption, SC#23XX
#23 NS
Bulk Sp. Gr. (SSD)
2.66
2.655
2.65
2.645
2.64
2.635
2.63
2.654
2.644
2.633
0
0.5
1
1.5
2
Absorption (%)
Mar-98
Feb-96
Dec-95

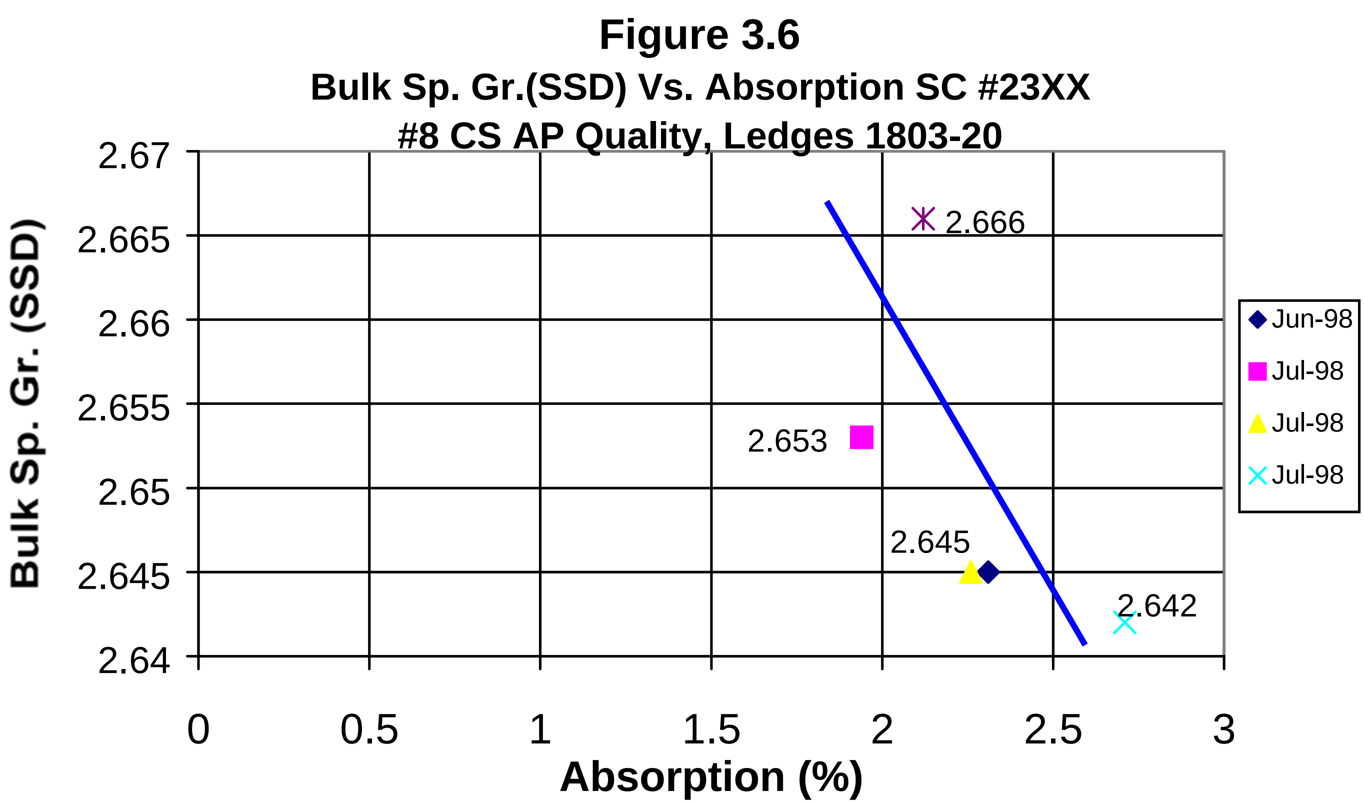
Figure 3.6
Bulk Sp. Gr.(SSD) Vs. Absorption SC #23XX
#8 CS AP Quality, Ledges 1803-20
Bulk Sp. Gr. (SSD)
2.67
2.665
2.66
2.655
2.65
2.645
2.64
2.666
2.653
2.645
2.642
0
0.5
1
1.5
2
2.5
3
Absorption (%)
Jun-98
Jul-98
Jul-98
Jul-98