Fundamentals of Concrete Mix Design

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Course: Concrete Fundamentals

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INTRODUCTION
TO
CONCRETE MIX DESIGN

SCOPE - This segment of the course is devoted to learning how to proportion select materials that, when properly mixed and properly placed, will produce an economical concrete mix that meets the requirements for placeability, consistency, strength, durability, and appearance.

OBJECTIVE - The objective of this lesson is to learn how to select and proportion the materials for quality concrete.

PURPOSE - Our purpose is to develop an understanding of how the components of concrete and the proportioning of those components affect the end product.

GOAL - Our goal is not to simply learn the mechanics of designing a quality concrete mix; it is to obtain the knowledge needed to:

- specify the most economical and practical combination of materials,
- provide the necessary quality assurance inspection,
- analyze and develop solutions to everyday problems that are related to materials and mix proportioning.

TERMINOLOGY

ABSORPTION (A) - Absorption is the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body. It is expressed as a percentage of the dry weight of the body. For example, the oven dry weight of a sample of sand is 60-pounds and its absorption is 5%. The weight of the sample after it has absorbed all of the moisture it can absorb is:

60 lb x 1.05 = 63 lbs

The amount of water absorbed by the 60-pound sample is:

63 lb - 60 lb = 3 lbs

ABSOLUTE VOLUME (V) - The absolute volume of a granular material is the volume of the solid matter in the particles; it does not include the volume of the voids between the particles. The absolute volume of a material is computed as follows:

$$\text{Absolute Volume} = \frac{\text{weight of material}}{\text{specific gravity of material x unit weight of water}}$$

For example, the specific gravity of a dry coarse aggregate (Gs) is 2.65. The unit weight of water is 62.4-lb/cu ft. The absolute volume of a 90-lb sample of the aggregate is:

Absolute Volume = 90 lb / (2.65 x 62.4 lb/cu ft) = 0.544 cu ft.

The absolute volume of a concrete mix can be determined if the weight and bulk specific gravity of the components are known. For a concrete mix with 90-lbs of coarse aggregate with Gs = 2.65, 60-lbs of fine aggregate with Gs = 2.63, 25-lbs of cement, and 12-lbs of water the absolute volume is computed as follows:

CA	=	90 lb / (2.65 x 62.4 lb/cu ft)	= 0.544 cu ft
FA	=	60 lb / (2.63 x 62.4 lb/cu ft)	= 0.366 cu ft
Cement	=	25 lb / (3.15 x 62.4 lb/cu ft)	= 0.127 cu ft
Water	=	12 lb / (1 x 62.4 lb/cu ft)	= 0.192 cu ft
		Total Volume	= 1.229 cu ft.

For the same mix containing 4% air the total volume would be:

Total Volume = 1.229 cu ft x 1.04 = 1.278 cu ft.

The volume of air in the mix is:

Air = 1.278 cu ft - 1.229 cu ft = 0.049 cu ft.

ADD-WATER (AW) - Add-water includes all water and liquid admixtures that are added to the mix in order to arrive at the amount of free water that is required by the mix design. The amount of add-water for a specific mix design changes due to changes in the aggregate moisture.

BULK SPECIFIC GRAVITY (Gs) – The bulk specific gravity of a material is the ratio of the weight of a specific absolute volume of the material, excluding the weight of water within the pores, to the weight of an equal volume of distilled water. Simply stated, it is the unit weight of a dry material (g_{dry}) divided by the unit weight of water (g_{water}).

$$Gs = g_{dry} / g_{water} \text{ or } g_{dry} = Gs \times g_{water}$$

To determine the unit weight of a substance like cement, multiply the specific gravity of the cement by the unit weight of water.

$$g_{cement} = 3.15 \times 62.4 \text{ lb/cu ft} = 196.56 \text{ lb/cu ft}$$

Bulk specific gravity of concrete materials			
Portland Cement		3.15	
Pozzolan	2.2	to	2.8
Natural Aggregates	2.4	to	2.9
Water		1.0	

Bulk specific gravity applies to porous materials. For non-porous materials the specific gravity and bulk specific gravity are the same.

BULK SPECIFIC GRAVITY SATURATED SURFACE DRY ($Gs_{(ssd)}$**)-** The bulk specific gravity saturated surface dry of a material is the ratio of the weight of a specific absolute volume of the material, including the weight of water within the pores, to the weight of an equal volume of distilled water. Simply stated, it is the unit weight of a saturated material divided by the unit weight of water and is computed as follows:

$$Gs_{(ssd)} = (1 + \text{Absorption}) \times Gs_{(dry)}.$$

For example, a sample of sand having an absorption of 5% and a specific gravity of 2.63 has a bulk specific gravity saturated surface dry that is computed as follows:

$$Gs_{(ssd)} = (1 + 0.05) \times 2.63 = 2.76.$$

BULK VOLUME – The volume of a granular material including the volume of the solid particles and the volume of the voids between the solid particles.

DRY RODDED UNIT WEIGHT – The dry rodded unit weight of aggregate is determined by compacting dry aggregate into a container of a known specific volume as per ASTM test method C 29. The weight of the aggregate is measured and divided by the volume of the container to yield the dry rodded unit weight in terms of weight per volume such as pounds per cubic foot. By knowing the dry rodded unit weight of a nominal maximum size coarse aggregate and the fineness modulus of the fine aggregate, the weight of the coarse aggregate needed per unit volume of concrete mix can be estimated.

FINENESS MODULUS (FM) - The fineness modulus (FM) is a factor obtained by adding the percentages of material in a sample of aggregate that is retained on each of the following sieves: #100, #50, #30, #16, #8, #4, 3/8", ¾", 1 ½", 3", 6". The result is divided by 100 to arrive at the fineness modulus. For conventional concrete the fineness modulus of the fine aggregate should range from 2.3 to 3.1. A higher fineness modulus represents a coarser material and a lower fineness modulus represents a finer material. Knowing the fineness modulus of aggregate gives you some indication of the amount of paste needed to make concrete using the aggregate. For instance, sand with a low fineness modulus has more voids in it and more particle surface, thus, more paste is needed to fill voids and cement the particles together than would be needed for a coarser sand.

Below is an example of the mechanical sieve analysis results of a fine and coarse aggregate with the fineness modulus computed.

	FINE AGGREGATE		COARSE AGGREGATE	
SIEVE SIZE	% PASSING	% RETAINED	% PASSING	% RETAINED
6"				
3"				
1 1/2"			100	0
3/4"			54.8	45.2
3/8"	100	0	10.4	89.6
#4	97.8	2.2	1.4	98.6
#8	80.1	19.9	0.8	99.2
#16	51.4	48.6	0	100
#30	35.2	64.8	0	100
#50	21.5	78.5	0	100
#100	8.8	91.2	0	100
		305.2		732.6
	FM =	3.05	FM =	7.33

FREE-WATER (FW) – Free-water is the amount of water in the mix that is available to help form the paste. (The paste is composed of free-water, cement, pozzolan, and aggregate smaller than the #200 sieve size.) Water that is absorbed by the aggregate is not free-water. The amount of free-water is shown on the mix design.

The batch plant operator must ensure that the amount of free-water in the mix does not vary from that called for in the mix design. Batch plant operators monitor aggregate moisture to determine if there is any free-water in the aggregate or if the aggregate is so dry that it will absorb water that is added to the mix. It is rare to have aggregate at the batch plant that is in the saturated surface dry condition where the amount of add-water would equal the amount of free-water called for in the mix. Batch plant operators have to compute the amount of add-water by subtracting the amount of aggregate free-water from the amount of free-water shown on the mix design. The equation for this is:

$$FW_{agg} = W_{agg} \text{ x } (MC_{agg} - A_{agg})$$

Add water = free-water shown on the mix design – aggregate free-water

For example, consider a concrete mix design that calls for 282-pounds of water (i.e. free-water) and contains 1100 pounds of fine aggregate and 2000 pounds of coarse aggregate. The mix design shows fine aggregate absorption to be 2% and coarse aggregate absorption to be 1%. The batch plant operator measures the aggregate moisture and finds that the fine aggregate moisture is at 5%. The coarse aggregate, just delivered, has a moisture content of 0.5%. The operator computes the add-water as follows:

Fine aggregate = 1100 lbs x (0.05 – 0.02) = + 33 lbs
Coarse aggregate = 2000 lbs x (0.005 – 0.01) = - 10 lbs
Aggregate free-water + 23 lbs

Add-water = water called for in the design - FW_{agg}

Add-water = 282 lbs – 23 lbs = 259 lbs.

POZZOLAN (p) - A pozzolan is a substance that, in-itself, has little or no cementitious properties but when combined with portland cement forms compounds possessing cementitious properties. Fly ash is the most widely used pozzolan.

SATURATED SURFACE DRY (SSD) - Saturated surface-dry is the condition of an absorptive material where the material is saturated but its surface is dry. Saturated surface dry aggregate neither absorbs water from or contributes water to the concrete mixture.

WATER-CEMENT RATIO (w/c) - The water-cement ratio of a concrete mix is the ratio of the weight of free-water in the mix to the weight of cement in the mix. It is computed on a weight basis by simply dividing the weight of the water in the mix by the weight of the cement in the mix. For example, for a mix containing 282 pounds of water and 564 pounds of cement the water-cement ratio would be:

w/c = 282 lbs / 564 lbs = 0.5

WATER-CEMENTITIOUS MATERIALS RATIO (w/(c+p)) - The water-cementitious material ratio is the ratio of the weight of free-water in the mix to the weight of cementitious materials in the mix. This term is applicable to a concrete mix that contains more than one type of cementitious material as does a mix with cement and pozzolan.

WEIGHT (W) - The term weight is commonly used in the construction industry to denote mass. Weight and mass would be the same if gravity were constant. For all practical purposes, when dealing with concrete components that are weighed in the same general area, the forces due to gravity change so little that weight and mass can be used interchangeably. When dealing with concrete components that are weighed at substantially different elevations the distinction between mass and weight must be made. In this training course the term weight will be used as if there were no difference between weight and mass.

VOLUME EQUIVALENCY - Proportioning by the volume equivalency method simply means that the volume of cementitious materials (cement + pozzolan) is the same as the volume of cement in a cement only mix. When proportioning by the volume equivalency method w/(c+p) will always be greater than w/c and can be computed by the following equation:

$$w/(c+p) = \frac{3.15 \times w/c}{3.15(1-Fv) + GpFv},$$

where Fv = percent fly ash by volume and Gp = specific gravity of the pozzolan.

For example, a mix having a water-cement ratio of 0.45 and containing 20 percent fly ash by volume with a specific gravity of 2.3 has a water-cementitious materials ratio computed as follows:

$$w/(c+p) = \frac{3.15 \times 0.45}{3.15(1-0.2) + (2.3 \times 0.2)} = 0.48$$

If the percent fly ash in a mix is given based on weight it has a volume equivalency that is computed by the following equation:

$$Fv = \frac{1}{1 + (Gp/3.15)((1/Fw)-1)}.$$

where Fv = percent fly ash by volume, Gp = specific gravity of the pozzolan and Fw = percent fly ash by weight.

For example, if a cementitious material is composed of 20% fly ash and 80% cement by weight, and the fly ash specific gravity is 2.3, the percent by volume or volume equivalency can be computed as follows:

$$Fv = \frac{1}{1 + (2.3/3.15)((1/0.2)-1)} = 0.255 \text{ or } 25.5\%$$

Percent cement by volume (Cv) = 100 – 25.5 = 74.5%.

WEIGHT EQUIVALENCY - Proportioning by the weight equivalency method simply means that the weight of cementitious materials (cement + pozzolan) is the same as the weight of cement in a cement only mix. When proportioning by the weight equivalency method, if the amount of mix free-water does not change w/c always equals w/(c+p). If the percent fly ash in a mix is given based on volume it can be converted to percent based on weight by the following equation:

$$Fw = \frac{1}{1 + (3.15/Gp)((1/Fv)-1)}.$$

For example, if a cementitious material is composed of 20% fly ash and 80% cement by volume, and the fly ash specific gravity is 2.3, the percent by weight or weight equivalency can be computed as follows:

$$Fv = \frac{1}{1 + (3.15/2.3)((1/0.2)-1)} = 0.154 \text{ or } 15.4\%$$

Percent cement by volume (Cv) = 100 – 15.4 = 84.5%.

YIELD, DESIGN YIELD, AND RELATIVE YIELD (Y, Yd, and Ry) – Yield is the measured volumetric quantity of concrete produced per batch. For example, a trial batch of concrete is batched from the following mix design batching weights:

Cement	558 lb
Water	204 lb
Coarse Aggregate	2016 lb
Fine Aggregate	1178 lb
Total Weight	3956 lb.

After mixing the unit weight is measured to be 145.7 lb/cu ft. The yield is determined as follows:

$$\text{yield} = \text{total weight / unit weight} = \frac{3956 \text{ lb}}{145.7 \text{ lb/cu ft}} = 27.15 \text{ cu ft.}$$

When working with inch-pound units the **design yield** is always 27 cubic feet.

Relative yield is the ratio of yield to the design yield.

Relative yield = yield / design yield = 27.15 / 27 = 1.006

After a trial mix of acceptable consistency, air content, and strength is batched, the trial mix proportions must be adjusted for yield so that the batch plant operator can accurately determine the amount of each ingredient needed to produce the exact volume of concrete that is called for. The adjustment is made by multiplying the relative yield by the individual mix design batching weights as follows:

Cement	558 lb x 1.006 = 555 lb/cu yd
Water	204 lb x 1.006 = 250 lb/cu yd
Coarse Aggregate	2016 lb x 1.006 = 1963 lb/cu yd
Fine Aggregate	1178 lb x 1.006 = 1117 lb/cu yd.

ABBREVIATIONS

A	absorption
ABS	absolute
abs	absorbed
AW	add-water
c+p	cement plus pozzolan or cementitious materials
CA	coarse aggregate
FA	fine aggregate
FM	fineness modulus
Fv	percent fly ash by volume expressed in decimal form
Fw	percent fly ash by weight expressed in decimal form
FW	free-water
Gp	specific gravity of pozzolan
Gc	specific gravity of cement
Gs	bulk specific gravity
$Gs_{(dry)}$	bulk specific gravity of dry aggregate
$Gs_{(SSD)}$	bulk specific gravity of saturated surface dry aggregate
gw	unit weight of water (i.e. 62.4 lb/cu. ft.)
MC	moisture content
OD	oven dry
P	pozzolan
Ry	relative yield
V	volume
W	weight
w/c	water-cement ratio
w/(c+p)	water-cementitious materials ratio
Y	yield
Yd	design yield (i.e. 27 cu. ft.)

MIX DESIGN PROCEDURE

This segment of the course is devoted to learning how to proportion select materials that, when properly mixed and properly placed, will produce an economical concrete mix that meets the requirements for placeability, consistency, strength, durability, and appearance. There are several methods for selecting and adjusting proportions for normal weight concrete. These include:

Arbitrary assignment (1:2:3), volumetric
Void ratio
Fineness modulus
Surface area of aggregates
Cement content
Estimated weight method
Absolute volume method

Chapter 9 in the Portland Cement Association publication entitled, Design and Control of Concrete Mixes, explains the absolute volume method of proportioning normal concrete mixtures. This procedure is detailed in the ACI 211.1, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete and has been adopted by the concrete industry as the industry standard procedure for mix proportioning.

The steps in proportioning a mix by the absolute volume method are shown below with reference to tables and figures found in Chapter 9 of PCA - Design and Control of Concrete Mixes.

1. Determine the required slump from Table 9-6 on page 155.
2. Determine the maximum aggregate size based on guidance found on page 152.
3. Estimate the quantity of mixing water and air content from Table 9-5 on page 154.
4. Select the water-cement ratio based on Tables 9-1, 9-2, and 9-3 on pages 150 and 151.
5. Calculate the cement content from the values obtained in steps 3 and 4 above. Reference page 156 for additional guidance.
6. Estimate the coarse aggregate content from Table 9-4 on page 152.
7. Estimate the fine aggregate content by the absolute volume method by adding the volumes determined in the steps above and subtracting the total from 27.
8. Adjust for aggregate moisture as explained on page 164.
9. Make trial batch and adjustments as explained on pages 164 and 165.

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