ACI Mix Design

Updated Version

ACI Mix Design

So-called “mix design” methods actually produce a first guess at the proper mix proportions. That trial mix is then made in the lab and tested for slump, strength and other pertinent properties and the mix proportions are adjusted based on the results.

The ACI mix design method is one of many methods available but it is probably the most widely used so that is the method we’ll use in this class. The method involves ten steps outlined on the next page.

Mix Design Steps

1. Select the slump
2. Select the NMAS
3. Estimate the water and air contents
4. Adjust the water content for aggregate shape
5. Determine the required strength
6. Select the w/cm ratio
7. Calculate the cement weight
8. Estimate the coarse aggregate content
9. Calculate the fine aggregate content
10. Adjust for aggregate moisture and absorption

ACI Mix Design

We'll work through the mix design steps listed in the previous slide using an example for a typical concrete mix for a non-air-entrained concrete.

Mix Design Example

Coarse aggregate = subangular crushed stone
Nominal maximum aggregate size = 3/4"
Design strength = 4500 psi
Specified slump = 1-2"

	Coarse Aggregate	Fine Aggregate
Unit weight (lb/ft^3) =	101	106
Bulk specific gravity (dry) =	2.574	2.548
Bulk specific gravity (SSD) =	2.623	2.592
Apparent specific gravity =	2.705	2.664
Absorption capacity (%) =	1.9	1.7
Fineness modulus =	2.51	2.90

Step 1: Select the slump

The choice of slump determines the workability of the mix. Workability encompasses a combination of PCC properties that are related to the rheology of the concrete mix: ease of mixing, ease of placing, ease of compacting, ease of finishing. You should aim for the stiffest mix that will provide adequate placement.

The following table shows some typical slump ranges for several different applications.

Step 1: Select the slump

Table 9-6. Recommended Slumps for Various Types of Construction

Concrete construction	Slump, mm (in.)	
	Maximum*	Minimum
Reinforced foundation walls and footings	75 (3)	25 (1)
Plain footings, caissons, and substructure walls	75 (3)	25 (1)
Beams and reinforced walls	100 (4)	25 (1)
Building columns	100 (4)	25 (1)
Pavements and slabs	75 (3)	25 (1)
Mass concrete	75 (3)	25 (1)

Source: Design and Control of Concrete Mixtures (PCA, 2003)

Step 1: Select the slump

For our mix design example, the slump has already been specified as 1-2".

Step 2: Select the NMAS

The maximum aggregate size will affect parameters such as cement paste content, workability and strength. In general, the maximum aggregate size is limited by the dimensions of the finished product and the room available inside the formwork, taking into account things such as rebar. If the coarse aggregate is too large the concrete may be difficult to consolidate and compact in the forms, resulting in a honeycombed structure or large air pockets.

Step 2: Select the NMAS

$$\text{NMAS} \le \frac{\text{narrowest dimension}}{5}$$

$$\text{NMAS} \le \frac{\text{depth of slab}}{3}$$

$$\text{NMAS} \le 0.75 \times \text{clear space}$$

Step 2: Select the NMAS

For our mix design example, the nominal maximum aggregate size has already been specified as 3/4".

Step 3: Estimate the water and air

The amount of mixing water basically determines the amount of cement paste in the mix. It depends on the desired slump, the size and shape of the aggregate and the amount of air present in the mix. Some air (called ***entrapped*** air) is normal and is a consequence of the mixing process. Admixtures can also be used to introduce ***entrained*** air in order to enhance the freeze/thaw durability of the concrete.

Step 3: Estimate the water and air

The table on the next slide recommends the amount of water per cubic yard of concrete as a function of the desired slump and the NMAS. The top half of the table is for non-air-entrained mixes and includes an estimate of the amount of entrapped air in the concrete.

The bottom half is for air-entrained mixes. It includes target air contents based on the expected severity of the freeze/thaw exposure.

Step 3: Estimate the water and air

Table 9-5 (Inch-Pound Units). Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate* ⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
	Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
Recommended average total air content, percent, for level of exposure:†								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	3.5	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

* These quantities of mixing water are for use in computing cement factors for trial batches. They are maximums for reasonably well-shaped angular coarse aggregates graded within limits of accepted specifications.

Source: Design and Control of Concrete Mixtures (PCA, 2003)

Step 3: Estimate the water and air

For the ¾" NMAS in our mix design example, the amount of entrapped air is estimated as 2%. For the desired slump of 1-2" the required water content is estimated to be 315 lb per cubic yard of cement.

Questions to Ponder

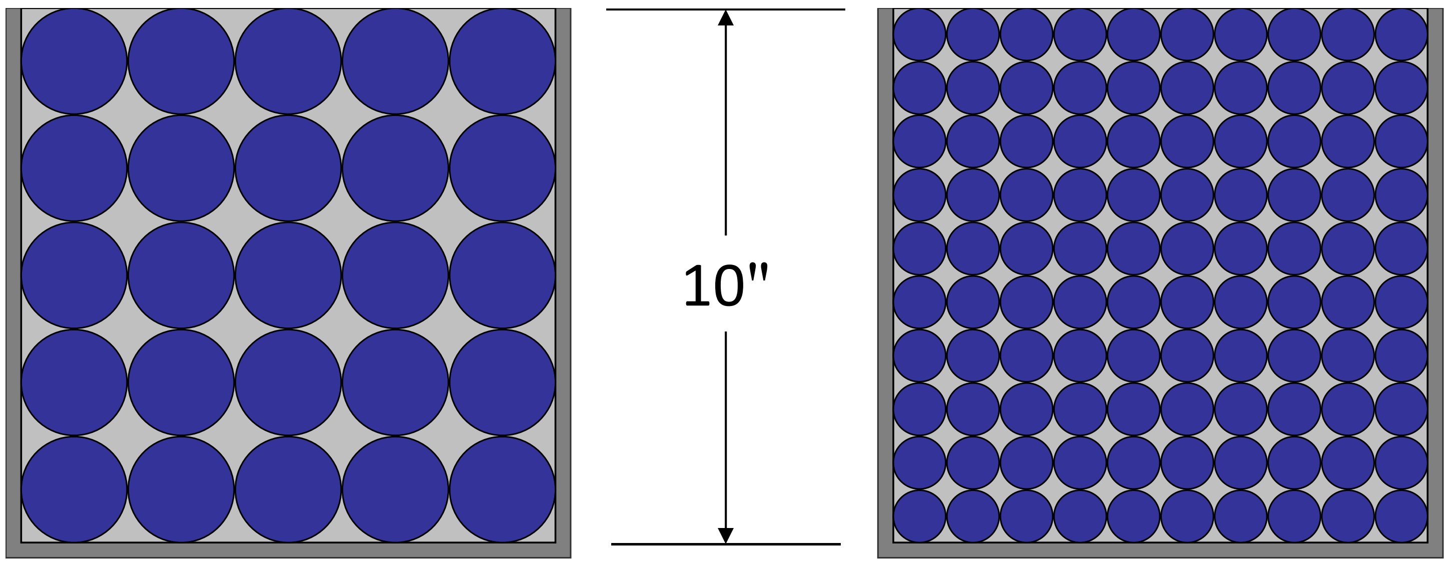
Why does the amount of water required to obtain a desired slump decrease with increasing NMAS?

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2

Questions to Ponder

The amount of water largely determines the amount of cement paste in the mix. The amount of cement paste needed to produce a workable concrete mix depends in part on the surface area of the aggregate to be coated. As shown in the next slide, larger aggregate has a lower ***specific surface*** (surface area per unit volume) so less cement paste is needed, thus less water is needed.

Effect of NMAS on Paste Volume

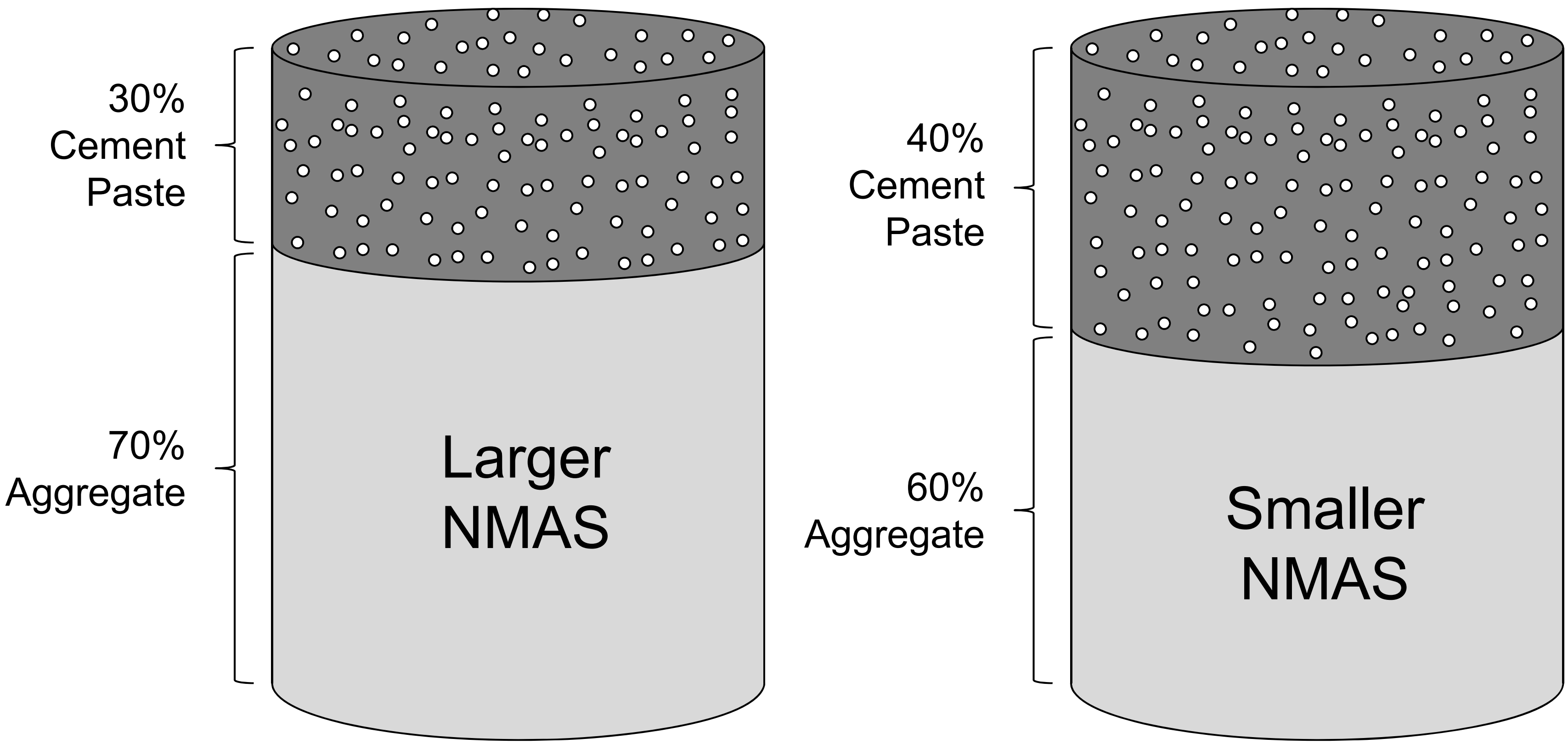


surface area = 11 ft^2 surface area = 22 ft^2

Questions to Ponder

A mix with a large NMAS may only require 30% by volume of cement paste while a mix with a smaller NMAS may require 40% by volume of cement paste. The mix with the larger NMAS therefore requires 25% less cement paste and thus 25% less water. This is illustrated in the next slide.

Effect of NMAS on Paste Volume



Questions to Ponder

Why does the amount of entrapped air in a concrete mix decrease with increasing NMAS?

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2

Questions to Ponder

The answer to this question is related to the previous question. The only place in the mix where there is entrapped air is in the cement paste. The air content in the table is the amount of air per unit volume of ***concrete***. If all of the entrapped air is in the cement paste and there is less cement paste, it stands to reason that the air content of the concrete will be lower.

Questions to Ponder

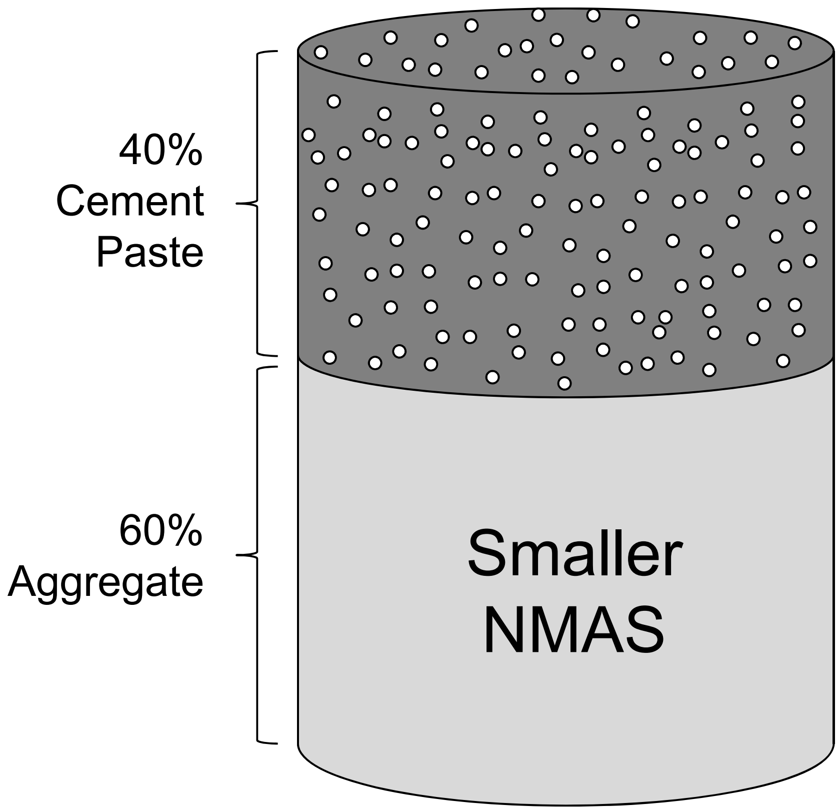
Why does the target air content in an air-entrained mix decrease with increasing NMAS?

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
Recommended average total air content, percent, for level of exposure:†								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	3.5	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

Questions to Ponder

The answer to this question is related to the previous two questions as well. The goal of air entrainment is to achieve a certain air content in the cement paste. If, for durability reasons, the required air content of the paste is the same in two mixes, but one requires 25% more paste (due to a smaller NMAS), then the target air content of the concrete will automatically be higher as shown in the next slide.

Air Content



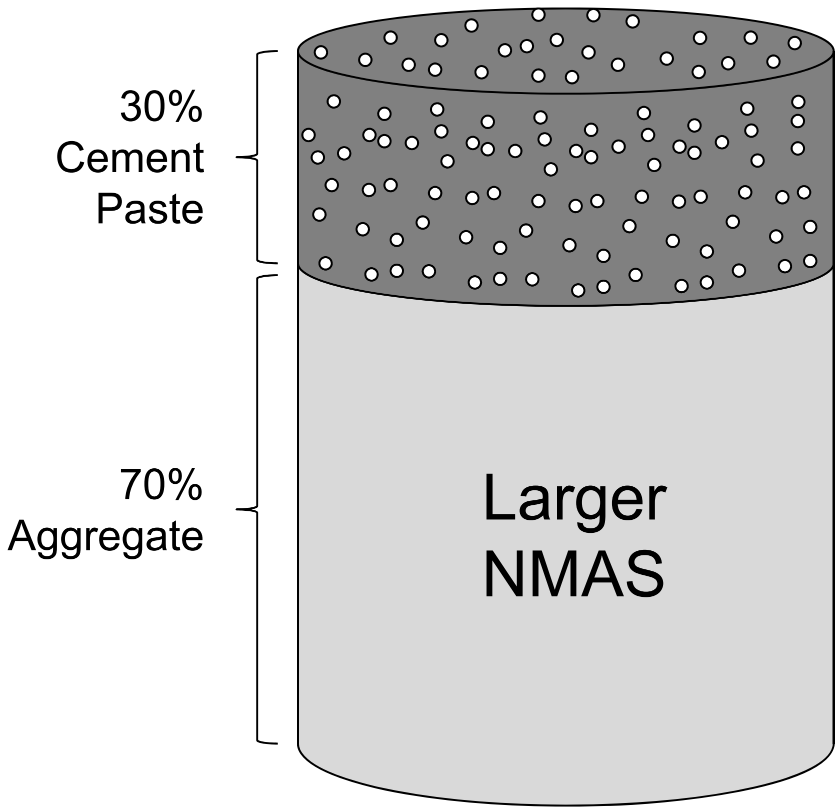
Paste Air Content

Assume 16%

Concrete Air Content

$0.4 \times 16\% = 6.4\%$

Air Content



<u>Paste Air Content</u>

Assume 16%

<u>Concrete Air Content</u>

$0.3 \times 16\% = 4.8\%$

Questions to Ponder

Why do you need less water in an air-entrained mix than a non-air-entrained mix with the same NMAS?

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
	Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—

Questions to Ponder

The short answer is that cement paste with a higher air content takes up more space. Mix proportioning is about having the right volume proportions of the various ingredients, so less cement and water are needed to produce the exact same volume of cement paste. In our example, 280 lb of water will produce the same volume of air-entrained cement paste as is produced by 315 lb of water in the non-air-entrained cement paste.

Step 3: Estimate the water and air

Table 9-5 (Inch-Pound Units). Approximate Mixing Water and Target Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

Slump, in.	Water, pounds per cubic yard of concrete, for indicated sizes of aggregate*							
	⅜ in.	½ in.	¾ in.	1 in.	1½ in.	2 in.**	3 in.**	6 in.**
	Non-air-entrained concrete							
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	285	245	210
6 to 7	410	385	360	340	315	300	270	—
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
	Air-entrained concrete							
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	225	200
6 to 7	365	345	325	310	290	280	260	—
Recommended average total air content, percent, for level of exposure:†								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	3.5	3.5	3.0
Severe exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

* These quantities of mixing water are for use in computing cement factors for trial batches. They are maximums for reasonably well-shaped angular coarse aggregates graded within limits of accepted specifications.

Source: Design and Control of Concrete Mixtures (PCA, 2003)

Step 4: Adjust for Aggregate Shape

An often overlooked part of the table used to estimate the water content is the passage at the bottom, which states that the estimates are based on an assumption of reasonably well-shaped ***angular*** coarse aggregate.

If you are using a rounded aggregate such as gravel rather than an angular aggregate such as crushed stone you need less water than is shown in the table. The table in the next slide estimates the adjustments needed.

Step 4: Adjust for Aggregate Shape

Aggregate Shape	Water Reduction (pounds per cubic yard)
Crushed stone (angular)	0
Crushed stone (subangular)	20
Gravel (some crushed)	35
Gravel (well rounded)	45

Step 4: Adjust for Aggregate Shape

The mix design example says the coarse aggregate is "subangular" so it is suggested that we reduce the amount of water by 20 lb/yd^3, so instead of 315 lb/yd^3 of water, we should start with

$$W_w = 315 - 20 = 295 \text{ lb/yd}^3$$

Questions to Ponder

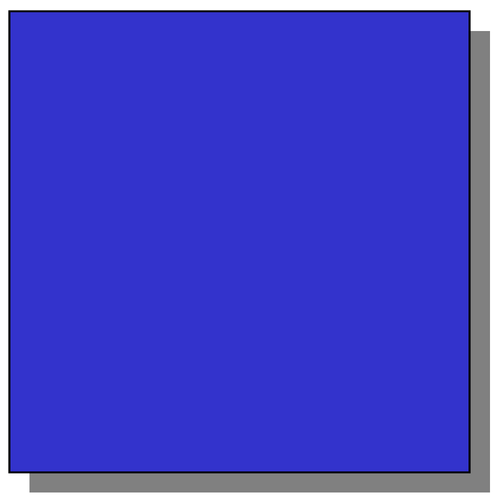
Why does the water required to obtain a given slump change as a function of aggregate shape?

Aggregate Shape	Water Reduction (pounds per cubic yard)
Crushed stone (angular)	0
Crushed stone (subangular)	20
Gravel (some crushed)	35
Gravel (well rounded)	45

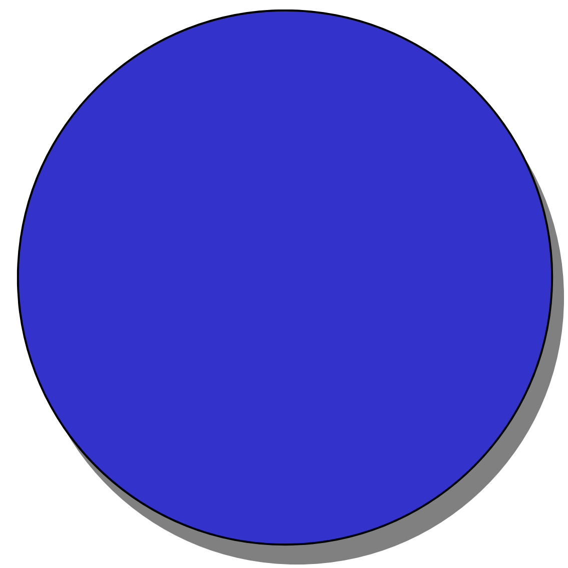
Questions to Ponder

Remember that the water content determines the paste content. Rounded aggregate has less surface area per unit volume of aggregate, as shown in the next slide, so you need less paste to coat the aggregate and thus less water.

Minimizing Surface Area



surface area = 6.0 ft^2/ft^3



surface area = 4.8 ft^2/ft^3

Step 5: Determine Required Strength

As we said in the last lecture, the required strength of the concrete mix is not the same as the design strength. The design strength is the minimum strength that is required from a structural standpoint. Since concrete strength can vary greatly from one batch to the next, you need to build in a factor of safety to ensure that most, if not all, of the concrete exceeds the design strength. If you don't yet know the variability, the table on the next slide estimates the overdesign you need to build into the mix.

Step 5: Determine Required Strength

Required Average Compressive Strength When Data Are Not Available to Establish a Standard Deviation

Specified compressive strength, f'_c, psi	Required average compressive strength, f'_{cr}, psi
Less than 3000	f'_c + 1000
3000 to 5000	f'_c + 1200
Over 5000	1.10 f'_c + 700

Adapted from ASTM C94

Step 5: Determine Required Strength

Since the design strength in our mix design example is 4500 psi and we don't yet know the variability of our mix from one batch to the next, we need to add 1200 psi to achieve an adequate factor of safety, so we need to design our mix for a strength of

$$f'_{cr} = f'_c + 1200 = 4500 + 1200 = 5700 \text{ psi}$$

Step 6: Select the w/cm ratio

The water-cement ratio is correlated with strength and durability. In general, lower water-cement ratios produce stronger, more durable concrete. If natural pozzolans (such as fly ash) are used then the ratio becomes a water-cementitious material ratio.

The following table relates the ***required*** 28-day compressive strength (including the overdesign factor) to the water-cement ratio for both non-air-entrained and air-entrained concrete mixes.

Step 6: Select the w/cm ratio

Table 9-3 (Inch-Pound Units). Relationship Between Water to Cementitious Material Ratio and Compressive Strength of Concrete

Compressive strength at 28 days, psi	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
7000	0.33	—
6000	0.41	0.32
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

$f'_{cr} \Rightarrow$

Strength is based on cylinders moist-cured 28 days in accordance with ASTM C 31 (AASHTO T 23). Relationship assumes nominal maximum size aggregate of about ¾ in. to 1 in.

Source: Design and Control of Concrete Mixtures (PCA, 2003)

Step 6: Select the w/cm ratio

Since our required concrete strength is 5700 psi, we will have to interpolate in the table to get the correct w/cm ratio. Our required strength is 70% of the way from the 5000-psi entry to the 6000-psi entry so:

$$w/cm = 0.48 + 0.7\left(0.41 - 0.48\right) = 0.43$$

Questions to Ponder

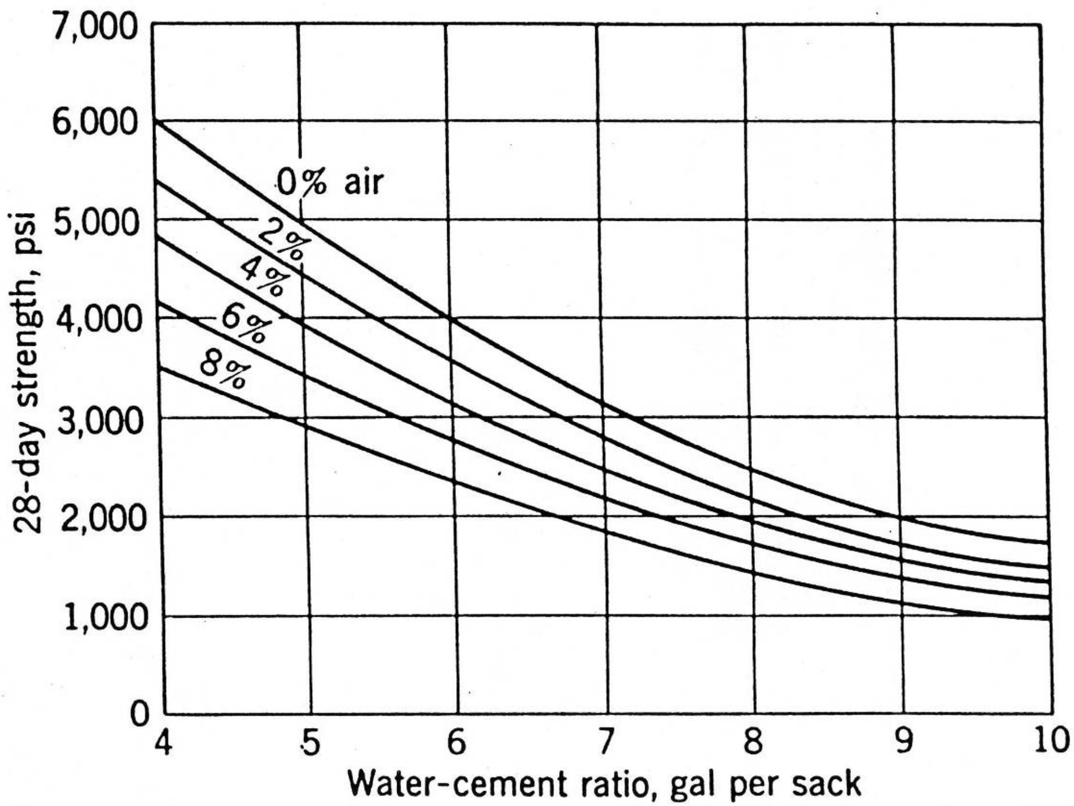
Why is the w/cm ratio different for air-entrained concrete compared to non-air-entrained concrete?

Compressive strength at 28 days, psi	Water-cementitious materials ratio by mass	
	Non-air-entrained concrete	Air-entrained concrete
7000	0.33	—
6000	0.41	0.32
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

Questions to Ponder

In a previous lecture, we said that entraining air to increase freeze/thaw durability comes as a price. As the air content of the cement paste increases, the concrete strength drops precipitously as shown in the next slide. To compensate for the loss of strength, you need to use a much lower w/cm ratio.

Effect of Air Content on Strength



Step 7: Calculate the cement content

Now that we know the amount of water in the mix and the required w/cm ratio, we can calculate the amount of cement we need in the mix:

$$W_{cement} = \frac{W_{water}}{\text{w/cm ratio}}$$

Step 7: Calculate the cement weight

Based on 295 lb of water and a 0.43 w/cm ratio, the amount of cement our design mix requires is

$$W_{cement} = \frac{295}{0.43} = 686\,lb$$

Step 8: Estimate coarse aggregate

Selection of coarse aggregate content is empirically based on mixture workability. The following table estimates the volume percentage of coarse aggregate (based on ***bulk*** volume) needed to produce concrete with a proper degree of workability for reinforced concrete construction. For things like pavement slabs that don't require as much workability, ACI allows the values to be increased by up to 10 percent.

Step 8: Estimate coarse aggregate

Table 9-4. Bulk Volume of Coarse Aggregate Per Unit Volume of Concrete

Nominal maximum size of aggregate, mm (in.)	Bulk volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate*			
	2.40	2.60	2.80	3.00
9.5 (⅜)	0.50	0.48	0.46	0.44
12.5 (½)	0.59	0.57	0.55	0.53
19 (¾)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (1½)	0.75	0.73	0.71	0.69
50 (2)	0.78	0.76	0.74	0.72
75 (3)	0.82	0.80	0.78	0.76
150 (6)	0.87	0.85	0.83	0.81

$\Leftarrow b/b_o$

*Bulk volumes are based on aggregates in a dry-rodded condition as described in ASTM C 29 (AASHTO T 19). Adapted from ACI 211.1.

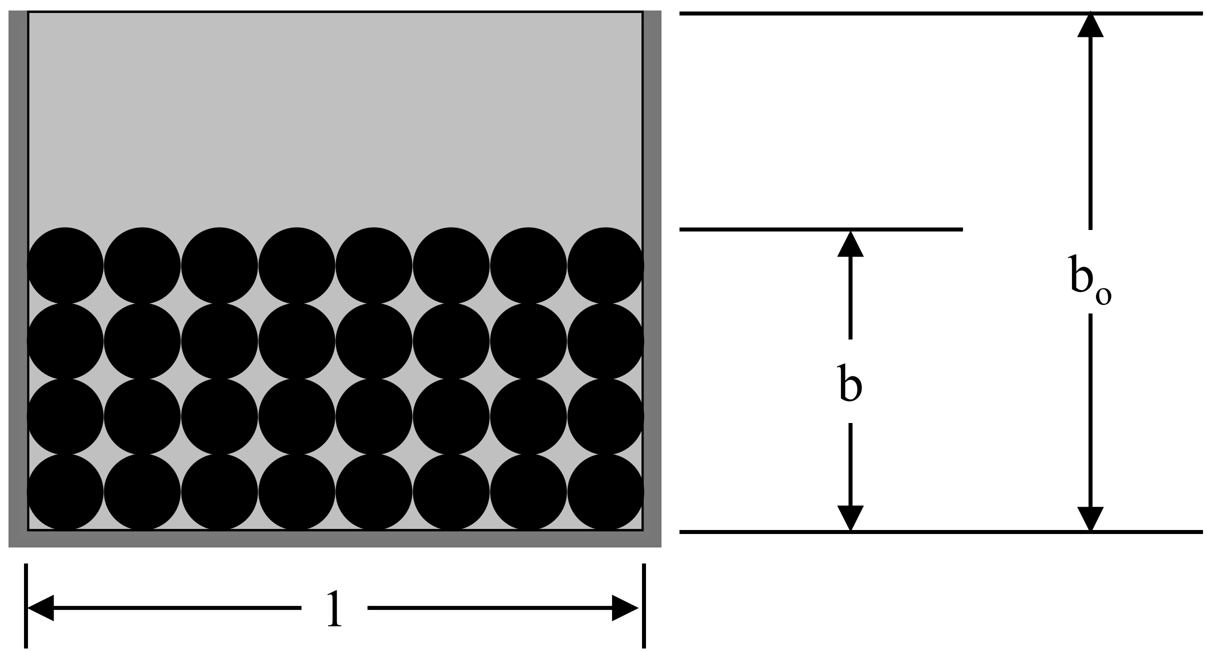
Source: Design and Control of Concrete Mixtures (PCA, 2003)

Step 8: Estimate coarse aggregate

The values in the table are called the b/b_o factor. In a nutshell, it tells you how big a box you would need to build to exactly contain all of the coarse aggregate in your mix (including all of the void spaces between the aggregate particles).

As shown in the next slide, if you are trying to make a volume of concrete with dimensions $1 \times 1 \times b_o$ you'd need to build a box with dimensions $1 \times 1 \times b$ to hold all the coarse aggregate.

What does b/b_o represent?



Ratio of bulk aggregate volume (b) to bulk concrete volume (b_o)

Step 8: Estimate coarse aggregate

The b/b_o factors are a function of the NMAS of the coarse aggregate and the fineness modulus of the fine aggregate. As we've said before, the larger the aggregate, the less cement paste is needed to coat the surface area, so the more room there is for coarse aggregate. Also, as the fineness modulus of the sand increases it becomes coarser and the blend of coarse and fine aggregate becomes less gap-graded. As a result you need slightly more sand and less gravel in the mix.

Step 8: Estimate coarse aggregate

Once you know how large your virtual box needs to be, you can calculate the weight of coarse aggregate needed to fill that box by multiplying the volume of the box by the dry-rodded unit weight of the coarse aggregate.

$$W_{gravel} = \left(b/b_o\right) V_{concrete}^{bulk} \gamma_{gravel}^{bulk}$$

Step 8: Estimate coarse aggregate

In our example, the fineness modulus of the sand is 2.90, which is halfway between 2.80 and 3.00, so we interpolate a b/b_o value of 0.61 for a ¾" NMAS and calculate the required coarse aggregate content from its dry-rodded unit weight as

$$W_{gravel} = (0.61)\left(27\,\frac{\cancel{ft^3}}{yd^3}\right)\left(101\,\frac{lb}{\cancel{ft^3}}\right) = 1663\ lb/yd^3$$

Step 9: Estimate fine aggregate

ACI provides two different methods to estimate the amount of fine aggregate needed. The first method, the ***estimated weight method***, uses typical values for the unit weight of concrete mixes to determine how much the concrete should weigh once it's mixed.

Once we've estimated the weight of all the other ingredients, whatever is still missing must be that of the sand.

Step 9: Estimate fine aggregate

Estimated Weight Method

$$W_{total} = W_{cement} + W_{gravel} + W_{sand} + W_{water}$$

$$\Downarrow$$

$$W_{sand} = W_{total} - \left(W_{cement} + W_{gravel} + W_{water} \right)$$

Step 9: Estimate fine aggregate

Estimated Weight Method

NMAS (in)	First Estimate of Concrete Unit Mass (lb/ft^3) Non-Air-Entrained Concrete	Air-Entrained Concrete
⅜	142.0	137.5
½	144.0	139.0
¾	146.5	141.5
1	148.5	143.5
1½	151.0	146.0
2	153.0	147.5
3	155.5	150.0
6	157.5	152.0

Step 9: Estimate fine aggregate

Estimated Weight Method

Based on our ¾" NMAS, the density of the concrete should be 146.5 lb/ft^3, so our concrete should weigh

$$\gamma_{\text{concrete}} = 146.5 \frac{\text{lb}}{\cancel{\text{ft}^3}}\left(27 \frac{\cancel{\text{ft}^3}}{\text{yd}^3}\right) = 3956 \text{ lb}/\text{yd}^3$$

Questions to Ponder

Why does the density rise with increasing NMAS?

NMAS (in)	First Estimate of Concrete Unit Mass (lb/ft^3) Non-Air-Entrained Concrete	Air-Entrained Concrete
⅜	142.0	137.5
½	144.0	139.0
¾	146.5	141.5
1	148.5	143.5
1½	151.0	146.0
2	153.0	147.5
3	155.5	150.0
6	157.5	152.0

Questions to Ponder

As we've said repeatedly, the larger the NMAS the less cement paste is needed to coat the surface area of the aggregate. Since cement paste is less dense than a typical aggregate, a mix with more cement paste will be less dense than a mix with less cement paste.

Questions to Ponder

So what is a typical density for cement paste?

To answer that, we'll start with the observation that the volume of the cement paste is equal to the sum of the volumes of the cement and water (if we ignore any entrapped air).

The weights of the cement and water can be found by dividing their volumes by their specific gravities and the unit weight of water.

Effect of NMAS on Unit Weight

$$V_{paste} = V_{water} + V_{cement}$$

$$\frac{W_{paste}}{RD_{paste}\,\cancel{\gamma_w}} = \frac{W_{water}}{RD_{water}\,\cancel{\gamma_w}} + \frac{W_{cement}}{RD_{cement}\,\cancel{\gamma_w}}$$

$$\frac{W_{water} + W_{cement}}{RD_{paste}} = \frac{W_{water}}{RD_{water}} + \frac{W_{cement}}{RD_{cement}}$$

Questions to Ponder

If we assume a typical w/cm of 0.5 then the weight of the water is 0.5 times the weight of the cement and the total weight of the cement paste is 1.5 times the weight of the cement. As shown on the next slide, this leads to a typical specific gravity of 1.83 for the cement paste.

Aggregate typically has a specific gravity of 2.5-2.7, so cement paste is 2/3 to 3/4 as dense as aggregate.

Effect of NMAS on Unit Weight

$$\text{Assume w/c} = 0.5$$

$$\frac{1.5\, \cancel{W_{cement}}}{RD_{paste}} = \frac{0.5\, \cancel{W_{cement}}}{1.00} + \frac{1.0\, \cancel{W_{cement}}}{3.15}$$

$$RD_{paste} = 1.83$$

$$RD_{aggregate} = 2.65\,(\text{typical})$$

Step 9: Estimate fine aggregate

Estimated Weight Method

If our concrete has a "typical" unit weight of 3956 lb per cubic yard of concrete then, using the estimated weight method, the amount of sand that is needed to complete the mix design is

$$W_{sand} = 3956 - (686 + 1663 + 295) = 1312\ \mathrm{lb/yd^3}$$

Step 9: Estimate fine aggregate

The estimated weight method is very approximate because it's based on "typical" unit weights. A more precise method is the ***absolute volume method***, which determines the volume occupied by each ingredient based on its bulk specific gravity (this is what is meant by the absolute volume) then subtracts those from 27 ft^3 (1 yd^3) to get the required <u>volume</u> of the sand. Since the entrapped or entrained air occupies some of that volume, it needs to be included, too.

Step 9: Estimate fine aggregate

Absolute Volume Method

$$V_{total} = V_{cement} + V_{gravel} + V_{sand} + V_{water} + V_{air}$$

$$\Downarrow$$

$$V_{sand} = V_{total} - \left(V_{cement} + V_{gravel} + V_{water}\right) - V_{air}$$

Step 9: Estimate fine aggregate

In this approach, we use the ***bulk*** specific gravities of the aggregate to determine their absolute volumes because all of the water in the mix is supposed to be in the cement paste and not in the pervious pores of the aggregate. We will later add some water to the mix to ensure the aggregate is SSD and doesn't try to absorb water from the cement paste.

Step 9: Estimate fine aggregate

Absolute Volume Method

$$V_{sand} = V_{total} - \left(V_{cement} + V_{gravel} + V_{water}\right) - V_{air}$$

$$V_{sand} = V_{total} - \frac{1}{\gamma_w}\left(\frac{W_{cement}}{3.15} + \frac{W_{gravel}}{G_{gravel}^{bulk}} + \frac{W_{water}}{1.00}\right) - V_{air}$$

$$W_{sand} = V_{sand} \times G_{sand}^{bulk} \times \gamma_w$$

Step 9: Estimate fine aggregate

Absolute Volume Method

We originally estimated that our mix would contain 2% entrapped air, which is 0.54 ft^3/yd^3 of concrete, so

$$V_{sand} = 27 - \frac{1}{62.4}\left(\frac{686}{3.15} + \frac{1663}{2.574} + \frac{295}{1.00}\right) - 0.54$$

$$V_{sand} = 27 - 18.57 - 0.54 = 7.89\ ft^3/yd^3$$

Step 9: Estimate fine aggregate

Absolute Volume Method

Now that we know the absolute volume of the sand, we can determine its weight from its specific gravity:

$$W_{sand} = 7.89 \times 2.548 \times 62.4 = 1254 \text{ lb/yd}^3$$

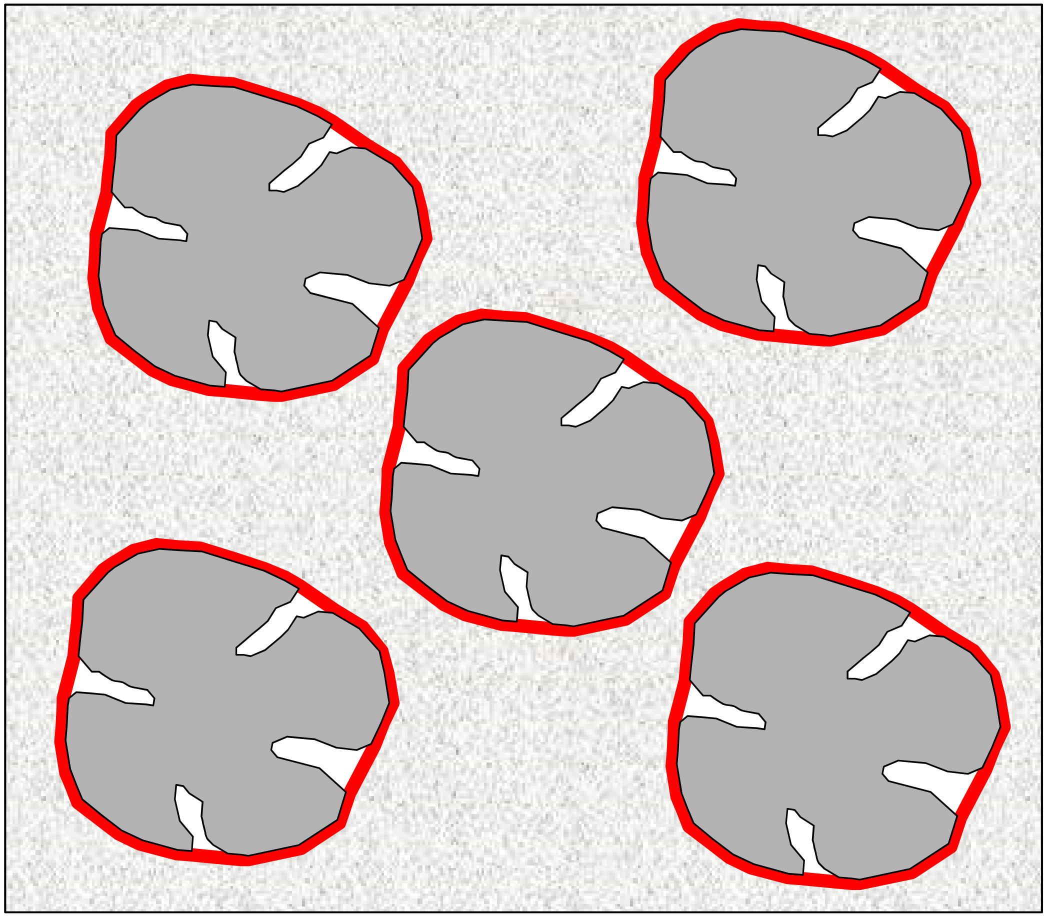
Step 10: Adjust for Moisture Content

The final step in the mix design (whether we used the absolute volume or estimated weight method) is to (1) add additional water to the mix to make sure the aggregate is saturated and doesn't absorb water from the cement paste, and (2) adjust the weights of the aggregate and the mixing water to account for the fact that the aggregate stockpiles at the batch plant will not be oven-dry.

Step 10: Adjust for Moisture Content

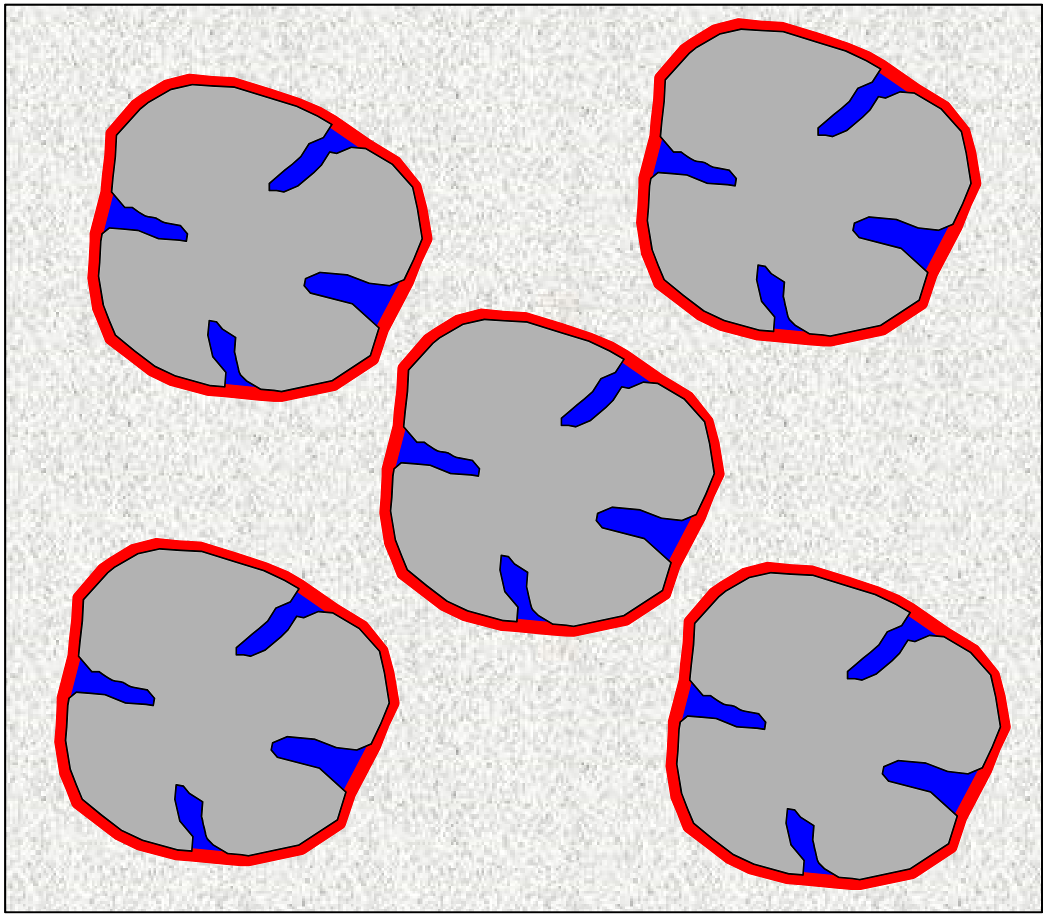
1. Increase W_{water} by an amount equal to the weight of water needed to saturate the fine and coarse aggregate.

Since we did our calculations based on bulk OD specific gravity …



… we've assumed the pervious pores are filled with air.

If we don’t add enough extra water to fill those pervious pores …



… the aggregate will suck water out of the cement paste.

Step 10: Adjust for Moisture Content

The amount of water needed to saturate the aggregate is just the product of the aggregate weight and the aggregate absorption:

$$\Delta W_{water} = (0.019)1663 + (0.017)1254 = 53\ \mathrm{lb}/\mathrm{yd}^3$$

$$W_{water} = 295 + 53 = 348\ \mathrm{lb}/\mathrm{yd}^3$$

Step 10: Adjust for Moisture Content

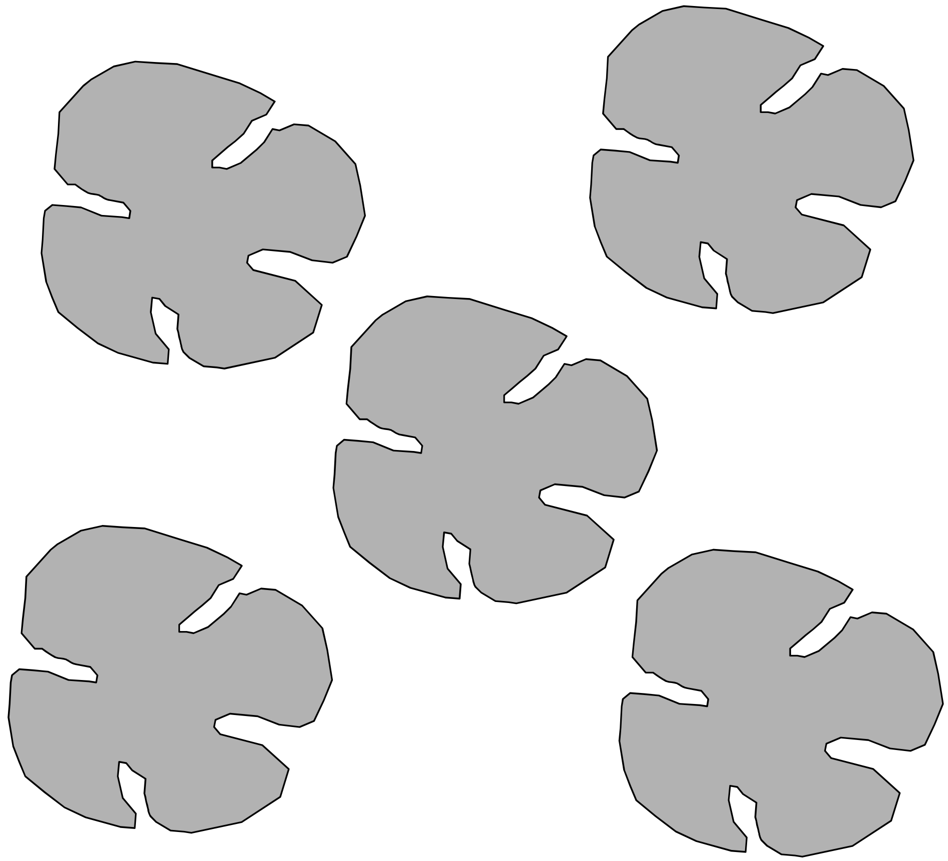
So, based on the absolute volume method calculations, our "laboratory" mix design (i.e., what we'd make in the laboratory using oven-dry aggregate) is

$$W_{water} = 348 \text{ lb/yd}^3$$
$$W_{cement} = 686 \text{ lb/yd}^3$$
$$W_{OD\ gravel} = 1663 \text{ lb/yd}^3$$
$$W_{OD\ sand} = 1254 \text{ lb/yd}^3$$

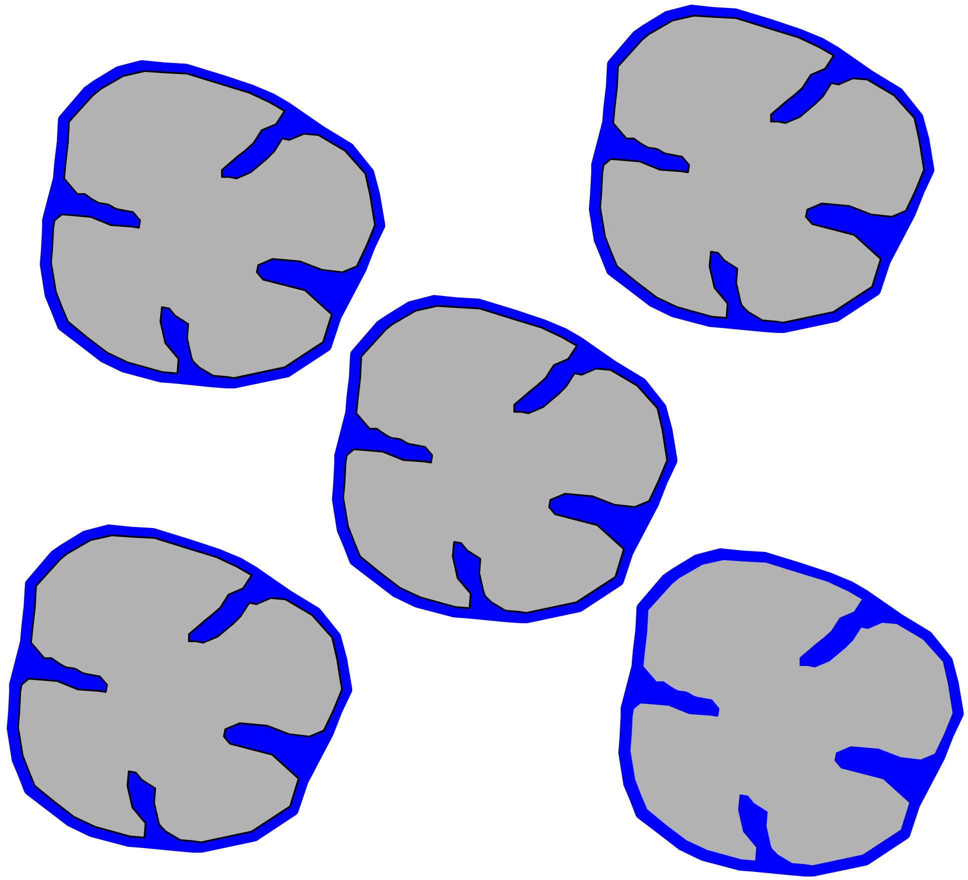
Step 10: Adjust for Moisture Content

1. Increase W_{water} by an amount equal to the weight of water needed to saturate the fine and coarse aggregate.
2. Increase W_{sand} and W_{gravel} to account for the current moisture contents of the aggregate in the batch plant stockpiles.

If our mix design calls for 1000 lb of dry aggregate …



… but the moisture content is currently 10% …



… we have to weigh up 1000 (1.10) = 1100 lb of moist aggregate.

Step 10: Adjust for Moisture Content

For our example, assume the sand stockpile has a moisture content of 6.2% and the gravel stockpile has a moisture content of 2.1% on the day we are going to batch our concrete mix. Then

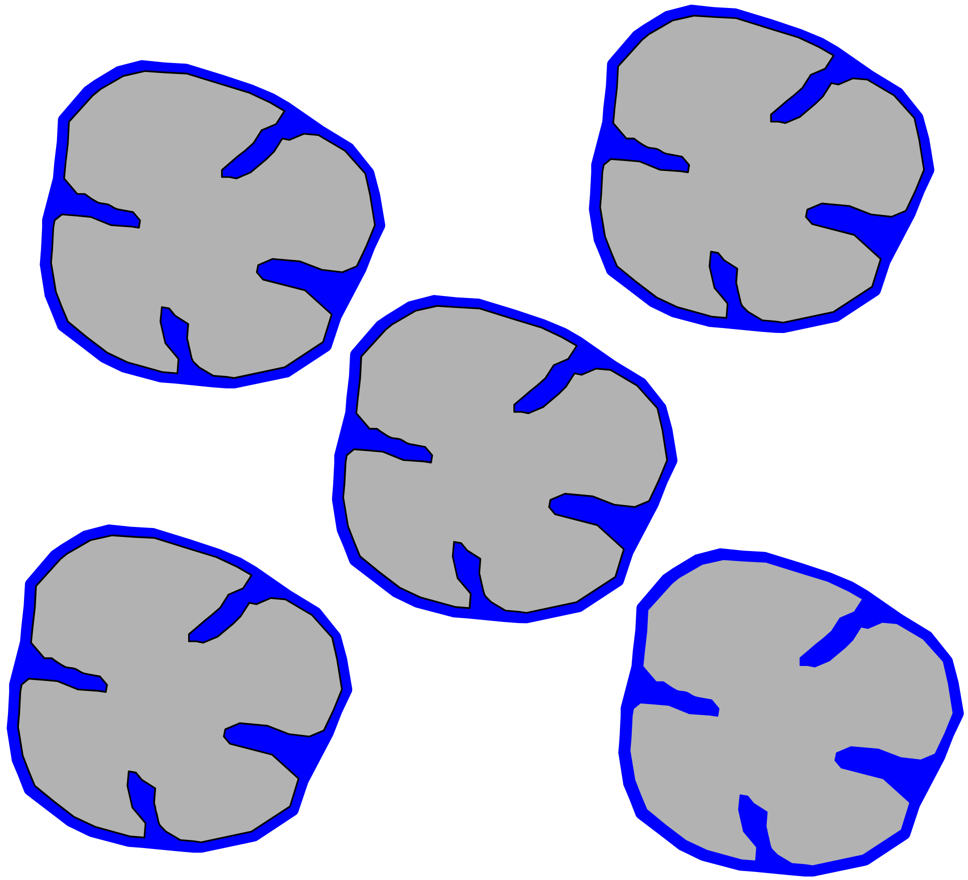
$$W_{\text{wet sand}} = (1.062)1254 = 1332 \text{ lb}/\text{yd}^3$$

$$W_{\text{wet gravel}} = (1.021)1663 = 1698 \text{ lb}/\text{yd}^3$$

Step 10: Adjust for Moisture Content

1. Increase W_{water} by an amount equal to the weight of water needed to saturate the fine and coarse aggregate.
2. Increase W_{sand} and W_{gravel} by an amount equal to the moisture contents of the aggregate stockpiles.
3. Decrease W_{water} by the same amount you increased W_{sand} and W_{gravel}.

Since we've weighed up 1000 lb of dry aggregate + 100 lb of water …



… we have to reduce the amount of water we add from the faucet by 100 lb.

Step 10: Adjust for Moisture Content

Since Mother Nature is providing some of the water needed in the mix, we can reduce the amount we add from the faucet by a like amount:

$$\Delta W_{\text{water}} = (1698 - 1663) + (1332 - 1254) = 113 \text{ lb/yd}^3$$

$$W_{\text{water}} = 348 - 113 = 235 \text{ lb/yd}^3$$

Step 10: Adjust for Moisture Content

So, our "field" mix (i.e., what we'd make in the field today using aggregate in its current moisture state) is

$$W_{water} = 235 \text{ lb/yd}^3$$
$$W_{cement} = 686 \text{ lb/yd}^3$$
$$W_{wet\ gravel} = 1663 \text{ lb/yd}^3$$
$$W_{wet\ sand} = 1254 \text{ lb/yd}^3$$