Mix Design Basics

Mix Design Goals

adequate workability

adequate strength

adequate durability

minimum cost

Cost of Materials

crushed stone = \$ 12/ton

concrete sand = \$ 9/ton

Type I cement = \$126/ton

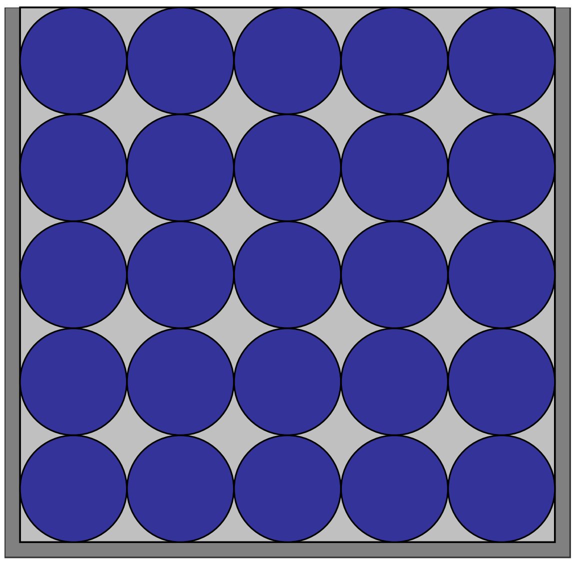
Minimum Cost = Minimum Cement

Minimizing ~~Cost~~ Cement

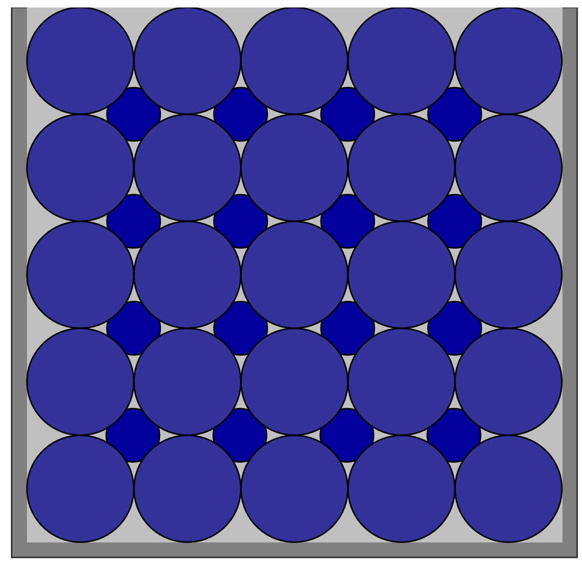
minimize the ***void space*** between aggregate particles that must be filled with cement paste

minimize the ***surface area*** of the aggregate particles that must be coated with cement paste

Minimizing Void Space



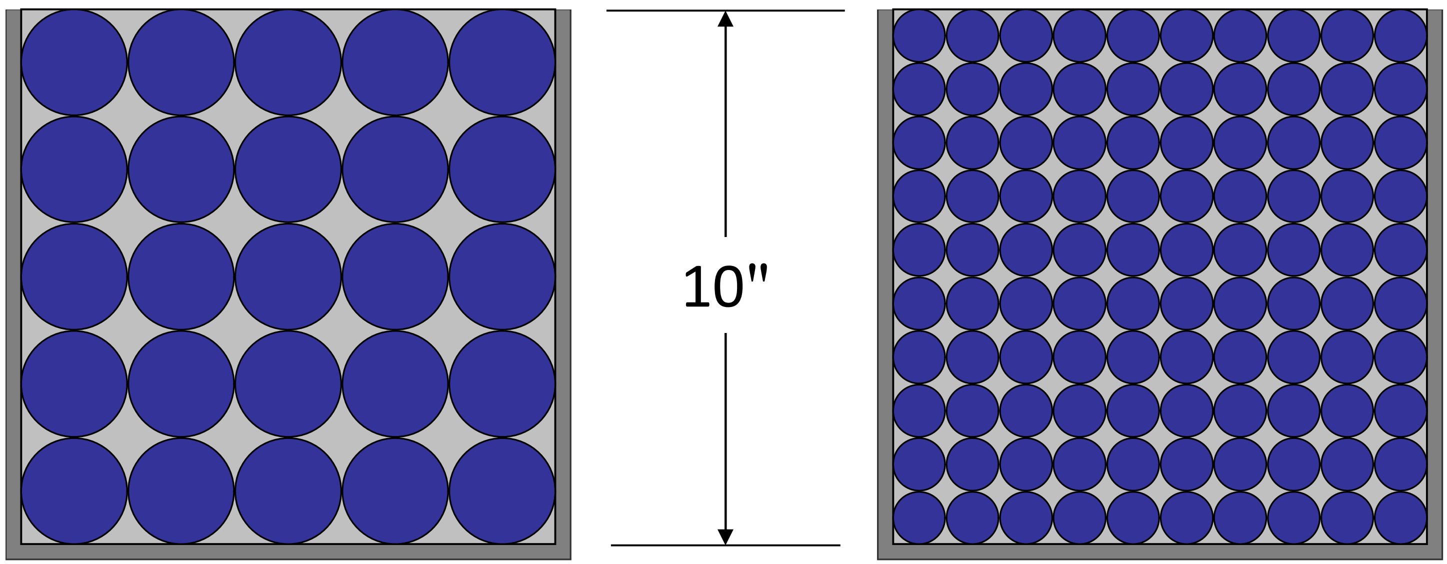
Void content = 48%



Void content = 41%

Use a gravel-sand blend with a dense gradation
to minimize the void content of the aggregate

Minimizing Surface Area

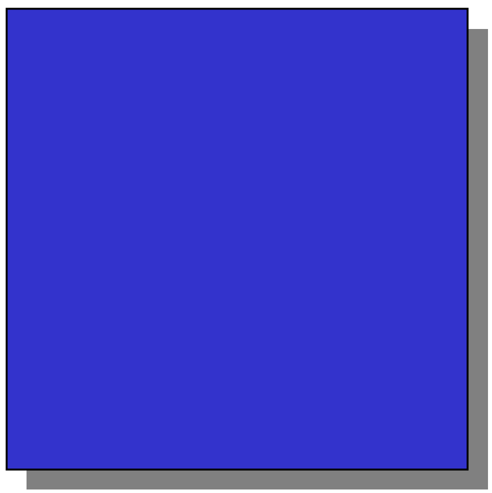


surface area = 11 ft^2

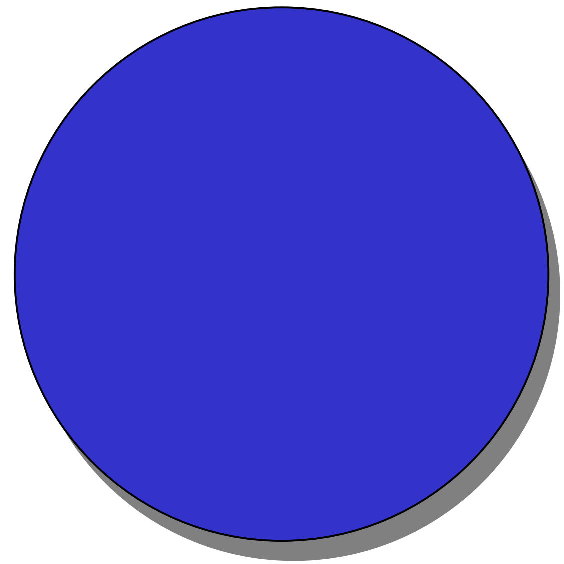
surface area = 22 ft^2

Use the largest NMAS you are allowed to in order to minimize the surface area per cubic yard of concrete

Minimizing Surface Area



surface area = 6.0 ft^2/ft^3



surface area = 4.8 ft^2/ft^3

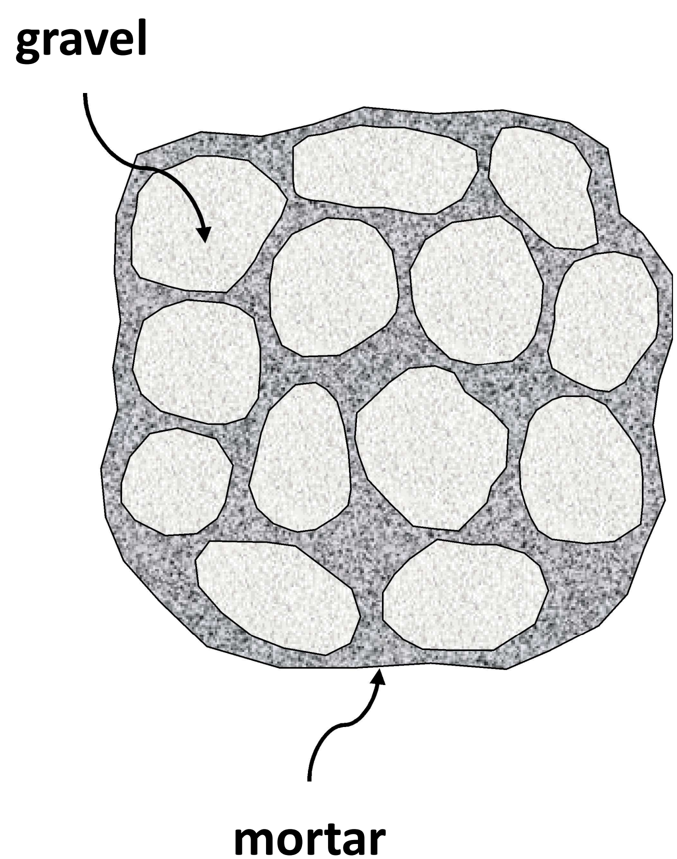
Use gravel instead of crushed stone if possible because it has a lower surface area per unit volume occupied

Obtaining Adequate Workability

To obtain good workability, you need enough mortar to fill the voids between the gravel particles, enough cement paste to fill the voids between sand particles, and enough water to both hydrate and lubricate the cement particles.

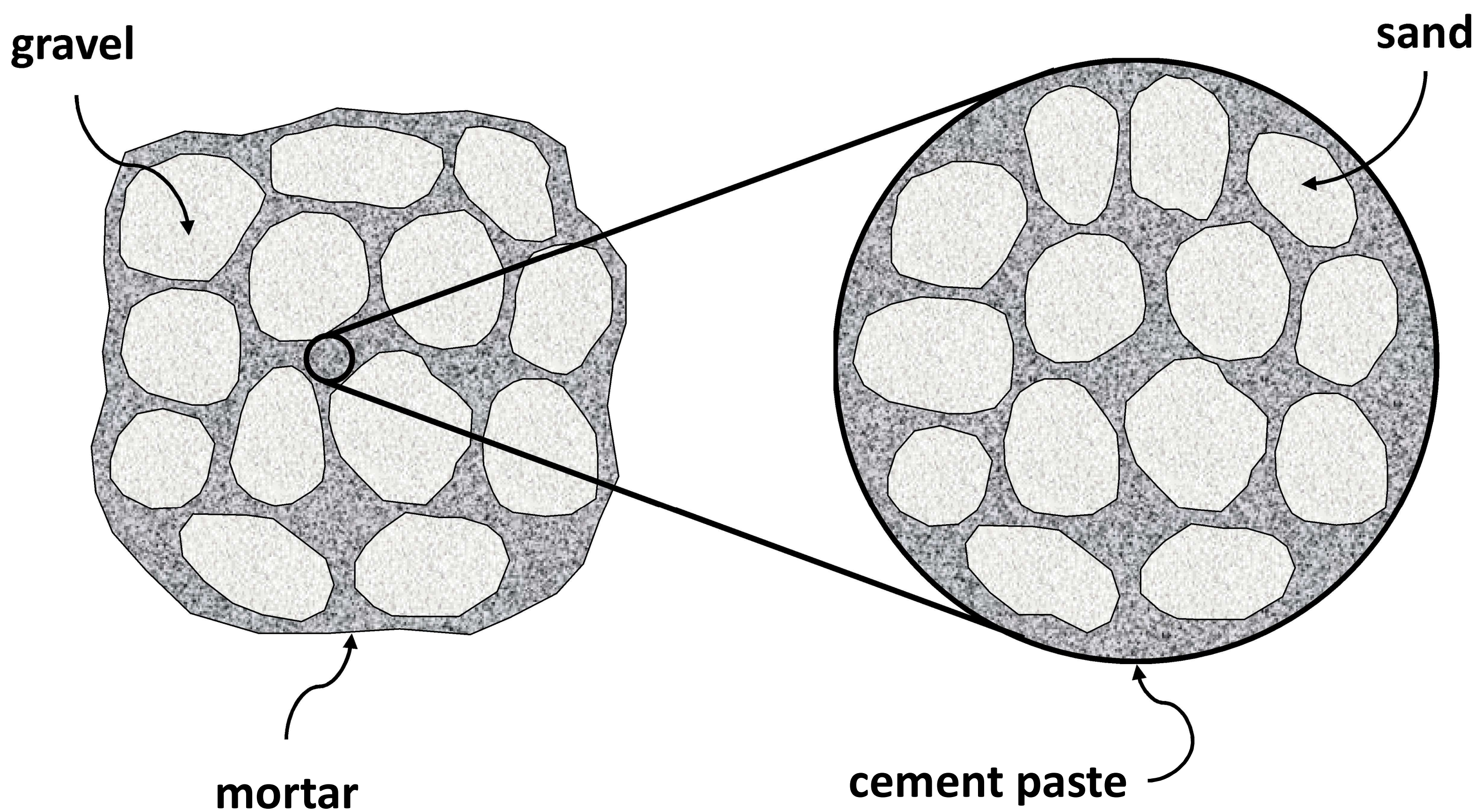
The main goal of the ACI mix design method is to get the relative volume proportions of the ingredients right in order to ensured good workability.

Obtaining Adequate Workability

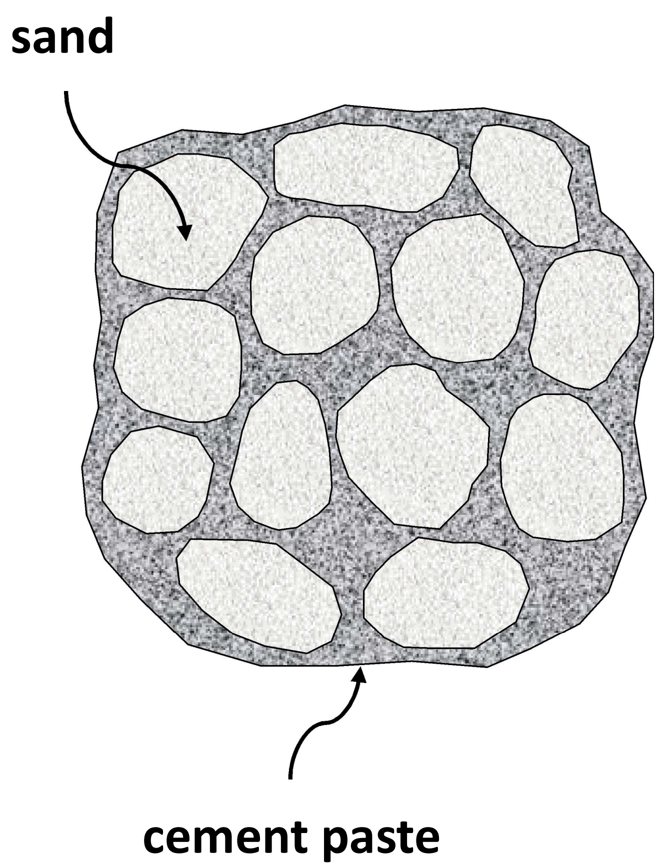


Need enough mortar to keep all the gravel particles apart.

Obtaining Adequate Workability

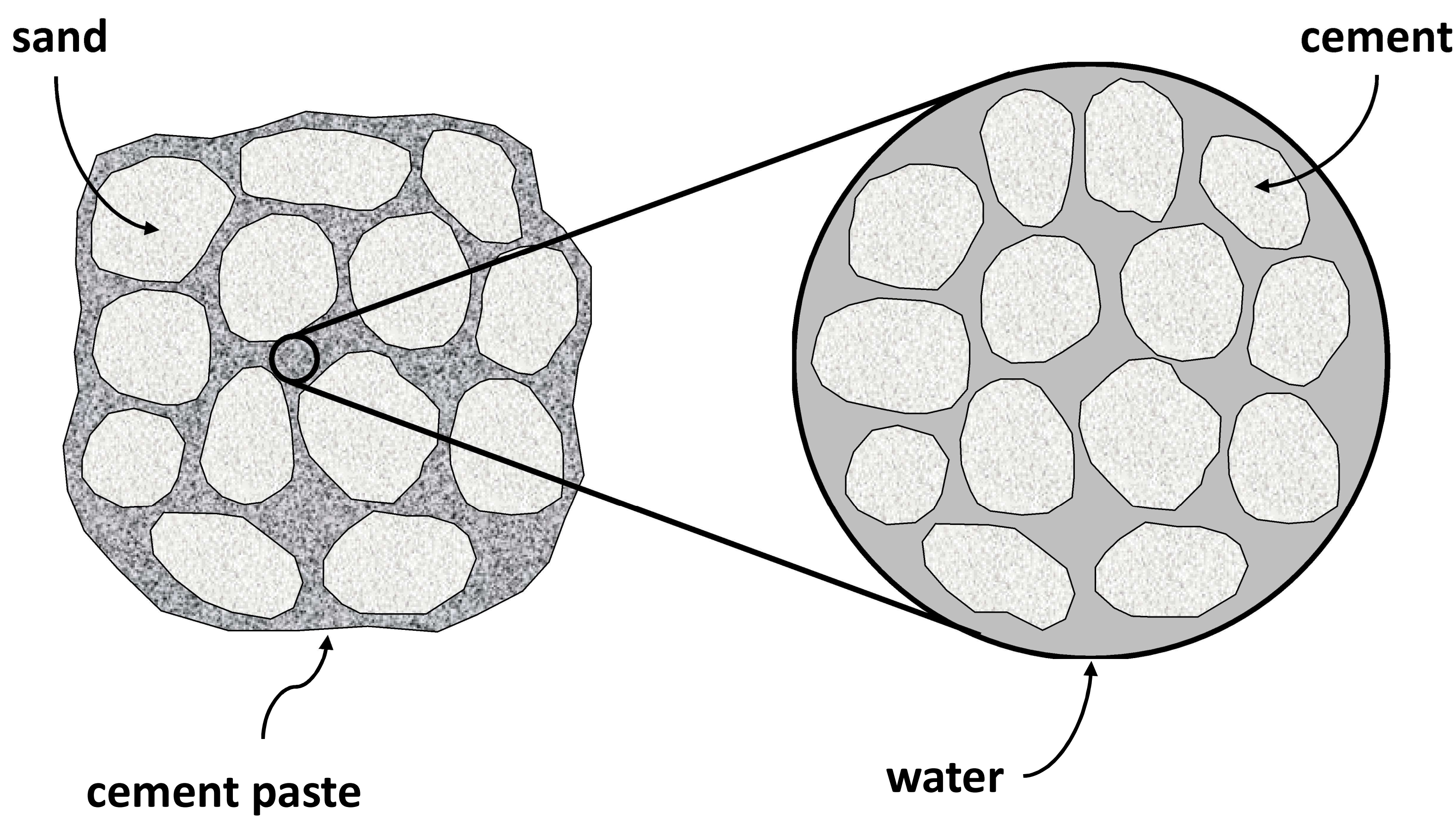


Obtaining Adequate Workability

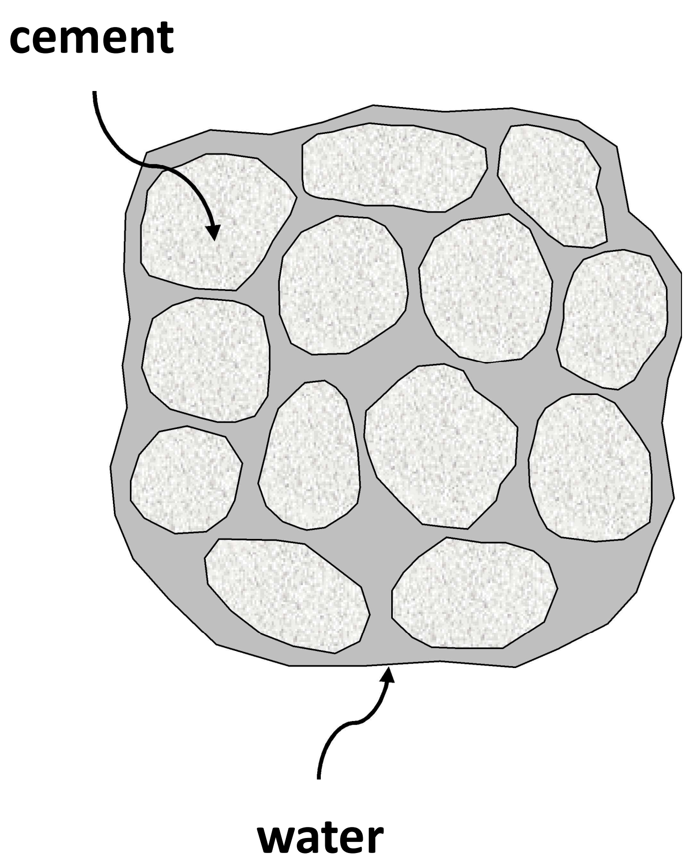


Need enough cement paste to keep all the sand grains apart

Obtaining Adequate Workability

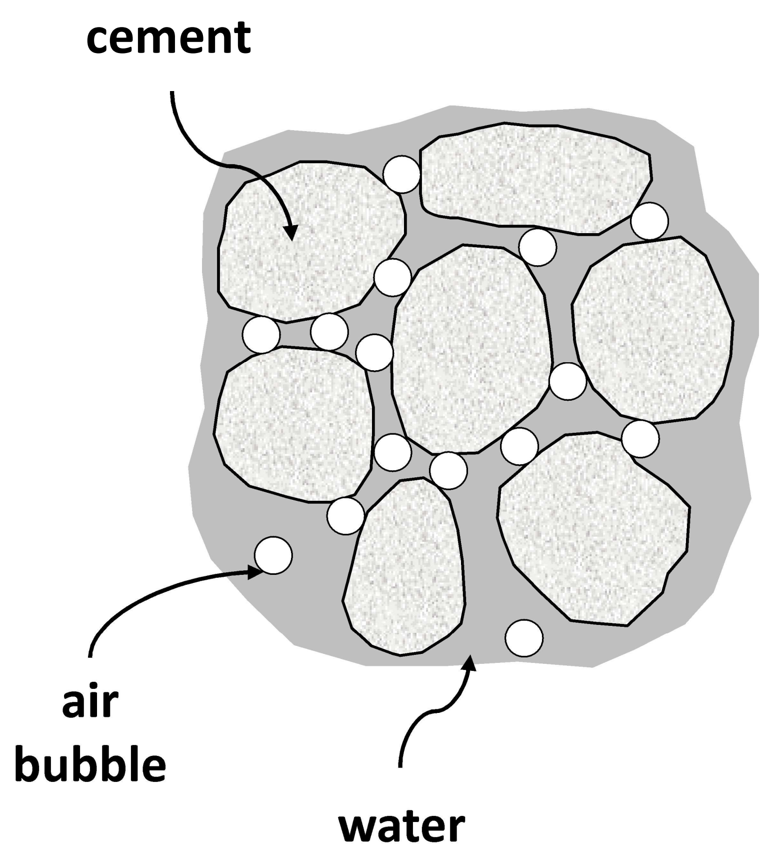


Obtaining Adequate Workability



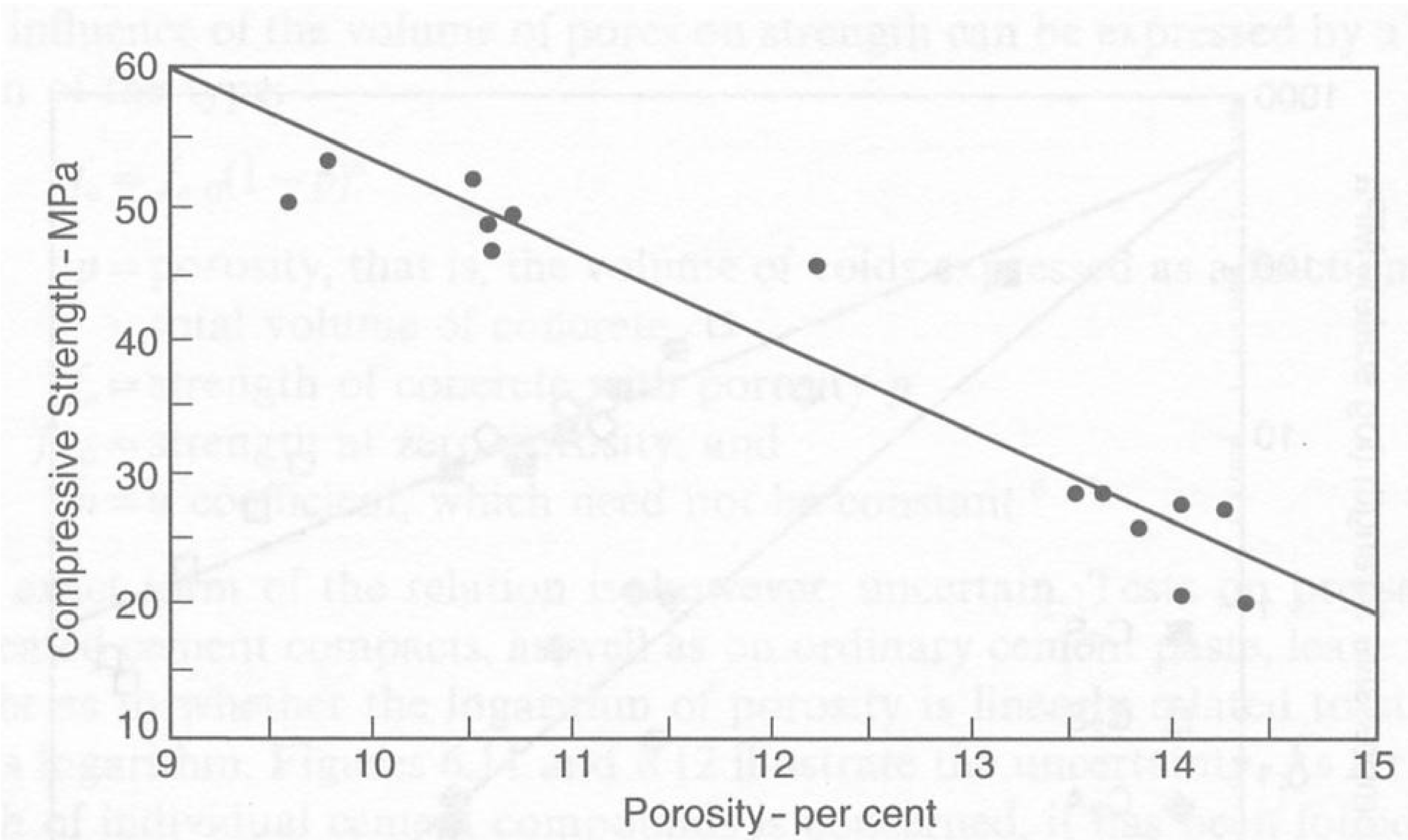
Need enough mixing water to lubricate all the cement grains

Obtaining Adequate Workability

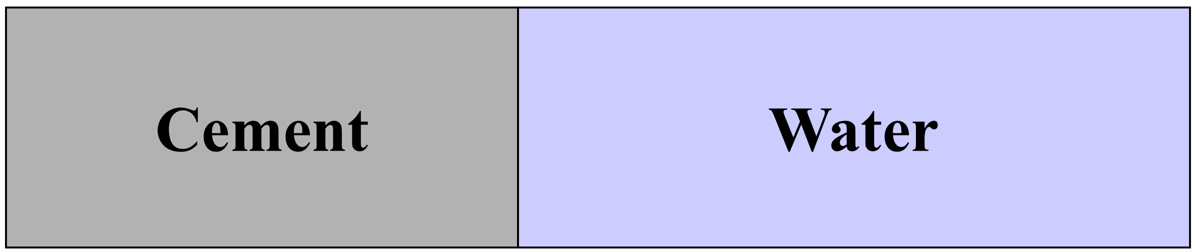


Air entrainment adds lubrication without adding additional water

Obtaining Adequate Strength

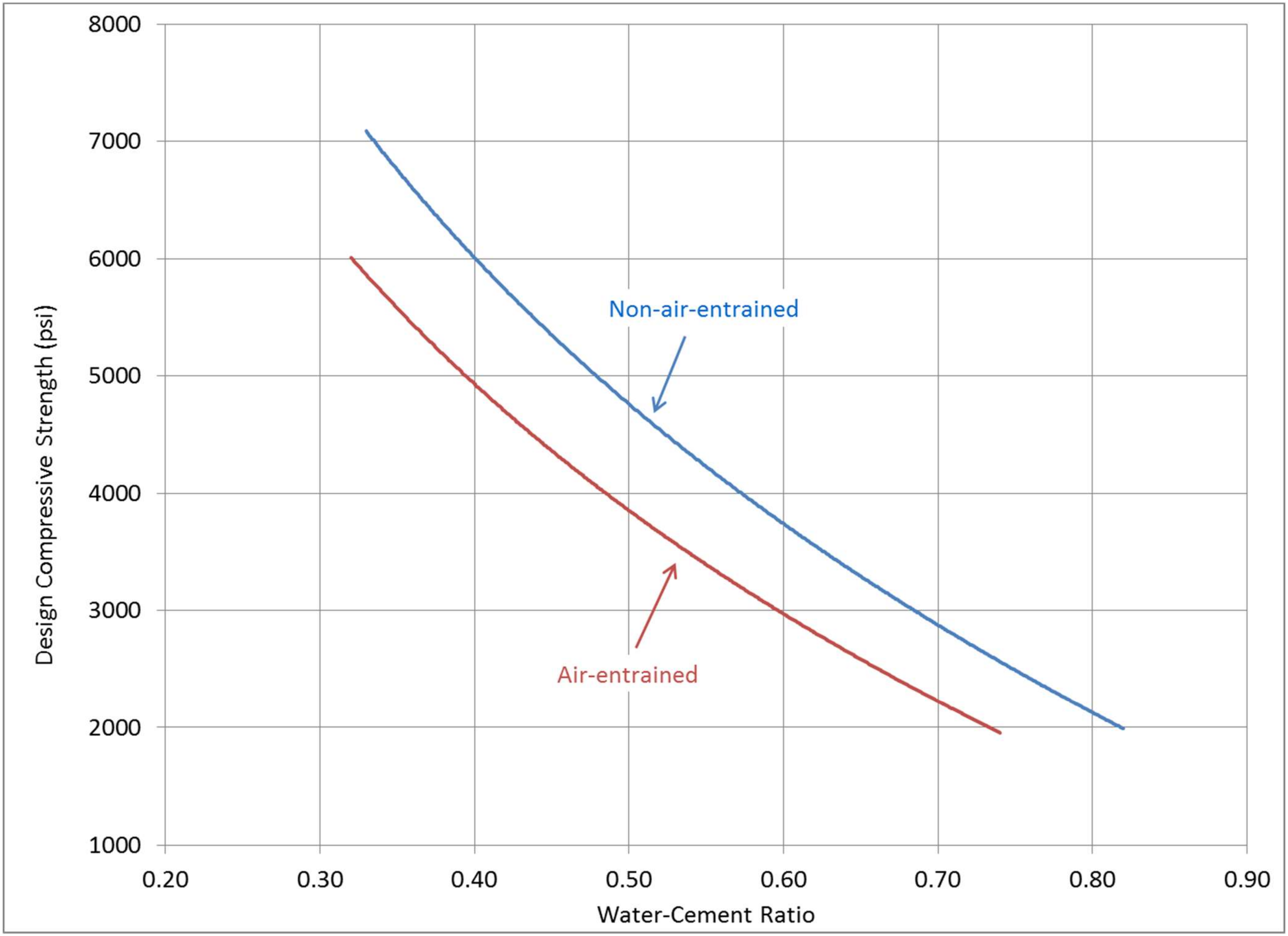


Water-Cement Ratio



0% Hydration

100% Hydration

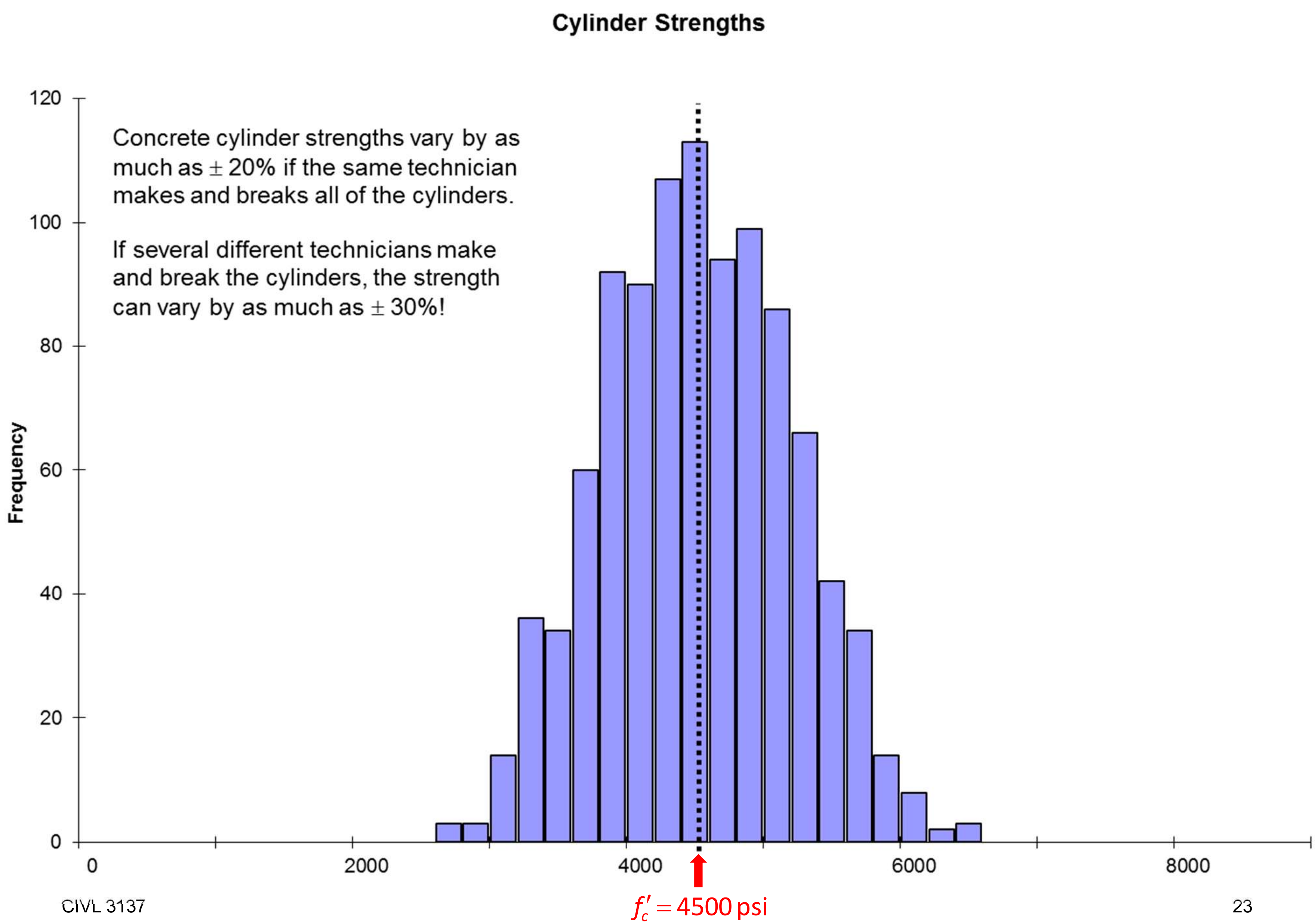


8000
7000
6000
5000
4000
3000
2000
1000
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Design Compressive Strength (psi)
Water-Cement Ratio
Non-air-entrained
Air-entrained

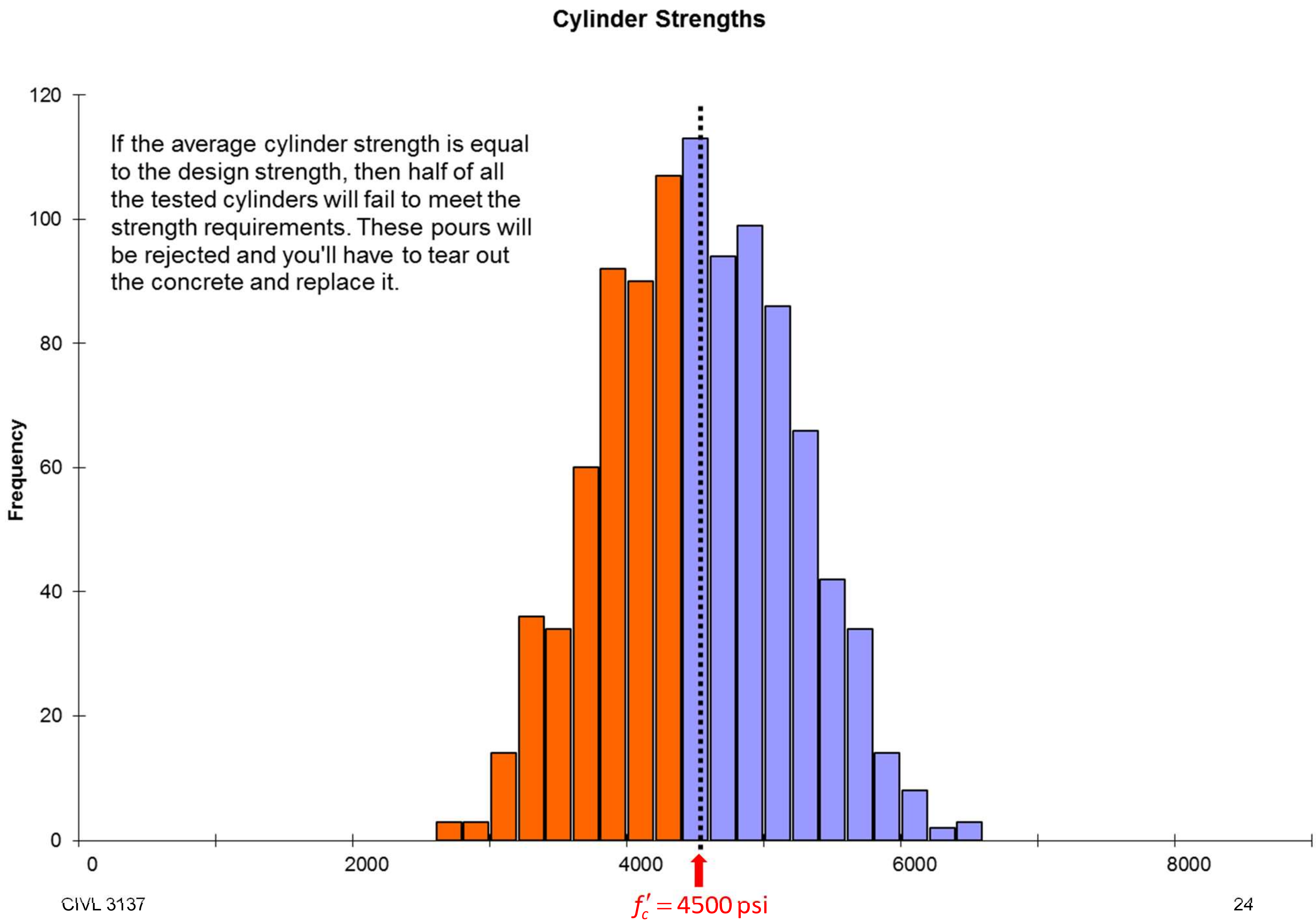
Obtaining Adequate Strength

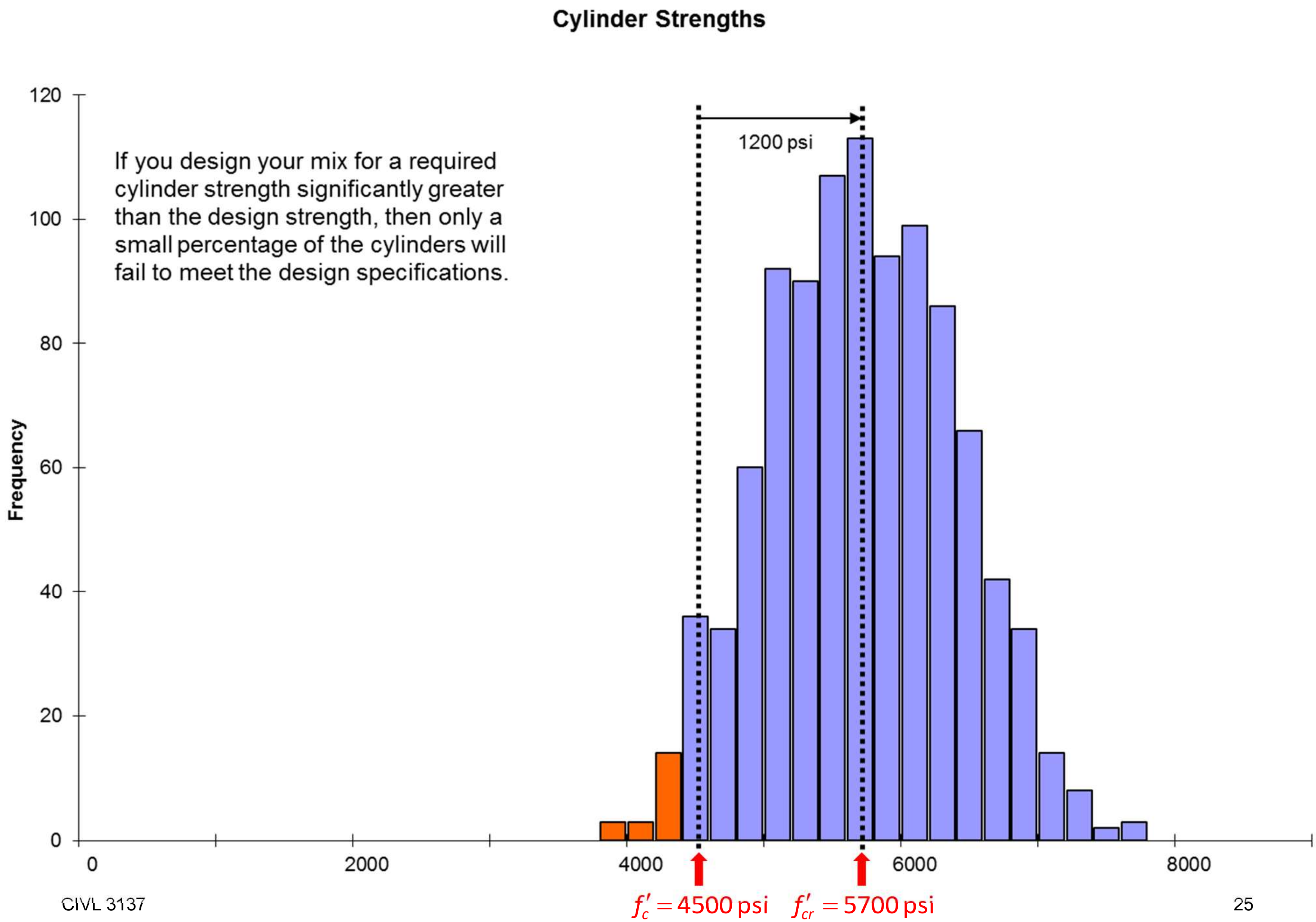
If the structural engineer designs a beam based on a concrete strength of 4500 psi, you have to design your concrete mix to have a strength much higher than that.

WHY?



Cylinder Strengths
Concrete cylinder strengths vary by as much as ± 20% if the same technician makes and breaks all of the cylinders.
If several different technicians make and break the cylinders, the strength can vary by as much as ± 30%!
Frequency
0
20
40
60
80
100
120
0
2000
4000
6000
8000
$f'_c = 4500$ psi


Cylinder Strengths
If the average cylinder strength is equal to the design strength, then half of all the tested cylinders will fail to meet the strength requirements. These pours will be rejected and you'll have to tear out the concrete and replace it.
Frequency
120
100
80
60
40
20
0
0
2000
4000
6000
8000
$f'_c = 4500$ psi


Cylinder Strengths
120
100
80
60
40
20
0
Frequency
0
2000
4000
6000
8000
1200 psi
If you design your mix for a required cylinder strength significantly greater than the design strength, then only a small percentage of the cylinders will fail to meet the design specifications.
$f'_c = 4500$ psi
$f'_{cr} = 5700$ psi

Overdesign Factors

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

ACI Mix Design

Mix Design Example

Coarse aggregate = subangular crushed stone

Nominal maximum aggregate size = 3/4"

Design strength (f'_c) = 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 (%) =	1.89	1.70
Fineness modulus =	2.51	3.00

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 2: Select the NMAS

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

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

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

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.

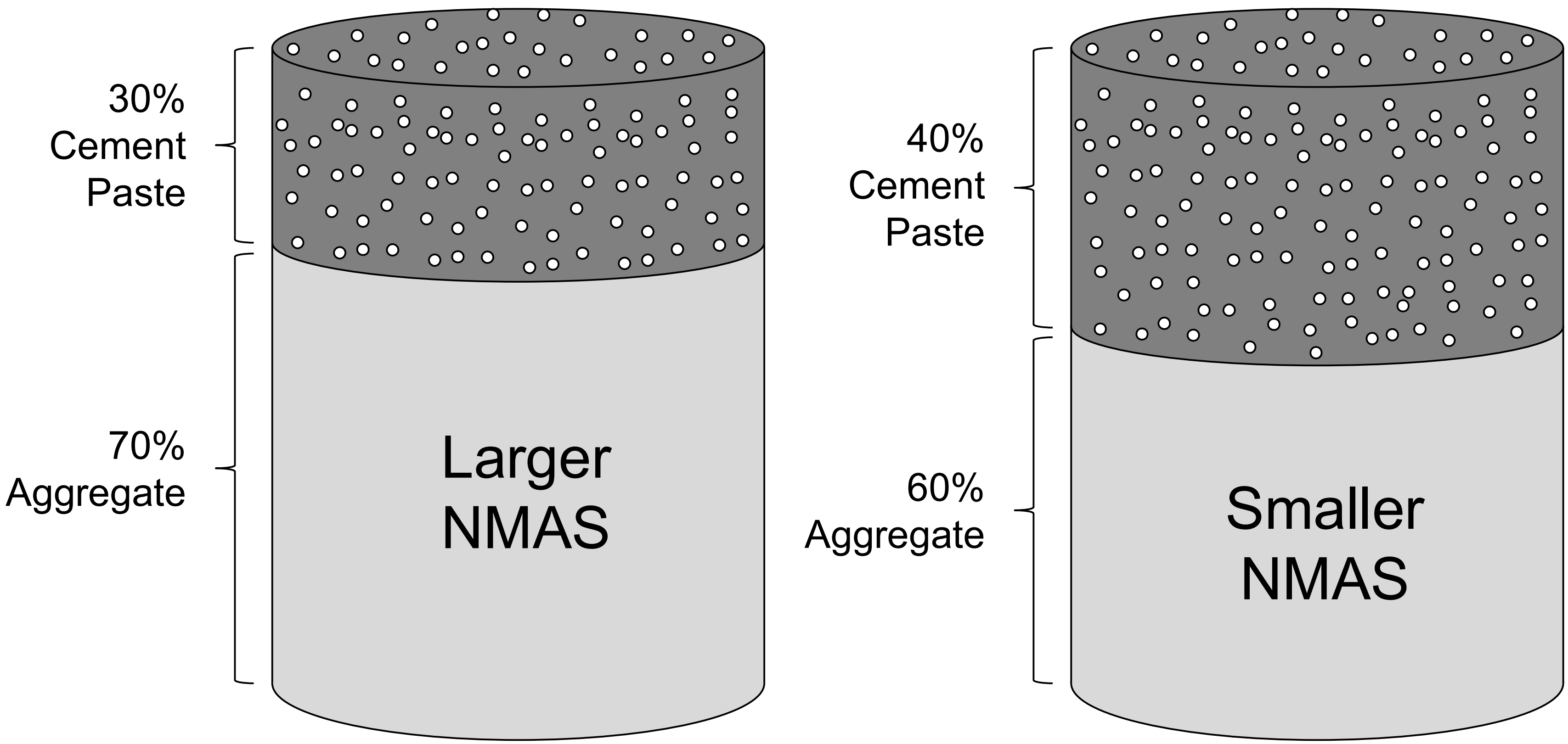
Source: Design and Control of Concrete Mixtures (PCA, 2003)

Questions to Ponder

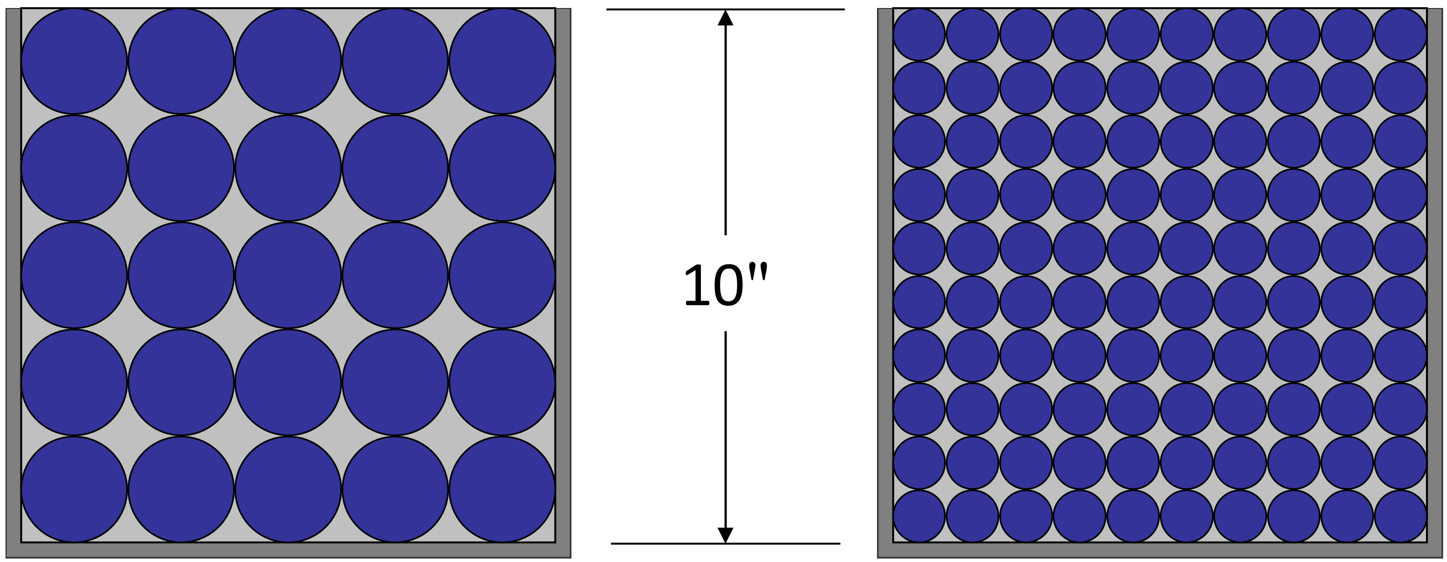
1. Why does the amount of water required to obtain a desired slump decrease with increasing NMAS?

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

Effect of NMAS on Paste Volume



Effect of NMAS on Paste Volume



surface area = 11 ft^2

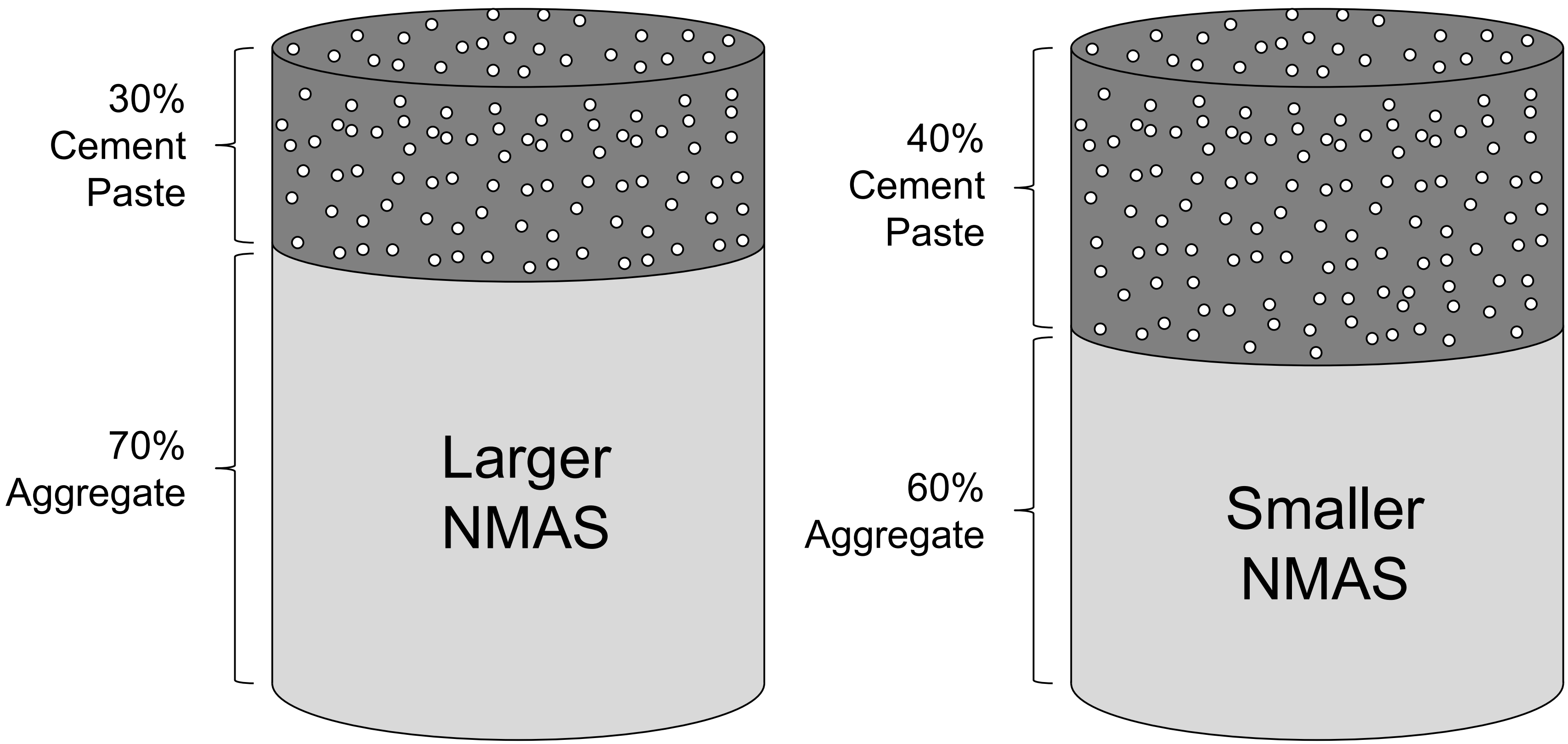
surface area = 22 ft^2

Questions to Ponder

2. 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

Effect of NMAS on Paste Volume

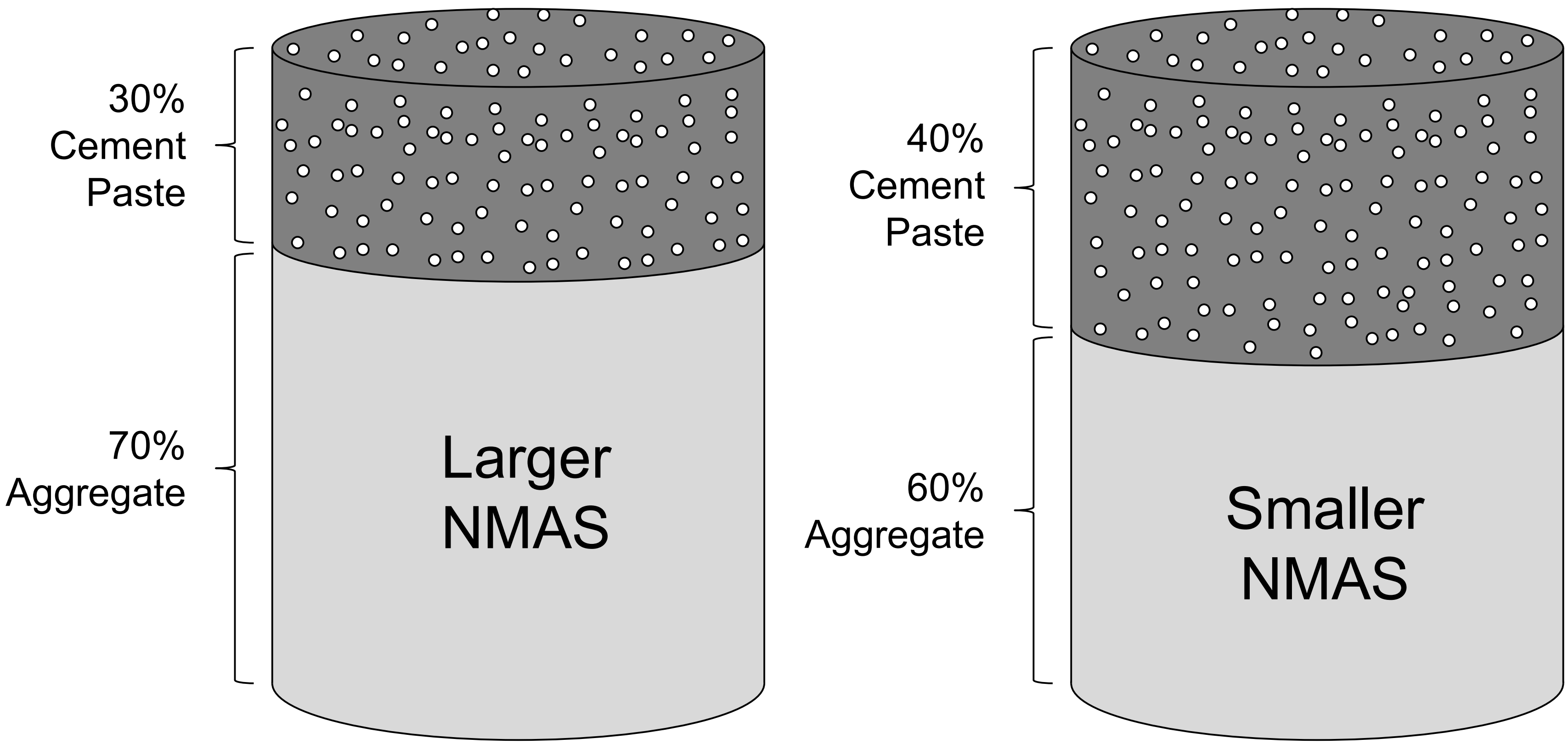


Questions to Ponder

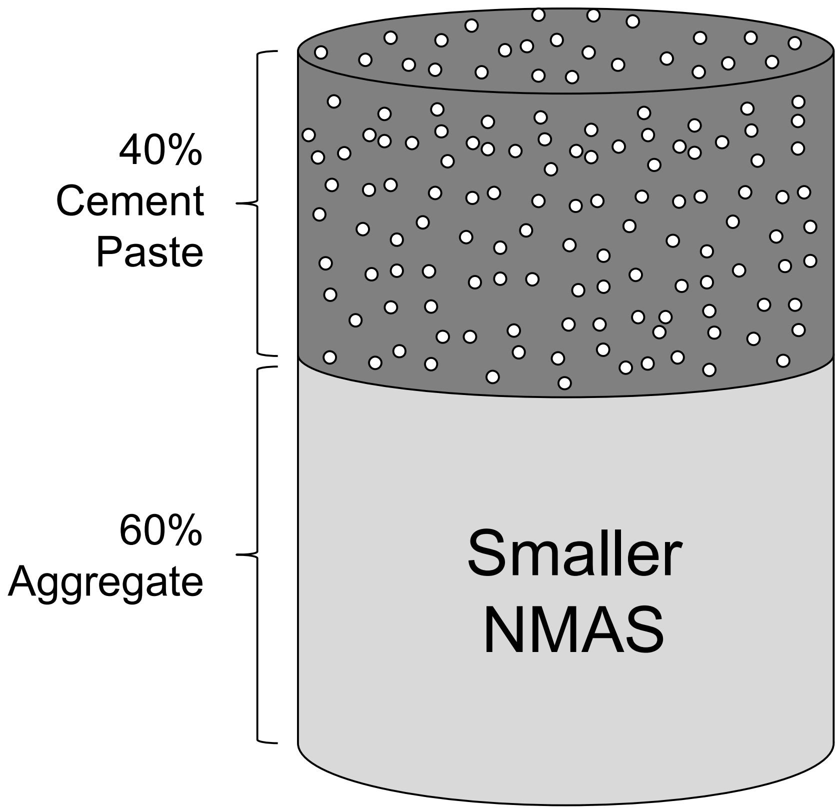
3. Why does the target air content in an air-entrained mix decrease with increasing NMAS?

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

Effect of NMAS on Paste Volume



Air Content



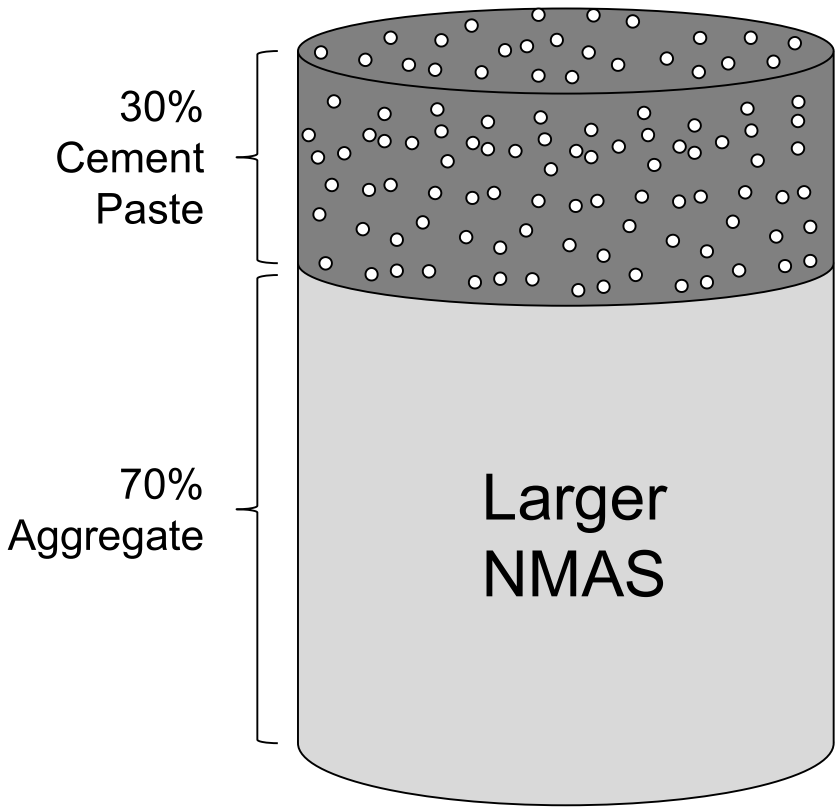
Paste Air Content

Assume 7%

Concrete Air Content

$0.4 \times 7\% = 2.8\%$

Air Content



Paste Air Content

Assume 7%

Concrete Air Content

$0.3 \times 7\% = 2.1\%$

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							
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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
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1 to 2	305	295	280	270	250	240	205	180
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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

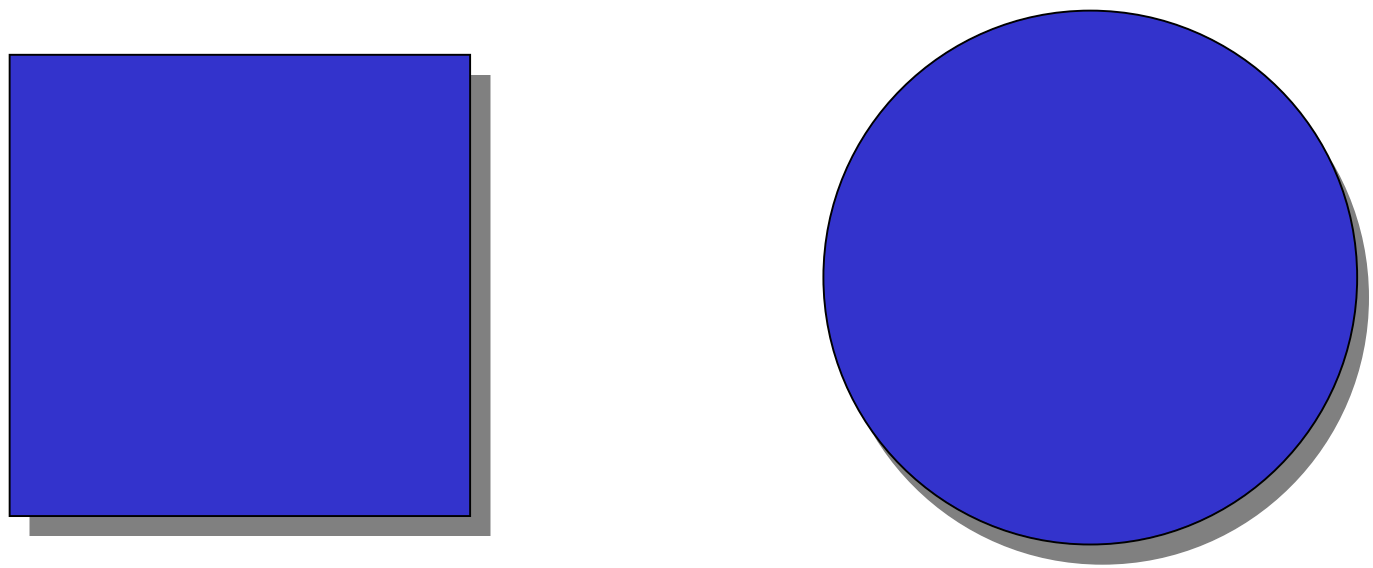
Aggregate Shape	Water Reduction (pounds per cubic yard)
Crushed stone (angular)	0
Crushed stone (subangular)	20
Gravel (some crushed)	35
Gravel (well rounded)	45

Questions to Ponder

4. 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

Minimizing Surface Area



surface area = 6.0 ft^2/ft^3

surface area = 4.8 ft^2/ft^3

Mix Design Example

Coarse aggregate = subangular crushed stone

Nominal maximum aggregate size = 3/4"

Design strength (f'_c) = 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 (%) =	1.89	1.70
Fineness modulus =	2.51	3.00

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 5: 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)

Overdesign Factors

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: Select the w/c ratio

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

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

Questions to Ponder

5. 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
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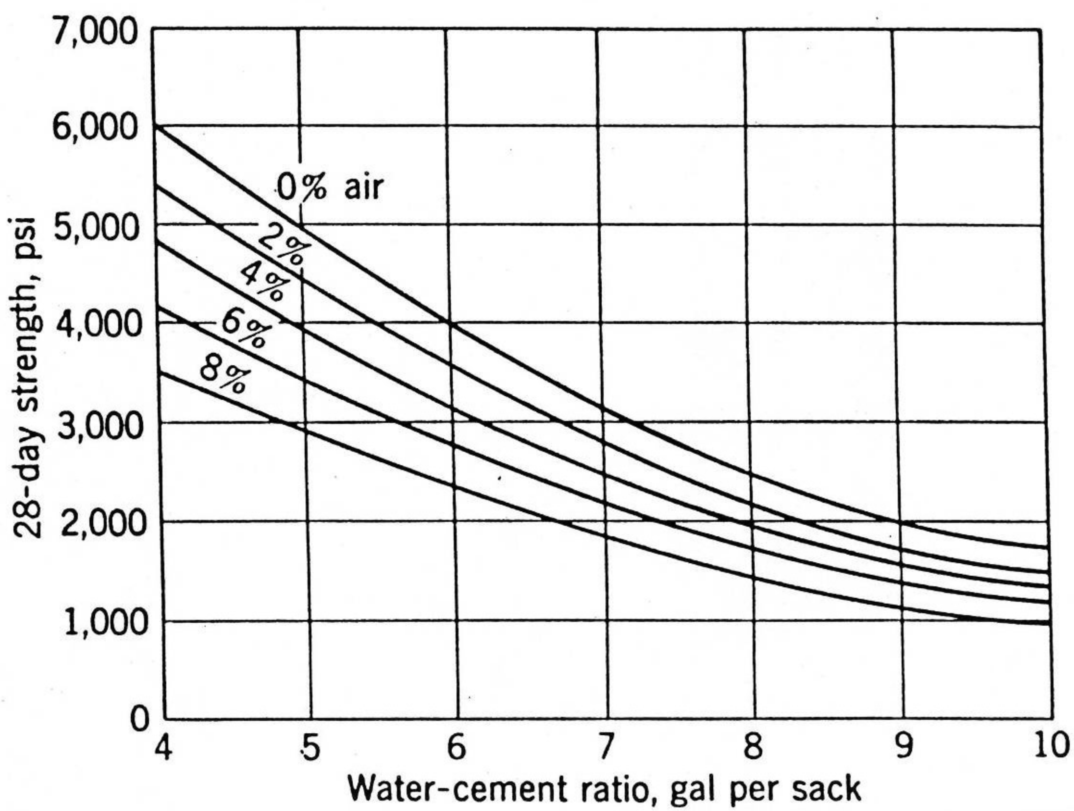
3000	0.68	0.59
2000	0.82	0.74

Effect of Air Content on Strength



Step 6: Calculate the cement weight

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

Step 7: Estimate coarse aggregate

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

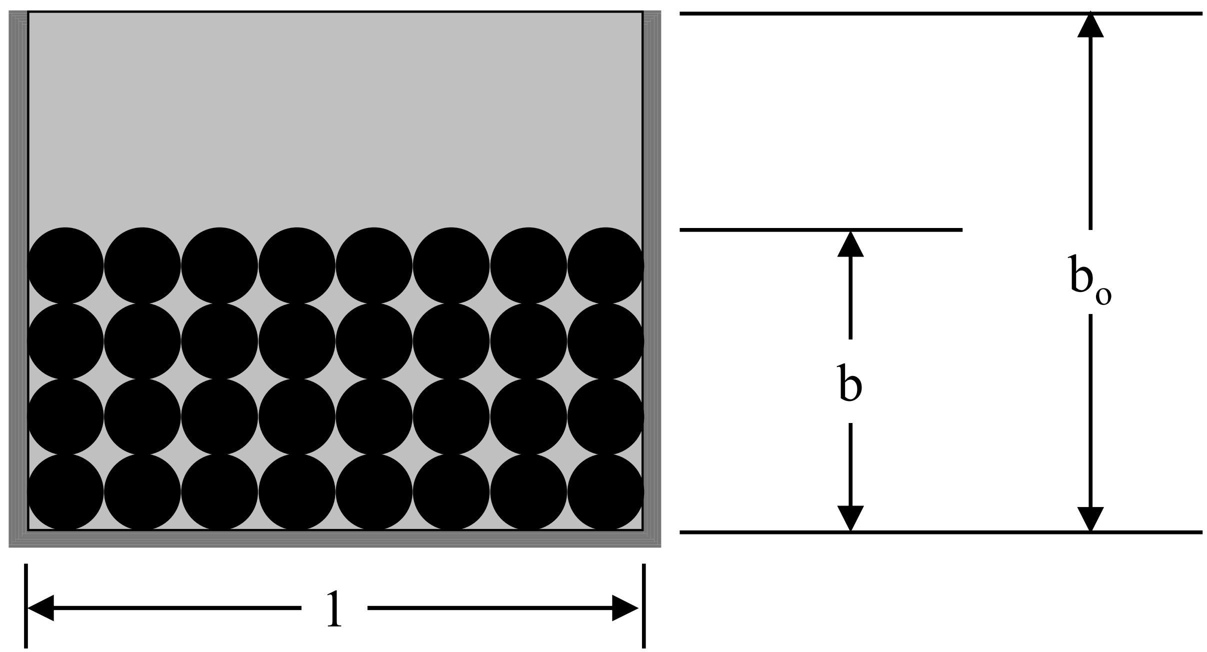
Nominal maximum size of aggregate, mm (in.)	Bulk volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate*			
	2.40	2.60	2.80	3.00
9.5 (⅜)	0.50	0.48	0.46	0.44
12.5 (½)	0.59	0.57	0.55	0.53
19 (¾)	0.66	0.64	0.62	0.60
25 (1)	0.71	0.69	0.67	0.65
37.5 (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)

What does b/b_o represent?



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

Mix Design Example

Coarse aggregate = subangular crushed stone

Nominal maximum aggregate size = 3/4"

Design strength (f'_c) = 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 (%) =	1.89	1.70
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Step 7: Estimate coarse aggregate

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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 7: Estimate coarse aggregate

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

$$W_{gravel} = V_{gravel}^{bulk}\gamma_{gravel}^{bulk} \Leftarrow \text{dry-rodded unit weight}$$

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

Step 8: Estimate fine aggregate

Estimated Weight Method

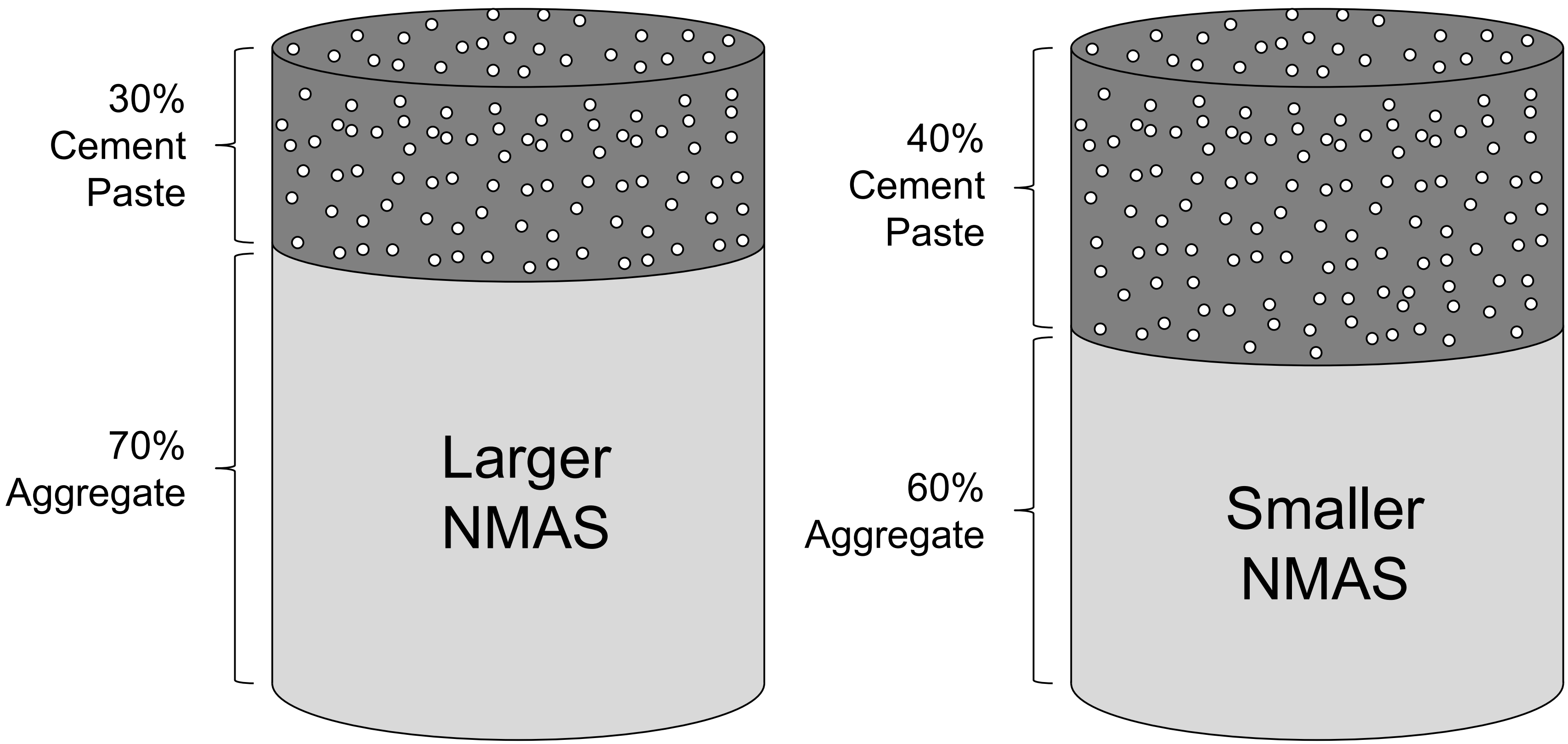
NMAS (in)	First Estimate of Concrete Unit Mass (lb/ft^3) Non-Air-Entrained Concrete	Air-Entrained Concrete
⅜	142.0	137.5
½	144.0	139.0
¾	146.5	141.5
1	148.5	143.5
1½	151.0	146.0
2	153.0	147.5
3	155.5	150.0
6	157.5	152.0

Questions to Ponder

6. Why does the unit weight 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

Effect of NMAS on Unit Weight



Effect of NMAS on Unit Weight

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

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

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

Effect of NMAS on Paste Volume

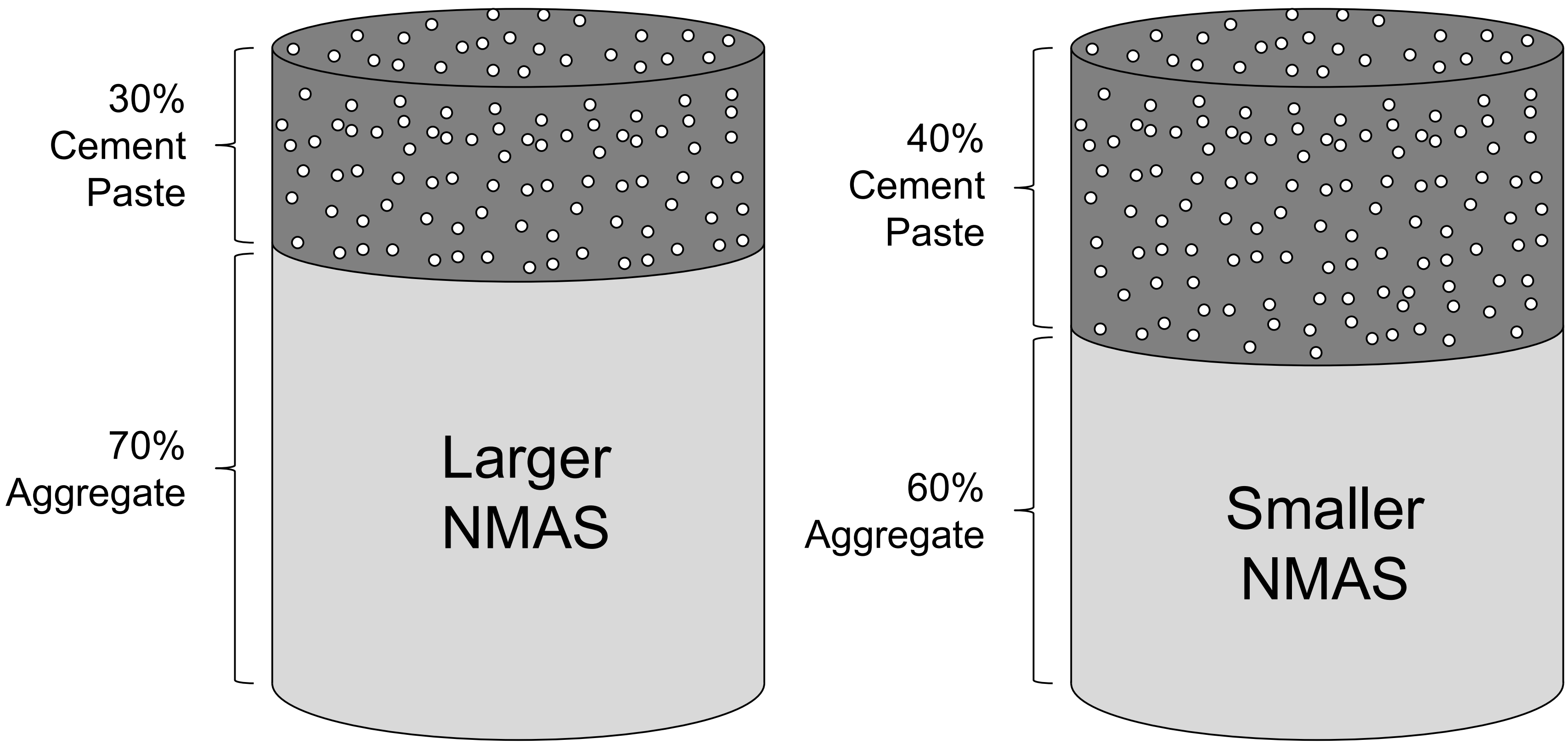
Assume w/c = 0.5

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

$$RD_{paste} = 1.83$$

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

Effect of NMAS on Unit Weight



Questions to Ponder

7. Why is the ratio of non-air-entrained density to air-entrained density a function of NMAS?

NMAS	First Estimate of Concrete Unit Mass (lb/ft^3)	
(in)	Non-Air-Entrained Concrete	Air-Entrained Concrete
⅜	142.0	137.5
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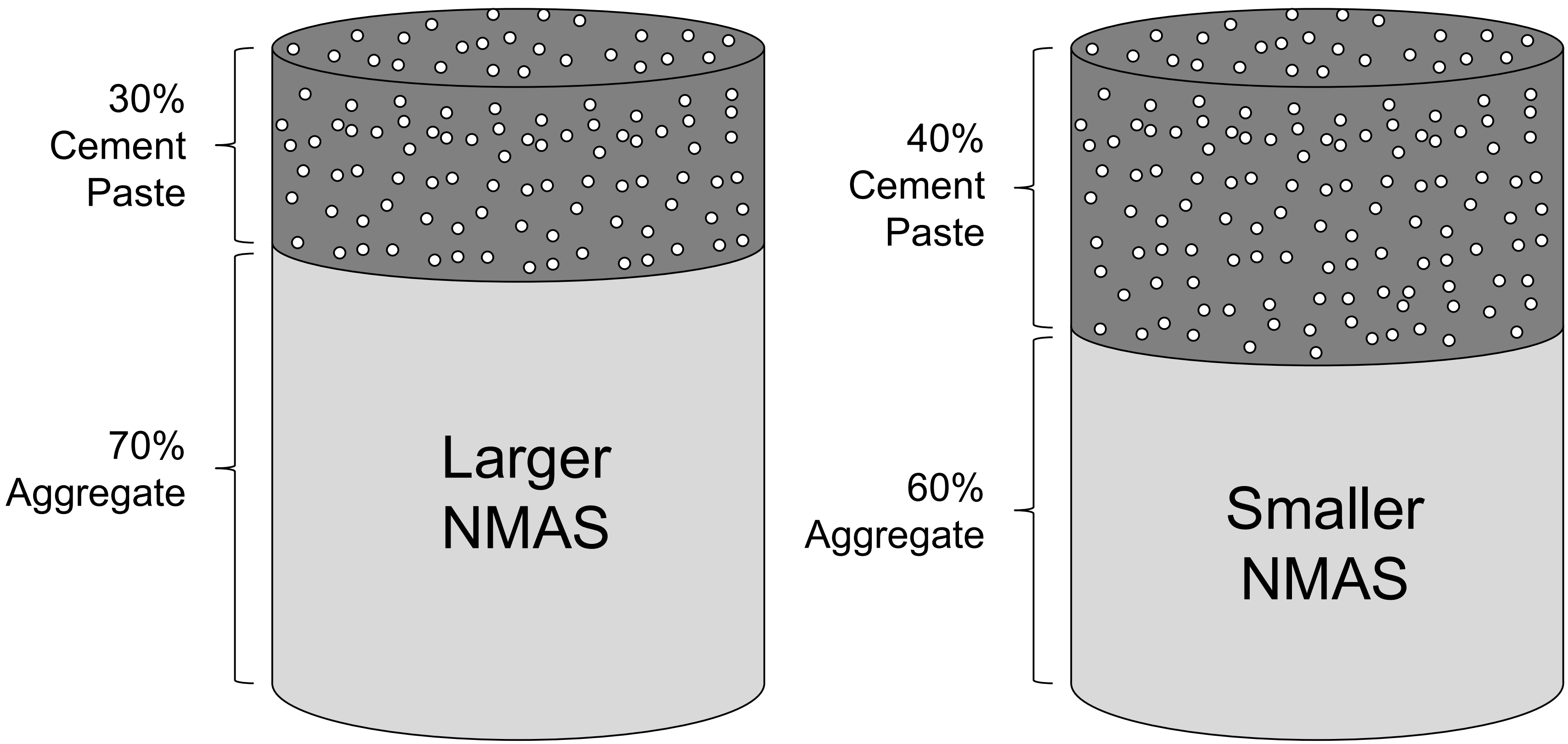
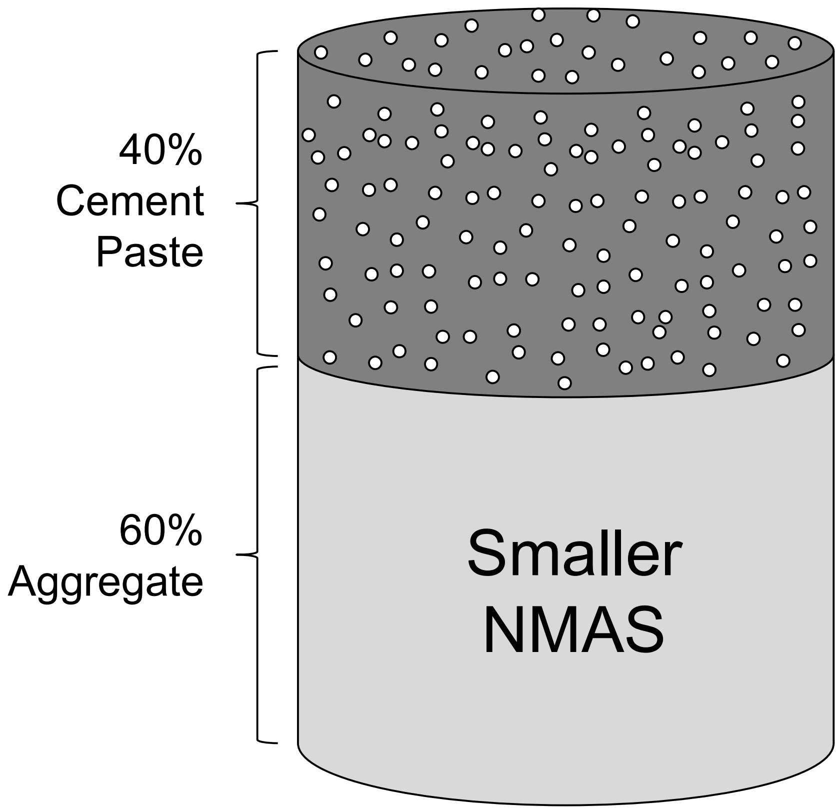
Effect of NMAS on Unit Weight



Air Content



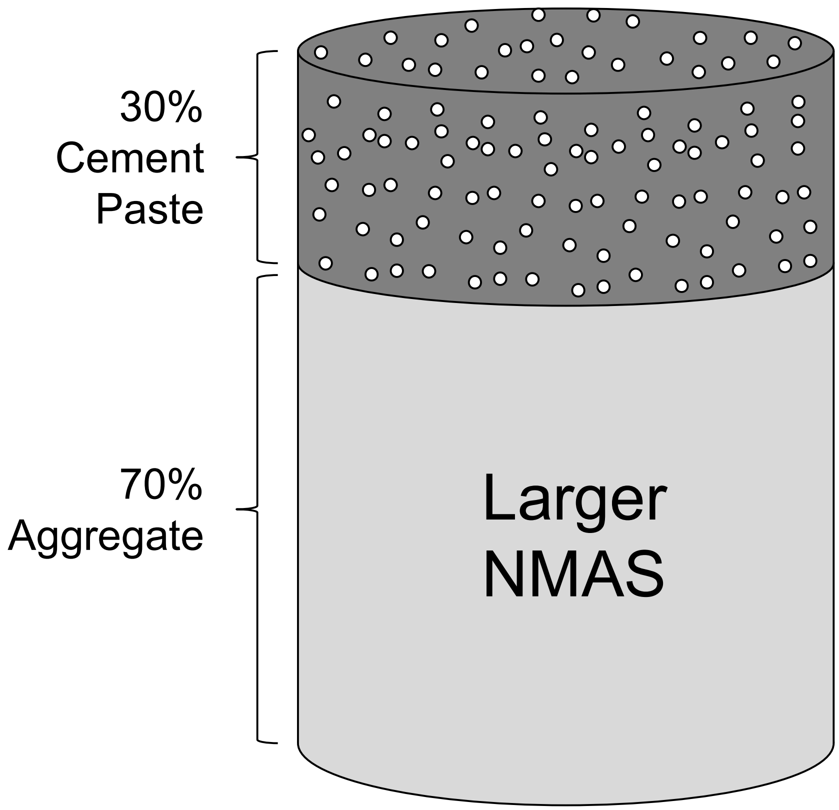
Paste Air Content

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>

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

Step 8: Estimate fine aggregate

Estimated Weight Method

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

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

Step 8: Estimate fine aggregate

Absolute Volume Method

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

$$\Downarrow$$

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

Step 8: Estimate fine aggregate

Absolute Volume Method

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

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

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

Mix Design Example

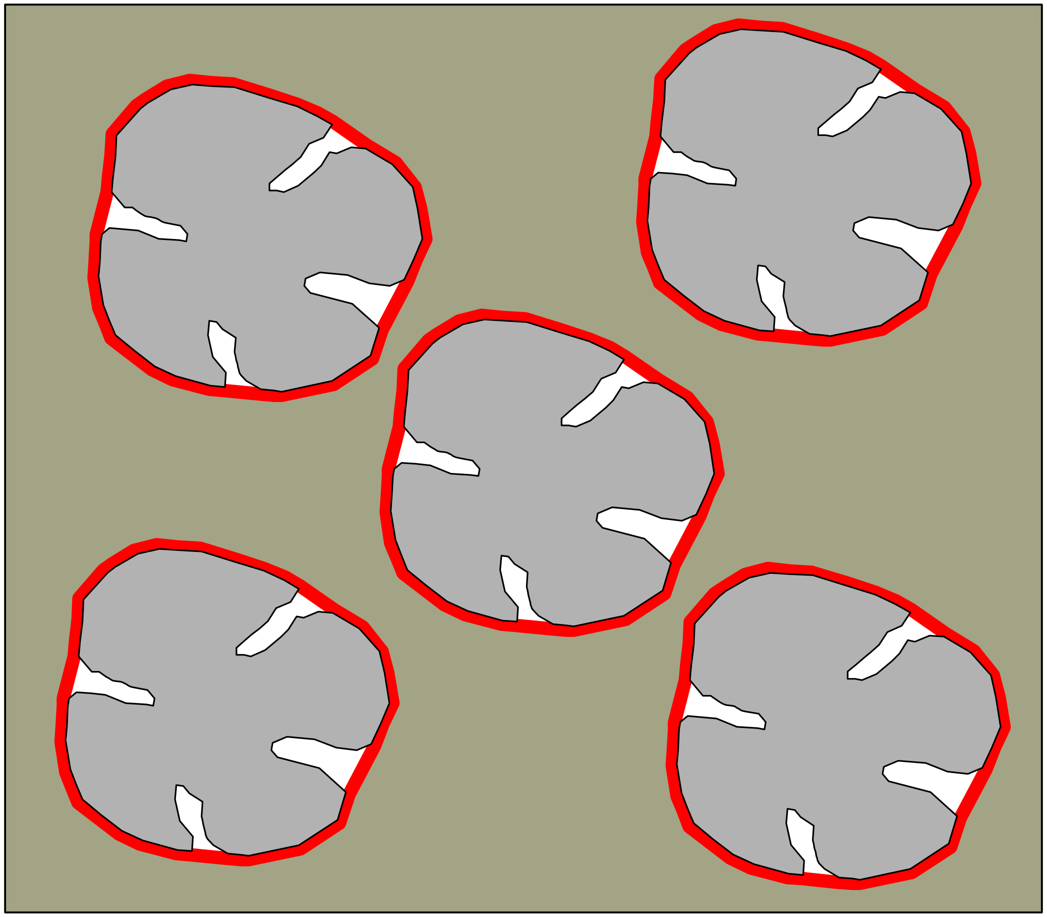
Nominal maximum aggregate size = 3/4"
Design strength (f'_c) = 4500 psi
Specified slump = 1-2"

	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 (%) =	1.89	1.70
Fineness modulus =	2.51	3.00

Step 9: Adjust for Aggregate Moisture

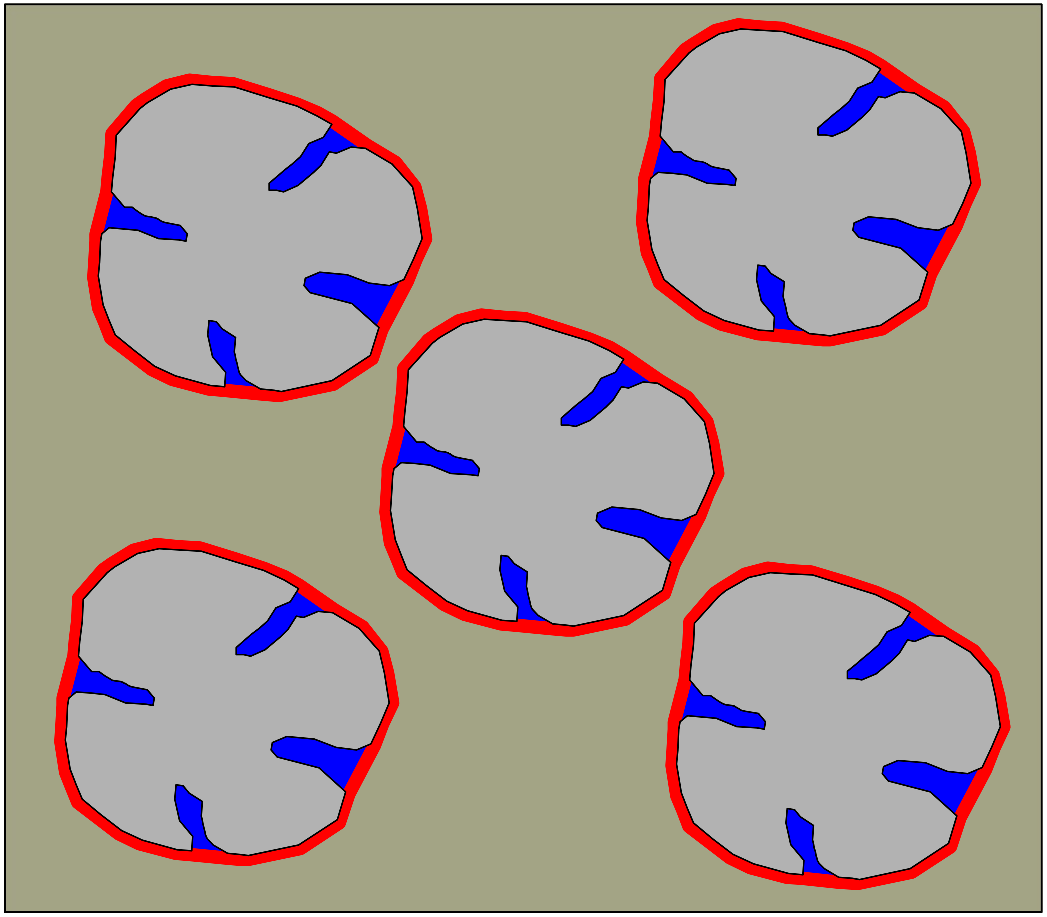
1. Increase W_{water} by an amount equal to the weight of water needed to saturate the fine and coarse aggregate.

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 water to fill those pervious pores …



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

Mix Design Example

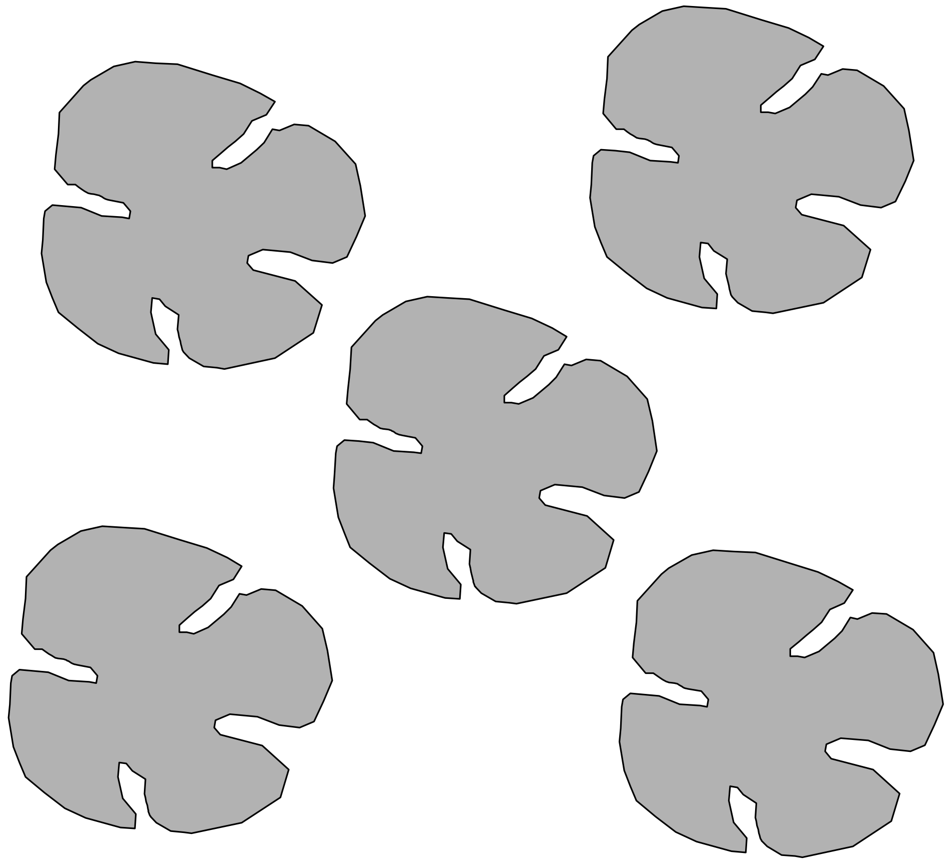
Nominal maximum aggregate size = 3/4"
Design strength (f'_c) = 4500 psi
Specified slump = 1-2"

	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 (%) =	1.89	1.70
Fineness modulus =	2.51	3.00

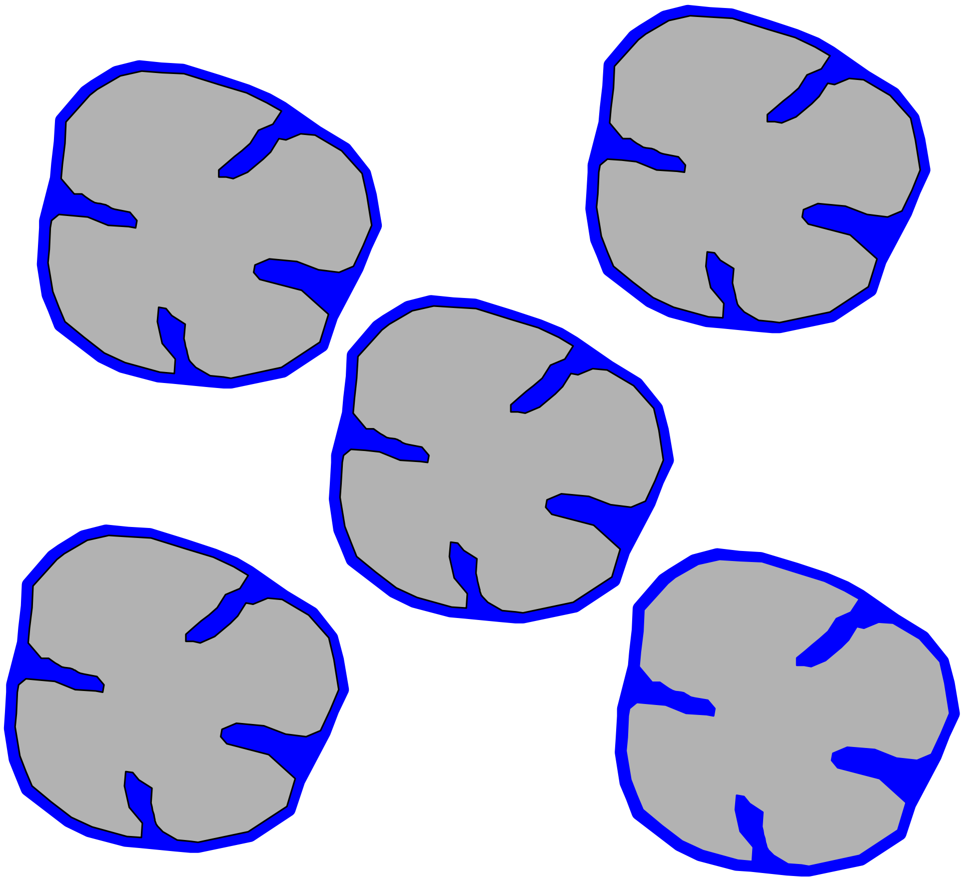
Step 9: Adjust for Aggregate Moisture

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.

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



… but the moisture content is actually 10% …



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

Mix Design Example

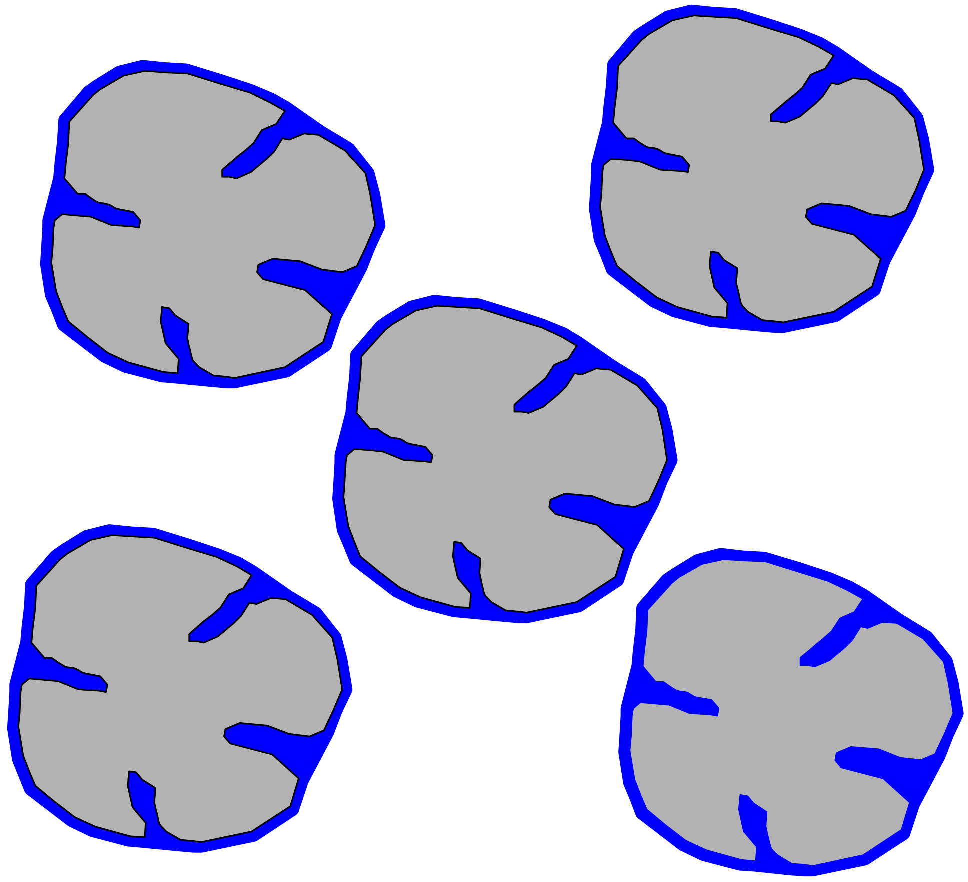
Nominal maximum aggregate size = 3/4"
Design strength (f'_c) = 4500 psi
Specified slump = 1-2"

	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 (%) =	1.89	1.70
Fineness modulus =	2.51	3.00

Step 9: Adjust for Aggregate Moisture

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 aggregate + 100 lb of water …



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