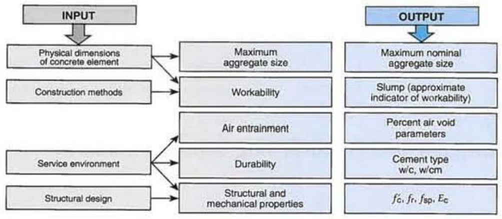
Designing Concrete Mixtures

There are three phases in the development of a concrete mixture: specifying, designing, and proportioning



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- Water/cement ratio (w/c ratio) theory states that for a given combination of materials and as long as workable consistency is obtained, the strength of concrete at a given age depends on the w/c ratio.
- The lower the w/c ratio, the higher the concrete strength.
- Whereas strength depends on the w/c ratio, economy depends on the percentage of aggregate present that would still give a workable mix.
- The aim of the designer should always be to get concrete mixtures of optimum strength at minimum cement content and acceptable workability.

Designing Concrete Mixtures

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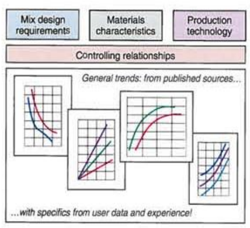

Mixture proportions	
Water	kg/m3 (lb/yd3)
Cement	kg/m3 (lb/yd3)
Fly ash	kg/m3 (lb/yd3)
Coarse aggregate	kg/m3 (lb/yd3)
Intermediate aggregate	kg/m3 (lb/yd3)
Fine aggregate	kg/m3 (lb/yd3)
Air content	%
Air-entraining admixture	ml (fl oz)
Water-reducing admixture	ml (fl oz)

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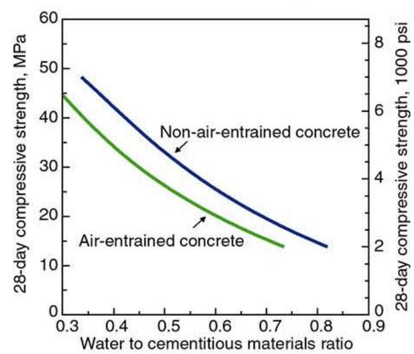

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- The most common method used in North America is that established by **ACI Recommended Practice 211.1**
- Any mix design procedure will provide a first approximation of the proportions and must be checked by trial batches.
- Local characteristics in materials should be considered.
- The following sequence of steps should be followed:
  - (1) determine the job parameters - aggregate properties, maximum aggregate size, slump, w/c ratio, admixtures,
  - (2) calculation of batch weight, and
  - (3) adjustments to batch weights based on trial mix.

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Air-Entrained Concrete

- One of the greatest advances in concrete technology was the development of air-entrained concrete in the late 1930s.
- Today, air entrainment is recommended for nearly all concretes, principally to improve resistance to freezing when exposed to water and deicing chemicals.
- Air-entrained concrete contains billions of microscopic air cells
- These relieve internal pressure on the concrete by providing tiny chambers for the expansion of water when it freezes.

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- Once the w/c ratio is established and the workability or consistency needed for the specific design is chosen, the rest should be simple manipulation with diagrams and tables based on large numbers of trial mixes.
- Such diagrams and tables allow an estimate of the required mix proportions for various conditions and permit predetermination on small unrepresentative batches.

ACI Mix Design

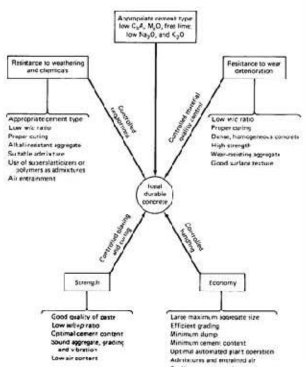
Basic Considerations

- **Workability** -- A good mix design must be capable of being placed and compacted, with minimal bleeding and segregation, and be finishable.
- Water requirements depend on the aggregate rather than the cement characteristics.
- Workability should be improved by redesigning the mortar faction rather than simply adding more water.

ACI Mix Design

The flowchart is a representation of the principal properties of "good" concrete

- cement
- w/c ratio
- aggregate
- cement paste and aggregate
- mixing
- placement and handling of fresh concrete
- curing



ACI Mix Design

Basic Considerations

- **Strength and Durability** – In general, the minimum compressive strength and a range of w/c ratios are specified for a given concrete mix.
- Possible requirements for resistance to freeze-thaw and chemical attack must be considered.
- Therefore, a balance or compromise must be made between strength and workability.

ACI Mix Design

Basic Considerations

- **Economy** -- The material costs are most important in determining the relative costs of different mixes.
- The labor and equipment costs, except for special concretes, are generally independent for the mix design.
- Since cement is more expensive than aggregate, it is clear that cement content should be minimized.
- This can be accomplished by
  1. using the lowest slump that will permit handling,
  2. using a good ratio of coarse to fine aggregate, and
  3. possible use of admixtures.

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- A measure of the degree of consistency and extent of workability is the ***slump***.
- In the slump test the plastic concrete specimen is formed into a conical metal mold as described in ASTM Standard C-143.
- The mold is lifted, leaving the concrete to "slump," that is, to spread or drop in height.

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Process of measuring the slump of fresh concrete

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- Here are some examples of different measures of slump:

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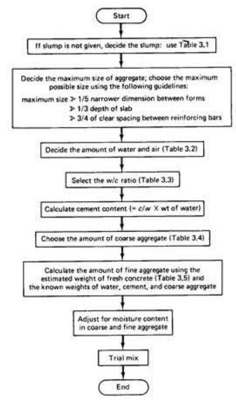
Process of measuring the slump of fresh concrete

ACI Mix Design

The flowchart is a representation of the principal properties of ACI mix design of concrete

- workability – slump
- water and air content
- w/c ratio
- cement
- coarse aggregate
- fine aggregate
- moisture adjustment
- trial mix



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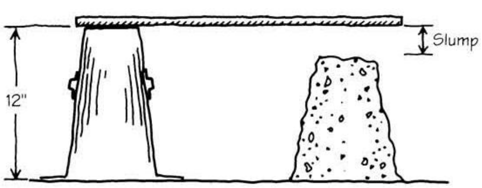
This drop in height is the slump measure of the degree of workability of the mix.



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Mix Design Procedures

1. **Required material information** -- sieve analyses of both fine and coarse aggregates, unit weight, specific gravities, and absorption capacities of aggregates.

2. **Choice of slump** -- Generally specified for a particular job. However, if not given, an appropriate value may be chosen from Table 1. As a general rule, the lowest slump that will permit adequate placement should be selected.

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Table 1. Recommended Slumps for Various Types of Construction

Concrete construction	Slump, mm (in.) Maximum*	Slump, mm (in.) 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)

ACI Mix Design

Mix Design Procedures

Approximate mixing water (lb./yd.^{3}) and air content for different slumps and nominal maximum sizes of aggregates

Non-Air-Entrained Concrete

	Maximum aggregate size (in.)							
Slump(in)	0.375	0.5	0.75	1	1.5	2	3	6
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 Content	3.0%	2.5%	2.0%	1.5%	1.0%	0.5%	0.3%	0.2%

ACI Mix Design

Mix Design Procedures

3. **Maximum aggregate size** -- The largest maximum aggregate size that will conform to the following limitations:
   - *Maximum size should not be larger than:*
     - *1/5 the minimum dimension of structural members,*
     - *1/3 the thickness of a slab, or*
     - *3/4 the clearance between reinforcing rods and forms. These restrictions limit maximum aggregate size to 1.5 inches, except in mass applications.*
   - Current thought suggests that a reduced maximum aggregate size for a given w/c ratio can achieve higher strengths. Also, in many areas, the largest available sizes are 3/4 in. to 1 in.

ACI Mix Design

Mix Design Procedures

Approximate mixing water (lb./yd.^{3}) and air content for different slumps and nominal maximum sizes of aggregates

Air-Entrained Concrete

	Maximum aggregate size (in.)							
Slump(in)	0.375	0.5	0.75	1	1.5	2	3	6
1 to 2	305	295	280	270	250	240	225	180
3 to 4	340	325	305	295	275	265	250	200
6 to 7	365	345	325	310	290	280	270	-
Air Content								
Mild	4.5%	4.0%	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%
Moderate	6.0%	5.5%	5.0%	4.5%	4.5%	4.0%	3.5%	3.0%
Extreme	7.5%	7.0%	6.0%	6.0%	5.5%	5.0%	4.5%	4.0%

ACI Mix Design

Mix Design Procedures

4. **Estimation of mixing water and air content** -- An estimation of the amount of water required for air-entrained and non-air-entrained concretes can be obtained from Table 2.

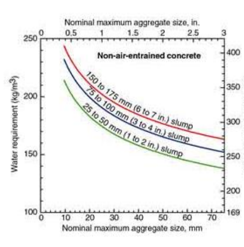
One major disadvantage of concrete is its susceptibility to damage by single or multiple freeze-thaw cycles.

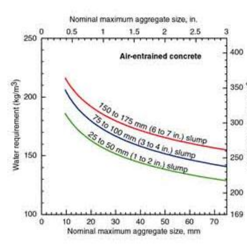
However, concrete can be made frost-resistant by using air-entraining admixtures.

Concrete is routinely air-entrained in the Northern U.S. and Canada.

ACI Mix Design

Mix Design Procedures





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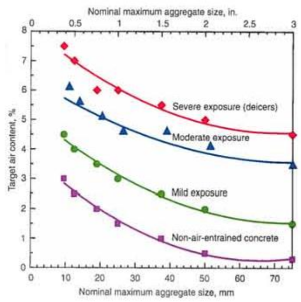
Mix Design Procedures



ACI Mix Design

Mix Design Procedures

6. **Calculation of cement content** – Once the water content and the w/c ratio is determined, the amount of cement per unit volume of the concrete is found by dividing the estimated water content by the *w/c* ratio.

$$\textit{weight of cement} = \frac{\textit{weight of water}}{w/c}$$

However, a minimum cement content is required to ensure good finishability, workability, and strength.

ACI Mix Design

Mix Design Procedures

5. **Water/cement ratio** - This component is governed by strength and durability requirements

   (a) Strength -- Without strength vs. w/c ratio data for a certain material, a conservative estimate can be made for the accepted 28-day compressive strength from Table 3.

   (b) Durability -- If there are severe exposure conditions, such as freezing and thawing, exposure to seawater, or sulfates, the w/c ratio requirements may have to be adjusted.

ACI Mix Design

Mix Design Procedures

7. **Estimation of coarse aggregate content** - The percent of coarse aggregate to concrete for a given maximum size and fineness modulus is given by Table 4.

   The value from the table multiplied by the dry-rodded unit weight (the oven-dry (OD) weight of coarse aggregate required per cubic foot of concrete).

   To convert from OD to saturated surface dry (SSD) weights, multiply by [1 + absorption capacity (AC)].

ACI Mix Design

Mix Design Procedures

Relationship between water/cement ratio and compressive strength of concrete

28-day Compressive Strength (psi)	Non-AE	AE
2,000	**0.82**	**0.74**
3,000	**0.68**	**0.59**
4,000	**0.57**	**0.48**
5,000	**0.48**	**0.40**
6,000	**0.41**	**0.32**
7,000	**0.33**	**---**

ACI Mix Design

Mix Design Procedures

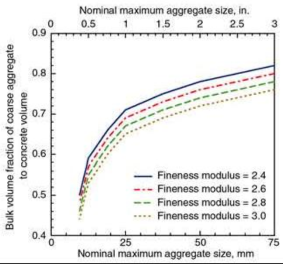
Volume of dry-rodded coarse aggregate per unit volume of concrete for different coarse aggregates and fineness moduli of fine aggregates

	Fineness Modulus						
Max Aggregate (in.)	2.4	2.5	2.6	2.7	2.8	2.9	3
0.375	**0.50**	**0.49**	**0.48**	**0.47**	**0.46**	**0.45**	**0.44**
0.500	**0.59**	**0.58**	**0.57**	**0.56**	**0.55**	**0.54**	**0.53**
0.750	**0.66**	**0.65**	**0.64**	**0.63**	**0.62**	**0.61**	**0.60**
1.000	**0.71**	**0.70**	**0.69**	**0.68**	**0.67**	**0.66**	**0.65**
1.500	**0.75**	**0.74**	**0.73**	**0.72**	**0.71**	**0.70**	**0.69**
2.000	**0.78**	**0.77**	**0.76**	**0.75**	**0.74**	**0.73**	**0.72**
3.000	**0.82**	**0.81**	**0.80**	**0.79**	**0.78**	**0.77**	**0.76**
6.000	**0.87**	**0.86**	**0.85**	**0.84**	**0.83**	**0.82**	**0.81**

ACI Mix Design

Mix Design Procedures

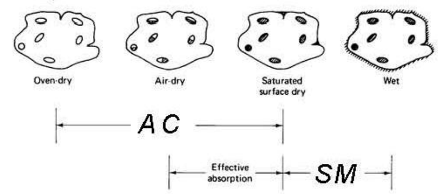
Volume of dry-rodded coarse aggregate per unit volume of concrete for different coarse aggregates and fineness moduli of fine aggregates



ACI Mix Design

Mix Design Procedures

9. **Adjustment for moisture in the aggregate** -- The water content of the concrete will be affected by the moisture content of the aggregate.



ACI Mix Design

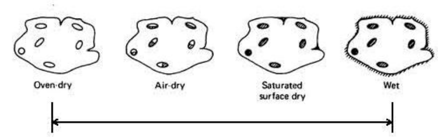
Mix Design Procedures

8. **Estimation of fine aggregate content** -- There are two standard methods to establish the fine aggregate content, the mass method and the volume method. We will use the "volume" method.
   - "Volume" Method -- This method is the preferred method, as it is a somewhat more exact procedure
   - The volume of fine aggregates is found by subtracting the volume of cement, water, air, and coarse aggregate from the total concrete volume.

ACI Mix Design

Mix Design Procedures

9. **Adjustment for moisture in the aggregate** -- The water content of the concrete will be affected by the moisture content of the aggregate.

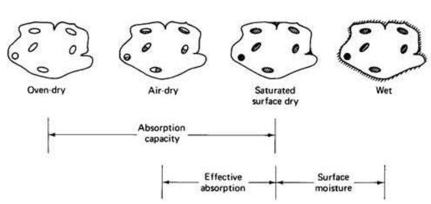


Moisture content $(MC) = AC + SM$

ACI Mix Design

Mix Design Procedures

9. **Adjustment for moisture in the aggregate** – The water content of the concrete will be affected by the moisture content of the aggregate.



ACI Mix Design

Mix Design Procedures

10. **Trial batch** – Using the proportions developed in the preceding steps, mix a trial batch of concrete using only as much water as is needed to reach the desired slump (but not exceeding the permissible w/c ratio).

ACI Mix Design

Mix Design Procedures

10. **Trial batch**

The fresh concrete should be tested for slump, unit weight, yield, air content, and its tendencies to segregate, bleed, and finishing characteristics. Also, hardened samples should be tested for compressive and flexural strength.

ACI Mix Design Example

- Concrete is required for an exterior column located above ground where substantial freezing and thawing may occur. The 28-day compressive strength should be 5,000 lb./in^2. The slump should be between 1 and 2 in. and the maximum aggregate size should not exceed ¾ in.
- The properties of the materials are as follows:
  - Cement : Type I, specific gravity = 3.15
  - Coarse Aggregate: Bulk specific gravity (SSD) = 2.70; absorption capacity = 1%; dry-rodded unit weight = 100 lb./ft.^{3}; surface moisture = 0%
  - Fine Aggregate: Bulk specific gravity (SSD) = 2.65; absorption capacity = 1.3%; fineness modulus = 2.70; surface moisture = 3%

ACI Mix Design Example

- **Step 1**. Required material information (already given).
- **Step 2**. Choice of slump. The slump is given, consistent with Table 1.

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)

- **Step 3**. Maximum aggregate size. Given: ¾ inches

ACI Mix Design Example

- **Step 4**. Estimation of mixing water and air content. Since freezing and thawing is important, the concrete must be air-entrained. From Table 2, the recommended air content is 6%; the water requirement is 280 lb./yd.^{3}.

	Maximum aggregate size (in.)							
Slump(in)	0.375	0.5	0.75	1	1.5	2	3	6
1 to 2	305	295	280	270	250	240	225	180
3 to 4	340	325	305	295	275	265	250	200
6 to 7	365	345	325	310	290	280	270	-
Air Content								
Mild	4.5%	4.0%	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%
Moderate	6.0%	5.5%	5.0%	4.5%	4.5%	4.0%	3.5%	3.0%
Extreme	7.5%	7.0%	6.0%	6.0%	5.5%	5.0%	4.5%	4.0%

ACI Mix Design Example

- **Step 5**. Water/cement ratio. From Table3, the estimate for required w/c ratio to give a 28-day strength of 5,000 psi.

28-day Compressive Strength (psi)	Non-AE	AE
2,000	0.82	0.74
3,000	0.68	0.59
4,000	0.57	0.48
5,000	0.48	0.40
6,000	0.41	0.32
7,000	0.33	---

ACI Mix Design Example

- **Step 6**. Calculation of cement content. Based on steps 4 and 5, the required cement content is:

$$weight\ of\ cement = \frac{280\ ^{lb}/_{yd.^3}}{0.4} = 700\ ^{lb}/_{yd.^3}$$

ACI Mix Design Example

- **Step 7**. Estimation of coarse aggregate content. Interpolating Table 4 for the fineness modulus of the fine aggregate of 2.70

Max Aggregate (in.)	Fineness Modulus 2.4	2.5	2.6	2.7	2.8	2.9	3
0.375	0.50	0.49	0.48	0.47	0.46	0.45	0.44
0.500	0.59	0.58	0.57	0.56	0.55	0.54	0.53
0.750	0.66	0.65	0.64	0.63	0.62	0.61	0.60
1.000	0.71	0.70	0.69	0.68	0.67	0.66	0.65
1.500	0.75	0.74	0.73	0.72	0.71	0.70	0.69
2.000	0.78	0.77	0.76	0.75	0.74	0.73	0.72
3.000	0.82	0.81	0.80	0.79	0.78	0.77	0.76
6.000	0.87	0.86	0.85	0.84	0.83	0.82	0.81

ACI Mix Design Example

- **Step 8**. Estimation of fine aggregate content by the absolute volume method.
  - Water: 280 lb./62.4 lb./ft.^{3} = 4.49 ft.^{3}
  - Cement: 700 lb./(3.15 x 62.4 lb./ft.^{3}) = 3.56 ft.^{3}
  - Coarse Aggregate: 1,701 lb./(2.70 x 62.4 lb./ft.^{3}) = 10.10 ft.^{3}
  - Air: 6% x 27ft.^{3}/yd.^{3} = 1.62 ft.^{3}

Total **19.77 ft.^{3}**

ACI Mix Design Example

- The coarse aggregate will occupy:

$$0.63 \times 27\,\mathrm{ft.}^3/\mathrm{yd.}^3 = 17.01\,\mathrm{ft.}^3/\mathrm{yd.}^3$$

Value from Table 4

- The OD weight of the coarse aggregate

$$17.01\,\mathrm{ft.}^3/\mathrm{yd.}^3 \times 100\,\mathrm{lb.}/\mathrm{ft.}^3 = 1{,}701\,\mathrm{lb.}/\mathrm{yd.}^3$$

Dry-Rodded Unit Weight

ACI Mix Design Example

- Therefore, the fine aggregate must occupy a volume of:

$$27\,\mathrm{ft.}^3 - 19.77\,\mathrm{ft.}^3 = 7.23\,\mathrm{ft.}^3$$

- The OD weight of the fine aggregate is:

$$7.23\,\mathrm{ft.}^3 \times 2.65 \times 62.4\,\mathrm{lb.}/\mathrm{ft.}^3 = 1{,}196\,\mathrm{lb.}$$

Specific Gravity of Fine Aggregate

Unit Weight of Water

ACI Mix Design Example

- **Step 8**. Estimation of fine aggregate content by the absolute volume method.

Temperature, °F	Density, lb./ft.^{3}
60	62.368
65	62.337
70	62.302
75	62.261
80	62.216
85	62.166

ACI Mix Design Example

- **Step 9**. Adjustment for moisture in the aggregate.
- Since the moisture level of the fine aggregate in our storage bins can vary, we will apply a simple rule to adjust the water required.
- Decrease the amount of water required by surface moisture content of the weight of the fine aggregate
- Increase the amount of aggregate by the amount equal to the surface moisture

ACI Mix Design Example

- **Step 9**. Adjustment for moisture in the aggregate.

The weight of aggregate from the stock pile is:

$$Weight_{Stock\ Pile} = Weight_{OD}(1 + MC)$$

The change in the weight water due to the moisture of the aggregate from the stock pile is:

$$\Delta Weight_{Water} = Weight_{OD}(SM)$$

$$Adjusted\ Weight_{Water} = Weight_{Water} - \Delta Weight_{Water}$$

ACI Mix Design Example

- Thus the estimated batch weights per yd.^{3} are:

Water	= 244 lb.
Cement	= 700 lb.
Coarse aggregate	= 1,718 lb.
Fine aggregate (wet)	= 1,247 lb.
Total	**= 3,909 lb./yd.^{3}**
	= 144.8 lb./ft.^{3}

ACI Mix Design Example

- **Step 9**. Compute stockpile weight based on moisture content
- Fine aggregate required from the stockpile is:

1,196 lb. (1 + 0.043) = 1,247.4 lb./yd.^{3} or 1,247 lb./yd.^{3}

Moisture Content 4.3%

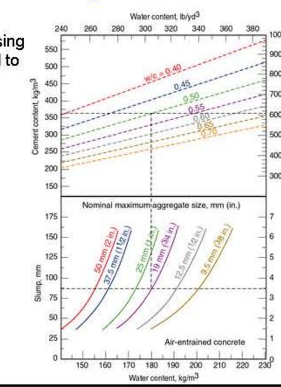
Moisture Content 1%

- Coarse aggregate required from the stockpile is:

1,701 lb. (1 + 0.01) = 1,718 lb./yd.^{3}

ACI Mix Design

- Information for concrete mixtures using particular ingredients can be plotted to illustrate the relationship between ingredients and properties:
  - Slump
  - Aggregate Size
  - w/c
  - Cement content



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- **Step 9**. Adjust the amount of water based on moisture content

The required mixing water required is:

280 lb. - 1196 lb. (0.043 – 0.013) ← fine aggregate

Moisture Content 4.3%

Absorption Capacity 1.3%

- 1,718 lb. (0.01 – 0.01) ← coarse aggregate

= 244.1 lb./yd.^{3} or 244 lb./yd.^{3}

End of ACI Mix Design

Questions?