A Review of ACI 301 Section 4, Concrete Mixtures

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ACI 301 Section 4 Covers Concrete Mixtures and Provides Guidance for the Following:

- **General**
  - Scope
  - Submittals
  - Quality Control
- **Products**
  - Materials
    - Performance and design requirements
      - Cementitious content
      - Slump
      - Size of Coarse Aggregate
      - Air content
      - Temperature
      - Resistance to ASR
    - Durability
      - Sulfate resistance
      - Freeze-thaw resistance
      - Low permiability
      - Corrosion protection of reinforcement
      - Strength and w/cm
      - Steel fiber-reinforced concrete
    - Proportioning
      - Standard Deviation
      - Required average strength
      - Documentation of average compressive strength
      - Field records
      - Trial mixtures

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Section 4.1.2 Submittals

- Mixture proportions
- Mixture strength data used for required average strength
- Concrete materials
  - Cementitious materials – manufacturer, types, shipping locations, mill certificates
  - Aggregate – manufacturer, quarry locations, statements of compliance
  - Admixtures – names, types, data sheets, certificates
  - Water –source, if non-potable documentation on effects on strength and set time
- Field test records
- Trial mixture records
- Durability – document mixtures meet requirements
- Resistance to ASR – document mixtures meet requirements
- Mixture proportioning adjustments – document if changes requested
- Concrete for floors – Table 4.1.2.9 minimum cementitious content
- Calcium chloride –request to use
- Volumetric batching – must request to use
- Limits on discharge – request if will exceed mixer revolution limits

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Section 4.1.3 Quality Control

ACI 301 provides very broad guidelines for Quality Control

- Maintain records documenting each material used
- Ensure that production and delivery conforms to measuring, batching, mixing, and delivery specifications
- Ensure concrete has the specified characteristics in freshly mixed state at delivery

4.1.4 Material Storage and Handling

- Cementitious materials
  - Keep dry and free from contaminants
- Aggregates
  - Store and handle to keep separate and avoid segregation, and allow for drainage.
- Water and ice
  - Protect from contamination
- Admixtures
  - Protect against contamination, evaporation, or damage. Provide agitation for suspensions or unstable solutions. Protect from freezing.

Section 4.2 Products

- *Section 4.2.1Materials*
  - Cementitious content
    - Portland - ASTM C150,
    - Blended hydraulic cement - ASTM C595 (excludes Type IS >70%)
    - Hydraulic cement - ASTM C1157 (performance cement)
    - Pozzolans - ASTM C618
    - Silica fume - ASTM C989
    - Use same cementitious materials in production as in field records or trial batches
  - Aggregates
    - Conform to ASTM C33
  - Admixtures
    - Air-entraining - ASTM C260
    - Water reducers - ASTM C494
    - Flowing concrete - ASTM C1017
    - Calcium chloride - ASTM D98

Section 4.2.2 Performance and Design Requirements

- Cementitious content
  - Adequate to satisfy strength, w/cm, durability, and finishability. Floors comply with Table 4.1.2.9

TABLE 4.2.2.1 — Minimum cementitious material content requirement for floors	
Nominal maximum size of aggregate, in.	Minimum cementitious material content
1-1/2"	470
1"	520
3/4"	540
3/8"	610

- Slump
  - Select slump at point of delivery, not to exceed 9 inches, or flow of 30 inches. Concrete shall not show signs visible signs of segregation
- Size of Coarse Aggregate
  - Unless otherwise specified, nominal size shall not exceed ¾ of minimum reinforcement spacing.

Section 4.2.2 Performance and Design Requirements

- Air content
  - Shall be entrained for Exposure Class F1, F2, F3.
  - Concrete for hard troweled slabs shall not exceed 3.0% total air.

- Temperature
  - Minimum – If 3 day average less than 40 degrees, concrete 40 to 55 degrees depending on concrete dimensions.
  - Maximum – Unless otherwise specified, 95 degrees.

- Resistance to ASR – 3 methods (Unless exposure class C0)
  - Test aggregates in accordance with ASTM C1293, one year test
  - *Test aggregates with cementitious material in accordance with ASTM C1567, maximum expansion of 0.1% at 16 days.*
  - Limits based on total alkali

4.2.2.7 Durability

ACI 301 references exposure classes for the following:

Exposure Class F - Freeze and thawing
Exposure Class S - Sulfate exposure
Exposure Class W - Concrete exposed to water requiring low permiability
Exposure Class C - Corrosion protection of reinforcement

The exposure classes are described in ACI 318

Exposure Class F – Freezing and thawing

Exposure Category F (Freezing and thawing exposure) is subdivided into four exposure classes:

Exposure Class	Concrete exposure characteristics
F0	Not exposed to cycles of freezing and thawing.
F1	Exposed to cycles of freezing and thawing and that will have limited exposure to water. Limited exposure to water implies some contact with water and water absorption; however, it is not anticipated that the concrete will absorb sufficient water to become saturated. The licensed design professional should review the exposure conditions carefully to support the decision that the concrete is not anticipated to become saturated before freezing. Even though concrete in this exposure class is not expected to become saturated, a minimum entrained air content of 3.5 to 6 percent is required to reduce the potential for damage in case portions of the concrete member become saturated.
F2	Exposed to cycles of freezing and thawing and that will have frequent exposure to water. Frequent exposure to water implies that some portions of the concrete will absorb sufficient water such that over time they will have the potential to be saturated before freezing. If there is doubt about whether to assign Exposure Classes F1 or F2 to a member, the more conservative choice, F2, should be selected. Exposure Classes F1 and F2 are conditions where exposure to deicing chemicals is not anticipated.
F3	Exposed to cycles of freezing and thawing with the same degree of exposure to water as Exposure Class F2. Additionally, concrete in Exposure Class F3 is anticipated to be exposed to deicing chemicals. Deicing chemicals can increase water absorption and retention (Spragg et al. 2011), which would enable the concrete to become saturated more readily.

Exposure Class F – Freezing and thawing

TABLE 4.2.2.7.b — For Exposure Category F: freezing and thawing exposure				
Exposure class	Maximum *w/cm*	Minimum f'_c, psi	Air Content	Additional requirements
F0	NA	NA	NA	NA
F1	0.45	4500	TABLE 4.2.2.7.b.1	NA
F2	0.45	4500	TABLE 4.2.2.7.b.1	NA
F3	0.45	4500	TABLE 4.2.2.7.b.1	TABLE 4.2.2.7.b.2

TABLE 4.2.2.1.b.1 — Total air content for concrete exposed to cycles of freezing and thawing		
Nominal maximum size of aggregate, in.	Air Content Exposure Class F2 and F3	Air Content Exposure Class F1
3/8"	7.5	6.0
1/2"	7.0	5.5
3/4"	6.0	5.0
1"	6.0	4.5
1-1/2"	5.5	4.5

Exposure Class S – Sulfate exposure

Exposure Category S (sulfate exposure) is subdivided into four exposure classes:

Exposure Class	Concrete exposure characteristics
S0	Conditions where the water-soluble sulfate concentration in contact with concrete is low and injurious sulfate attack is not a concern.
S1 **S2** **S3**	Structural concrete members in direct contact with soluble sulfates in soil or water. Seawater exposure is classified as Exposure Class S1. The severity of exposure increases from Exposure Class S1 to S3 based on the more critical value of measured water-soluble sulfate concentration in soil or the concentration of dissolved sulfate in water.

TABLE 4.2.2.7.a — For Exposure Category S: sulfate exposure			**Required cementitious materials* - types**			Additional Requirements
Exposure class	Maximum *w/cm*	Minimum f'_c, psi	ASTM C150	ASTM C595	ASTM C1157	
S0	NA	NA	NA	NA	NA	NA
S1	0.50	4000	II	IP(MS), IS(<70)(MS)	MS	NA
S2	0.45	4500	V	IP(HS), IS(<70)(HS)	HS	No calcium chloride admixtures
S3	0.45	4500	V + pozzolan or slag cement	IP(HS)+ pozzolan or slag cement, or IS(<70)(HS)+ pozzolan or slag cement	HS + pozzolan or slag cement	No calcium chloride admixtures

Exposure Class W – Concrete in contact with water requiring low permiability

Exposure Category W (in contact with water requiring low-permeability concrete) is subdivided into two exposure classes:

Exposure Class	Concrete exposure characteristics
W0	Members are dry in service or in contact with water, but there are no specific requirements for low permeability.
W1	If there is need for concrete with low permeability to water and the penetration of water into concrete might reduce the durability of the member. An example is a foundation wall below the water table.

TABLE 4.2.2.7.c — For Exposure Category W: In contact with water requiring low-permeability concrete

Exposure class	Maximum *w/cm*	Minimum f'_c, psi	Additional minimum requirements
W0	NA	NA	NA
W1	0.50	4000	NA

Exposure Class C – Corrosion protection of reinforcement

Exposure Category C (conditions requiring corrosion protection of reinforcement) is subdivided into three exposure classes:

Exposure Class	Concrete exposure characteristics
C0	Exposure conditions do not require additional protection against the initiation of corrosion of reinforcement.
C1	Non-prestressed and prestressed concrete members, depending on the degree of exposure to external sources of moisture and chlorides in service. Examples of exposures to external sources of chlorides include concrete in direct contact with deicing chemicals, salt, salt water, brackish water, seawater, or spray from these sources.
C2	

TABLE 4.2.2.7.d — For Exposure Category C: Conditions requiring corrosion protection of reinforcement

Exposure class	Maximum *w/cm*	Minimum f'_c, psi	Maximum water-soluble chloride ion (Cl^-) content in concrete by weight of cement
C0	NA	NA	1.00
C1	NA	NA	0.30
C2	0.40	5000	0.15

ACI 301 Section 4.2.3 – Proportioning

Definitions

- f'_c – Design compressive strength
- f'_{cr} – Required average compressive strength ($f'c$ + overdesign)
- S_s – Standard deviation

ACI 301 Section 4.2.3 – Proportioning

There are two paths for mixture designs:

1) Field data is available
2) No field data, run trial mixtures

ACI 301 Section 4.2.3 – Proportioning

Field Data Method

1. Step one for the field data method is determining a ***standard deviation***

ACI 301 Section 4.2.3.2 – Standard Deviation

Standard deviation - a quantity calculated to indicate the extent of deviation for a group as a whole.

Field testing data may be used to determine a standard deviation (Ss). The standard deviation is for the *producing plant*, not the mixture.

ACI 301 Section 4.2.3.2 – Standard Deviation

Ss Data Requirements

a) Data no more than 24 months old
b) Data spans no less than 45 day
c) Mixture design used for data must be of same class of concrete and within 1000 psi of proposed mixtures

ACI 301 Section 4.2.3.2 – Standard Deviation

A Ss may be determined by using 30 or more consecutive test records. As few as 15 may be used, however, there is a k-factor applied which increases the standard deviation.

Table 4.2.3.3.a.1 - k-factor for increasing sample standard deviation for number of tests considered

Total number of tests considered	k-factor for increasing sample standard deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Example: Field test data with 18 records has standard deviation of 500. K-factor 1.16 is used.

500 x 1.16 = 580 psi is adjusted Ss

ACI 301 Section 4.2.3.2 – Standard Deviation

The Ss may also be determined using two groups of consecutive test records that total at least 30 compressive strength tests. Neither of the two sets of records may have less than 10 test records. No k-factor applied if the total of two records is 30 or more.

ACI 301 Section 4.2.3.2 – Standard Deviation

How is a Sc calculated?

For a single set of records

$$s_s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{(n-1)}}$$

For two sets of records

$$s_s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 + n_2 - 2)}}$$

EXCEL has build in functions for determining standard deviations

Concrete Statistical Analysis Report

Example Standard Deviation Spreadsheet

Producer : XXX Ready Mix

Report Date 9/20/2018

Design Strength : 4000 psi

Mix Design # : 2045

TEST #	DATE	CONTRACTOR	PROJECT	SET #	SLUMP	%AIR	7 DAY	28 DAY	28 DAY	28 DAY (avg)
1	01/05/18	ABC Inc.	XZY Building	1001	4.0	4.0	3680	4600	4675	4638
2	01/06/18	ABC Inc.	XZY Building	1002	4.5	5.0	3560	4450	4520	4485
3	01/07/18	ABC Inc.	XZY Building	1003	4.0	4.0	3490	4365	4430	4398
4	01/08/18	ABC Inc.	XZY Building	1004	5.0	5.0	3320	4150	4215	4183
5	01/09/18	ABC Inc.	XZY Building	1005	5.0	6.0	3290	4850	5280	5065
6	01/10/18	ABC Inc.	XZY Building	1006	4.0	4.0	3550	4440	4510	4475
7	01/11/18	ABC Inc.	XZY Building	1007	5.0	5.0	3780	4725	4800	4763
8	01/12/18	ABC Inc.	XZY Building	1008	4.0	4.0	3190	3990	4050	4020
9	01/13/18	ABC Inc.	XZY Building	1009	4.0	5.0	3690	4615	4685	4650
10	01/14/18	ABC Inc.	XZY Building	1010	4.5	5.5	3540	4425	4495	4460
11	01/15/18	ABC Inc.	XZY Building	1011	4.8	4.5	3350	4190	4255	4222
12	01/16/18	ABC Inc.	XZY Building	1012	3.5	4.3	3325	4155	4225	4190
13	01/17/18	ABC Inc.	XZY Building	1013	5.0	4.3	3750	4690	4765	4728
14	01/18/18	ABC Inc.	XZY Building	1014	4.0	5.4	3190	3750	3590	3670
15	01/25/18	ABC Inc.	XZY Building	1015	6.0	3.9	3450	4315	4380	4348
16	01/26/18	ABC Inc.	XZY Building	1016	4.5	4.0	2980	3725	3785	3755
17	01/27/18	ABC Inc.	XZY Building	1017	5.0	5.5	3780	5380	5420	5400
18	01/28/18	ABC Inc.	XZY Building	1018	5.0	5.0	3520	4400	4470	4435
19	02/07/08	ABC Inc.	XZY Building	1019	4.0	4.0	3450	4315	4380	4348
20	02/08/08	ABC Inc.	XZY Building	1020	4.0	5.0	3290	4115	4180	4148
21	02/09/08	ABC Inc.	XZY Building	1021	5.0	6.0	3245	4055	4120	4088
22	02/10/08	ABC Inc.	XZY Building	1022	5.5	4.5	3650	4900	4950	4925
23	02/18/18	ABC Inc.	XZY Building	1023	4.6	5.5	3420	4275	4345	4310
24	02/19/18	ABC Inc.	XZY Building	1024	4.8	4.4	3940	4925	5005	4965
25	02/20/18	ABC Inc.	XZY Building	1025	4.0	5.0	3720	4650	4725	4688
26	02/21/18	ABC Inc.	XZY Building	1026	4.0	4.0	3240	4050	4115	4082
27	03/02/18	ABC Inc.	XZY Building	1027	5.0	5.0	3350	4188	4255	4221
28	03/03/18	ABC Inc.	XZY Building	1028	5.0	4.0	3240	4190	4115	4152
29	03/04/18	ABC Inc.	XZY Building	1029	4.0	4.8	3120	3600	3650	3625
30	03/05/18	ABC Inc.	XZY Building	1030	3.5	6.0	3325	4144	4225	4185
			AVERAGES		4.5	4.8	3448			4387
			STANDARD DEVIATION		0.6	0.7	229			404

30 records, spanning 60 day period.
Ss = 404 psi

What is a Good Standard Deviation? ACI 214

Table 3.2-Standards of quality control

Overall variation					
Class of operation	Standard deviation for different control standards (psi)				
	Excellent	Very Good	Good	Fair	Poor
General construction testing	Below 400	400-500	500-600	600-700	Above 700
Laboratory trial batches	Below 200	200-250	250-300	300-350	Above 350

ACI 301 Section 4.2.3 – Proportioning

Field Data Method

- Step two for the field data method is determining the ***required average strength*** for the proposed mixture

ACI 301 Section 4.2.3.3 – Required Average Strength

If there were no field data records available, thus no standard deviation, then the required average strength would be as follows:

Table 4.2.3.3.b - Required average compressive strength $\boldsymbol{f'_{cr}}$

f'_c, psi	f'_{cr}, psi
Less than 3000	$f'_c + 1000$
3000 to 5000	$f'_c + 1200$
Over 5000	$1.1f'_c + 700$

ACI 301 Section 4.2.3.3 – Required Average Strength

When field records are available and a standard deviation has been calculated, the required average strength is calculated as follows:

Table 4.2.3.3.a - Required average compressive strength f'_{cr}, when data are not available to establish a sample standard deviation, psi

f'_c, *psi*	f'_{cr}, psi	
	Use the larger of:	Equation
5000 or less	$f'_{cr} = f'_c + 1.34ks_s$	(4-3)
	$f'_{cr} = f'_c + 2.33ks_s - 500$	(4-4)
Over 5000	$f'_{cr} = f'_c + 1.34ks_s$	(4-3)
	$f'_{cr} = 0.90f'_c + 2.33ks_s$	(4-5)

ACI 301 Section 4.2.3 – Proportioning

Field Data Method

- Step three for the field data method is documenting the ***average compressive strength*** of the proposed mixture

ACI 301 Section 4.2.3.4 - Documentation of Average Compressive Strength

Field strength data for the proposed mixture must:

- Consist of at least 10 consecutive strength tests
- Span a period of not less than 45 days
- Must be equal to or greater than the required average strength.

ACI 301 Section 4.2.3.4 - Documentation of Average Compressive Strength

If the proposed mixture is the same mixture used to determine the Ss, then that data may be used to document average compressive strength.

Or, it may be different, as long as it is of the same class and within 1000 psi in strength.

Example 1 for Field Data Method

- Design Strength Required - 4500 psi
- Plant has 35 records of a 4000 psi mixture design, which is used to determine a standard deviation
- Plant has 12 records of the 4500 psi mixture design which is proposed for use, which uses same materials as the 4000 psi mixture design.

Example 1 for Field Data Method

- Standard deviation from the 35 tests records for the 4000 psi mixtures is calculated and it is 560 psi.

- The average strength of the 12 test records for the 4500 psi mixture is calculated and it is 5425 psi at 28 days.

- The required average strength is calculated Table 4.2.3.3(a)1 as follows:

  - Fcr = 4500 + 1.34(560) = 5250 psi
  - Fcr = 4500 + 2.33(560) - 500 = 5305 psi
  - Use the larger, 5305 psi = required average strength

- The average strength 5424 psi > required avg. strength 5305 psi, mixture qualifies.

Example 2 for Field Data Method

- Design Strength Required - 3500 psi
- Plant does not have Ss calculated
- Plant has 14 records of the 3500 psi mixture design which is proposed for use.

Example 2 for Field Data Method

- The average strength of the 14 test records for the 3500 psi mixture is calculated and it is 4850 psi at 28 days.

- The required average strength is calculated Table 4.2.3.3.b as follows:

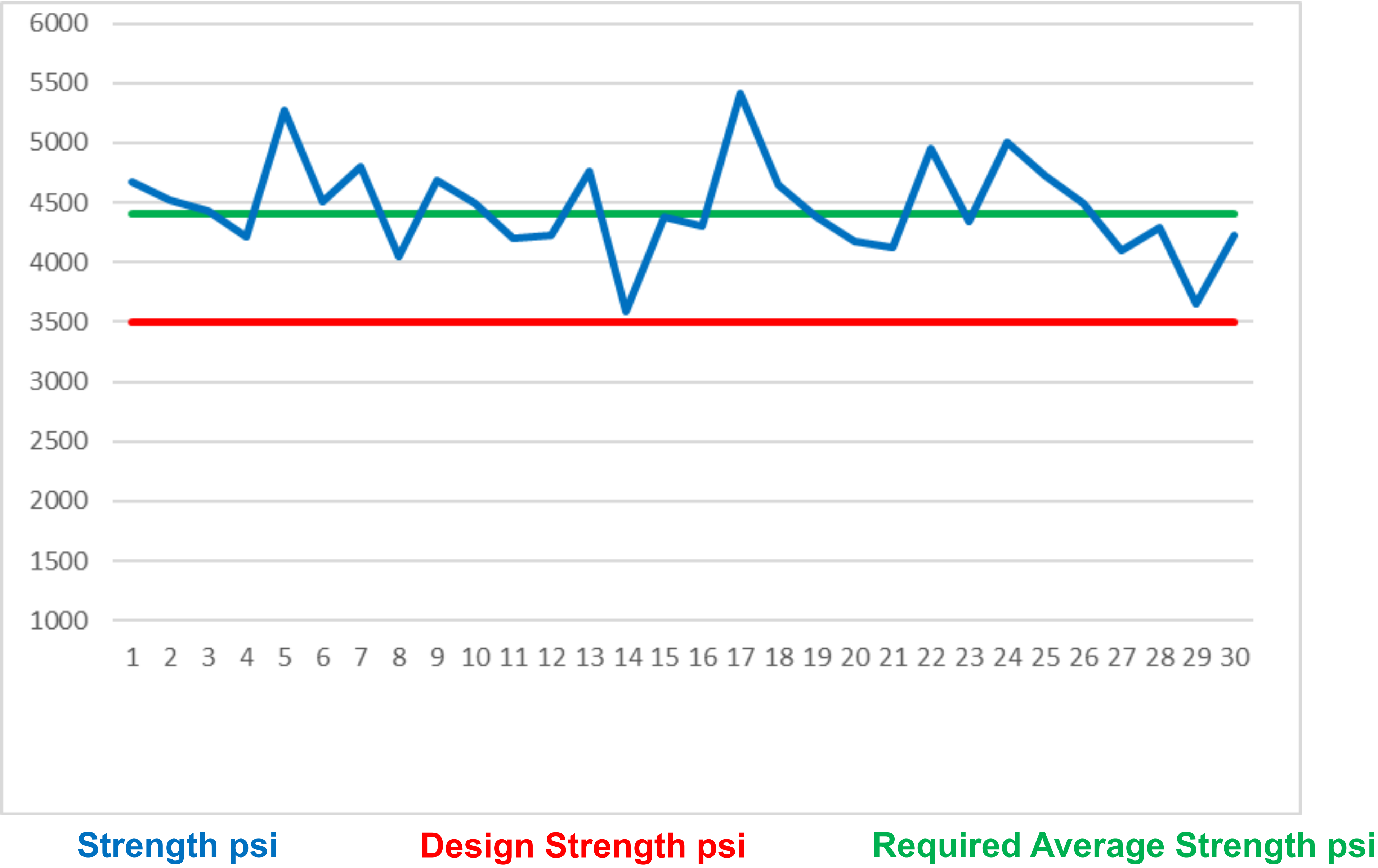
  - Fcr = 3500 + 1200 = 4700psi

- The average strength 4850 psi > required avg. strength 4700 psi, mixture qualifies.

Summary for Field Data Method

1. Collect field test records
2. Determine standard deviation
3. Determined required average strength
4. Document average compressive strength of proposed mixture design
   a. May be the mixture design whose data was used for standard deviation
   b. May be a different mixture design, document with 10 or more consecutive test records (must be same class of concrete within +/- 1000 psi)

Summary for Field Data Method



ACI 301 Section 4.2.3 – Proportioning

Trial Mixture Method

1. Step one for the trial mixture method is to use materials and material combinations complying with applicable ACI 301 sections

2. Step two, determine required average strength based on Ss and Table 4.2.3.3a if field test records are available.

3. If no field test records, use Table 4.2.3.3b for default required average strength

ACI 301 Section 4.2.3 – Proportioning

Trial Mixture Method

3. Step three

   Make at least three trial mixtures for each class of concrete with a range of proportions that will establish the w/cm and relative proportions and will encompass the required average strength.

In other words, develop a three-point curve

ACI 301 Section 4.2.3 – Proportioning

Three Point Curve Example

	Low Point	Mid Point	High Point
Cement	360	480	600
Fly ash	90	120	150
Stone	1850	1850	1850
Sand	1333	1180	1027
Water	267	275	283

W/Cm	0.59	0.46	0.38
Slump	5.00	5.00	5.00
Air	5.00	5.00	5.00

Total Cem.	450	600	750
% Fly ash	20	20	20
28-day psi	3680	5860	6750

Set up mixtures with a low, mid, and high cementitious content. Target same slump and air.

**Constant % fly ash content*
**Constant stone content*

*other methods may be used

ACI 301 Section 4.2.3 – Proportioning

Three Point Curve Example

	Low Point	Mid Point	High Point
Cement	360	480	600
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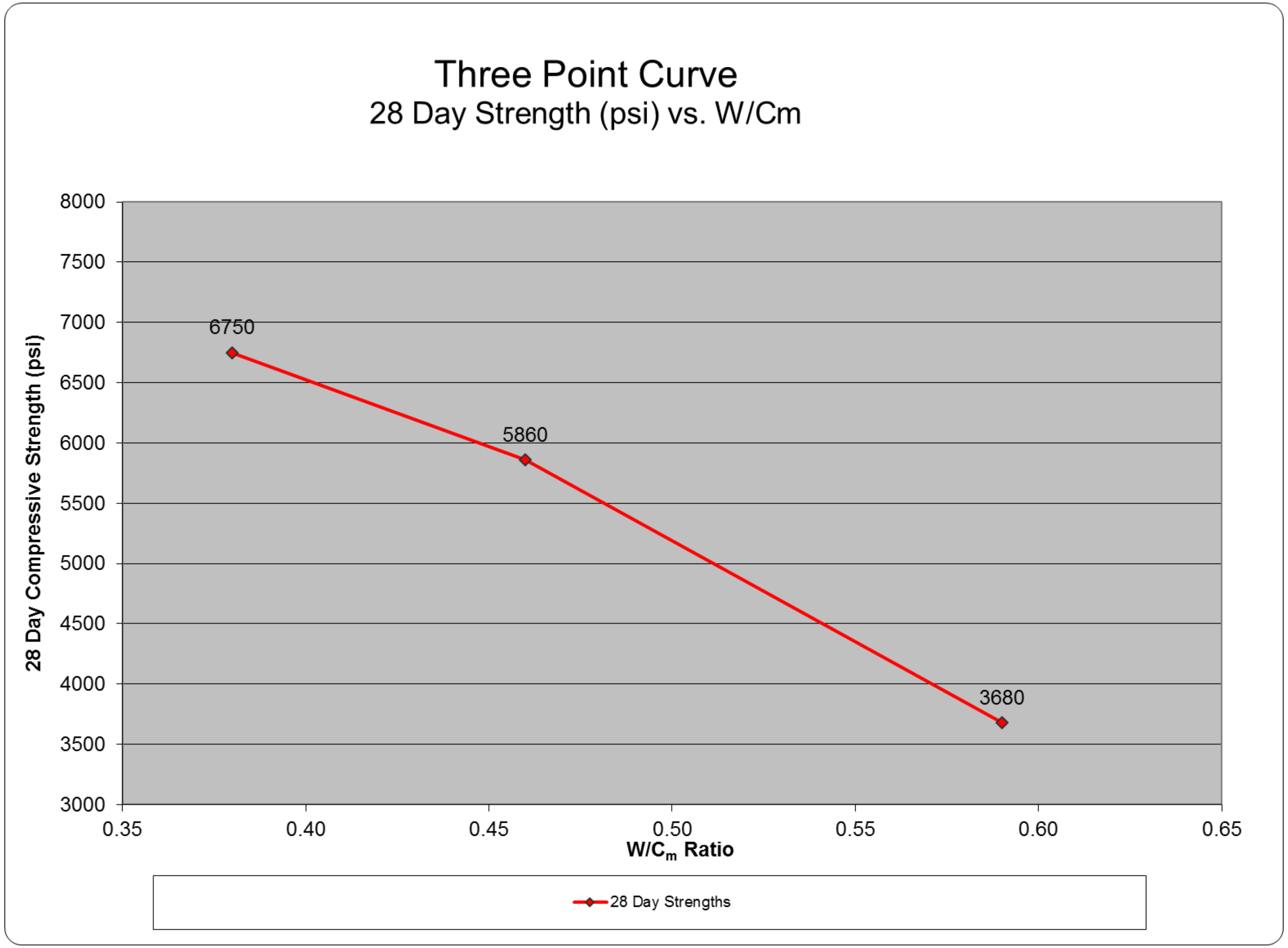
% Fly ash	20	20	20
28-day psi	3680	5860	6750

Set up mixtures with a low, mid, and high cementitious content. Target same slump and air.

**Constant % fly ash content*
**Constant stone content*

**other methods may be used*

Trial Mixtures – Data is Plotted on a Strength vs. W/Cm Ratio



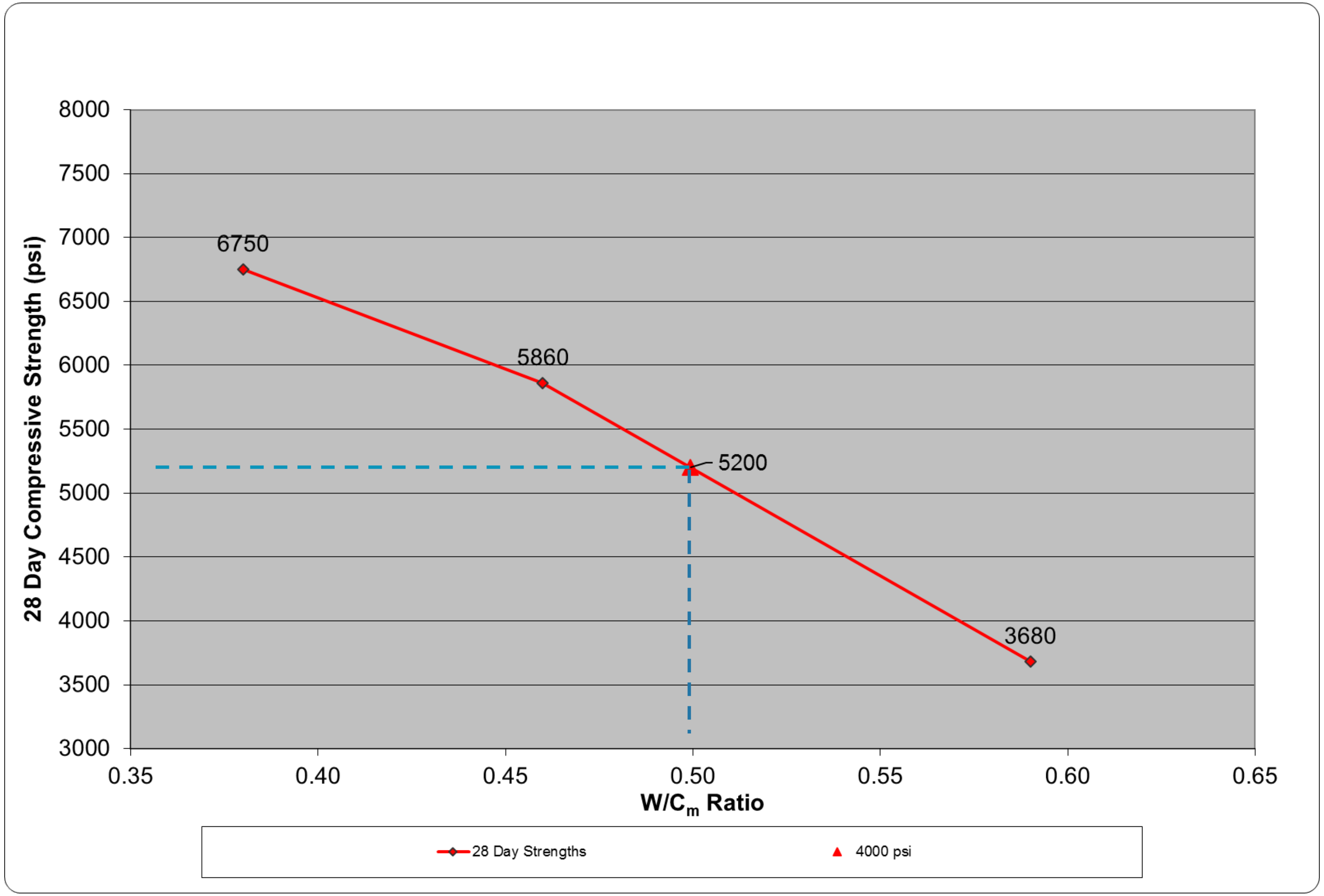
Any strength mixture between 3680 psi and 6750 psi can be proportioned from the curve

Trial Mixtures – Data is Plotted on a Strength vs. W/Cm Ratio

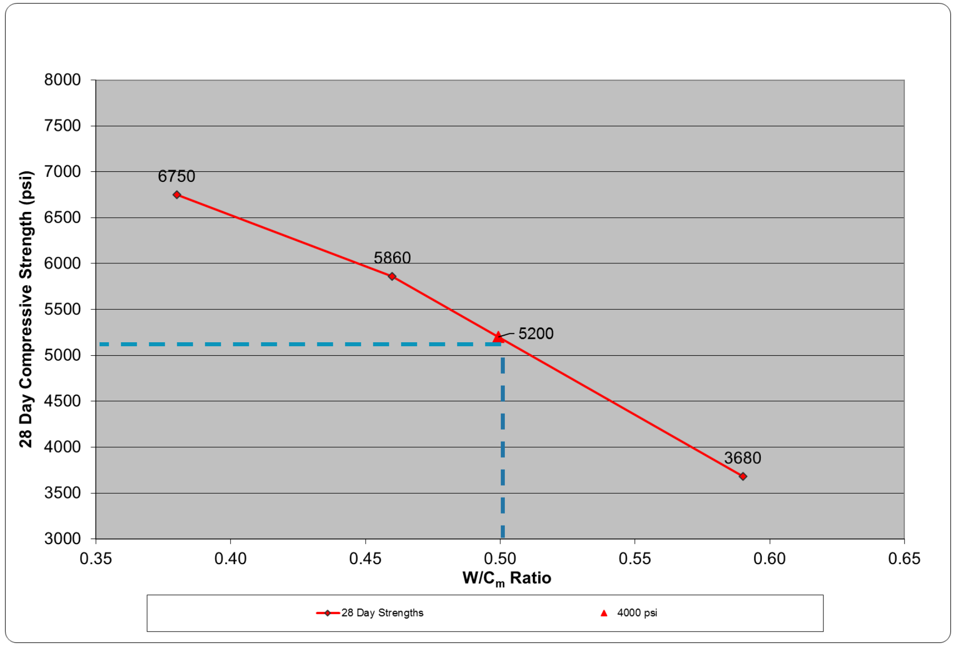
Example 1:

- A mixture with a design strength of 4000 psi at 28 days is required.
- Assume no field data so the over design based on Table 4.2.3.3b will be 1200 psi.
- Required average strength needed is 4000 + 1200 = 5200 psi at 28 days.

Trial Mixtures – Data is Plotted for a 4000 psi design strength with required average strength of 5200 psi



Trial Mixtures – Data is Plotted for a 4000 psi design strength with required average strength of 5200 psi



New mixture is proportioned from curve

- W/Cm ratio for 5200 psi is 0.52
- Calculated total cementitious is 545 lbs/cy
- 20% fly ash replacement
  - cement is 436 lbs.
  - fly ash 109 lb.
- Calculate water (454 lbs. x 0.52)
- Stone is constant
- Sand is calculated to yield 27.0 cu.ft./yd

New 4000 psi mixture design

Cement	436
Fly ash	109
Stone	1850
Sand	1239
Water	271
W/Cm	0.50

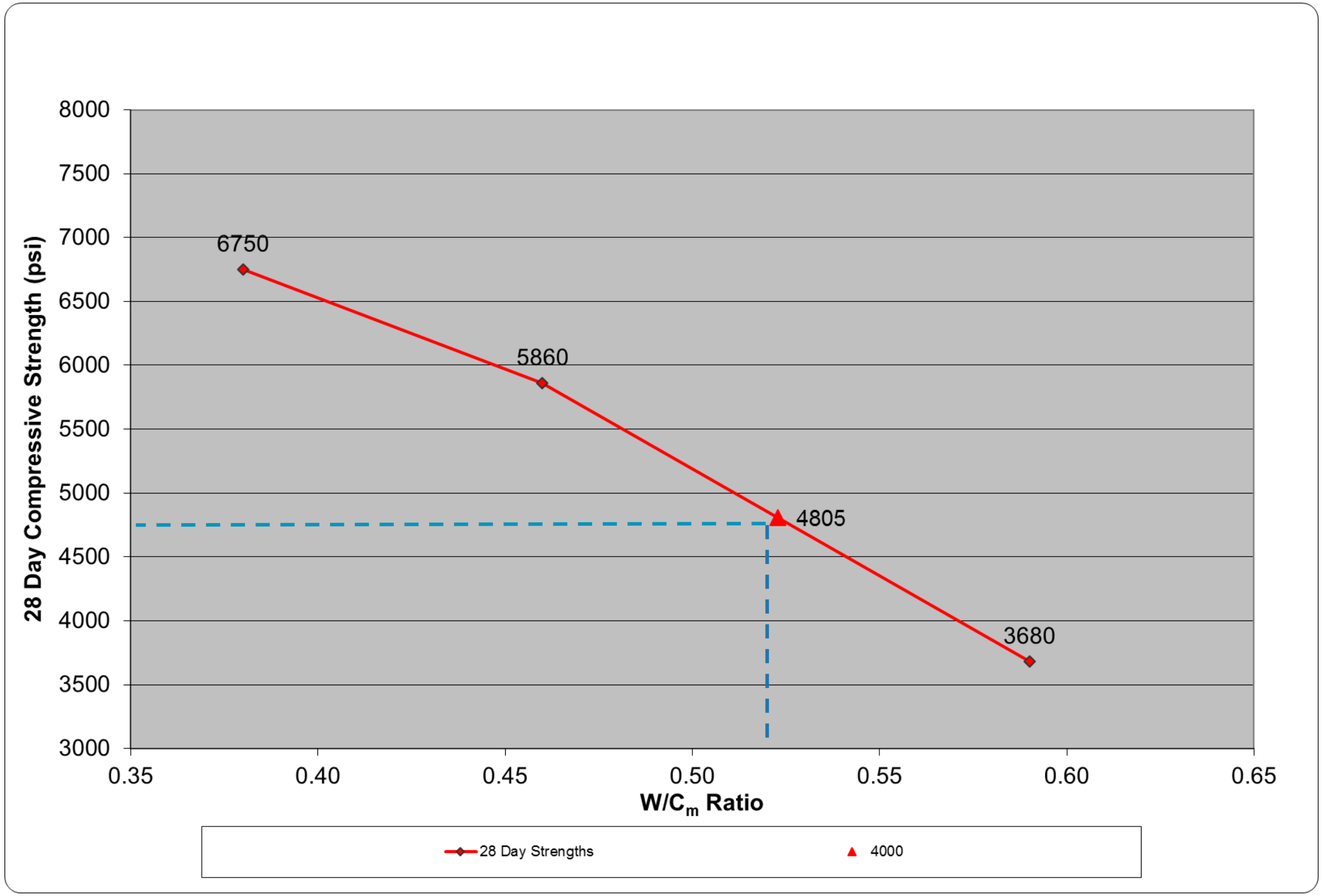
Trial Mixtures – Data is Plotted on a Strength vs. W/Cm Ratio

Example 2:

- The same design strength of 4000 psi at 28 days is required.
- Field data of 30 records of similar materials within 1000 psi is available.
- Ss of 475 psi has been determined.
- Based on Table 4.2.3.3a the over design will be 637 psi.
- Required average strength needed is 4000 + 637 = 4637 psi at 28 days.

Trial Mixtures – Data is Plotted on a Strength vs. W/Cm Ratio

Example 2:



New 4000 psi mixture design

Cement	414
Fly ash	104
Stone	1850
Sand	1265
Water	270
W/Cm	0.52

This mixture requires 28 less lbs.' of cementitious material, based on Ss

Summary for Trial Mixture Method

1. Run trial mixtures that encompass range of strengths and W/Cm needed

2. Determined 28 day compressive strengths

3. Determined required average strength
    a) Field records and Ss available, use Table 4.3.3.2.a
    b) No field records, use Table 4.3.3.2.b

4. Proportion proposed mixtures from the curve.

Questions ???