Chapter 22 | APPENDIX (Nonmandatory Information)

X1. Calculation of the Average Compressive Strength (f'_{cr}), Necessary to Meet the Strength Requirements of Sections 18.4.1, 18.4.2, and 18.4.3

This Appendix in ASTM **C94/C94M** is advisory, nonmandatory information provided primarily to instruct the concrete manufacturer on how to proportion concrete mixtures to achieve a target average strength such that the probability of failing the strength acceptance criteria in Section 18.4 is low. The strength acceptance criteria referenced in Section 18.4 are the same as in ACI 318-11, *Building Code for Structural Concrete* [1] and incorporated in a specification format in ACI 301-10, *Specification for Structural Concrete* [2]. These elements of the ACI standards form advisory information in this Appendix, but are mandatory parts of the ACI Building Code and thus specification on applicable projects. The concrete manufacturer develops the concrete mixture proportions based on these requirements and collects documentation, either from laboratory batches or strength records from previous projects that demonstrate that the concrete mixture proposed for a project will achieve the average concrete strength as per these requirements. These are then provided in a submittal to the design engineer for review before the project proceeds, if so requested.

The user of ASTM **C94/C94M** should keep two things in mind during this discussion. This part of **C94/C94M** is advisory as indicated by the title Nonmandatory Information. The concrete manufacturer is not required to proportion concrete mixtures as stated in this Appendix. The second thing to keep in mind is that unless the project is under the jurisdiction of the ACI Building Code, there may be a different set of acceptance criteria for concrete for a particular project. Even for projects governed by an adopted building code that references ACI 318, the project specifications may have more restrictive requirements than the ACI Building Code, but are not permitted to be at a lower standard. ASTM **C94/C94M** can cover a wide range of concrete projects. In many cases, the purchaser may choose not to test the concrete. In these cases, when concrete is ordered with a strength requirement, it still behooves the concrete manufacturer to use these concepts to protect both the interest of the manufacturer and that of the customer. Finally, there are no requirements in **C94/C94M** on developing submittals in accordance with this Appendix. The purchaser is permitted to request information about concrete mixtures being furnished as addressed in Section 6 on Ordering Information (Chapter 6).

The strength acceptance criteria recognize that there is variability in the process—from the ingredient materials, batching and mixing, delivery, and strength testing. An exact result should not be expected from concrete as might be expected with any other manufactured product. Thereby the acceptance criteria are statistically based. The goal is to balance the risk to the manufacturer and the purchaser and to minimize the risk to each party, that is, the risk that the producer's acceptable product is rejected, and the risk that the purchaser accepts unacceptable product. Some of the basis of the risk associated with ACI acceptance criteria are discussed in other references [3,4,5]. Fundamentally, when the purchaser indicates a strength requirement in the order for ready-mixed concrete, the concrete manufacturer will proportion the concrete mixture to achieve an average strength that is higher than the specified strength such that there is a small probability that any specific measured strength test result will be less than the strength specified by the purchaser. This difference between the purchaser-stated strength and the target average strength is often referred to as the *over-design* and represents a safety factor to minimize the occurrence of strength test results with values below the designer's specified strength.

The various criteria available to a specification writer can, and occasionally will, present a stumbling block to a reasonable over-design because of careless wording, such as: *No strength test result shall be less than the design strength of 4000 psi at 28 days.* Because the over-design strength relies on statistical probability concepts, the statement of a zero tolerance for a failing test result as stated is an upheaval of the system of the standards as are currently used in the industry. The acceptance and rejection criteria for concrete are based on probability statistics because it is rare for even two companion cylinders to produce identical strengths, much less for two test results from separate loads of concrete to be the same value. Acceptable concrete strengths have been based on statistical

Example 22.A Frequency distribution of 100 strength test results.

2480	2840	3110	3250	3400	3520	3630	3750	3910	4150
2530	2870	3130	3290	3410	3530	3640	3790	3940	4160
2580	2890	3140	3310	3450	3530	3670	3810	3940	4230
2620	2930	3140	3310	3450	3540	3670	3820	3960	4250
2640	2970	3160	3330	3470	3540	3680	3830	4030	4270
2730	3000	3180	3340	3470	3570	3690	3830	4030	4290
2740	3000	3200	3340	3480	3570	3710	3850	4050	4330
2780	3020	3210	3360	3490	3590	3720	3870	4070	4350
2781	3040	3210	3380	3510	3600	3720	3890	4090	4490
2800	3080	3240	3390	3510	3610	3740	3890	4110	4560

The data are grouped in ranges of 200 psi:

Range	Range Midpoint	Number of Results
2100 – 2299	2200	0
2300 – 2499	2400	1
2500 – 2699	2600	4
2700 – 2899	2800	8
2900 – 3099	3000	7
3100 – 3299	3200	12
3300 – 3499	3400	16
3500 – 3699	3600	18
3700 – 3899	3800	14
3900 – 4099	4000	9
4100 – 4299	4200	7
4300 – 4499	4400	3
4500 – 4699	4600	1

The following statistical parameters are determined from the results:

Number of tests, n	= 100
Average, $\bar{X}$	= 3500 psi
Standard deviation, s	= 474 psi
Coefficient of variation, V	= 13.5 %

probability concepts for decades, with stated levels of acceptance ranging from one in ten to one in one hundred. Probabilities and probability distributions are the essence of concrete pass-fail specifications, be they in ACI 318 or of some other origin.

The standard deviation of strength test results is used to quantify variability. The standard deviation is a quantitative measure of a manufacturer's ability to control their product. The lower the standard deviation, the better control is indicated. A component of this variability that is beyond the control of the manufacturer is the strength testing performed by an independent testing agency. The testing component variability gets large when testing practices are poor. In a series of articles on quality control Obla discusses various factors that impact the variability of concrete, from ingredient materials, batching, production, delivery, strength testing, and specifications [6].

The sample standard deviation is calculated by the equation below. The point to note is this is the sample standard deviation and (n-1) is used in the denominator.

$$s=\sqrt{\frac{\sum_{i=1}^{n}(X_i-\overline{X})^2}{n-1}} =\sqrt{\frac{(X_1-\overline{X})^2+(X_2-\overline{X})^2+\ldots+(X_n-\overline{X})^2}{n-1}} \quad (1)$$

Where:
s = standard deviation,
X_i = individual strength test (avg of companion cylinders),
$\overline{X}$ = average of n strength test results, and
n = number of tests.

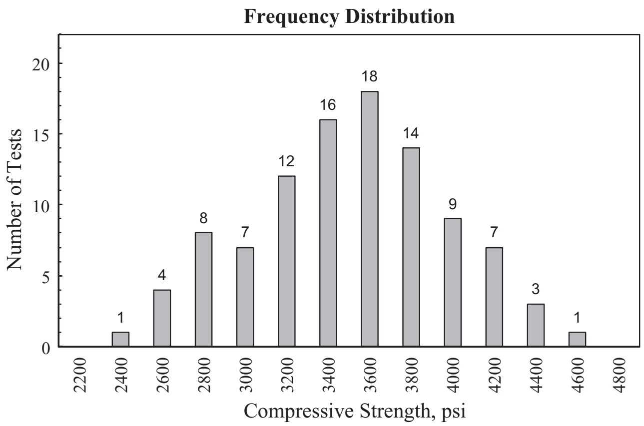
When a large set of test data is collected, one of the processes of evaluating the data is to construct a frequency distribution. In **Example 22.A**, 100 strength test results are collected and the number of tests within small ranges of 200 psi is counted. The data can then be plotted as in **Fig. 22.A** as a visual representation of the frequency distribution of this data set.

The visual frequency distribution shows that the data set follows a pattern with increasing frequency of test results centered on the middle of the distribution. This pattern is represented by the normal or Gaussian distribution, often referred to as the bell curve shown in **Fig. 22.B**. There are various types of statistical distributions with different characteristics. Strength test results tend to follow this normal distribution. Test results of high strength concrete may have a slight skew to the normal distribution [3].

The normal distribution curve has several useful properties as follows:

- The peak of the curve occurs at the average of the data.
- The curve is symmetrical about the average, that is, 50 % of the tests will be on either side of the average.

FIG. 22.A Frequency distribution of 100 strength test results.



- The spread of the curve is characterized by the standard deviation. The greater the spread, the higher the standard deviation (or greater the variability).
- Statistical theory can be used to predict the percentage of tests within (or outside) a particular range. If the total area under the curve represents 100 % of the results, a portion of that area is proportional to the number of tests within that range. For example, if the area under the bell curve in Fig. 22.B on the right of 4000 psi is 20 %, then statistical theory indicates that 20 % of the test results will be higher than 4000 psi.

The normal distribution curve is defined by the mean (average) test value and the standard deviation. The abscissa (x-axis) in this case is the strength. The ordinate (y-axis) is the number of tests in each range. The referenced horizontal distance is measured in units of standard deviation, denoted by σ (sigma). The multiplier to σ is identified as z. Thus, $z\sigma$ defines a horizontal distance from the mean in terms of number of standard deviations. The proportion of area under the curve between the mean and a point $z\sigma$ defines the percentage of tests expected to lie in that defined area. For example at the point + 1.0 σ the area under the curve between the mean and that line represents 34.13 % of the total area. To estimate the percentage of strength tests within a range of ± 1 σ about the mean, this would be 2 × 34.13 % = 68.26 %.

Other values for percentage of tests for different commonly used values of z are provided in Table 22.A. The second column of Table 22.A estimates the total percentage of tests between $z\sigma$ and $+z\sigma$. The portion of tests falling below or above that value of $z\sigma$ equals one-half of the portion outside the prescribed limits. For $z = 1.64$, 90 % of the test results fall within ± 1.64 σ about the mean, and 5 % will be greater than + 1.64 σ, while 5 % will be less than − 1.64 σ.

A distinction is included here between statistical nomenclature and concrete test values through the following definitions:

σ (sigma) = the standard deviation for the entire population of possible test results.

s (lowercase) = the sample standard deviation for the data set that is an estimate of the standard deviation of the population of strength tests.

Table 22.A can be used to illustrate the impossible situation set by the specification clause mentioned earlier. If the specification requires 100 % of all tests to be greater than the specified compressive strength, the strength level for which the mixture has to be designed will be significantly high to avoid the

FIG. 22.B Normal distribution curve for strength test results.

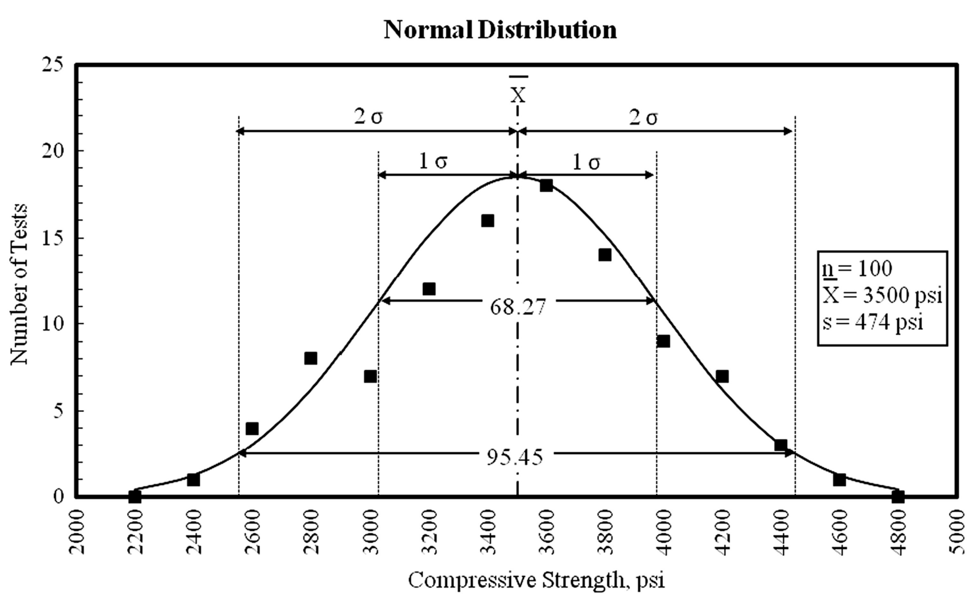


TABLE 22.A Percent of Tests (rounded off) at Different Levels of "zσ"

z	Percent of Tests Within ±zσ	Percent of Tests Less Than $\bar{X}$ - zσ	
0.84	60	20	1 in 5
1.00	68	16	1 in 6.3
1.28	80	10	1 in 10
1.34	82	9	1 in 11
1.64	90	5	1 in 20
1.96	95	2.5	1 in 40
2.00	95.5	2.25	1 in 44
2.33	98	1.00	1 in 100
3.00	99.8	0.10	1 in 1000
4.00	99.98	0.01	1 in 5000

possibility of one failing test. If f'_c is 4000 psi and the standard deviation is 600 psi, a concrete mixture proportioned to produce an average strength of 4000 + (2.33 × 600) = 5400 psi will have a 1.0 % probability of a failing test result. To approach a 0 % probability of failure the mixture should achieve an average strength of 4000 + (4.0 × 600) = 6400 psi. The impact of this type of a specification clause should be brought to the attention of the specifier so an opportunity is provided for a correction.

Another point to note regarding the variability of strength test results is that the standard deviation increases as the average strength increases [3]. It is therefore not useful to look at standard deviation in isolation without reference to the mean or average value of the data set. The standard deviation should not be compared when the mean and average are significantly different. For these purposes, the coefficient of variation, *V*, is sometimes used. The coefficient of variation is the standard deviation expressed as a percentage of the average. Variability of two sets of data with significant different averages or means can be compared using the coefficient of variation.

X1.1 $_{S1}$ *Section 18.4 of this specification contains the same strength requirements as those contained in ACI 318 and ACI 301, except it does not require the submittal of the data and calculation of the average strength, f'_{cr} necessary to meet those ACI Code and Specifications.* $_{S2}$ *This Appendix does not include all of the detailed requirements of the ACI Code and Specification that will govern a submittal for their respective purposes.* $_{S3}$ *The following material is intended to guide users of this specification when no formal submittal is required.*

S1 and **S2** are reminders that ASTM C94/C94M has established in Section 18.4 that strength requirements of this specification mirror those of ACI 318 and ACI 301 and are applicable unless the project specifications state alternative test acceptance criteria. It also points out that C94/C94M does not require any submittal documenting how the required average strength is determined, the mixture proportions, or submittal of strength tests associated with the proposed mixture. The purchaser can request information on the mixture proportions or any other information, as addressed in Section 6, and the manufacturer is obliged to provide that information. Detailed discussion on the submittal requirements of ACI 318 and ACI 301 are not presented here. It should be pointed out that ACI 301 is not required to exactly follow ACI 318, only that it be at least as conservative as ACI 318. In fact, there are some differences, and ACI 301 is more conservative than ACI 318 for its strength submittal requirements.

S3 declares that the information within this Appendix is intended as only a guide to users when no formal submittal is required. This is consistent in that an Appendix to an ASTM standard contains only nonmandatory and advisory information. Section 18.4, however, states the acceptance criteria for concrete strength is a mandatory requirement in the event over-riding concrete acceptance criteria are not a part of the specifications for a project. A project specification that references ASTM C94/C94M includes the requirements of Section 18.4 by default. The over-design for strength presented in this Appendix reduces the risk for a manufacturer to meet these acceptance criteria. It should also be noted that ASTM C94/C94M is adopted by reference in the ACI 318 Building Code. There is no conflict because the acceptance criteria are the same.

X1.1.1 $_{S1}$ *Table X1.1 provides the statistical formulas that can be used to calculate the required average strength f'_{cr} when historical statistical data are available.* $_{S2}$ *The formula to achieve a satisfactory average of three consecutive strength tests as required in 18.4.1 is (Eq. X1.1) of Table X1.1.* $_{S3}$ *The formulas for the minimum strength of an individual strength test result as required in 18.4.2 and 18.4.3 are (Eq. X1.2) and (Eq. X1.3) in Table X1.1.* $_{S4}$ *Since the average strength, f'_{cr}, must be high enough to conform to both averages of three consecutive tests and the requirements on minimum strength of a test, the one which requires highest average strength (f'_{cr}) governs.*

S1 refers to the Table X1.1 that contains the ACI 318 [1] formulas used to calculate the required average strength (f'_{cr}) for a concrete mixture based on the specified compressive strength (f'_c). Table X1.1 addresses the situation when there is a strength test record on a similar mixture produced from the concrete plant from which a standard deviation can be calculated. The standard deviation established from the strength test record from prior projects represents the level of concrete quality produced by the plant.

In ACI standards, it suggests that the standard deviation should represent mixtures of the similar type and produced under similar conditions. For the mixture type, it says that the specified strength for the test record and the proposed project

TABLE X1.1 ***Required Average Compressive Strength when Data are Available to Establish a Standard Deviation***

Inch-pound System			SI System		
Specified Strength f'_c, *psi*	*Required Average Strength* f'_{cr}, *psi*		*Specified Strength* f'_c, *MPa*	*Required Average Strength* f'_{cr}, *MPa*	
f'_c *equal to or less than 5000*	*Use the larger from Eq X1.1 and X1.2*		f'_c *equal to or less than 35*	*Use the larger from Eq X1.1 and X1.2m*	
	$f'_{cr} = f'_c + 1.34s$	*(X1.1)*		$f'_{cr} = f'_c + 1.34s$	*(X1.1)*
	$f'_{cr} = f'_c + 2.33s - 500$	*(X1.2)*		$f'_{cr} = f'_c + 2.33s - 3.45$	*(X1.2m)*
greater than 5000	*Use the larger from Eq X1.1 and X1.3*		*greater than 35*	*Use the larger from Eq X1.1 and X1.3*	
	$f'_{cr} = f'_c + 1.34s$	*(X1.1)*		$f'_{cr} = f'_c + 1.34s$	*(X1.1)*
	$f'_{cr} = 0.90f'_c + 2.33s$	*(X1.3)*		$f'_{cr} = 0.90f'_c + 2.33s$	*(X1.3)*

where:

f'_c = *the specified compressive strength,*
f'_{cr} = *the required average compressive strength*
s = *the standard deviation.*

should be within 1000 psi. This is addressed in Section X1.1.2. Similar conditions can have a subjective interpretation. It may not mean concrete produced at the same plant. If the concrete was furnished from two plants with the same materials and similar batch plant set up and with the same testing agency involved, this can be considered similar. If a test record represents non-air-entrained concrete, it is not appropriate to use that for an air-entrained concrete mixture even at the same strength level. Producing air-entrained concrete tends to be more variable. It is important to recognize that the standard deviation determined and the over-design strength established serves to protect the manufacturer and the purchaser. The manufacturer reduces the risk of failing the acceptance criteria with proper use of these concepts. The purchaser is ensured that there is improved probability that the concrete furnished for the work will be what is needed by the design.

Neither Section 18 nor this Appendix actually state that mixture proportions be established to the ACI 318 requirements. The formulas of Table A1.1 are the same as the ACI formulas, but without a reference the other requirements are not applicable. The other details involve the age of a test record, combining two groups of tests, and other specific details are not addressed in this Appendix. Good judgment is primarily implied.

S2 and **S3** state the basis for the over-design on strength. The concrete manufacturer sets the target strength of the proposed concrete mixture such that there is less than a 1 % probability of failing the acceptance criteria in Section 18.4. The equations in Table X1.1 are directly linked to the criteria in Section 18.4. The assumption is that the same standard deviation (variability) assumed will be applicable for the upcoming project, and that the average strength level of test results during the project will be maintained at the required average strength (f'_{cr}). This is not a requirement, just an assumption, and this is the situation in which the concepts of the normal distribution of strength test results are put to practice. This applies only when a standard deviation from a strength test record of a similar concrete mixture can be established.

The first acceptance criterion (see Section 18.4.1) is that the average of three consecutive strength test results should be equal to or exceed the specified strength (f'_c). Equation X1.1 is related to this criterion. The *z-value* of 1.34 is derived from the 1 % probability of failure in Table 22.A of 2.33. Since three consecutive tests are included, 1.34 is derived from ($2.33/\sqrt{3}$). So equation X1.1 indicates that the mixture should be over-designed by a strength of 1.34 times the standard deviation greater than the specified strength [7]. If the criteria was such that it was stated on the basis of five tests, the *z-value* would have been ($2.33/\sqrt{5} = 1.04$).

The second acceptance criterion (see Section 18.4.2) states that no individual strength test should be more than 500 psi below the specified strength, when the specified strength is 5000 psi or less. Equation X1.2 is related to this criterion. The *z-value* selected is 2.33 and sets the 1 % probability of failing this acceptance criterion. The required average strength of the concrete mixture is designed for an over-design strength of 2.33 times the standard deviation greater than ($f'_c - 500$) psi. When the specified strength is greater than 5000 psi, the acceptance criterion (see Section 18.4.3) states that no individual strength should be less than ($0.90\ f'_c$). Equation X1.3 is related to this acceptance criterion. The required average strength of the concrete mixture is designed for an over-design strength of 2.33 times the standard deviation greater than $0.90\ f'_c$.

From the values obtained from the two equations, the higher value is selected for the required average strength. This is stated in **S4**. The concrete mixture is proportioned to achieve an average strength of this required average strength (f'_{cr}) or higher. For equations X1.1 and X1.2 they converge to the same value of f'_{cr} when the standard deviation is 505 psi. If the standard deviation is less than 505 psi, equation X1.1 gives the value of f'_{cr}. If the standard deviation is greater than 505 psi, equation X1.2 gives the value of f'_{cr}.

When concrete mixtures are designed to this level, and the operational and testing variability is the same as assumed, the probability of failing the acceptance criteria in Section 18.4 is 1 % or a 1 in 100 probability. Section 18.4 establishes two acceptance criteria for concrete strength. The second one for individual strength test results depends on the specified strength. Both these criteria must be met.

X1.1.2 *$_{S1}$ The first step in the process of calculating the over-design above f'_c or the required average strength is to determine if a record of 30 consecutive tests is available for the proposed mixture or similar mixture with a design strength within 1000 psi [6.6 MPa] of the specified compressive strength proposed for use. $_{S2}$ If it is a new mixture or strength level and no standard deviation data is available then Table X1.2 provides default levels of over-design equal to 1000, 1200, or (1.10 f'_c + 700) psi.*

S1 addresses two aspects. The first aspect indicates that the standard deviation should be calculated from a test record that is comprised of at least 30 consecutive tests. The second aspect indicates that the test record should be from a similar mixture where the strength should be within 1000 psi of the specified strength of the project under consideration. What is unclear in this is the term *design strength*. It is presumed to mean specified strength for the project represented by the strength test record. This discussion on the requirements for the strength test record was discussed under Section X1.1.1. The requirement for 30 tests is from the ACI standards [1,2]. It is felt that 30 tests is a reasonable minimum number to obtain a good estimate of the standard deviation. The tests should also not be collected from one or two days of production because the variability will be less and probably not representative of what happens over the duration of a project that can last through changing seasons and several changing material shipments. The ACI standards permit two test records to be pooled to calculate an average standard deviation if the total number of tests is at least 30. Accumulating 30 test results from two mixes is often a burden for plants in more rural areas, considering the volume of concrete that might be tested. Utilizing more than two sets of test records to achieve the pooled standard deviation is not prohibited by C94/C94M and is often the only solution available in situations when there are a smaller number of acceptance tests on typical mixtures for each project. If the total number of tests is greater than 15 and fewer than 30, these standards also provide some multipliers to increase the standard deviation because there is a higher uncertainty of the estimate of the standard deviation with a smaller number of tests. If there are fewer than 15 tests for a test record, the standard deviation basis for determining the required average strength cannot be used on a project subject to ACI 318, and Table X1.2 would apply.

S2 is a direction to use the over-design values of Table X1.2 if the strength test records are not available to calculate a standard deviation. These Table X1.2 values are suggested for use to be more conservative with the strength level furnished because the variability of the production facility cannot be quantified. If standard deviation of a facility is greater than around 650 psi, the values in Table X1.2 will result in a lower over-design than that determined using the standard deviation. ACI 214R-11 [3] describes a 650 psi standard deviation as a *fair* standard of control and 700 psi or greater as a *poor* standard of control.

Appendix X1.1 does not suggest a limit on the age of the test record as does ACI 318, which states that the test record should be less than 24 months old. The concrete manufacturer should use the most accurate data available considering the quality constants or changes in materials and the systems in place for quality control.

While this Appendix does not address submittals, the next part is to document to the purchaser (the designer) that the proposed mixture can achieve the required average strength, f'_{cr}, or greater. This can be done by using a strength test record from

TABLE X1.2 ***Required Average Compressive Strength When Data Are Not Available to Establish a Standard Deviation***

Inch-pound System		SI System	
Specified Strength, f'_c, psi	Required Average Strength f'_{cr}, psi	Specified Strength, f'_c, MPa	Required Average Strength f'_{cr}, MPa
Less than 3000	$f'_c + 1000$	Less than 21	$f'_c + 7.0$
3000 to 5000	$f'_c + 1200$	21 to 35	$f'_c + 8.5$
greater than 5000	$1.10f'_c + 700$	greater than 35	$1.10f'_c + 5.0$

where:

f'_c = the specified compressive strength
f'_{cr} = the required average compressive strength
s = the standard deviation

a previous project; the same test record used to calculate the standard deviation can be used, or laboratory trial batches can be performed to document the strength and other properties of the concrete mixture. Interpolation is permitted between strength levels with different mixture proportions, typically varying cement content or w/cm.

X1.1.3 S1 *Table X1.3 provides calculated values of over-design and required average strength for selected standard deviations and specified strength levels.* S2 *Because of the large ranges of strength and standard deviations, the gray shaded areas are considered unusual or not likely to be encountered.*

Table X1.3 provides calculations of the over-design and average strengths arrived at from the previous sections. The upper half of the table provides the over-design necessary based on the specified strength (f'_c) and the plant's standard deviation from a strength test record. For example if the plant's standard deviation is 700 psi and the project's specified strength is 3000 psi the formulas of Table X1.1 calculate a needed over-design of 1131 psi. The lower segment of the table adds the over-design (1131 psi) to the specified strength and displays the required average strength, which in this instance is 4131 psi.

Several areas are shaded in Table X1.3 because the standard deviations are considered either unusual or inappropriate. It is considered unusual to obtain a very low standard deviation in the range of 300 to 500 psi when producing concrete strengths at 10,000 psi and higher. On the other side, very high standard deviation for lower strength concrete is generally indicative of a very low level of quality control. Using the fixed overdesign values from Table X1.2 will result in a lower value of required average strength. However, if the real variability of the producer is high as indicative of the high standard deviation, the risk of failing the strength acceptance criteria increases.

The following chart (Example 22.B) of sample calculations demonstrates the method of the development of Table X1.3 from the formulas of Table X1.1.

TABLE X1.3 Over-design Necessary to Conform to Specified Compressive Strength*

Required Over Design–Inch-Pound Units						
f'_c, psi	Standard Deviation from field data					no SD data
Specified	300	500	700	900	1,100	unknown
Strength	Over design above f'_c					
less than 3000						f'_c + 1000
3,000	402	670	1,131	1,597	2,063	1,200
5,000	402	670	1,131	1,597	2,063	1,200
7,000	402	670	938	1,397	1,863	1,400
9,000	402	670	938	1,206	1,663	1,600
11,000	402	670	938	1,206	1,474	1,800
13,000	402	670	938	1,206	1,474	2,000
15,000	402	670	938	1,206	1,474	2,200
17,000	402	670	938	1,206	1,474	2,400
Required Average Strength–Inch-Pound Units						
f'_c, psi	Standard Deviation from field data					no SD data
Specified	300	500	700	900	1,100	unknown
Strength	f'_{cr}, Required Average Strength, psi					
less than 3000						f'_c + 1000
3,000	3,402	3,670	4,131	4,597	5,063	4,200
5,000	5,402	5,670	6,131	6,597	7,063	6,200
7,000	7,402	7,670	7,938	8,397	8,863	8,400
9,000	9,402	9,670	9,938	10,206	10,663	10,600
11,000	11,402	11,670	11,938	12,206	12,474	12,800
13,000	13,402	13,670	13,938	14,206	14,474	15,000
15,000	15,402	15,670	15,938	16,206	16,474	17,200
17,000	17,402	17,670	17,938	18,206	18,474	19,400
	Shaded Areas identify levels of specified strength where the standard deviation should be considered unusual or inappropriate					

* *Only inch-pound units part of table X1.3 from C94/C94M is reproduced here.*

EXAMPLE 22.B Over-design calculations.

		Formula X1.1	Formula X1.2	Formula X1.3	
Specified Strength, f'_c	Standard Deviation (s)	1.34 s	2.33s – 500	2.33 s – 0.1 f'_c	Table X1.2
3000	500	**670**	665	...	...
5000	500	**670**	...	665	...
7000	500	**670**	...	465	...
4000	300	**402**	199	...	...
5000	700	938	**1131**	---	...
7000	700	**938**	---	931	...
3000	700	938	**1131**	...	...
5000	unknown	...	...	...	**1200**
6000	unknown	...	...	...	**1300**[A]
7000	900	1206	...	**1397**	...

[A] 0.10 f'_c + 700
Bold = control for the set of values.

The formula ($f'_{cr} = 0.90\, f'_c + 2.33s$) is represented differently for formula X1.3 for over-design value and indicated as ($2.33s - 0.10\, f'_c$) when f'_c is greater than 5000 psi.

References

[1] ACI Committee 318, "Building Code Requirements for Structural Concrete and Commentary," *ACI 318-11*, American Concrete Institute, Farmington Hills, MI, 2011, pp. 65–76.

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