

Chapter 9: Evaluation and acceptance of Hardened Concrete

9.1 Variation in strength of concrete

The strength of concrete produced in sites is varied between mixes and even in in the same mix due to the following reasons:

Principals sources of strength variation

Variations due to the properties of concrete	Variations due to testing methods
•Changes in w/cm caused by: -Poor control of water -Excessive variation of moisture in aggregate or variable aggregate moisture measurements -Retempering •Variations in water requirement caused by: -Changes in aggregate grading, absorption, particle shape -Changes in cementitious and admixture properties -Changes in air content -Delivery time and temperature changes •Variations in characteristics and proportions of ingredients: -Aggregates -Cementitious materials, including pozzolans -Admixtures •Variations in mixing, transporting, placing, and consolidation •Variations in concrete temperature and curing	•Improper sampling procedures •Variations due to fabrication techniques: -Handling, storing, and curing of newly made cylinders -Poor quality, damaged, or distorted molds •Changes in curing: -Temperature variation -Variable moisture control -Delays in bringing cylinders to the laboratory -Delays in beginning standard curing •Poor testing procedures: -Specimen preparation -Test procedure -Uncalibrated testing equipment

9.2 Definitions

- **Concrete sample**—a portion of concrete, taken at one time, from a single batch or single truckload of concrete.
- **Single cylinder (cube) strength or individual strength**—the strength of a single cylinder; a single cylinder strength does not constitute a test result.
- **Companion cylinders**—cylinders made from the same sample of concrete.
- **Strength test or strength test result**—the average of two or more single-cylinder strengths of specimens made from the same concrete sample (companion cylinders) and tested at the same age.
- **Range**: the difference between the maximum and minimum strengths of individual concrete specimens comprising one strength test result.
- **Test record**—a collection of strength test results of a single concrete mixture.

Concrete tests for strength are typically treated as if they fall into a distribution pattern similar to the normal frequency distribution curve illustrated in Figures below.

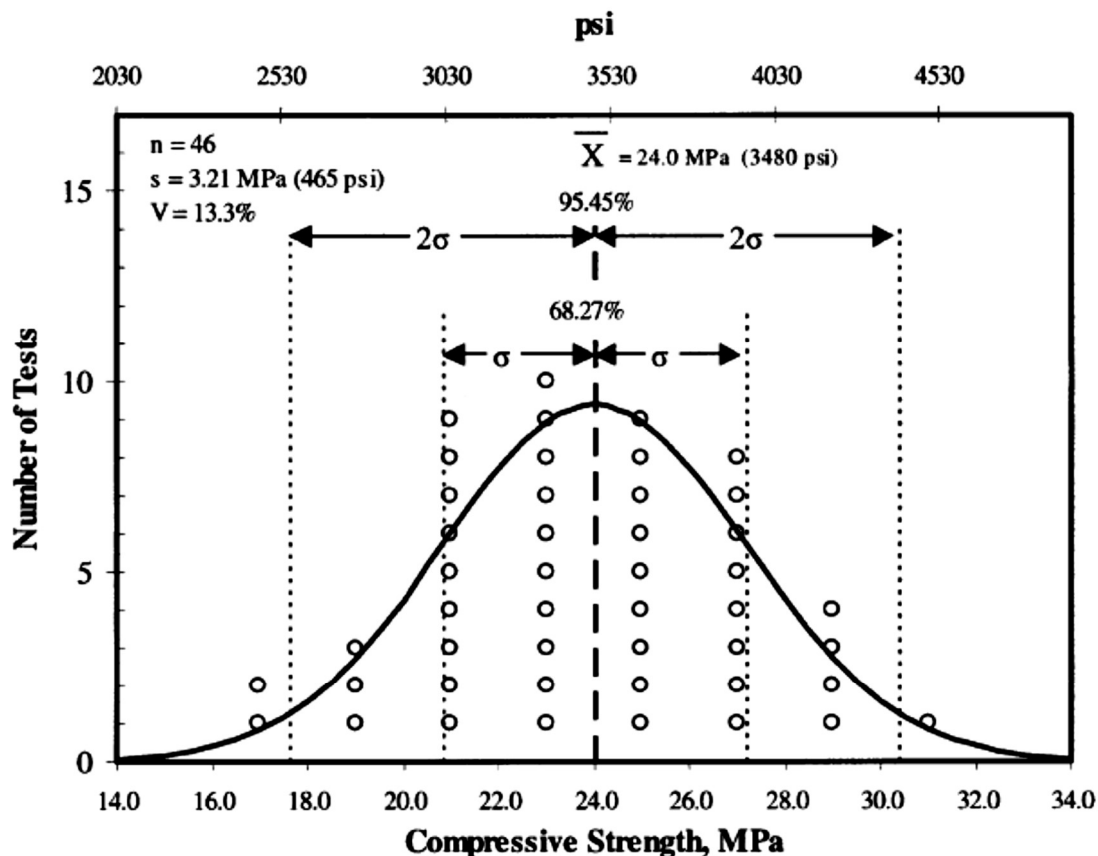


Fig. 3.1—Frequency distribution of strength data and corresponding assumed normal distribution.

When there is good control, the strength test values will tend to cluster near to the average value, that is, the histogram of test results is tall and narrow. As variation in strength results

increases, the spread in the data increases and the normal distribution curve becomes lower and wider as shown below.

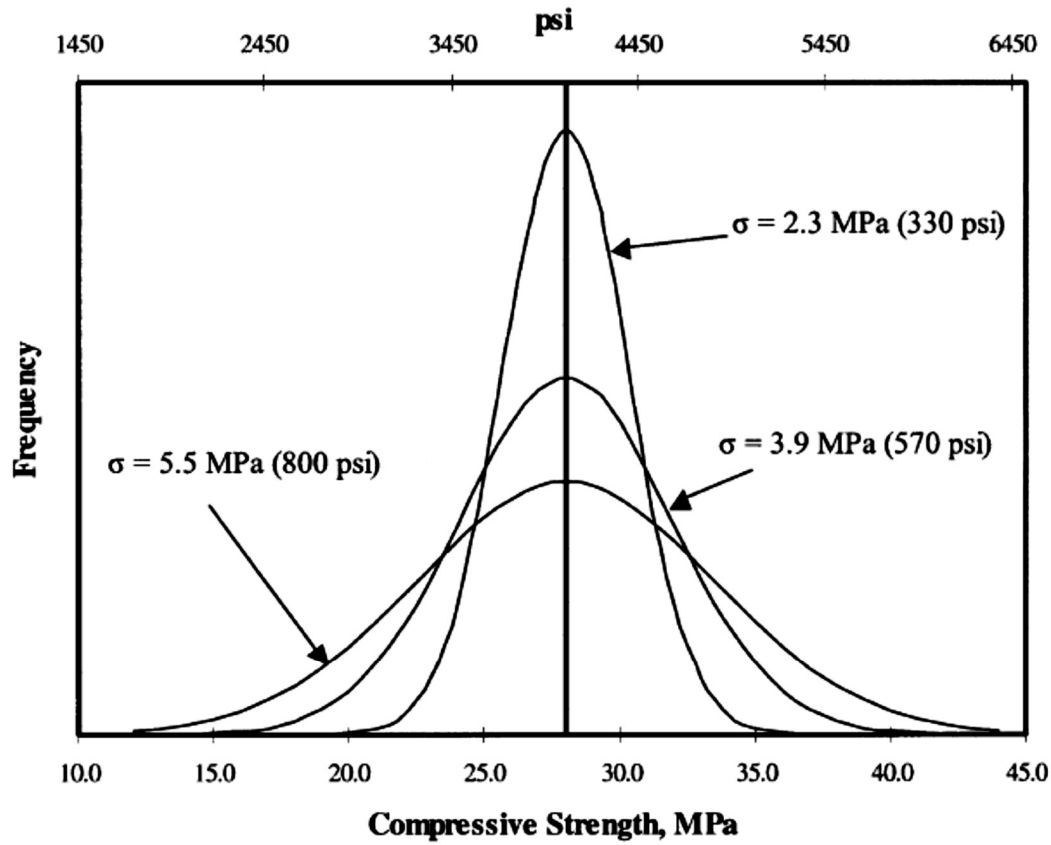


Fig. 3.2—Normal frequency curves for three different distributions with the same mean but different variability.

The normal distribution can be fully defined mathematically by two statistical parameters: the mean and standard deviation.

9.3 Strength variations

Variations in strength test results can be traced to two different sources:

1. Variations in testing methods; and
2. Variations in the properties or proportions of the constituent materials in the concrete mixture, variations in the production, delivery or handling procedures, and variations in climatic conditions.

9.4 Producer's Risk and Consumer's Risk

Producer's Risk

- Rejection of concrete that is up-to-standard
- Higher cost price

Consumer's Risk

- Acceptance of concrete that is sub-standard
- Stringent acceptance criteria.

Risks depend on:

- Number of samples.
- Accuracy of test methods.
- Acceptance Criteria

9.5 Review on Standards for Acceptance Testing and Criteria of Concrete

There are several international standards which can be applied to accept hardened concrete; among them:

- (ACI 318R-19), "Building Code Requirements for Structural Concrete".
- (ACI 214R-11), "Guide to Evaluation of Strength Test Results of Concrete"
- BS EN 206:2013, "Concrete - Specification, performance, production and conformity".
- IS 456:2000

9.5.1 ACI 318R-19

Evaluation of hardened concrete shall be based on strength tests. A strength test is the average of the compressive strengths of at least two 15 x 30 cm. cylinders or at least three 10 x 20 cm cylinders made from the same sample of concrete and tested at 28 days or at test age designated for f'_c .

Frequency of testing

- (a) Samples for preparing strength test specimens of each concrete mixture placed each day shall be taken in accordance with (1) through (3):
- (1) At least once a day.
 - (2) At least once for each 115 m³ of concrete.
 - (3) At least once for each 465 m² of surface area for slabs or walls.
- (b) On a given project, if total volume of concrete is such that frequency of testing would provide fewer than five strength tests for a given concrete mixture, strength test specimens shall be made from at least five randomly selected batches or from each batch if fewer than five batches are used.

(c) If the total quantity of a given concrete mixture is less than 38m^3 , strength tests are not required if evidence of satisfactory strength is submitted to and approved by the building official.

Acceptance criteria for standard-cured specimens

- (a) Strength level of a concrete mixture shall be acceptable if (1) and (2) are satisfied:
- (1) Every average of any three consecutive strength tests equals or exceeds f_c' .
 - (2) No strength test falls below f_c' by more than 3.5 MPa if f_c' is 35 MPa or less; or by more than $0.10f_c'$ if f_c' exceeds 35 MPa.
- (b) If either of the above requirements is not satisfied, steps shall be taken to increase subsequent strength tests. The steps taken to increase the values of subsequent strength tests will depend on the particular circumstances but could include one or more of (a) through (g):
- a) Increase in cementitious materials content;
 - b) Reduction in or better control of water content;
 - c) Use of a water-reducing admixture to improve the dispersion of cementitious materials;
 - d) Other changes in mixture proportions;
 - e) Reduction in delivery time;
 - f) Closer control of air content;
 - g) Improvement in the quality of the testing, including strict compliance with standards

Investigation of strength tests

If any strength test of standard-cured cylinders falls below f_c' by more than the limit allowed for acceptance, steps shall be taken to ensure that structural adequacy of the structure is not jeopardized

If the likelihood of low-strength concrete is confirmed and calculations indicate that structural adequacy is significantly reduced, tests of cores drilled from the area in question shall be permitted. In such cases, three cores shall be taken for each strength test that falls below f_c' by more than the limit allowed for acceptance

Concrete in an area represented by core tests shall be considered structurally adequate if (1) and (2) are satisfied:

- (1) The average of three cores is equal to at least $0.85 f_c'$.
- (2) No single core is less than $0.75 f_c'$.

If criteria for evaluating structural adequacy based on core strength results are not met, and if the structural adequacy remains in doubt, the responsible authority shall be permitted to order a strength evaluation using other in-place testing techniques for the questionable portion of the structure or take other appropriate action. In-place tests of concrete, such as probe penetration,

rebound hammer, or pullout test may be useful in determining whether a portion of the structure actually contains low-strength concrete. This issue becomes under Strength Evaluation of Existing Structures.

9.5.2 ACI 214R-11

Specimens for each test result: 2 concrete cylinders of 150×300 mm or; 3 concrete cylinders of 100×200 mm.

- Evaluation of standard of quality control through Table 4.3 and Table 4.4 in ACI 214R-11
 - Standard deviation
 - Coefficient of variation

Table 4.3—Standards of concrete control for $f'_c \leq 5000$ psi (35 MPa) $f'_{cube} = 43.7$ MPa

Overall variation					
Class of operation	Standard deviation for different control standards, psi (MPa)				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 400 (below 2.8)	400 to 500 (2.8 to 3.4)	500 to 600 (3.4 to 4.1)	600 to 700 (4.1 to 4.8)	Above 700 (above 4.8)
Laboratory trial batches	Below 200 (below 1.4)	200 to 250 (1.4 to 1.7)	250 to 300 (1.7 to 2.1)	300 to 350 (2.1 to 2.4)	Above 350 (above 2.4)
Within-batch variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Table 4.4—Standards of concrete control for $f'_c \geq 5000$ psi (35 MPa) $f'_{cube} = 43.7$ MPa

Overall variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
General construction testing	Below 7.0	7.0 to 9.0	9.0 to 11.0	11.0 to 14.0	Above 14.0
Laboratory trial batches	Below 3.5	3.5 to 4.5	4.5 to 5.0	5.0 to 7.0	Above 7.0
Within-batch variation					
Class of operation	Coefficient of variation for different control standards, %				
	Excellent	Very good	Good	Fair	Poor
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Estimation of standard deviation or coefficient of variation

- applies a simple approach is to compare overall variability and within-batch variability using standard deviation or coefficient of variation (Table 4.3 and 4.4).
- ACI 214R-11 requires a minimum of 30 test results to calculate of standard deviation or coefficient of variation.
- When Number of test results is less 30, a conservative approach is applied. the sample standard deviation should be increased by up to 16% to account for greater uncertainty in the estimated population standard deviation.

Calculation of Equivalent characteristic compressive strength

To calculate the equivalent (actual) characteristic (specified) compressive strength from the target mean strength obtained from the test results at lab.

Obtained average target mean strength = f_m

Specified characteristic strength = f_c

Margin = $k \cdot s$

K - the required level of concrete quality,

S - calculated standard deviation from the obtained test results at lab.

$$f_m = f_c + k \cdot s$$

$$f_c = f_m - k \cdot s$$

Application

It is required to comment on the quality of a concrete for a raft foundation, the measurement of compressive strength of 17 test results. What is the actual compressive strength if the degree of confidence is 95% and do approve or disapprove this concrete, knowing that the specified (characteristic strength is 20 MPa).

Test Result No	f_m MPa	Deviation	Squared deviation
1	21.8	2.8	7.84
2	18.4	-0.6	0.36
3	17.7	- 1.3	1.69
4	21.5	2.5	6.25
5	18.6	- 0.4	1.6
6	17.3	-1.7	2.89
7	20.9	1.9	3.61
8	14.2	-4.8	23.04
9	15.3	-3.7	13.69
10	18.7	- 0.3	0.09
11	18.1	- 0.9	0.81
12	19.3	0.3	0.09
13	14.7	- 4.3	18.49
14	21.3	2.3	5.29
15	23.1	4.1	16.81
16	20	1.0	1.0
17	22.1	3.1	9.61
	Average=19		Sum = 111.72

$$s = \sqrt{\frac{111.72}{17}} = 2.56 \text{ MPa}$$

$$F_c' = 19 - 1.64 \times 2.56 = 14.8 \text{ MPa less than required 20 MPa}$$

Therefore, this concrete is disapproved. Redesign should be carried out based on $f_c' = 14.8 \text{ MPa}$.

9.5.3 BS EN 206:2013

Clause 8.2: Conformity control for designed concrete

Acceptance testing

Individual strength test variation should not be more than $\pm 15\%$ of the average of these three specimens.

Acceptance criteria

Criteria for individual results

Each individual test result, f_{ci} , shall satisfy:

$$f_{ci} \geq (f_{ck} - 4) \text{ N/mm}^2$$

Criteria for mean results

Method A: Initial production (until 35 test results are obtained)

The mean strength of non-overlapping or overlapping groups of three consecutive results shall satisfy:

$$f_{cm} \geq (f_{ck} + 4) \text{ N/mm}^2$$

Method B: Continuous production (when 35 test results are available)

$$f_{cm} \geq (f_{ck} + 1,48\sigma) \text{ N/mm}^2$$

The Mean strength of the consecutive test results $\geq$ (Specified grade strength + 1.48 $\times$ standard deviation MPa).

9.5.4 IS 456:2000

- Acceptance criteria applies to 28 days compressive strength
- Validation of sample for acceptance criteria:
 - 1- Test result should be average of three specimens.
 - 2- Individual variation should not be more than $\pm 15\%$ of the average of these three specimens.

For example M25 concrete is used, results of three specimens were 28.5 MPa, 26 MPa and 29 MPa, average is 27.83 MPa, deviation from mean is 2.4%, -6.57% and 4.2% respectively. The sample is valid for acceptance criteria.

- Acceptance Criteria

Specified Grade	Mean of the group of 4 non-overlapping consecutive test results in N/mm^2		Individual Test results in N/mm^2
M15	• $\geq (f_{ck} + 0.825 \times \text{established standard deviation}) \text{ N/mm}^2$. • $\geq (f_{ck} + 3) \text{ N/mm}^2$	Whichever is greater value	$\geq (f_{ck} - 3) \text{ N/mm}^2$
M20 or above	• $\geq (f_{ck} + 0.825 \times \text{established standard deviation}) \text{ N/mm}^2$. • $\geq (f_{ck} + 4) \text{ N/mm}^2$	Whichever is greater value	$\geq (f_{ck} - 4) \text{ N/mm}^2$