Chapter 5

CONCRETE MATERIAL

5.1 GENERAL

5.1.1 Scope

The provisions of this chapter shall apply to the design of reinforced and prestressed concrete structures specified in chapters 6, 8, 9 shall be applicable for normal weight aggregate only unless otherwise specified.

5.1.2 Notation

C_c = creep coefficient
Ec = modulus of elasticity of concrete
Es = modulus of elasticity of reinforcement
Et = modulus of elasticity of concrete at the age of loading t
f_c' = specified compressive strength of concrete
f_{cr}' = required average compressive strength of concrete used as the basis for selection of concrete proportions
f_y = specified yield strength of reinforcement
K = coefficient of shrinkage
s = standard deviation
w_c = unit weight of concrete
ε_{cc} = creep strain in concrete
ε_{sh} = shrinkage of plain concrete
ρ = area of steel relative to that of the concrete.

5.2 CONSTITUENTS OF CONCRETE

5.2.1 Cement

5.2.1.1 Cement shall conform to one of the following specifications :

(a) "BDS EN 197-1:2003
(b) "Specification for Portland Cement" (ASTM C150 / C150M - 09)
(c) "Specification for Blended Hydraulic Cement" (ASTM C595 / C595M - 10),
(d) " ASTM C1157 / C1157M - 10 "

5.2.1.2 Cement used in the construction shall be the same as that used in the concrete mix design.

5.2.2 Aggregates

5.2.2.1 Concrete aggregates shall conform to the standards “Coarse and Fine Aggregates from Natural Sources for Concrete” (BDS 243 : 1963); “Specification for Concrete Aggregates” (ASTM C33 / C33M - 08).

5.2.2.2 Maximum nominal size of coarse aggregate shall be the minimum of the following :

(a) $\frac{1}{5}$ the narrowest dimension between sides of forms,

(b) $\frac{1}{3}$ the depth of slabs,

(c) $\frac{3}{4}$ the minimum clear spacing between individual reinforcing bars, or bundles of bars, or prestressing tendons or ducts.

The above limitations may be relaxed if, in the judgment of the engineer, workability and methods of consolidation are such that concrete can be placed without honeycomb or voids.

5.2.2.3 Coarse aggregate made from Grade A bricks as specified in BDS 208 "Specification for Common Building Clay Bricks" may be used in different types slab and non structural elements, except in applications where the ambient environmental conditions may impair the performance of concrete made of such aggregates.

5.2.3 **Water**

5.2.3.1 Water used in mixing concrete shall be clean and free from injurious amounts of oils, acids, alkalis, salts, organic materials, or other substances that may be harmful to concrete or reinforcement.

5.2.3.2 For concrete wherein aluminium members will be embedded, mixing water shall not contain harmful amounts of chloride ion as indicated in Sec 5.5.3.

5.2.3.3 Nonpotable water shall not be used in concrete except the following conditions:

(a) Selection of concrete proportions shall be based on concrete mixes using water from the same source.

(b) Nonpotable water is permitted only if specified comparative mortar test cubes made with nonpotable water produce at least 90 per cent of the strength achieved with potable water.

5.2.4 **Admixtures**

5.2.4.1 Prior approval of the engineer shall be required for the use of admixtures in concrete. All admixtures shall conform to the requirements of this section and Sec 2.4.5 of Part 5.

5.2.4.2 Admixture used in the work shall be the same as that used in the concrete mix design.

5.2.4.3 Admixtures containing chloride other than impurities from admixture ingredients shall not be used in concrete containing embedded aluminium, or in concrete cast against permanent galvanized metal forms (see Sec 5.5.1.2 and 5.5.2.1).

5.2.4.4 Air entraining admixtures, if used in concrete, shall conform to "Specification for Air entraining Admixtures for Concrete" (ASTM C260 - 06).

5.2.4.5 Water reducing admixtures, retarding admixtures, accelerating admixtures, water reducing and retarding admixtures, and water reducing and accelerating admixtures, if used in concrete, shall conform to "Specification for Chemical Admixtures for Concrete" (ASTM C494 / C494M - 10) or "Specification for Chemical Admixtures for use in Producing Flowing Concrete" (ASTM C1017 / C1017M - 07).

5.2.4.6 Fly ash or other pozzolans used as admixtures shall conform to "Specification for Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Portland Cement Concrete " (ASTM C618 - 08a).

5.2.4.7 Ground granulated blast-furnace slag used as an admixture shall conform to "Specification for Ground Iron Blast Furnace Slag for use in Concrete and Mortar" (ASTM C989 - 09a).

5.3 STEEL REINFORCEMENT

5.3.1 General

5.3.1.1 Steel reinforcement for concrete shall conform to the provisions of this section and those of Sec 2.4.6 of Part 5.

5.3.1.2 Modulus of elasticity Es for reinforcement shall be taken as 200 kN/mm2.

5.3.1.3 Reinforcing bars to be welded shall be indicated on the drawings and welding procedure to be used shall be specified. Reinforcing bars otherwise conforming to BDS ISO 6935-2:2006, shall also possess material properties necessary to conform to welding procedures specified in "Structural Welding Code - Reinforcing Steel" (AWS D1.4) of the American Welding Society.

5.3.2 Deformed Reinforcement

5.3.2.1 Deformed reinforcing bars shall conform to one of the following specifications:

(a) "Specification for Steel Bars and Wires for the Reinforcement of Concrete" (BDS 1313),

(b) "Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement" (ASTM A615 / A615M - 09b),

(c) "Specification for Rail Steel Deformed and Plain Bars for Concrete Reinforcement" Including Supplementary Requirements S1 (ASTM A996 / A996M - 09b including S1),

(d) "Specification for Axle Steel Deformed and Plain Bars for Concrete Reinforcement" (ASTM A996 / A996M - 09b),

(e) "Specification for Low Alloy Steel Deformed Bars for Concrete Reinforcement" (ASTM A706 / A706M - 09b),

(f) "Specification for Cold Worked Steel Bars for the Reinforcement of Concrete" (BS 4461).

5.3.2.2 Deformed reinforcing bars with a specified yield strength f_y exceeding 410 N/mm2 shall be permitted, provided f_y shall be the stress corresponding to a strain of 0.35 percent and the bars otherwise conform to one of the ASTM specifications listed in Sec 5.3.2.1 (Also see Sec 6.1.2.5).

5.3.2.3 Galvanized reinforcing bars shall comply with "Specification for Zinc Coated (Galvanized) Steel Bars for Concrete Reinforcement " (ASTM A767 / A767M - 09). Epoxy coated reinforcing bars shall comply with "Specifications for Epoxy Coated Reinforcing Steel Bars" (ASTM A775 / A775M - 07b). Galvanized or epoxy coated reinforcement shall also conform to one of the standards listed in Sec 5.3.2.1 above.

5.3.3 Plain Reinforcement

5.3.3.1 Plain bars shall conform to one of the specifications listed in Section 5.3.2.1 (a), (b), (c) or (d).

5.3.3.2 Plain wire shall conform to "Specification for Steel Wire, Plain, for Concrete Reinforcement" (ASTM A82 / A82M - 07) except that for wire with a specified yield strength fy exceeding 410 N/mm2, fy shall be the stress corresponding to a strain of 0.0035.

5.3.3.3 Plain bars and wire may be used as ties, stirrups and spirals for all structural members and for all reinforcement in structures up to 4-storey high.

5.3.4 Structural Steel, Steel Pipe or Tubing

5.3.4.1 Structural steel used with reinforcing bars in composite compression members meeting the requirements of Sec 6.3.10.8 or 6.3.10.9 shall conform to one of the following specifications:

(a) "Specification for Structural Steel" (ASTM A36 / A36M - 08),

(b) "Specification for High Strength Low Alloy Structural Steel"(ASTM A242 / A242M - 04(2009)),

(c) "Specification for High Strength Low Alloy Structural Manganese Vanadium Steel" (ASTM A572 / A572M - 07),

(d) "Specification for High Strength Low Alloy Columbium-Vanadium Steels of Structural Quality" (ASTM A572 / A572M - 07),

(e) "Specification of High Strength Low Alloy Structural Steel with 50 ksi (345 Mpa) Minimum Yield Point to 4 in (100 mm) Thick" (ASTM A588 / A588M - 05).

5.3.4.2 Steel pipe or tubing for composite compression members composed of a steel encased concrete core meeting the requirements of Sec 6.3.10.7 shall conform to one of the following specifications:

(a) Grade B of "Specification for Pipe, Steel, Black and Hot Dipped, Zinc Coated Welded and Seamless" (ASTM A53 / A53M - 07).

(b) "Specification for Cold Formed Welded and Seamless Carbon Steel Structural Tubing in Rounds and Shapes" (ASTM A500 / A500M - 10).

(c) "Specification for Hot Formed Welded and Seamless Carbon Steel Structural Tubing " (ASTM A501 - 07).

5.4 WORKABILITY OF CONCRETE

Concrete mix proportions shall be such that the concrete is of adequate workability and can properly be compacted. Suggested ranges of values of workability of concrete for some placing conditions, are given in Table 6.5.1.

Table 6.5.1: Suggested Workability of Concrete for Various Placing Conditions

Placing Conditions	Degree of Workability	Values of Workability
Concreting of thin sections with vibration	Very low	20-10 seconds Vee-Bee time or 0.75-0.80 compacting factor
Concreting of lightly reinforced sections with vibration	Low	10-5 seconds Vee-Bee time or 0.80-0.85 compacting factor
Concreting of lightly reinforced sections without vibration or heavily reinforced section with vibration	Medium	5-2 seconds Vee-Bee time or 0.85-0.92 compacting factor or 25-75 mm slump for 20* mm aggregate
Concreting of heavily reinforced sections without vibration	High	Above 0.92 compacting factor or 75-125 mm slump for 20* mm aggregate

* For smaller aggregates the values will be lower

5.5 DURABILITY OF CONCRETE

5.5.1 Special Exposures

5.5.1.1 For concrete intended to have low permeability when exposed to water, the water cement ratio shall not exceed 0.50.

5.5.1.2 For corrosion protection of reinforced concrete exposed to brackish water, sea water or spray from these sources, the water cement ratio shall not exceed 0.4.

If minimum concrete cover required by Sec 8.1.8 is increased by 12 mm, water cement ratio may be increased to 0.45.

5.5.1.3 The water cement ratio required in Sec 5.5.1.1 and 5.5.1.2 above and Table 6.5.2 shall be calculated using the weight of cement meeting the requirements of BDS EN-197-1 or ASTM C595 / C595M - 10 or C1157 / C1157M - 10, plus the weight of fly ash or pozzolan satisfying ASTM C618 - 08a and/or slag satisfying ASTM C989 - 09a, if any.

5.5.2 Sulphate Exposures

5.5.2.1 Concrete to be exposed to sulphate containing solutions or soils shall conform to the requirements of Table 6.5.2 or be made with a cement that provides sulphate resistance with the maximum water cement ratio provided in Table 6.5.2.

5.5.2.2 Calcium chloride shall not be used as an admixture in concrete exposed to severe or very severe sulphate containing solutions, as defined in Table 6.5.2.

5.5.3 Corrosion of Reinforcement

5.5.3.1 For corrosion protection, maximum water soluble chloride ion concentrations in hardened concrete at ages from 28 to 42 days contributed from the ingredients including water, aggregates, cementitious materials, and admixtures, shall not exceed the limits of Table 6.5.3. When testing is performed to determine water soluble chloride ion content, test procedure shall conform to AASHTO T260, "Methods of Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials".

5.5.3.2 When reinforced concrete will be exposed to brackish water, sea water, or spray from these sources, requirements of Sec 5.5.1.1 and 5.5.1.2 for water cement ratio, or concrete strength and minimum cover requirements of Sec 8.1.8 shall be satisfied.

5.5.4 Minimum Concrete Strength

Minimum concrete strength for structural use of reinforced concrete shall be 20 N/mm^2. However, for buildings up to 4 storey, the minimum concrete strength may be relaxed to 17 N/mm^2.

Table 6.5.2 : Requirements for Normal Weight Aggregate Concrete Exposed to Sulphate Containing Solutions

Sulphate Exposure	Water Soluble Sulphate (SO_4) in Soil, per cent by Weight	Sulphate (SO_4) in Water, (ppm)	Cement Type[1]	Maximum Water Cement Ratio, by Weight
Negligible	0.00-0.10	0 – 150	-	-

Moderate2	0.10-0.20	150 -1500	Other than CEM I and B type	0.50
Severe	0.20-2.00	1500 - 10,000	Other than CEM-I and B type	0.45
Very severe	Over 2.00	Over 10,000	Other than CEM-I and B type	0.45

Note : [1] For types of cement see ASTM C 150 and C 595

[2] Sea water

3 Pozzolan that has been determined by test or service record to improve sulphate resistance when used in concrete containing Type V cement.

Table 6.5.3: Maximum Chloride Ion Content for Corrosion Protection

Type of Member	Maximum Water Soluble Chloride Ion (Cl-) in Concrete, Per Cent by Weight of Cement
Prestressed concrete	0.06
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture in service	1.00
Other reinforced concrete construction	0.30

5.6 CONCRETE MIX PROPORTION

5.6.1 General

5.6.1.1 Proportions of materials for concrete shall be such that :

(a) Workability and consistency are achieved for proper placement into forms and around reinforcement, without segregation or excessive bleeding;

(b) Resistance to special exposures to meet the durability requirements of Sec 5.5 are provided; and

(c) Conformance with strength test requirements of Sec 5.12 is ensured.

5.6.1.2 Where different materials are to be used for different portions of the proposed work, each combination shall be evaluated.

5.6.1.3 Concrete proportions, including water cement ratio, shall be established on the basis of field experience and/or trial mixtures with materials to be employed (Sec 5.6.2) except as permitted in Sec 5.6.3 or required by Sec 5.5.

5.6.2

Proportioning Concrete Mix on the Basis of Field Experience and/or Trial Mixtures

5.6.2.1 Standard Deviation

(a) A standard deviation shall be established where test records are available in a concrete production facility. Test records from which a standard deviation is calculated shall meet the following requirements :

i) These shall represent materials, quality control procedures, and conditions similar to those expected for the proposed work. Deviations in materials and proportions for the proposed work shall be more restricted than those within the test records.

ii) Test records shall represent concrete produced to meet a specified strength f_c' within 7 N/mm^2 of that specified for the proposed work.

iii) The record shall consist of at least 30 consecutive tests or two groups of consecutive tests totaling at least 30 tests as defined in Sec 5.12.2.4 except as provided in (b) below.

(b) Where a concrete production facility does not have test records meeting the requirements of (a) above but does have a record based on 15 to 29 consecutive tests, a standard deviation shall be established as the product of the calculated standard deviation and the modification factor specified in Table 6.5.4. However, the test records shall meet the requirements (i) and (ii) of (a) above and represent only a single record of consecutive tests that span a period of not less than 45 calendar days.

Table 6.5.4 : Modification Factor for Standard Deviation when Less Than 30 Tests are Available

No. of Tests*	Modification Factor for Standard Deviation **
Less than 15	see Sec 5.6.2.2(b)
15	1.16
20	1.08
25	1.03
30 or more	1.00

* Interpolate for intermediate numbers of tests

** Modified standard deviation to be used to determine the required average strength f_{cr}' from 5.6.2.2(a).

5.6.2.2 Required Average Strength

(a) Required average compressive strength f_c' used as the basis for selection of concrete proportions shall be the larger of the values given by Eq (5.6.1) and (5.6.2) using a standard deviation calculated in accordance with Sec 5.6.2.1(a) or 5.6.2.1(b) above.

$$f_{cr}' = f_c' + 1.34s \quad (5.6.1)$$

$$f_{cr}' = f_c' + 2.33s - 3.5 \quad (5.6.2)$$

(b) b) When a concrete production facility does not have field strength test records for calculation of standard deviation meeting the requirements of Sec 5.6.2.1(a) or 5.6.2.1(b), the required average strength shall be determined from Table 6.5.5 and documentation of the average strength shall be in accordance with the requirements of Sec 5.6.2.3 below.

Table 6.5.5 : Required Average Compressive Strength when Data are not Available to Establish a Standard Deviation

Specified Compressive Strength f_c' N/mm^2	Required Average Compressive Strength, f_{cr}' N/mm^2

Less than 20	f'_c + 7.0
20 to 35	f'_c + 8.5
Over 35	f'_c + 10.0

5.6.2.3 Documentation of Average Strength

Documentation shall be prepared to demonstrate that the proposed concrete proportions will produce an average compressive strength equal to or greater than the required average compressive strength (Sec 5.6.2.2). Such documentation shall consist of one or more field strength test records or trial mixtures.

(a) When test records are used to demonstrate that proposed concrete proportions will produce the required average strength f'_{cr} (Sec 5.6.2.2) such records shall represent materials and conditions similar to those expected. Deviations in materials, conditions and proportions within the test records shall not have been more restricted than those for proposed work. For the purpose of documenting average strength potential, test records consisting of less than 30 but not less than 10 consecutive tests are acceptable provided the test records encompass a period of time not less than 45 days. Required concrete proportions shall be permitted to be established by interpolation between the strengths and proportions of two or more test records each of which meets other requirements of this section.

(b) When an acceptable record of field test results is not available, concrete proportions may be established based on trial mixtures meeting the following restrictions :

i) Combination of materials shall be those for the proposed work.

ii) Trial mixtures having proportions and consistencies required for the proposed work shall be made using at least three different water cement ratios or cement contents that will produce a range of strengths encompassing the required average strength .

iii) Trial mixtures shall be designed to produce a slump within ±20 mm of the maximum permitted, and for air entrained concrete the air content shall be within ±0.5 per cent of the maximum allowable.

iv) For each water cement ratio or cement content, at least three test cylinders for each test age shall be made and cured in accordance with "Method of Making and Curing Concrete Test Specimens in the Laboratory" (ASTM C192 / C192M - 07). Cylinders shall be tested at 28 days or at test age designated for the determination of f'_c .

v) From the results of cylinder tests, a curve shall be plotted showing the relationship between the water cement ratio or cement content and the compressive strength at designated test age.

vi) Maximum water cement ratio or minimum cement content for concrete to be used in the proposed work shall be that shown by the above curve to produce the average strength required by Sec 5.6.2.2 unless a lower water cement ratio or higher strength is required by Sec 5.5.

5.6.3 **Proportioning by Water Cement Ratio**

5.6.3.1 If the data required in Sec 5.6.2 are not available, concrete proportions shall be based on water cement ratio limits specified in Table 6.5.6 when approved by the engineer.

Table 6.5.6 : Maximum Permissible Water Cement Ratios for Concrete when Strength Data from Field Experience or Trail Mixers are not Available

Specified Compressive Strength*, f'_c	**Absolute Water Cement Ratio by Weight**

N/mm²	Concrete other than air-entrained	Air-entrained concrete
17	0.66	0.54
20	0.60	0.49
25	0.50	0.39
30	0.40	**
35	**	**

* 28 day strength. With most materials, water cement ratios shown will provide average strengths greater than that required in Sec 5.6.2.2.

** For strengths above 30 N/mm^2 (25 N/mm^2 for air entrained concrete) concrete proportions shall be established by methods of Sec 5.6.2.

5.6.3.2 Table 6.5.6 shall be used only for concrete to be made with cements meeting strength requirements for Types I, IA, II, IIA, III, IIIA, or V of "Specification for Portland Cement" (ASTM C150 / C150M - 09), or Types IS, IS-A, IS (MS), IS-A(MS), I(SM), I(SM)-A, IP, IP-A, I(PM), I(PM)-A, IP(MS), IP-A(MS), or P of "Specification for Blended Hydraulic Cements" (ASTM C595 / C595M - 10), and shall not be applied to concrete containing lightweight aggregates or admixtures other than those for entraining air.

5.6.3.3 Concrete proportioned by water cement ratio limits prescribed in Table 6.5.6 shall also conform to special exposure requirements of Sec 5.5 and to compressive strength test criteria of Sec 5.12.

5.6.4 Average Strength Reduction

As data become available during construction, amount by which value of f_c' must exceed specified value of f_c' may be reduced, provided:

(a) 30 or more test results are available and the average of test results exceeds that required by Sec 5.6.2.2(a) using a standard deviation calculated in accordance with Sec 5.6.2.1(a), or

(b) 15 to 29 test results are available and the average of test results exceeds that required by Sec 5.6.2.2(a) using a standard deviation calculated in accordance with Sec 5.6.2.1(b), and provided further that special exposure requirements of Sec 5.5 are met.

5.7 Preparation of Equipment and Place of Deposit

Preparation before concrete placement shall include the following:

(a) All equipment for mixing and transporting concrete shall be clean.

(b) All debris shall be removed from spaces to be occupied by concrete.

(c) Forms shall be properly cleaned and coated.

(d) Masonry filler units that will be in contact with concrete shall be soaked thoroughly.

(e) Reinforcement shall be thoroughly clean of deleterious coatings.

(f) Water shall be removed from place of deposit before concrete is placed unless a tremie is used or unless otherwise permitted by the engineer.

(g) All laitance and other unsound material shall be removed before additional concrete is placed against hardened concrete.

5.8 MIXING

5.8.1

All concrete shall be mixed thoroughly until there is a uniform distribution of materials and shall be discharged completely before the mixer is recharged.

5.8.2

Ready mixed concrete shall be mixed and delivered in accordance with the requirements of "Specification for Ready Mixed Concrete" (ASTM C94) or "Specification for Concrete Made by Volumetric Batching and Continuous Mixing" (ASTM C685).

5.8.3

Job mixed concrete shall be mixed in accordance with the following:

(a) Mixing shall be done in a batch mixer of approved type.

(b) Mixer shall be rotated at a speed recommended by the manufacturer.

(c) Mixing shall be continued for at least 90 seconds after all materials are in the drum, unless a shorter time is shown to be satisfactory by the mixing uniformity tests of "Specification for Ready Mixed Concrete" (ASTM C94).

(d) Materials handling, batching, and mixing shall conform to the applicable provisions of "Specification for Ready Mixed Concrete" (ASTM C94).

(e) A detailed record shall be kept to identify:

i) number of batches produced;

ii) proportions of materials used;

iii) approximate location of final deposit in structure;

iv) time and date of mixing and placing.

5.9 CONVEYING

5.9.1

Concrete shall be conveyed from the mixer to the place of final deposit by methods that will prevent segregation or loss of materials.

5.9.2

Conveying equipment shall be capable of providing a supply of concrete to the place of deposit without segregation of ingredients and without interruptions sufficient to permit loss of plasticity between successive increments.

5.10 DEPOSITING

5.10.1

Concrete shall be deposited as near its final position as practical to avoid segregation due to rehandling or flowing.

5.10.2

Concreting shall be carried on at such a rate that concrete is at all times plastic and flows readily into spaces between and around the reinforcement.

5.10.3

Concrete that has partially hardened or been contaminated by foreign materials shall not be deposited in the structure.

5.10.4

Retempered concrete or concrete that has been remixed after initial set shall not be used.

5.10.5

After concreting is started, it shall be carried on as a continuous operation until placing of a panel or section, as defined by its boundaries or predetermined joints, is completed except as permitted or prohibited by Sec 5.16.4.

5.10.6

Top surfaces of vertically formed lifts shall be generally level.

5.10.7

When construction joints are required, joints shall be made in accordance with Sec 5.16.4.

5.10.8

All concrete shall be thoroughly consolidated by suitable means during placement and shall be thoroughly worked around reinforcement and embedded fixtures and into corners of forms.

5.11 CURING

5.11.1

Concrete (other than high early strength) shall be maintained above 10oC and in a moist condition for at least the first 7 days after placement, except when cured in accordance with Sec 5.11.3.

5.11.2

High early strength concrete shall be maintained above 10oC and in a moist condition for at least the first 3 days, except when cured in accordance with Sec 5.11.3.

5.11.3 Accelerated Curing

5.11.3.1 Curing by high pressure steam, steam at atmospheric pressure, heat and moisture or other accepted processes, shall be permitted to accelerate strength gain and reduce time of curing.

5.11.3.2 Accelerated curing shall provide a compressive strength of the concrete at the load stage considered, at least equal to the required design strength at that load stage.

5.11.3.3 Curing process shall be such as to produce concrete with a durability at least equivalent to that obtained for concrete cured by the method of Sec 5.11.1 or 5.11.2.

5.11.4

When required by the engineer, supplementary strength tests in accordance with Sec 5.12.4 shall be performed to assure that curing is satisfactory.

5.12 EVALUATION AND ACCEPTANCE OF CONCRETE

5.12.1 General

5.12.1.1 Concrete shall be proportioned to provide an average compressive strength as prescribed in Sec 5.6.2.2 as well as to satisfy the durability criteria of Sec 5.5. Concrete shall be produced to limit frequency of strengths below f_c' to that prescribed in Sec 5.12.3.3.

5.12.1.2 Requirements of shall be based on tests of cylinders made and tested as prescribed in Sec 5.12.3.

5.12.1.3 Unless otherwise specified, f_c' shall be based on 28 day tests. Test age for f_c' shall be indicated in design drawings or specifications, if it is different from 28 days.

5.12.1.4 Splitting tensile strength tests shall not be used as a basis for field acceptance of concrete.

5.12.2 Frequency of Testing

5.12.2.1 Samples for strength tests of each class of concrete placed each day shall be taken not less than once a day, nor less than once for each 60 m3 of concrete, nor less than once for each 250 m2 surface area for slabs or walls.

5.12.2.2 On a given project, if the total volume of concrete is such that frequency of testing required by Sec 5.12.2.1 above would provide less than three strength tests for a given class of concrete, tests shall be made from at least three randomly selected batches or from each batch if three or fewer batches are used.

5.12.2.3 When the total quantity of a given class of concrete is less than 20 m3, strength tests are not required when evidence of satisfactory strength is submitted to and approved by the engineer.

5.12.2.4 A strength test result shall be the average of the strengths of two cylinders made from the same sample of concrete and tested at 28 days or at the test age designated in accordance with Sec 5.12.1.3.

5.12.3 Laboratory Cured Specimens

5.12.3.1 Samples for strength tests shall be taken in accordance with "Method of Sampling Freshly Mixed Concrete" (ASTM C172 - 08).

5.12.3.2 Cylinders for strength tests shall be moulded and laboratory cured in accordance with "Practice for Making and Curing Concrete Test Specimens in the Field" (ASTM C31 / C31M - 09) and tested in accordance with "Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM C39 / C39M - 09a).

5.12.3.3 Strength level of an individual class of concrete shall be considered satisfactory if both of the following requirements are met :

(a) Average of three consecutive strength tests (see Sec 5.12.2.4) equals or exceeds f_c'

(b) No individual strength test (average of two cylinders) falls below by more than 3.5 N/mm^2.

5.12.3.4 If either of the requirements of Sec 5.12.3.3 are not met, steps shall be taken to increase the average of the subsequent strength test results. Requirements of Sec 5.12.5 shall be satisfied if the requirement of Sec 5.12.3.3(b) is not met.

5.12.4 Field Cured Specimens

5.12.4.1 The engineer may require strength tests of cylinders cured under field conditions to check adequacy of curing and protection of concrete in the structure.

5.12.4.2 Field cured cylinders shall be cured under field conditions in accordance with "Practice for Making and Curing Concrete Test Specimens in the Field" (ASTM C31 / C31M - 09).

5.12.4.3 Field cured test cylinders shall be moulded at the same time and from the same samples as laboratory cured test cylinders.

5.12.4.4 Procedures for protecting and curing concrete shall be improved when the strength of field cured cylinders at the test age designated for determination of f_c' is less than 85 per cent of that of companion laboratory cured cylinders. The 85 per cent limitation shall not apply if field cured strength exceeds f_c' by more than 3.5 N/mm2.

5.12.5 Investigation of Low Strength Test Results

5.12.5.1 If the result of any strength test (Sec 5.12.2.4) of laboratory cured cylinders falls below the specified value of by more than 3.5 N/mm2 (Sec 5.12.3.3(b)) or if tests of field cured cylinders indicate deficiencies in protection and curing (Sec 5.12.4.4), steps shall be taken to assure that the load carrying capacity of the structure is not jeopardized.

5.12.5.2 If the likelihood of low strength concrete is confirmed and computations indicate that load carrying capacity may have been significantly reduced, tests of cores drilled from the area in question may be required in accordance with "Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete" (ASTM C42 / C42M - 04). In such cases, three cores shall be taken for each strength test more than 3.5 N/mm2 below the specified value of f_c'.

5.12.5.3 If concrete in the structure is expected to be dry under service conditions, cores shall be air dried for 7 days before test and shall be tested dry. If concrete in the structure is expected to be more than superficially wet under service conditions, cores shall be immersed in water for at least 40 hours and be tested wet.

5.12.5.4 Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 per cent of f_c' and if no single core is less than 75 per cent of f_c'. Additional testing of cores extracted from locations represented by erratic core strength results shall be permitted.

5.12.5.5 If the criteria of Sec 5.12.5.4 above are not met, and if structural adequacy remains in doubt, the responsible authority may order load tests for the questionable portion of the structure, or take other appropriate action.

5.13 PROPERTIES OF CONCRETE

5.13.1 Strength

Strength of concrete shall be based on f_c' determined in accordance with the provisions of Sec 5.12.1.

5.13.2 Modulus of Elasticity

5.13.2.1 Modulus of elasticity Ec for stone aggregate concrete may be taken as 44 wc1.5 $\sqrt{f_c'}$ (N/mm2) for values of wc between 15 and 25 kN/m3 and f_c' in N/mm2. For normal density concrete, Ec may be taken as 4700$\sqrt{f_c'}$.

5.13.2.2 Modulus of elasticity Ec for brick aggregate concrete may be taken as 3750$\sqrt{f_c'}$.

5.13.3 Creep

The final (30 year) creep strain in concrete ε_{cc} shall be predicted from

$$\varepsilon_{cc} = \frac{\text{stress}}{E_t} c_c \qquad (5.13.1)$$

where

E_t is the modulus of elasticity of the concrete at the age of loading *t*,

c_c is the creep coefficient.

The creep coefficient may be estimated from Fig 6.5.1. In this figure, for uniform sections, the effective section thickness is defined as twice the cross-sectional area divided by the exposed perimeter. If drying is prevented by immersion in water or by sealing, the effective section thickness shall be taken as 600 mm.

It can be assumed that about 40%, 60% and 80% of the final creep develops during the first month, 6 months and 30 months under load respectively, when concrete is exposed to conditions of constant relative humidity.

5.13.4 **Shrinkage**

An estimate of the drying shrinkage of plain concrete may be obtained from Fig 6.5.2. Recommendations for effective section thickness and relative humidity are given in Sec 5.13.3.

Fig 6.5.2 relates to concrete of normal workability made without water reducing admixtures; such concretes shall have an original water content of about 190 l/m3. Where concrete is known to have a different water content, shrinkage shall be regarded as proportional to water content within the range 150 l/m3 to 230 l/m3.

The shrinkage of plain concrete is primarily dependent on the relative humidity of the air surrounding the concrete, the surface area from which moisture can be lost relative to the volume of concrete and on the mix proportion. It is increased slightly by carbonation and self desiccation and reduced by prolonged curing.

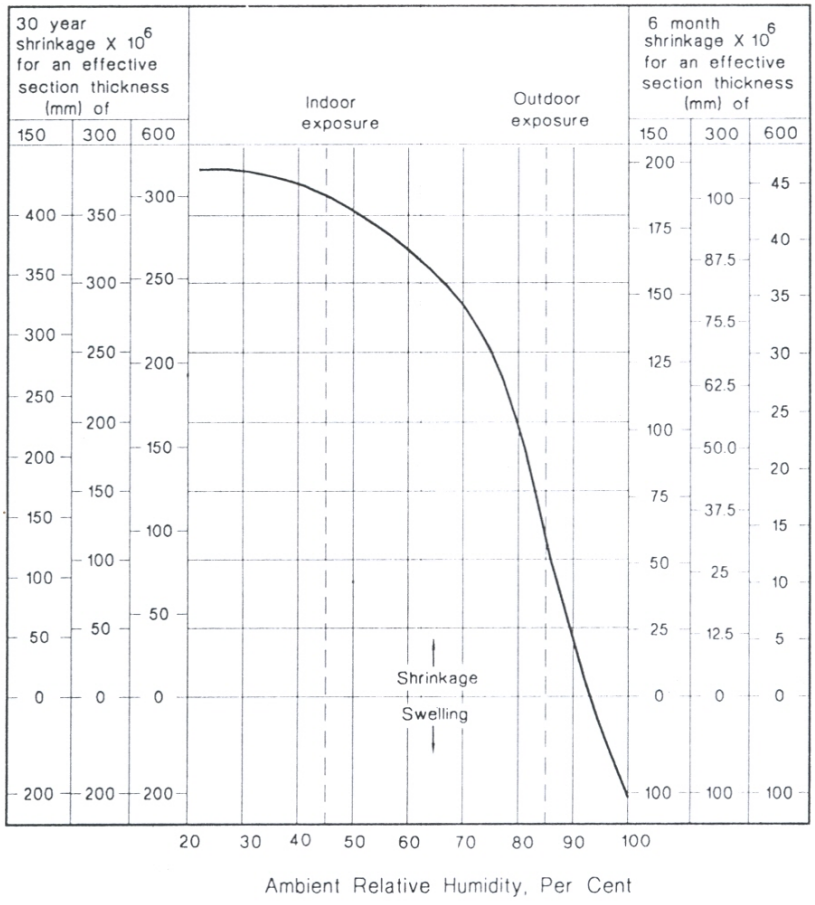

Fig. 6.5.2 Drying Shrinkage of Normal-Weight Concrete

An estimate of the shrinkage of symmetrically reinforced concrete sections may be obtained from :

$$\frac{\varepsilon_{sh}}{1+\kappa\rho} \qquad (5.13.2)$$

Where

ε_{sh} is the shrinkage of the plain concrete;

ρ is the area of steel relative to that of the concrete;

K is a coefficient, taken as 25 for internal exposure and as 15 for external exposure.

5.13.5 **Thermal Strains**

Thermal strains shall be calculated from the product of a suitable coefficient of thermal expansion and a temperature change. The temperature change can be determined from the expected service conditions and climatic data. Externally exposed concrete does not respond immediately to air temperature change, and climatic temperature ranges may require adjustment before use in movement calculations.

The coefficient of thermal expansion of concrete is dependent mainly on the expansion coefficients for the aggregate and the cement paste, and the degree of saturation of the concrete. The thermal expansion of aggregate is related to mineralogical composition (See Table 6.5.7)

Table 6.5.7: Thermal Expansion of Rock Group and Related Concrete

Aggregate Type	Typical Coefficient of Expansion (1 × 10-6/oC)	
	Aggregate	**Concrete**
Flint, quartzite	11	12
Granite, basalt	7	10
Limestone	6	8

Cement paste has a coefficient of thermal expansion that is a function of moisture content, and this affects the concrete expansion as shown in Fig 6.5.3. It may be seen that partially dry concrete has a coefficient of thermal expansion that is approximately 2 10-6/oC greater than the coefficient for saturated concrete.

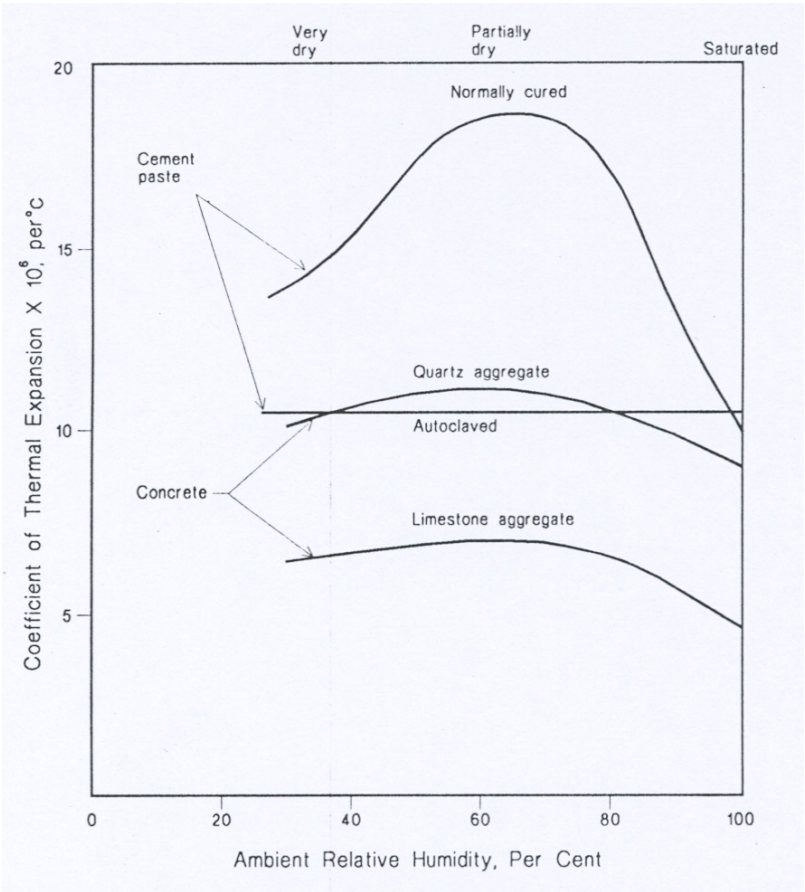

Fig. 6.5.3 Effect of Dryness upon the Coefficient of Thermal Expansion of Hardened Cement and Concrete

5.14 CONCRETING IN ADVERSE WEATHER

5.14.1

Concreting shall be avoided during periods of near freezing weather.

5.14.2

During hot weather, proper attention shall be given to ingredients, production methods, handling, placing, protection, and curing to prevent excessive concrete temperatures or water evaporation that could impair required strength or serviceability of the member or structure.

5.14.3

During rainy weather, proper protection shall be given to ingredients, production methods, handling and placing of concrete. If required in the opinion of the engineer, the concreting operation shall be postponed and newly placed concrete shall be protected from rain after forming proper construction joint for future continuation.

5.15 SURFACE FINISH

5.15.1 Type of Finish

A wide variety of finishes can be produced. Surface cast against forms may be left as cast, e.g. plain or profiled, the initial surface may be removed, e.g. by tooling or sandblasting, or the concrete may be covered, e.g. by paint or tiles; combinations of these techniques may also be adopted, e.g. a ribbed profile with bush hammered ribs. Upper surfaces not cast against forms may be trowelled smooth or profiled, e.g. by tamping; the initial surface may be removed, e.g. by spraying , or it may be covered, e.g. by a screed or plastic floor finish. When selecting the type of finish, consideration shall be given to the ease of producing a finish of the required standard, the viewing distance and the change of appearance with time. In the case of external surfaces, account shall be taken of the weather pattern at the particular location, any impurities in the air and the effect of the shape of the structure upon the flow of water across its surface. Such considerations will often preclude the specification of surfaces of uniform colour as these are very difficult to produce and deteriorate with time, particularly if exposed to the weather.

5.15.2 Quality of Finish

A high quality finish is one that is visually pleasing; it may include colour variations and physical discontinuities but these are likely to be distributed systematically or randomly over the whole surface rather than being concentrated in particular areas. When deciding on the quality of finish to be specified, consideration should be given to the viewing distance and the exposure conditions.

There is no method whereby the quality of finish that will be accepted can unequivocally be defined. To achieve the quality required calls for good communication between experienced personnel conversant with the production of finishes and close collaboration with the site. The quality of finish can be identified in the following very broad terms:

(a) Class 2 applies to surfaces that are to be exposed to view but where appearance is not critical; such surfaces might be the walls of fire escape stairs or plant rooms and columns and beams of structures that are normally viewed in the shade, e.g. car parks and warehouses;

(b) Class 1 is appropriate to most surfaces exposed to view including the external walls of industrial, commercial and domestic buildings;

(c) Special class is appropriate to the highest standards of appearance, such as might be found in prestigious buildings, where it is possible to justify the high cost of their production.

(d) These broad descriptions may be amplified by written descriptions of the method of finish, by photographs, by samples or by reference to existing structures.

5.15.3 Type of Surface Finish

Smooth off-the-form and board marked finishes are not recommended for external use, but where they are specified for interior use the following types may be quoted for the guidance of both designers and contractor.

Designers should appreciate that it is virtually impossible to achieve dense, flat, smooth, even coloured blemish free concrete surfaces directly from the form work. Some degree of making good is inevitable, even with precast work.

(a) Type A finish : This finish is obtained by the use of properly designed formwork or moulds of timber, plywood, plastics, concrete or steel. Small blemishes caused by entrapped air or water may be expected, but the surface should be free from voids, honeycombing or other blemishes.

(b) Type B finish : This finish can only be obtained by the use of high quality concrete and formwork. The concrete shall be thoroughly compacted and all surfaces shall be true, with clean arises. Only very minor surface blemishes shall occur, with no staining or discoloration from the release agent.

(c) Type C finish : This finish is obtained by first producing a type B finish. The surface is then improved by carefully removing all fins and other projections, thoroughly washing down, and then filling the most noticeable surface blemishes with a cement and fine aggregate paste to match the colour of the original concrete. The release agent should be carefully chosen to ensure that the concrete surface will not be stained or discoloured. After the concrete has been properly cured, the face shall be rubbed down, where necessary, to produce a smooth and even surface.

5.15.4 Production

The quality of a surface depends on the constituents and proportions of the concrete mix, the efficiency of mixing, the handling and compaction of the concrete and its curing. The characteristics of the formwork and the release agent may also be of critical importance. Requirements may be stated for any aspect of production that might contribute towards the achievement of the required type of quality of finish.

5.15.5 Inspection and Making Good

The surface of the concrete shall be inspected for defects and for conformity with the specification and, where appropriate, for comparison with approved sample finishes. Subject to the strength and durability of the concrete being unimpaired, the making good of surface defects may be permitted but the standard of acceptance shall be appropriate to the type and quality of the finish specified and ensure satisfactory performance and durability. On permanently exposed surfaces great care is essential in selecting the materials and the mix proportions to ensure that the final colour of the faced area blends with the parent concrete in the finished structure.

Voids can be filled with fine mortar, preferably incorporating styrene butadiene rubber (SBR) or polyvinyl acetate (PVA), while the concrete is still green or when it has hardened. Fine cracks can be filled by wiping a cement grout, an SBR, PVA or latex emulsion, a cement/SBR or a cement/PVA slurry across them. Fins and other projections shall be rubbed down.

5.15.6 Protection

High quality surface finishes are susceptible to damage during subsequent construction operations and temporary protection may have to be provided in vulnerable areas. Examples of such protective measures include the strapping of laths to arrises and the prevention of rust being carried from exposed starter bars to finished surfaces.

5.16 FORMWORK

5.16.1 Design of Formwork

5.16.1.1 Forms shall result in a final structure that conforms to shapes, lines, and dimensions of the members as required by the design drawings and specifications.

5.16.1.2 Forms shall be substantial and sufficiently tight to prevent leakage of mortar.

5.16.1.3 Forms shall be properly braced or tied together to maintain position and shape.

5.16.1.4 Forms and their supports shall be designed so as not to damage previously placed structure.

5.16.1.5 Design of formwork shall include consideration of the following factors:

(a) Rate and method of placing concrete;

(b) Construction loads, including vertical, horizontal and impact loads;

(c) Special form requirements for construction of shells, folded plates, domes, architectural concrete, or similar types of elements.

5.16.1.6 Forms for prestressed concrete members shall be designed and constructed to permit movement of the member without damage during application of prestressing force.

5.16.2 Removal of Forms and Shores

5.16.2.1 No construction loads shall be supported on, nor any shoring removed from, any part of the structure under construction except when that portion of the structure in combination with remaining forming and shoring system has sufficient strength to support safely its weight and loads placed thereon.

5.16.2.2 Sufficient strength shall be demonstrated by structural analysis considering proposed loads, strength of forming and shoring system, and concrete strength data. Structural analysis and concrete strength test data shall be furnished to the engineer when so required.

5.16.2.3 No construction loads exceeding the combinations of superimposed dead load plus specified live load shall be supported on any unshored portion of the structure under construction, unless analysis indicates adequate strength to support such additional loads.

5.16.2.4 Forms shall be removed in such a manner as not to impair safety and serviceability of the structure. All concrete to be exposed by form removal shall have sufficient strength not to be damaged thereby.

5.16.2.5 Forms supporting prestressed concrete members shall not be removed until sufficient prestressing has been applied to enable prestressed members to carry their dead load and anticipated construction loads.

5.16.3 Conduits and Pipes Embedded in Concrete

5.16.3.1 Conduits, pipes and sleeves of any materials not harmful to concrete and within the limitations specified herein shall be permitted to be embedded in concrete with the approval of the engineer, provided they are not considered to replace structurally the displaced concrete.

5.16.3.2 Conduits and pipes of aluminium shall not be embedded in structural concrete unless effectively coated or covered to prevent aluminium concrete reaction or electrolytic action between aluminium and steel.

5.16.3.3 Conduits, pipes, and sleeves passing through a slab, wall, or beam shall not impair significantly the strength of the construction.

5.16.3.4 Conduits and pipes, with their fittings, embedded within a column shall not displace more than 4 per cent of the area of cross-section on which strength is calculated or which is required for fire protection.

5.16.3.5 Except when drawings for conduits and pipes are approved by the engineer, conduits and pipes embedded within a slab, wall or beam (other than those merely passing through) shall satisfy the following:

(a) They shall not be larger in outside dimension than $\frac{1}{3}$ the overall thickness of slab, wall, or beam in which they are embedded.

(b) They shall not be spaced closer than 3 diameters or widths on centre.

(c) They shall not impair significantly the strength of the construction.

5.16.3.6 Conduits, pipes and sleeves shall be permitted to be considered as replacing structurally in compression the displaced concrete provided :

(a) They are not exposed to rusting or other deterioration.

(b) They have nominal inside diameter not over 50 mm and are spaced not less than 3 diameters on centres.

5.16.3.7 Pipes and fittings shall be designed to resist effects of the material, pressure, and temperature to which they will be subjected.

5.16.3.8 No liquid, gas, or vapour, except water not exceeding 30oC nor 0.3 N/mm2 pressure, shall be placed in the pipes until the concrete has attained its design strength.

5.16.3.9 In solid slabs, piping, unless it is for radiant heating, shall be placed between the top and bottom reinforcements.

5.16.3.10 Concrete cover for pipes, conduits, and fittings shall be not less than 40 mm for concrete exposed to earth or weather, nor 20 mm for concrete not exposed to weather or in contact with ground.

5.16.3.11 Reinforcement with an area not less than 0.002 times the area of concrete section shall be provided normal to piping.

5.16.3.12 Piping and conduit shall be so fabricated and installed that cutting, bending, or displacement of reinforcement will not be required.

5.16.4 **Construction Joints**

5.16.4.1 Surface of concrete construction joints shall be cleaned and laitance removed.

5.16.4.2 Immediately before new concrete is placed, all construction joints shall be wetted and standing water removed.

5.16.4.3 Construction joints shall be so made and located as not to impair the strength of the structure. Provision shall be made for transfer of shear and other forces through construction joints. See Sec 6.13.3.15(j).

5.16.4.4 Construction joints in floors shall be located within the middle third of spans of slabs, beams and girders. Joints in girders shall be offset a minimum distance of two times the width of intersecting beams.

5.16.4.5 Beams, girders, or slabs supported by columns or walls shall not be cast or erected until concrete in the columns or walls is no longer plastic.

5.16.4.6 Beams, girders, haunches, drop panels and capitals shall be placed monolithically as part of a slab system unless otherwise shown in the design drawings or specifications.

5.17 SHOTCRETE

5.17.1 General

Shotcrete shall be defined as mortar or concrete pneumatically projected at high velocity onto a surface. Except as specified in this section, shotcrete shall conform to the provisions of this Code regarding plain concrete or reinforced concrete.

5.17.2 Proportions and Materials

Shotcrete proportions shall be such that suitable placement is ensured using the delivery equipment selected, and shall result in finished in place hardened shotcrete meeting the strength requirements of Chapter 6.

5.17.3 Aggregate

Coarse aggregate, if used, shall not exceed 20 mm in size.

5.17.4 Reinforcement

The maximum size of reinforcement shall be 16 mm Ø bars unless it can be demonstrated by preconstruction tests that adequate embedment of larger bars can be achieved. When 16 mm Ø or smaller bars are used, there shall be a minimum clearance of 60 mm between parallel reinforcing bars. When bars larger than 16 mm Ø are permitted, there shall be a minimum clearance between parallel bars equal to six diameters of the bars used. When two curtains of steel are provided, the curtain nearest the nozzle shall have a spacing equal to 12 bar diameters and the remaining curtain shall have a minimum spacing of 6 bar diameters.

Lap splices in reinforcing bars shall be by the noncontact lap splice method with at least 50 mm clearance between bars. The engineer may permit the use of contact lap splices when necessary for the support of the reinforcement, provided it can be demonstrated by means of preconstruction testing that adequate embedment of the bars at the splice can be achieved and provided further that the splices are placed so that the plane containing the centres of the two spliced bars is perpendicular to the surface of the shotcrete work. Shotcrete shall not be applied to spirally tied columns.

5.17.5 Preconstruction Tests

When required by the engineer a test panel shall be shot, cured, cored or sawn, examined and tested prior to commencement of the project. The sample panel shall be representative of the project and simulate job conditions as closely as possible. The panel thickness and reinforcing shall reproduce the thickest and the most congested area specified in the structural design. It shall be shot at the same angle, from a similar distance, using the same nozzleman and with the same concrete mix design that will be used on the project.

5.17.6 Rebound

Any rebound or accumulated loose aggregate shall be removed from the surfaces to be covered prior to placing the initial or any succeeding layers of shotcrete. Rebound shall not be reused as aggregate.

5.17.7 Joints

Except where permitted, unfinished work shall not be allowed to stand for more than 30 minutes unless all edges are sloped thin. Before placing additional material adjacent to previously applied work, sloping and square edges shall be cleaned and wetted.

5.17.8 Damage

An in-place shotcrete which exhibits sags or sloughs, segregation, honeycombing, sand pockets or other obvious defects shall be removed and replaced.

5.17.9 Curing

During the curing periods, shotcrete shall be maintained above 5oC and in moist condition. In initial curing, shotcrete shall be kept continuously moist for 24 hours after placement is complete. Final curing shall continue for seven days after shotcreting, for three days if high early strength cement is used, or until the specified strength is obtained. Final curing shall consist of a fog spray or an approved moisture retaining cover or membrane. In sections of a depth in excess of 300 mm, final curing shall be the same as that for initial curing.

5.17.10 Strength Test

Strength test for shotcrete shall be made by an approved agency on specimens which are representative of the work and which have been water soaked for at least 24 hours prior to testing. When the maximum size aggregate is larger than 10 mm, specimens shall consist of not less than three 75 mm diameter cores or 75 mm cubes. When the maximum size aggregate is 10 mm or smaller, specimens shall consist of not less than three 50 mm diameter cores or 50 mm cubes. Specimens shall be taken in accordance with one of the following:

(a) From the work: taken at least one from each shift but not less than one for each 20 m^3 of shotcrete;

(b) From test panels: taken not less than once each shift nor less than one for each 20 m^3 of shotcrete placed. When the maximum size aggregate is larger than 10 mm, the test panels shall have a minimum dimension of 450 mm by 450 mm. When the maximum size aggregate is 10 mm or smaller, the test panels shall have a minimum dimension of 300 mm by 300 mm. Panels shall be gunned in the same position as the work, during the course of the work and by the same nozzlemen doing the work. The condition under which the panels are cured shall be the same as the work.

The average strength of three cores from a single panel shall be equal to or exceed $0.85\ f_c'$ with no single core less than $0.75\ f_c'$. The average strength of three cubes taken from a single panel must equal or exceed f_c' with no individual cube less than f_c' . To check testing accuracy, locations represented by erratic core strengths may be retested.

5.17.11 Inspections

5.17.11.1 Inspection During Placement

When shotcrete is used for columns and beams, a special inspector is required. The special inspector shall provide continuous inspection to the placement of the reinforcement and shotcreting and shall submit a statement indicating compliance with the plans and specifications.

5.17.11.2 Visual Examination for Structural Soundness of In-place Shotcrete

Completed shotcrete work shall be checked visually for reinforcing bar embedment, voids, rock pocket, sand streaks and similar deficiencies by examining a minimum of three 75 mm cores taken from three areas chosen by the engineer which represent the worst congestion of reinforcing bars occurring in the project. Extra reinforcing bars may be added to noncongested areas and cores may be taken from these areas. The cores shall be examined by the special inspector and a report submitted to the engineer prior to final approval of the shotcrete.

5.17.12 Equipment

The equipment used in construction testing shall be the same equipment used in the work requiring such testing unless substitute equipment is approved by the engineer.