BUILDING DIGEST

CENTRAL BUILDING RESEARCH INSTITUTE INDIA

DESIGN OF HIGH STRENGTH CONCRETE MIXES

Introduction

With the trend towards the wider use of prestressed concrete for bridges and buildings, the engineer in the field is becoming increasingly interested in the principles and techniques involved in the design of high strength concrete mixes. This digest outlines simple procedures for the design of such mixes.

High strength concrete

A concrete with a cube strength at 28 days in excess of 4000 p.s.i. may be designated as high strength concrete. The Indian Standard Code of Practice for Prestressed Concrete (I.S. 1343-1960) specifies minimum cube strengths of 5000 and 6000 p.s.i. respectively for post-tensioned and pretensioned concrete work. Experience has shown that a mix with a cube strength of 5000 to 6000 p.s.i. is likely to prove most economical. Within this range, the cost of high strength concrete is only about 15% higher than that of concrete with a cube strength of 2500 p.s.i. specified in I.S. 456-1953 for Reinforced Concrete Construction. Thus with 15% increase in cost, more than 100% improvement in strength may be realized.

High early strength

When pretensioned products are mass-produced in a factory, it is desirable that the concrete attains high early strength enabling the early release of moulds. To achieve such high early strength, the use of high early strength cement and steam-curing are resorted to. The production of such concrete is outside the scope of this digest. The treatment here is confined to high strength concrete mixes made out of normal Portland Cement and cured in the usual manner.

Factors influencing the strength of concrete

Among the more important factors affecting the strength are the following :

i. Water-cement ratio,

ii. Aggregate-cement ratio,

iii. Grading, surface texture, shape and strength of aggregate particles,

iv. Maximum size of the aggregate,

v. Degree of compaction

and

vi. Conditions of curing.

General Principles of Mix Design

It is often said that the design of a concrete mix is more of an art than a science. This is because of the numerous variables involved. Some of the principles underlying mix design are listed below.

i. The lower the water-cement ratio the higher is the strength, provided the resulting mix can be properly compacted.

ii. In mixes leaner than 1:3 (cement: aggregate) an increase in strength of as much as 14% can be realized by careful grading of the aggregate—coarse as well as fine.

iii. Bulking of sand which occurs at low percentages of moisture has to be allowed for in arriving at the quantity of mixing water.

iv. The densest concrete is generally the strongest but it may not have such good workability as may be obtained by a slight change in proportions of sand and aggregate.

v. For a given grading of aggregates and specified workability, the water required for a unit volume of concrete is constant irrespective of the cement content of the mix.

vi. With a given grading and proportion of aggregates, workability can sometimes be increased by increasing the cement content and hence the water content per unit volume of the mix. It must, however, be noted that this can be done only within limits. If the cement content is very low, the mix becomes porous. If, on the other hand, mix is too rich, there will be excessive shrinkage. Hence, it is specified in I.S. 1343-1960 that for prestressed concrete work the number of bags of cement per 100 cu. ft., shall not be less than 21 bags or 2352 lbs., nor more than 30 bags or 3360 lbs.

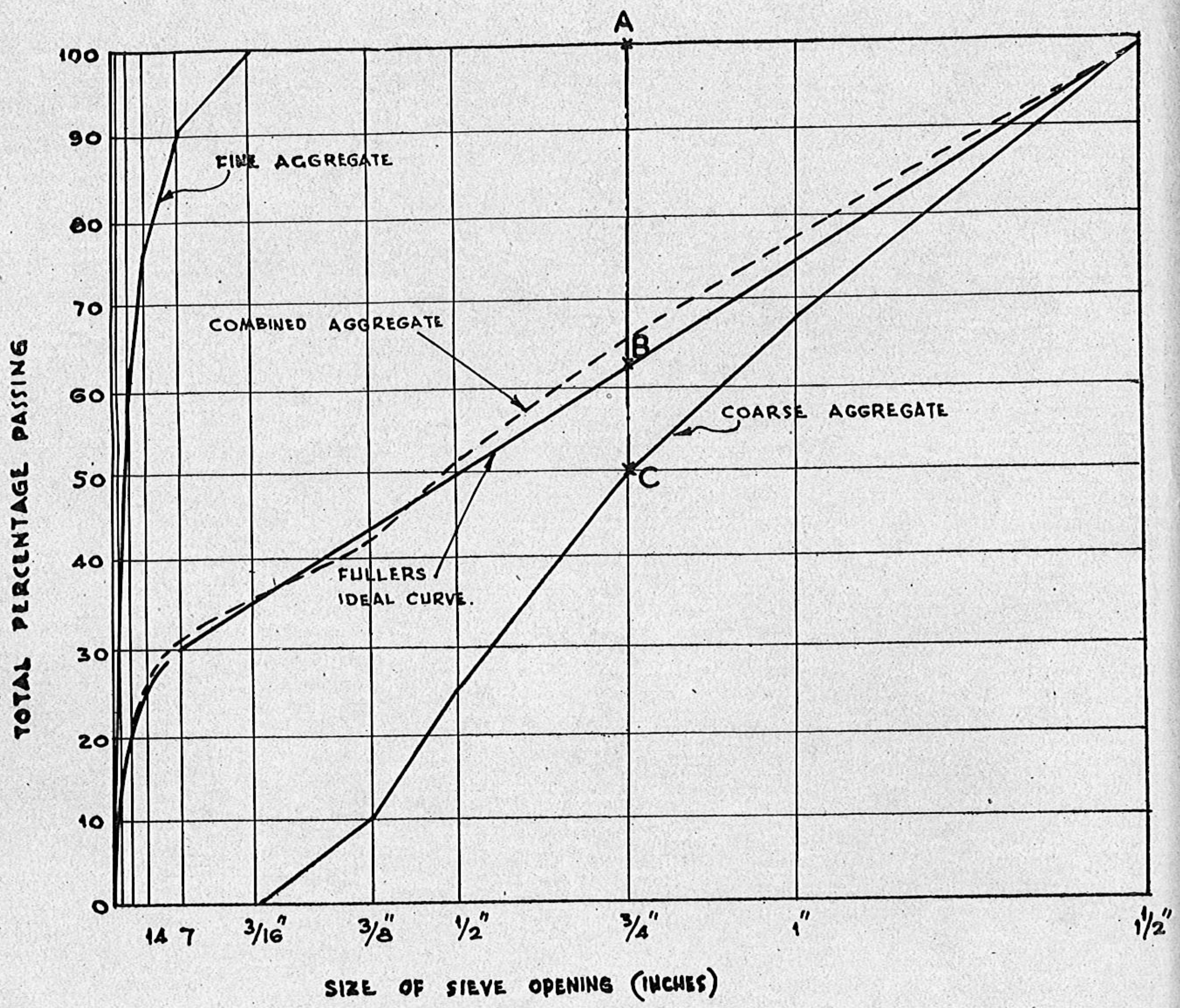

FIG. I

IDEAL GRADING CURVE (FULLERS IDEAL CURVE) OF THE COMBINED AGGREGATE FOR BEST STRENGTH.

SIEVE OPENING	1 1/2"	1"	3/4"	1/2"	3/8"	3/16"	No. 7	No. 14	No. 25	No. 50	No. 100
PERCENTAGE PASSING.	100	75	63	51	44	35	30	28	21	18	10

VALUES FOR PLOTTING FULLERS IDEAL CURVE

vii. The strength is directly proportional to cement aggregate ratio over a small range provided the slump and consequently the unit water content of the mix is maintained constant.

viii. If the maximum size of aggregate is reduced it will be found necessary to increase the percentage of sand.

Based on these general principles, mix-design for any specified job is usually carried out in two steps :

i. Computation of a trial mix.

ii. Laboratory tests to confirm its suitability.

Mix Design Methods

The strength of a mix is usually specified by its cube strength at 28 days. However, in designing a mix the variation in strength that is to be expected is to be taken into account. We have the following relation connecting the average and minimum strengths :

Average cube strength = Minimum cube strength + k times Standard Deviation

where, k is a coefficient which depends on the number of cubes whose strength can be permitted to drop below the minimum cube strength specified. If it is demanded that only one out of every 100 cubes tested might show compressive strength less than the minimum, the value of the coefficient k is 2.33. The Standard Deviation would depend on the degree of control expected to be available at the site. Table 5 gives values of Standard Deviation corresponding to various degrees of control. The Standard Deviation corresponding to good control may be taken as 600 p.s.i. Thus, for example, if the minimum cube strength specified for the job is 6000 p.s.i. and good control is assumed, the average cube strength for which the mix is to be designed may be arrived at as follows :

average cube strength $= 6000 + 2.33 \times 600 = 7400$ p.s.i.

There are several methods available for designing a concrete mix. The absolute volume method and the ideal grading method being particularly suitable for use in the field are described in this digest.

Method of Ideal Grading (Fuller's Method)

i. Sieve analysis of coarse and fine aggregates as specified in I.S. 383-1952 shall be carried out.

ii. The results of the sieve analysis are plotted on a graph marking percentages passing as ordinates and sieve apertures of the complete set of IS sieves ranging from No. 100 to the maximum size of the aggregate, as abscissae.

iii. Fuller's ideal grading curve given in figure 1 is next plotted on the same graph.

iv. Trial proportions of coarse to fine aggregates are fixed in the ratio of AB to BC illustrated in Fig. 1. The intercepts are usually chosen at an aperture representing one-half the maximum size of the aggregate. Thus for $1\frac{1}{2}''$ aggregate, the intercepts are measured at an aperture of $\frac{3}{4}''$.

v. Mixing coarse and fine aggregates in proportions arrived at in step (iv), the grading curve of the mixture is worked out and plotted in the same graph.

vi. Minor adjustments, if found necessary, are next made so that the grading curve of the mixture approximates as closely as possible to the Fuller's ideal grading curve.

vii. The water-cement ratio for the average strength desired is read off from Table 1.

viii. The aggregate-cement ratio for the required average strength is obtained from Fig. 2, consistent with an assumed compacting factor taken from table 2 for the particular type of work.

ix. Making use of the information obtained in steps (vii) and (viii) and the ratio of the coarse to fine aggregates arrived at in step (vi), the quantities of the coarse aggregate, fine aggregate, cement and water are worked out and the trial mix made.

x. The trial mix is examined to see if it is workable. If not, the aggregate cement ratio is altered keeping the water-cement ratio unaltered.

xi. When a mix with satisfactory workability is obtained, cubes are made and tested to see whether the mix develops the required strength.

The Absolute Volume Method

The absolute volume method can best be understood by following the worked example given below :

Example:—Design a most suitable concrete mix to have a minimum cube strength of 5300 p.s.i. at 28 days for a post tensioned prestressed concrete bridge girder. Good control is available at the site. Crushed stones of maximum size of 3/4 in. and clean river sand are available. The specific gravity of cement is 3.15 and the properties of aggregates are as follows :

Serial No.	Material	Type	Max. size inch	Fineness Modulus	Bulk density	Specific gravity	Moisture content	Absorption
1.	Coarse aggregate	Crushed stone	3/4 in.	—	100 lbs./cft.	2.69	5%	0.5%
2.	Fine aggregate	River Sand	3/16	2.8	—	2.64	1%	0.7%

The proportions are computed as follows :

i. For the good degree of control available at site, Standard Deviation is read from Table 5 as 600 lbs per sq. in.

ii. The maximum variation of the cube strength corresponding to the difference between the average and the minimum cube strength,

$= 2.33 \times$ Standard Deviation

$= 2.33 \times 600$

$= 1400$ p.s.i.

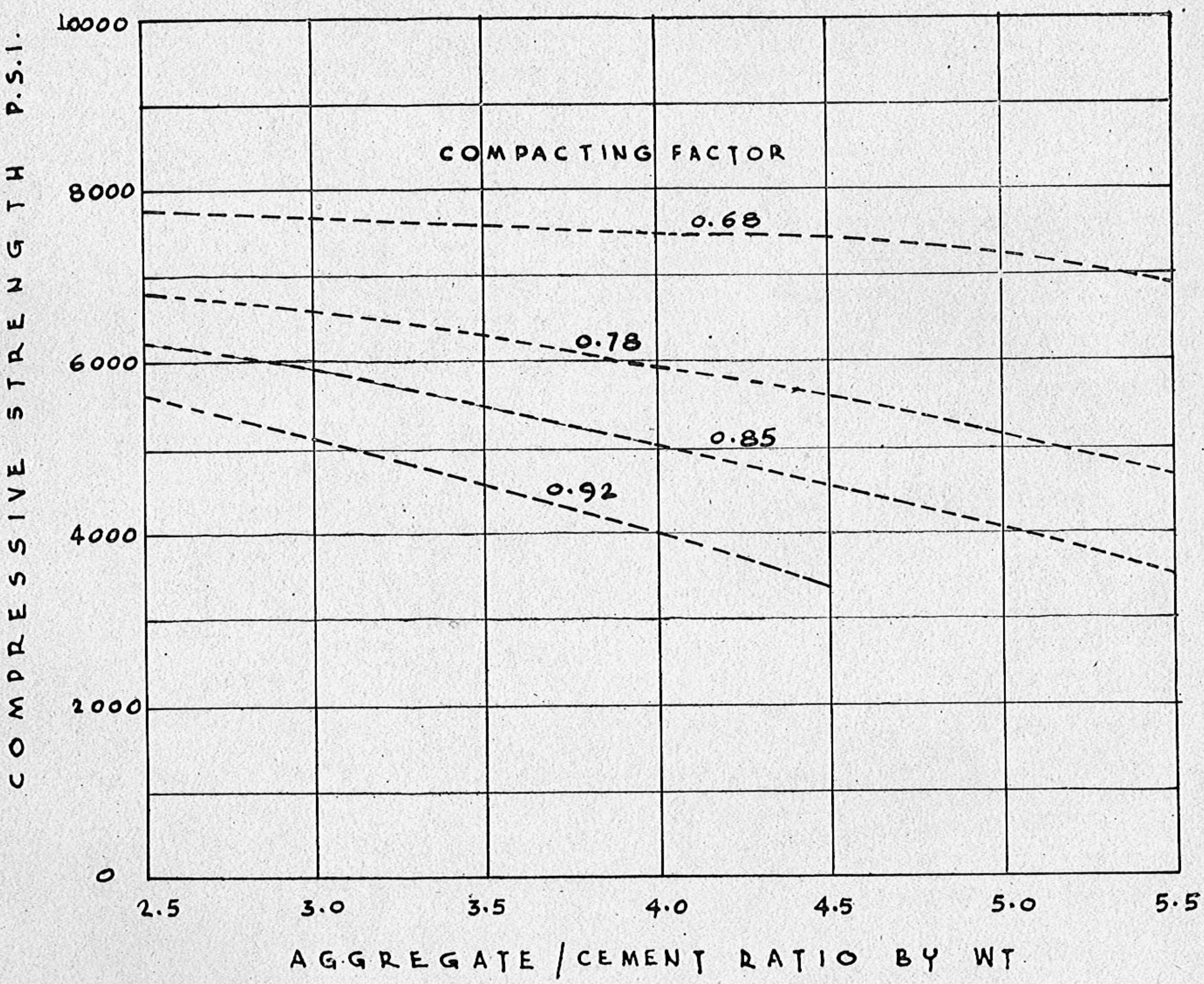

FIG. 2

TYPICAL RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND AGGREGATE /CEMENT RAT

iii. Average cube strength to be aimed at is worked out as minimum cube strength+variation obtained from (ii) $= 5300 + 1400$
$= 6700$ p.s.i.

iv. Water-cement ratio for the average strength of 6700 p.s.i. is obtained from Table 1, as 0.4, that is 45 lbs. per cwt. of cement.

v. Depending on the workability desired, the minimum slump for the particular type of work is read from Table 2 as 3 inches against item (iii). As high frequency vibrators are invariably used for high strength mixes, the actual slump to be aimed at according to the note under Table 2 is only one third of that given in the table, which works out to 1 inch slump.

vi. The approximate quantity of mixing water for the slump arrived at is read from table 3, which prescribes 308 lbs. of mixing water per cubic yard of concrete for 3/4 in. maximum size aggregate.

vii. From (iv) and (vi) the required cement content per cubic yard of concrete is worked out as

$$= \frac{308 \times 112}{45}$$

$$= 766 \text{ lbs.}$$

viii. The quantity of coarse aggregate per unit volume of concrete is estimated from Table 4. For a fine aggregate having fineness modulus of 2.8 and maximum size of aggregate being 3/4 in. Table 4 indicates 0.67 c. ft. of coarse aggregate on a dry rodded basis per cubic foot of concrete. Therefore, coarse aggregate per cubic yard of concrete is $0.67 \times 27 = 18.09$ c. ft. or a weight of 1809 lbs on the basis of the given dry rodded bulk density of 100 lbs. per c. ft.

ix. With the quantities of cement, water and coarse aggregate established and the approximate entrapped casual air content (as opposed to purposely entrained air) also read off from Table 3, quantity of sand is calculated as follows :

a. Solid volume of cement $= \frac{766}{3.15 \times 62.4}$
$= 3.90$ c. ft.

b. Volume of water $= \frac{308}{62.4} = 4.93$ c. ft.

c. Solid Volume of coarse aggregate $= \frac{1809}{2.68 \times 62.4} = 10.82$ c. ft.

d. Volume of entrapped air per cu. yard of concrete $= 0.02 \times 27 = 0.54$ c. ft.
(read from table 3)

e. Solid volume of materials other than sand in one cubic yard of mix is obtained by addition of the quantities computed in a, b, c, and d $= 20.19$ c. ft.

f. Solid volume of sand obtained by subtracting the solid volume of other materials from the total volume of concrete $= 27 - 20.19$
$= 6.81$ c. ft.

g. Required weight of sand in the mix $= 6.81 \times 2.64 \times 62.4$
$= 1123$ lbs.

x. The estimated batch quantities per cubic yard of concrete are :

a.	Cement	766 lbs.
b.	Water	308 lbs.
c.	Sand (dry)	1123 lbs.
d.	Coarse aggregate	1809 lbs.

xi. Corrections for the moisture content of the aggregates are next made as follows.

Sand contains 5% moisture and coarse aggregate contains 1% moisture.

a. The amount of moist sand to be weighed
$= 1123 \times 1.05$
$= 1178$ lbs.

b. Moist coarse aggregate to be weighted is $= 1809 \times 1.01$
$= 1827$ lbs.

The free water on aggregates in excess of their absorption must be considered as providing a part of the water required for the mix. Since the absorption percentages of sand and coarse aggregate are respectively 0.7% and 0.5%, and the total moisture contents are 1% and 5%.

a. the free water content of sand $= 1\% - 0.7\% = 0.3\%$

b. the free water content of coarse aggregate $= 5\% - 0.5\% = 4.5\%$

weight of mixing water contributed by sand and coarse aggregate $= \frac{0.3}{100} \times 1123 + \frac{4.5}{100} \times 1809$
$= 85$ lbs.

the extra quantity of mixing water to be added is $= 308 - 85$
$= 223$ lbs.

xiii. Therefore the final quantities per cubic yard of concrete incorporating the moisture corrections for the aggregates are :

a.	Cement	766 lbs.
b.	Water	233 lbs.
c.	Sand	1179 lbs.
d.	Coarse aggregate	1827 lbs.

Proportion by weight is 1 : 1.54 : 2.375
say 1:1.5:2.4 with water-cement ratio of 0.4.

As far as possible, weigh batching should be employed. If more water is required than indicated, the cement factor must be increased maintaining the water-cement ratio constant.

TABLE 1

Compressive Strength of Concrete for various water-cement ratios*

W/C Ratio	Probable average cube strength at 28 days p.s.i.
0.35	7500
0.44	6250
0.53	5000
0.62	4000

** These average strengths are for concretes containing not more than the percentages of entrapped air shown in table 3.*

TABLE 2

Recommended Slumps (or Compacting Factor) for Various Types of Construction

Type of construction	Slump, inches* Max.	Slump, inches* Min.	Compacting factor
(i) Reinforced foundation, walls and footings	5	2	0.85 to 0.92
(ii) Plain footings, caissons and sub structure walls	4	1	0.85 to 0.92
(iii) Slabs, beams, reinforced walls and building columns	6	3	0.85 to 0.92
(iv) Pavements	3	2	0.78 to 0.85
(v) Heavy mass construction	3	1	0.78 to 0.85

** When high frequency vibrators are used, the values of slumps given should be reduced to about one-third and the corresponding compacting factors for use in. Fig. 3 are given in the table.*

TABLE 3

Approximate Mixing Water Requirements for Different Slumps and Maximum Size of Aggregate*

Slump, inches	Water, lbs. per cubic yard of concrete for indicated max. size of aggregate (in inches)						
	3/8	½	¾	1	1½	2	3
1 to 2	350	333	308	300	275	258	242
3 to 4	383	367	342	325	300	283	260
6 to 7	408	383	358	342	316	300	283
Approximate amount of entrapped air, percent	3	2.5	2	1.5	1	0.5	0.3

** These quantities of mixing water are for use in computing cement factors for trial batches. If more water is required than shown, the cement factor estimated from the quantities should be increased to maintain desired water-cement ratio, except as otherwise indicated by laboratory tests for strength. If less water is required than shown, the cement factor, estimated from these quantities, should not be decreased except as indicated by laboratory tests for strength.*

TABLE 4

Volumes of Coarse Aggregate Per Unit Volume of Concrete*

Max. size of aggregate in	Volume of dry rodded coarse aggregate per unit volume of concrete for different fineness modulii of sand			
	2.40	2.60	2.80	3.00
3/8″	0.51(0.46)	0.48(0.44)	0.46(0.42)	0.44(0.40)
½″	0.61(0.55)	0.58(0.53)	0.56(0.51)	0.54(0.49)
¾′	0.72(0.65)	0.69(0.63)	0.67(0.61)	0.65(0.59)
1″	0.77(0.70)	0.75(0.68)	0.73(0.66)	0.70(0.64)
1½″	0.84(0.76)	0.81(0.74)	0.79(0.72)	0.77(0.70)
2″	0.87(0.79)	0.85(0.77)	0.83(0.75)	0.80(0.73)
3″	0.92(0.84)	0.90(0.82)	0.88(0.80)	0.86(0.78)

** Volumes are based on aggregates in dry rodded condition as described in method of test for unit weight of aggregate (See I.S. 383). The quantities indicated in brackets are for ordinary reinforced concrete work where greater workability at lower strength is desired.*

TABLE 5*

Standard Deviation of Concrete Strengths for Various Degrees of Control

	Control	Standard Deviation (lbs per sq. in.)	2.33 × Standard Deviation@
Excellent	Strict supervision and control over mix proportions; specified-water-cement ratio.	400	930
Very good	Slightly less strict than for "excellent" but still a high standard of supervision.	500	1,160
Good	Resonable control, but with perhaps less constant supervision.	600	1,400
Fair	Normal Standard for good average work.	800	1,860
Poor	Little or no supervision.	1,000	2,330
Uncontrolled	No attempt at correct proportioning.	1,200	2,790

* *Extracted from the paper "The Application of Statistics to Concrete Quality" by F. R. Himsworth Proceedings of the Symposium on Mix Design and Quality Control, Cement and Concrete Association, 1954.*

@ *A range of ± the figure in this column will include practically all results (theoretically 98%) so long as conditions are stable, not of course allowing for any gross errors in proportioning.*

There is a demand for short notes, summarising available information on selected building topics for the use of Engineers and Architects in India. To meet the need this Institute is bringing out a series of Building Digests from time to time and the present one is the ninth in the series.

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