Contents

Testing Equipments for Finding Strength of Concrete

7
CHAPTER

Strength of Concrete

General

The compressive strength of concrete is one of the most important and useful properties of concrete. In most structural applications concrete is employed primarily to resist compressive stresses. In those cases where strength in tension or in shear is of primary importance, the compressive strength is frequently used as a measure of these properties. Therefore, the concrete making properties of various ingredients of mix are usually measured in terms of the compressive strength. Compressive strength is also used as a qualitative measure for other properties of hardened concrete. No exact quantitative relationship between compressive strength and flexural strength, tensile strength, modulus of elasticity, wear resistance, fire resistance, or permeability have been established nor are they likely to be. However, approximate or statistical relationships, in some cases, have been established and these give much useful information to engineers. It should be emphasised that compressive strength gives only an approximate value of these properties and that other tests specifically designed to determine these properties should be useful if more precise results are required. For instance, the indicated compressive strength increases as the specimen size decreases, whereas the modulus of elasticity decreases. The modulus of elasticity in this case does not follow the compressive strength. The other case where the compressive strength does no indicate the useful property of concrete is when the concrete is subjected to freezing and thawing. Concrete containing about 6 per cent of entrained air which is relatively weaker in strength is found to be more durable than dense and strong concrete.

The compressive strength of concrete is generally determined by testing cubes or cylinders made in laboratory or field or cores drilled from hardened concrete at site or from the non-destructive testing of the specimen or actual structures. The testing of hardened concrete is discussed in the subsequent chapter.

Strength of concrete is its resistance to rupture. It may be measured in a number of ways, such as, strength in compression, in tension, in shear or in flexure. All these indicate strength with reference to a particular method of testing. When concrete fails under a compressive load the failure is essentially a mixture of crushing and shear failure. The mechanics of failure is a complex phenomena. It can be assumed that the concrete in resisting failure, generates both cohesion and internal friction. The cohesion and internal friction developed by concrete in resisting failure is related to more or less a single parameter *i.e.,* w/c ratio.

The modern version of original water/cement ratio rule can be given as follows:

For a given cement and acceptable aggregates, the strength that may be developed by workable, properly placed mixture of cement, aggregate and water (under the same mixing, curing and testing conditions) is influenced by:

(*a*) Ratio of cement to mixing water;

(*b*) Ratio of cement to aggregate;

(*c*) Grading, surface texture, shape, strength and stiffness of aggregate particles;

(*d*) Maximum size of aggregate.

In the above it can be further inferred that water/cement ratio primarily affects the strength, whereas other factors indirectly affect the strength of concrete by affecting the water/cement ratio.

Water/Cement Ratio

Strength of concrete primarily depends upon the strength of cement paste. It has been shown in Chapter I that the strength of cement paste depends upon the dilution of paste or in other words, the strength of paste increases with cement content and decreases with air and water content. In 1918 Abrams presented his classic law in the form:

$$S = \frac{A}{B^x}$$

where x = water/cement ratio by volume and for 28 days results the constants A and B are 14,000 lbs/sq. in. and 7 respectively.[7.1]

Abrams water/cement ratio law states that the strength of concrete is only dependent upon water/cement ratio provided the mix is workable. In the past many theories have been propounded by many research workers. Some of them held valid for some time and then underwent some changes while others did not stand the test of time and hence slowly disappeared. But Abrams' water/cement ratio law stood the test of time and is held valid even *today as a fundamental truth in concrete-making practices. No doubt some modifications have been suggested but the truth of the statement could not be challenged.*

Strictly speaking, it was Feret who formulated in as early as 1897, a general rule defining the strength of the concrete paste and concrete in terms of volume fractions of the constituents by the equation:

$$S = K\left(\frac{c}{c+e+a}\right)^2$$

where S = Strength of concrete

c, e and a = volume of cement, water and air respectively and

K = a constant.

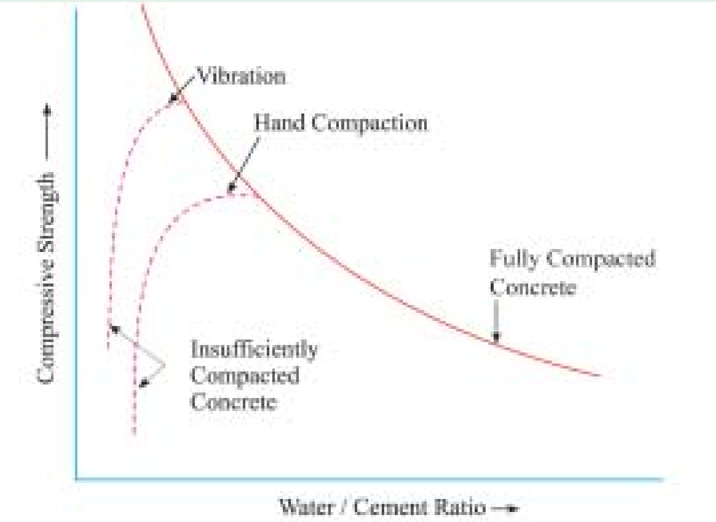
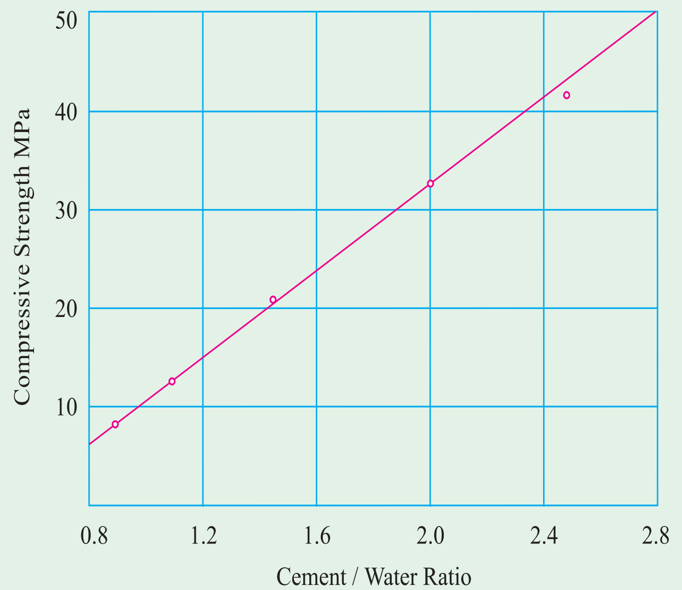


Fig. 7.1. The relation between strength and water/cement ratio of concrete.



In this expression the volume of air is also included because it is not only the water/cement ratio but also the degree of compaction, which indirectly means the volume of air filled voids in the concrete is taken into account in estimating the strength of concrete. The relation between the water/cement ratio and strength of concrete is shown in Fig. 7.1. It can be seen that lower water/cement ratio could be used when the concrete is vibrated to achieve higher strength, whereas comparatively higher water/cement ratio is required when concrete is hand-compacted. In both cases when the water/cement ratio is below the practical limit the strength of the concrete falls rapidly due to introduction of air voids.

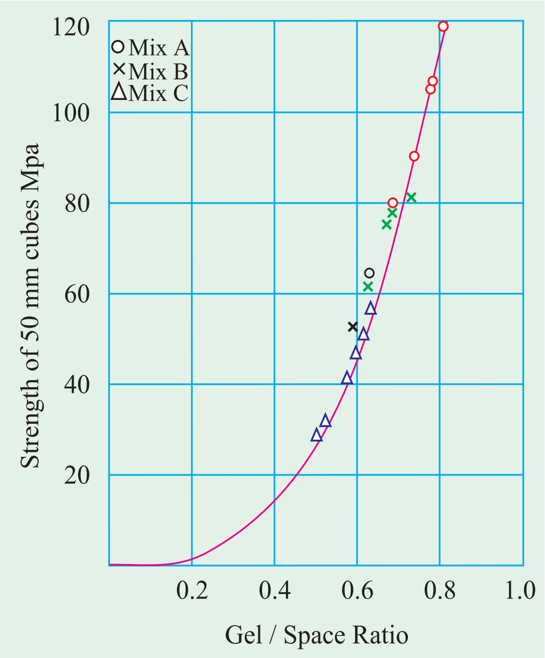
The graph showing the relationship between the strength and water/cement ratio is approximately hyperbolic in shape. Sometimes it is difficult to interpolate the intermediate value. From geometry it can be deduced that if the graphs is drawn between the strength and the cement/water ratio an approximately linear relationship will be obtained. This linear relationship is more convenient to use than water/cement ratio curve for interpolation. Fig. 7.2 shows the relationship between compressive strength and cement/water ratio.

Gel/Space Ratio

Many research workers commented on the validity of water/cement ratio law as propounded by Duff Abrams. They have forwarded a few of the limitations of the water/cement ratio law and argued that Abrams water/cement ratio law can only be called a rule and not a law because Abrams' statement does not include many qualifications necessary for its validity to call it a law. Some of the limitations are that the strength at any water/cement ratio depends on the degree of hydration of cement and its chemical and physical properties, the temperature at which the hydration takes place, the air content in case of air entrained concrete, the change in the effective water/cement ratio and the formation of fissures and cracks due to bleeding or shrinkage.

Instead of relating the strength to water/cement ratio, the strength can be more correctly related to the solid products of hydration of cement to the space available for formation of this product. Powers and Brownyard have established the relationship between the strength and gel/space ratio.[7.2] This ratio is defined as the ratio of the volume of the hydrated cement paste to the sum of volumes of the hydrated cement and of the capillary pores.

Power's experiment showed that the strength of concrete bears a specific relationship with the gel/space ratio. He found the relationship to be 240 x^3, where x is the gel/space ratio and 240 represents the intrinsic strength of the gel in MPa for the type of cement and specimen used.[7.3] The strength calculated by Power's expression holds good for an ideal case. Fig. 7.3 shows the relationship between strength and gel/space ratio. It is pointed out that the relationship between the strength and water/cement ratio will hold



good primarily for 28 days strength for fully compacted concrete, whereas, the relationship between the strength and gel/space ratio is independent of age. Gel/space ratio can be calculated at any age and for any fraction of hydration of cement. The following examples show how to calculate the gel/space ratio.

Calculation of gel/space ratio for complete hydration

Let C = weight of cement in gm.

V_C = specific volume of cement = 0.319 ml/gm.

W_O = volume of mixing water in ml.

Assuming that 1 ml. of cement on hydration will produce 2.06 ml of gel,

Volume of gel = C x 0.319 x 2.06

Space available = C x 0.319 + W_O

$$\therefore \quad \text{Gel/Space ratio} = x = \frac{\text{Volume of gel}}{\text{Space available}} = \frac{0.657\,C}{0.319\,C + W_O}$$

Calculation of gel/space ratio for partial hydration

Let α = Fraction of cement that has hydrated

Volume of gel = C x α x 0.319 x 2.06

Total space available $C\,V_C\,\alpha + W_O$

$$\therefore \quad \text{Gel/space ratio} = x = \frac{2.06 \times 0.319 \times C\alpha}{0.319\,C\alpha + W_O}.$$

Example: Calculate the gel/space ratio and the theoretical strength of a sample of concrete made with 500 gm. of cement with 0.5 water/cement ratio, on full hydration and at 60 per cent hydration.

$$\text{Gel/space ratio on full hydration} = \frac{0.657\,C}{0.319\,C + W_O} = 0.802 \text{ say } 0.8$$

$\therefore$ Theoretical strength of concrete = 240 x $(0.8)^3$ = 123 MPa

Gel/space ratio for 60 percent hydration.

$$x = \frac{0.657\,C}{0.319\,C\alpha + W_O} = \frac{0.657 \times 500 \times 0.6}{0.319 \times 500 \times 0.6 + 250} = \frac{197.1}{345.7} = \mathbf{0.57}$$

Theoretical strength of concrete at 60 per cent hydration = 240 x $(0.57)^3$ = **44.4 MPa**

There is a lot of difference between the theoretical strength of concrete and actual strength of concrete. Actual strength of concrete is much lower than the theoretical strength estimated on the basis of molecular cohesion and surface energy of a solid assumed to be perfectly homogeneous and flawless. The actual reduction of strength is due to the presence of flaws. Griffith postulated his theory on the flaws in concrete. He explains that the flaws in concrete lead to a high stress concentrations in the material under load, so that a very high stress is reached in and around the flaws with the result that the material gets fractured around this flaw while the average stress on the material, taking the cross section of the material as a whole, remains comparatively low. The flaws vary in size. The high stress concentration takes place around a few of the larger flaws. This situation leads to failure of the material at a much lower stress intensity considering the whole process. Presence of bigger flaws brings down the actual strength to a much lower value than the theoretical strength.

Cement paste in concrete contains many discontinuities such as voids, fissures, bleeding channels, rupture of bond due to drying shrinkage and temperature stresses etc. It has been difficult to explain how exactly these various flaws contribute to the reduction in actual strength of concrete. However, Griffith's theory which explains the failure of concrete has been accepted to satisfactorily explain the failure of brittle materials such as concrete.

Gain of Strength with Age

The concrete develops strength with continued hydration. The rate of gain of strength is faster to start with and the rate gets reduced with age. It is customary to assume the 28 days strength as the full strength of concrete. Actually concrete develops strength beyond 28 days also. Earlier codes have not been permitting to consider this increase of strength beyond 28 days for design purposes. The increase in strength beyond 28 days used to get immersed with the factor of safety. With better understanding of the material, progressive designers have been trying to reduce the factor of safety and make the structure more economical. In this direction, the increase in strength beyond 28 days is taken into consideration in design of structures. Some of the more progressive codes have been permitting this practice. Table 7.1 gives the age factors for permissible compressive stress in concrete, as per British Code.

Table 7.1. Age Factors for Permissible Compressive Stress in Concrete as per British Code

Minimum age of member when full design load is applied, months	*Age factor for low-strength concrete*	*Additional strength for high strength concrete MPa*
1	1.00	0
2	1.10	4.2
3	1.16	5.5
6	1.20	7.7
12	1.24	10.2

Earlier IS code 456 of 1978 considered age factor and allowed the increase in design stress in the lower columns in multistorey buildings. Earlier only one type of cement i.e., cement governed by IS- 269 of 1976 was used in which case there was appreciable increase in strength after 28 days. After gradation of OPC the present day cements particularly 53 grade cements, being ground finer, the increase in strength after 28 days is nominal. Most of the strength developments in respect of well cured concrete will have taken place by 28 days. Therefore, allowing age factor is not generally found necessary. Therefore, in IS 456 of 2000, the clause is revised.

Bandra Worli Sea Link Project - an artist's impression.
In this 8 lane bridge 60 MPa concrete is going to be used.
Courtesy : Hindustan Construction Company.

The clause states "There is normally a gain of strength beyond 28 days. The quantum of increase depends upon the grade and type of cement, curing and environmental conditions etc. The design should be based on 28 days characteristic strength of concrete unless there is an evidence to justify a higher strength for a particular structure due to age"

The table number 7.2 gives the grades of concrete as per IS-456 of 2000

Table 7.2. Grades of Concrete as per IS - 456 of 2000

Group	Grade Designation	Specified characterstic compressive strength of 150 mm cube at 28 days in N/mm²
Ordinary Concrete	M 10	10
	M 15	15
	M 20	20
Standard Concrete	M 25	25
	M 30	30
	M 35	35
	M 40	40
	M 45	45
	M 50	50
	M 55	55
High Strength Concrete	M 60	60
	M 65	65
	M 70	70
	M 75	75
	M 80	80

Permissible stresses in concrete is given in Table. 7.3 and 7.4. (IS 456 of 2000)

Table 7.3. Permissible stresses in Concrete
All values in N/mm² (IS 456 of 2000)

Grade of concrete	Permissible stress in compression		Permissible stress in Bond (average) for Plain Bars in tension
	Bending	Direct	
M 10	3.0	2.5	—
M 15	5.0	4.0	0.6
M 20	7.0	5.0	0.8
M 25	8.5	6.0	0.9
M 30	10.0	8.0	1.0
M 35	11.5	9.0	1.1
M 40	13.0	10.0	1.2
M 45	14.5	11.0	1.3
M 50	16.0	12.0	1.4

Note: The bond stress may be increased by 25 per cent for bars in compression.

Table 7.4. Permissible shear stress in concrete as per IS 456 of 2000

$\frac{100 \times As}{bd}$	Permissible shear stress in concrete N/mm² Grades of concrete					
(1)	M 15 (2)	M 20 (3)	M 25 (4)	M 30 (5)	M 35 (6)	M 40 and above (7)
≤ 0.15	0.18	0.18	0.19	0.20	0.20	0.20
0.25	0.22	0.22	0.23	0.23	0.23	0.23
0.50	0.29	0.30	0.31	0.31	0.31	0.32
0.75	0.34	0.35	0.36	0.37	0.37	0.38
1.00	0.37	0.39	0.40	0.41	0.42	0.42
1.25	0.40	0.42	0.44	0.45	0.45	0.46
1.50	0.42	0.45	0.46	0.48	0.49	0.49
1.75	0.44	0.47	0.49	0.50	0.52	0.52
2.00	0.44	0.49	0.51	0.53	0.54	0.55
2.25	0.44	0.51	0.53	0.55	0.56	0.57
2.50	0.44	0.51	0.55	0.57	0.58	0.60
2.75	0.44	0.51	0.56	0.58	0.60	0.62
3.00 and Above	0.44	0.51	0.57	0.60	0.62	0.63

Many a time it may be necessary to estimate the strength of concrete at an early age. One may not be able to wait for 28 days. Many research workers have attempted to estimate the strength of concrete at 1, 3 or 7 days and correlate it to 28 days strength. The relationship between the strength of concrete at a lower age and 28 days depends upon many factors such as compound composition of cement, fineness of grinding and temperature of curing etc. Furthermore mixes with low water/cement ratio gains strength, expressed as a percentage of long term strength, more rapidly than that of concrete with higher water/cement ratio. This is presumably because the cement particles are held at a closer interval in case of low water/cement ratio than that of higher water/cement ratio, in which case there is a much better possibility for the formation of continuous system of gel which gives more strength. Many research workers have forwarded certain relationships between 7

Bandra Worli Sea Link Project under construction with high performance concrete.
Courtesy : Hindustan Construction Company.

days strength and 28 days strength. In Germany the relation between 28 days strength, σ_{28} and the 7 days strength, σ_7 is taken to lie between,

$$\sigma_{28} = 1.4\,\sigma_7 + 150 \quad \text{and} \quad \sigma_{28} = 1.7\,\sigma_7 + 850$$

σ being expressed in pounds/sq. inch.

Another relation suggested is of the type

$$f_{28} = K_2(f_7)^{K1}$$

where, f_7 and f_{28} are the strengths at 7 and 28 days respectively and K_1 and K_2 are the coefficients, which is different for different cements and curing conditions.

The value of K_1 ranges from 0.3 to 0.8 and that of K_2 from 3 to 6.

The strength of concrete is generally estimated at 28 days by crushing field test cubes or cylinders made from the representative concrete used for the structure. Often it is questioned about the utility of ascertaining 28 days strength by which time considerable amount of concrete will have been placed and the works may have progressed. It is then rather too late for remedial measures, if the result of the test cube at 28 days is too low. On the other hand, the structure will be uneconomical if the result of the test cube is too high.

It is, therefore, of tremendous advantage to be able to predict 28 days strength within a few hours of casting the concrete so that we have a good idea about the strength of concrete, so that satisfactory remedial measures could be taken immediately before it is too late. There are many methods for predicting the 28 days strength, within a short period of casting. Out of these the method suggested by Prof. King is found to have good field correlations.

Accelerated Curing test

In the acclerated curing test the standard cubes are cast, they are covered with top plate and the joints are sealed with special grease to prevent drying. Within 30 minutes of adding water, the cubes having sealed effectively, are placed in an air-tight oven which is then switched on. The oven temperature is brought to 93°C in about one hour time. It is kept at this temperature for 5 hours. At the end of this period the cubes are removed from oven, stripped, cooled, and tested. The time allowed for this operation is 30 minutes.

The strength of concrete is determined within 7 hours of casting and this acclerated strength shows good relationship with 7 and 28 days strengths of normally cured concrete. Fig. 7.4 shows relationship between acclereated strength and normally cured concrete strength at 7 and 28 days.

One of the main factors that affects the rate of gain of strength is the fineness of cement. It has been estimated that particles of cement over 40 micron in size contribute to the compressive strength of concrete only over long periods, while those particles smaller than 25 to 30 micron contribute to the 28 days strength, those particles smaller than 20 to 25 micron contribute to the 7 days strength, and particles smaller than 5 to 7 micron contribute to the 1 or 2 days strength.

Relative gain of strength with the time of concretes made with different water/cement ratio using ordinary Portland cement is shown in Fig. 7.5.

Maturity Concept of Concrete

While dealing with curing and strength development, we have so far considered only the time aspect. It has been pointed out earlier that it is not only the time but also the temperature during the early period of hydration that influence the rate of gain of strength *of concrete. Since the strength development of concrete depends on both time and temperature it can be said that strength is a function of summation of product of time and temperature. This summation is called maturity of concrete.*

Maturity = Σ (time x temperature)

The temperature is reckoned from an origin lying between –12 and –10°C. It was experimentally found that the hydration of concrete continues to take place upto about –11°C. Therefore, –11°C is taken as a datum line for computing maturity.

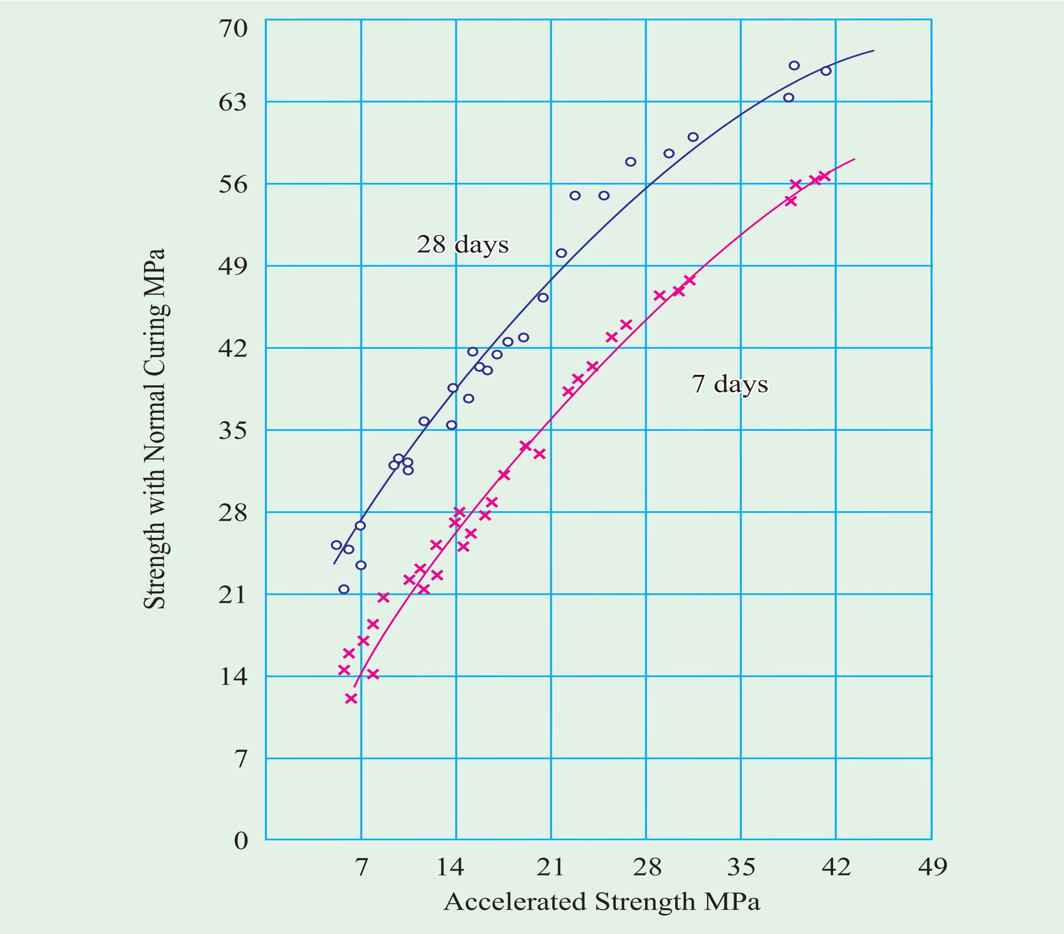
Maturity is measured in degree centigrade hours (°C hrs) or degree centigrade days (°C days). Fig. 7.6. shows that the strength plotted against the logarithm of maturity gives a straight line.

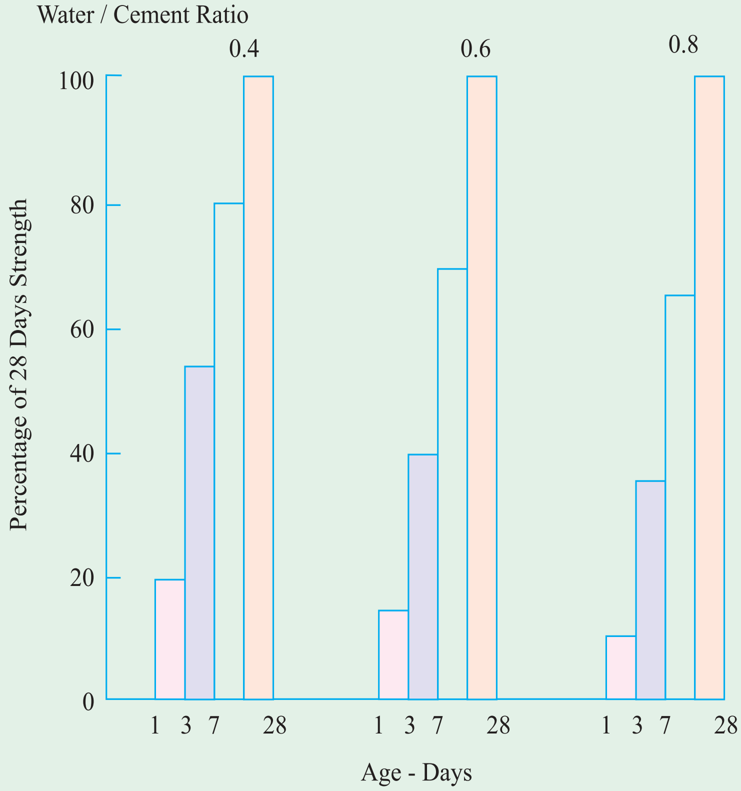
A sample of concrete cured at 18°C for 28 days is taken as fully matured concrete. Its maturity would be equal to

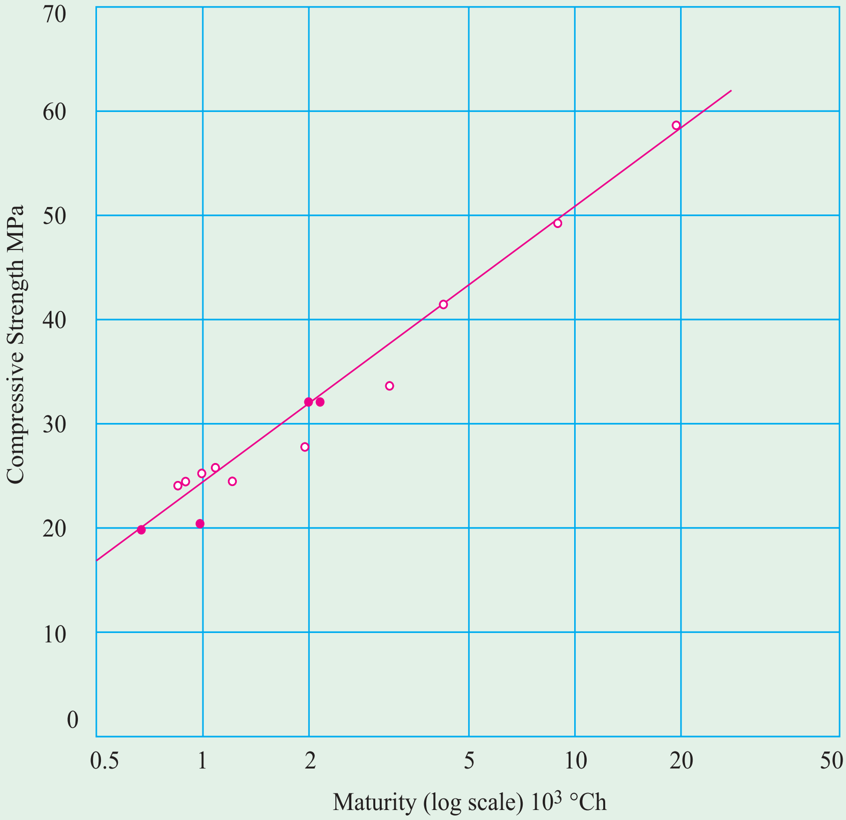
28 x 24 x [18 – (–11)] = 19488°C h.

However, in standard calculations the maturity of fully cured concrete is taken as 19,800°Ch.. (The discrepancy is because of the origin or the datum is not exactly being –11 C as used in calculation).

If the period is broken into smaller intervals and if the corresponding temperature is recorded for each interval of time, the summation of the product of time and temperature will




Water / Cement Ratio
0.4
0.6
0.8
100
80
60
40
20
0
Percentage of 28 Days Strength
1 3 7 28
1 3 7 28
1 3 7 28
Age - Days


70
60
50
40
30
20
10
0
Compressive Strength MPa
0.5
1
2
5
10
20
50
Maturity (log scale) 10^3 °Ch

give an accurate picture of the maturity of concrete. In the absence of such detailed temperature history with respect to the time interval, the maturity figure can be arrived at by multiplying duration in hours by the average temperature at which the concrete is cured. Of course, the maturity calculated as above will be less accurate.

Maturity concept is useful for estimating the strength of concrete at any other maturity as a percentage of strength of concrete of known maturity. In other words, if we know the strength of concrete at full maturity (19,800°Ch), we can calculate the percentage strength of identical concrete at any other maturity by using the following equation given by Plowman.

Strength at any maturity as a percentage of strength at maturity of

$$19{,}800°\text{Ch.} = A + B \log_{10} \frac{(\text{maturity})}{10^3}$$

The values of coefficients, A and B depend on the strength level of concrete. The values are given in Table 7.5

Table 7.5. Plowman's Coefficients for Maturity Equation[7.5]

Strength after 28 days at 18°C (Maturity of 19,800°Ch): MPa	Coefficient	
	A	B
Less than 17.5	10	68
17.5 – 35.0	21	61
35.0 – 52.5	32	54
52.5 – 70.0	42	46.5

The values of A and B are plotted against the cube strength at the maturity of 19,800° Ch. A straight line relationship will be obtained indicating that they are directly proportional to the strength. Plowman divided the strength into 4 zones as shown in Table 7.5 and has assigned the values of A and B for each zone. It is to be noted that the maturity equation holds good for the initial temperature of concrete less than about 38°C. Fig. 7.7 gives the value of constant A and B when strength and temperature are expressed in lbs/sq inch and °F respectively.

The following examples illustrate the theory:

***Example 1:** The strength of a sample of fully matured concrete is found to be 40.00 MPa find the strength of identical concrete at the age of 7 days when cured at an average temperature during day time at 20°C, and night time at 10°C.*

Maturity of concrete at the age of 7 days

$$= \Sigma\,(\text{time x Temperature})$$
$$= 7 \times 12 \times [20 - (-11)] + 7 \times 12 \times [10 - (-11)]$$
$$= 7 \times 12 \times 31 + 7 \times 12 \times 21$$
$$= 4368°\text{Ch.}$$

The strength range of this concrete falls in Zone III for which the constant A is 32 and B is 54.

$\therefore$ *the percentage strength of concrete at maturity of 4368°Ch.* $= A + B \log_{10} \dfrac{(4368)}{1000}$

$$= 32 + 54 \times \log_{10}(4.368) = 32 + 54 \times 0.6403 = 66.5$$

∴ *The strength at 7 days* $= 40.0 \times \frac{66.5}{100} = 26.5$ *MPa*

Example 2: *Laboratory experiments conducted at (Pune) on a particular mix showed a strength of 32.5 MPa for fully matured concrete. Find whether formwork can be removed for an identical concrete placed at Srinagar at the age 15 days when the average temperature is 5°C if the concrete is likely to be subjected to a stripping stress of 25.0 MPa.*

Strength of fully matured concrete = 32.5 MPa. Maturity of identical concrete at 15 days when cured at a temperature of 5°C = 15 x 24 x [5 – (– 11)]

$$= 15 \times 24 \times 16 = 5760°\text{Ch}.$$

This concrete falls in Zone No. II for which the value of constants are

$$A = 21 \quad \text{and} \quad B = 61.$$

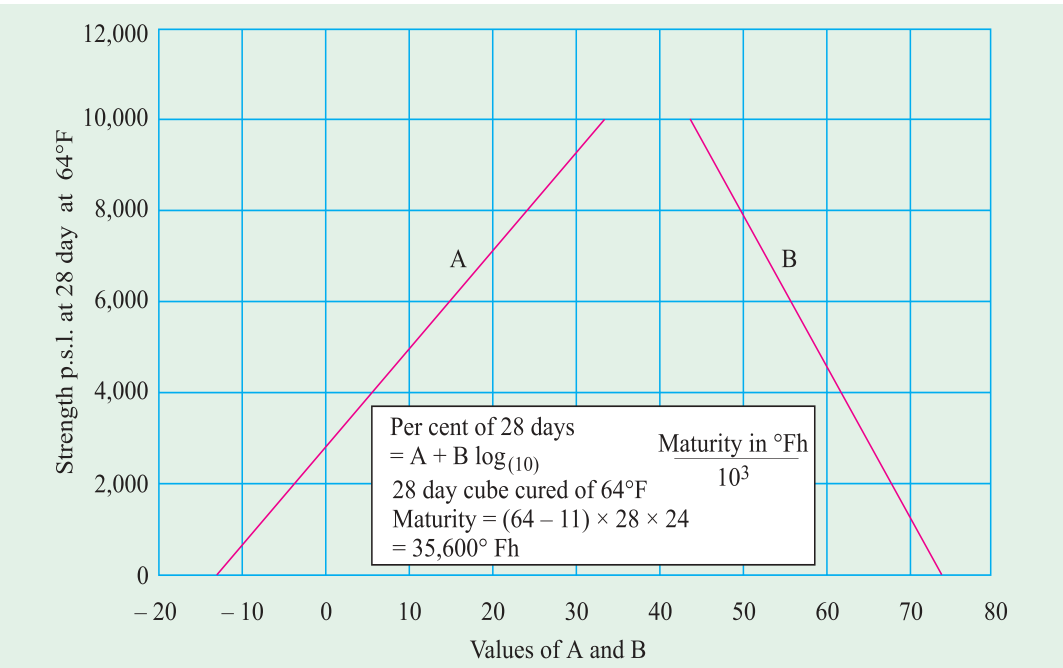
$$\text{Percentage of strength} = A + B \log_{10} \frac{(\text{Maturity})}{1000} = 21 + 61 \log_{10} \left(\frac{(5760)}{1000}\right)$$

$$= 21 + 61 \times \text{Log}_{10}\, 5.760$$

$$= 21 + 61 \times 0.7604 = 67.38$$

∴ *The strength of concrete at 15 days* $= 32.5 \times \frac{67.38}{100} = 21.9$ *MPa.*

Since the strength of concrete is less than the stress to which it is likely to be subjected while stripping the formwork, the concrete may fail. Therefore, the formwork cannot be removed at 15 days time.



If the strength at a given maturity is known, then the number of days required to reach the same strength at any other temperature can also be calculated from,

$$\frac{M}{24[t-(-11)]}$$

where, M = Maturity for the given strength, and t the alternative temperature in centigrade.

In the above example for reaching the same strength, number of days required,

$$= \frac{M}{24[t-(-11)]} = \frac{19800}{24[5-(11)]} = \frac{19800}{24 \times 16} = \text{ 52 days.}$$

This is to say that the concrete cured at 5°C would take about 52 days to achieve full maturity.

Effect of Maximum size of Aggregate on Strength

At one time it was thought that the use of larger size aggregate leads to higher strength. This was due to the fact that the larger the aggregate the lower is the total surface area and, therefore, the lower is the requirement of water for the given workability. For this reason, a lower water/cement ratio can be used which will result in higher strength.

However, later it was found that the use of larger size aggregate did not contribute to higher strength as expected from the theoretical considerations due to the following reasons.

The larger maximum size aggregate gives lower surface area for developments of gel bonds which is responsible for the lower strength of the concrete. Secondly bigger aggregate size causes a more heterogeneity in the concrete which will prevent the uniform distribution of load when stressed.

When large size aggregate is used, due to internal bleeding, the transition zone will become much weaker due to the development of microcracks which result in lower compressive strength.

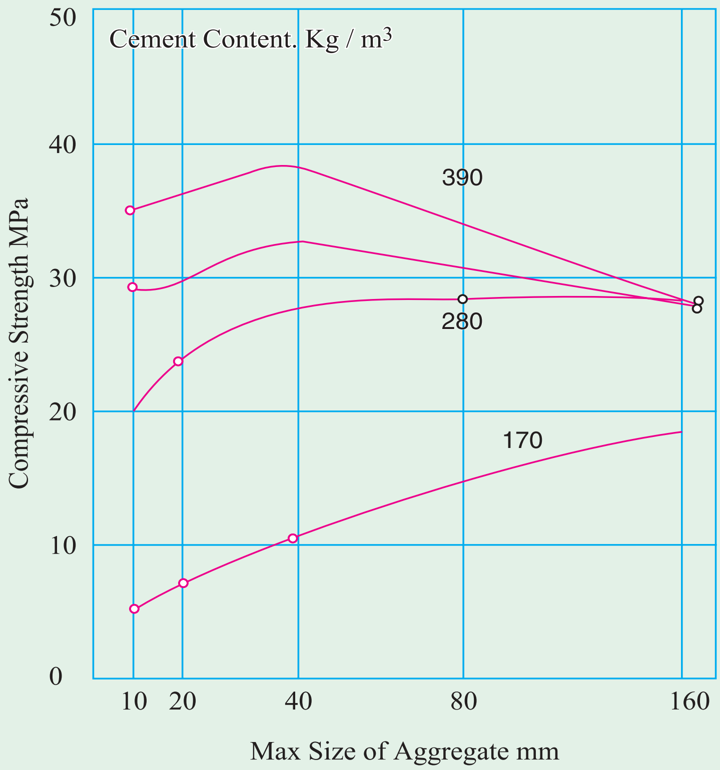
Generally, high strength concrete or rich concrete is adversely affected by the use of large size aggregate. But in lean mixes or weaker concrete the influence of size of the aggregate gets reduced. It is interesting to note that in lean mixes larger aggregate gives highest strength while in rich mixes it is the smaller aggregate which yields higher strength. Fig. 7.8. shows the influence of maximum size of aggregate on compressive strength of concrete.[7.6] Fig. 7.9. depicts the influence of size of aggregate on compressive strength of concrete for different w/c ratio.

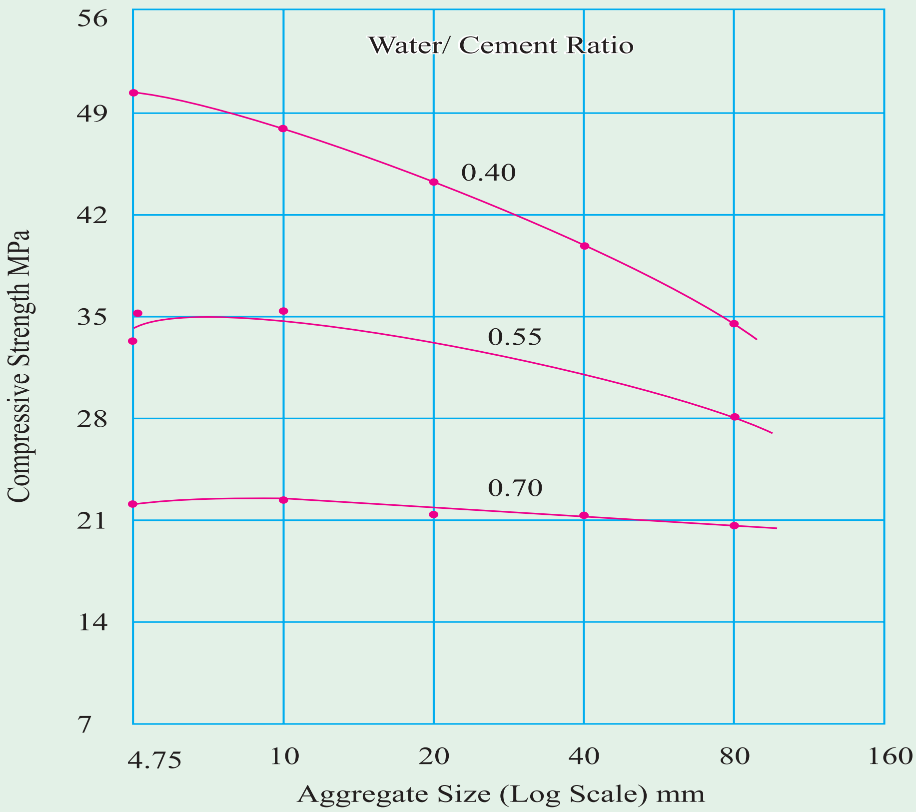
Relation Between Compressive and Tensile Strength

In reinforced concrete construction the strength of the concrete in compression is only taken into consideration. The tensile strength of concrete is generally not taken into consideration. But the design of concrete pavement slabs is often based on the flexural strength of concrete. Therefore, it is necessary to assess the flexural strength of concrete either from the compressive strength or independently.

As measurements and control of compressive strength in field are easier and more convenient, it has been customary to find out the compressive strength for different conditions and to correlate this compressive strength to flexural strength. Having established a satisfactory relationship between flexural and compressive strength, pavement, can be designed for a specified flexural strength value, or this value could be used in any other situations when required.

It is seen that strength of concrete in compression and tension (both direct tension and flexural tension) are closely related, but the relationship is not of the type of direct


Cement Content. Kg / m3
390
280
170
Compressive Strength MPa
0
10
20
30
40
50
10
20
40
80
160
Max Size of Aggregate mm


Water/ Cement Ratio
0.40
0.55
0.70
Compressive Strength MPa
7
14
21
28
35
42
49
56
4.75
10
20
40
80
160
Aggregate Size (Log Scale) mm

proportionality. The ratio of the two strengths depends on general level of strength of concrete. In other words, for higher compressive strength concrete shows higher tensile strength, but the rate of increase of tensile strength is of decreasing order.

The type of coarse aggregate influences this relationship. Crushed aggregate gives relatively higher flexural strength than compressive strength. This is attributed to the improved bond strength between cement paste and aggregate particles. The tensile strength of concrete, as compared to its compressive strength, is more sensitive to improper curing. This may be due to the inferior quality of gel formation as a result of improper curing and also due to the fact that improperly cured concrete may suffer from more shrinkage cracks.

The use of pozzolanic material increases the tensile strength of concrete.

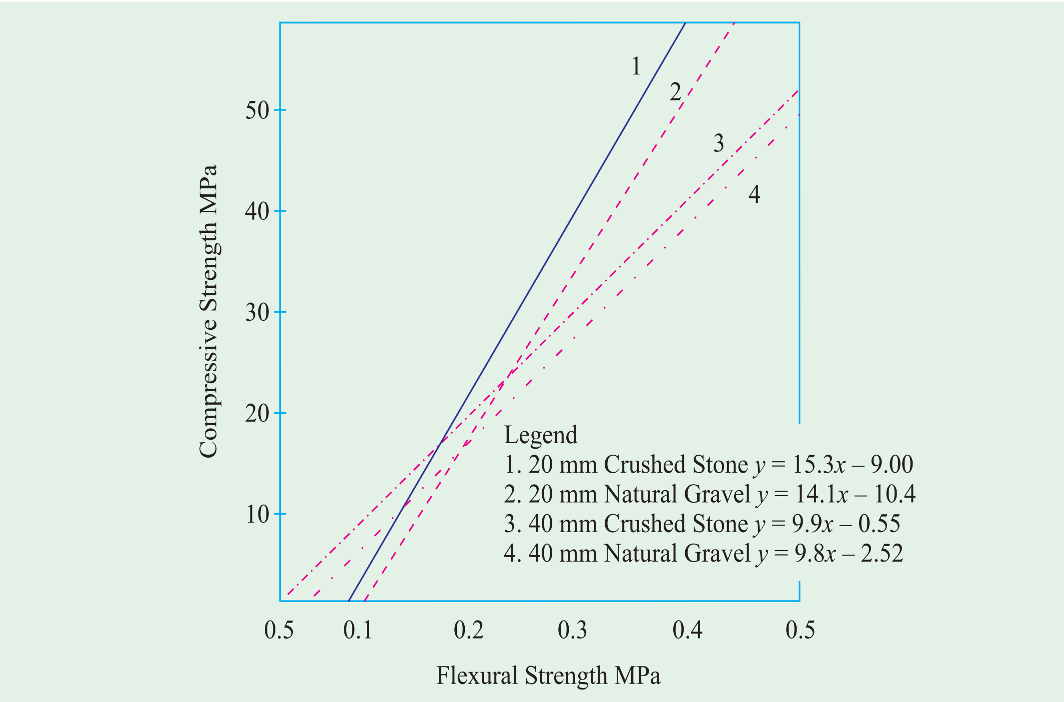
From the extensive study, carried out at Central Road Research Laboratory (CRRI) the following statistical relationship between tensile strength and compressive strength were established.

(*i*) $y = 15.3x - 9.00$ *for 20 mm maximum size aggregate.*

(*ii*) $y = 14.1x - 10.4$ *for 20 mm maximum size natural gravel.*

(*iii*) $y = 9.9x - 0.55$ *for 40 mm maximum size crushed aggregate.*

(*iv*) $y = 9.8x - 2.52$ *for 40 mm maximum size natural gravel. Where* y *is the compressive strength of concrete MPa and* x *is the flexural strength of concrete MPa.*



Subjecting all the data to statistical treatment the following general relationship has been established at CRRI between flexural and compressive strength of concrete:

$$y = 11x - 3.4$$

Fig. 7.10 shows the relationships between compressive strength and flexural strength of concrete for various aggregates.

The flexural strength of concrete was found to be 8 to 11 per cent of the compressive stength of the concrete for higher ranges of concrete strength (greater than 25 MPa) and 9 to 12.8 per cent for lower ranges of concrete strength (less than 25 MPa) as shown in Table 7.6.

The flexural to compressive strength ratio was higher with aggregate of 40 mm maximum size than with those of 20 mm maximum size. In general the ratio was found to be slightly higher in the case of natural gravel as compared to crushed stone.

Flexural strength of concrete is usually found by testing plain concrete beams. Two methods of loading of the beam specimen for finding out flexural strength are practised:

Table 7.6. Flexural Strength Expressed as Percentages of Compressive Strength of Concrete using Gravel and Crushed Stone Aggregate[7.7]

Compressive Strength MPa	Flexural Strength as Percentage of Compressive Strength per cent			
	Gravel Aggregate with Maximum size		Crushed Stone Aggregate with Maximum Size	
	20 mm	40 mm	20 mm	40 mm
49	8.7	-	7.7	-
42	9.0	10.8	7.9	10.2
35	9.3	10.9	8.2	10.3
28	9.9	11.1	8.6	10.2
21	10.8	11.3	9.3	10.3
14	12.5	12.0	10.8	10.5
Average	10.0	11.2	8.8	10.3

Central point loading and third points loading

Experience shows that the variability of results is less in third-point loading. The results of the flexural strength tested under central and third-points loading with constant span to depth ratios of 4 were analyzed statistically and the following general relationship was obtained at Central Road Research Laboratory.

$$x_1 = x_2 + 0.72$$

where, x_1 = *flaxural strength (MPa) of concrete under central point loading and*

x_2 = *flexural strength (MPa) of concrete under third point loading.*

In all the cases the central loading gave higher average value than the third-point loading irrespective of the size of the sample. The higher strength obtained in the case of central loading may be attributed to the fact that the beam is being subjected to the maximum stress at a pre-determined location not necessarily the weakest. In the standard methods for finding the flexural strength of concrete, the span to depth ratio of the specimen is kept at 4. If the span to depth ratio is increased or decreased, the flexural strength was found to alter. A change in this ratio by one induced 3 per cent and 2.5 per cent change in strength when tested by third-point and central point loading respectively. With the increase in span to depth ratio the flexural strength decreased.

The rate of stress application was found to influence the flexural strength of concrete to a very significant extent. The strength increased upto about 25 per cent with increase in stressing rate compared to the standard rate of 0.7 MPa per minute. The increase was found more with the leaner mixes.

There are number of empirical relationships connecting tensile strength and compressive strength of concrete. One of the common relationships is shown below.

$$\text{Tensile Strength} = K\ (\text{Compressive Strength})^n$$

where, value of K varies from 6.2 for gravels to 10.4 for crushed rock (average value is 8.3) and value of n may vary from 1/2 to 3/4

Further data obtained at the Laboratories of Portland Cement Association giving the relationship between compressive and tensile strength of concrete is shown in Table 7.7.

Table 7.7. Relation Between Compressive and Tensile Strength of Concrete[7.8]

Compressive Strength of Cylinders	Strength Ratio		
MPa	Modulus of repture* to compressive strength	Direct tensile strength to compressive strength	Direct tensile strength to modulus of rupture
7	0.23	0.11	0.48
14	0.19	0.10	0.53
21	0.16	0.09	0.57
28	0.15	0.09	0.59
35	0.14	0.08	0.59
42	0.13	0.08	0.60
49	0.12	0.07	0.61
56	0.12	0.07	0.62
63	0.11	0.07	0.63

*Determined under third-point loading.

The Indian Standard IS = 456 of 2000 gives the following relationship between the compressive strength and flexural strength

$$\text{Flexural Strength} = 0.7\sqrt{f_{ck}}$$

where f_{ck} is the characteristic compressive strength of concrete in N/mm^2

Bond Strength

We can consider the bond strength from two different angles; one is the bond strength between paste and steel reinforcement and the other is the bond strength between paste and aggregate. Firstly, let us consider the bond strength between paste and steel reinforcement.

Bond strength between paste and steel reinforcement is of considerable importance. A perfect bond, existing between concrete and steel reinforcement is one of the fundamental assumptions of reinforced concrete. Bond strength arises primarily from the friction and adhesion between concrete and steel. The roughness of the steel surface is also one of the factors affecting bond strength. The bond strength of concrete is a function of compressive strength and is approximately proportional to the compressive strength upto about 20 MPa. For higher strength, increase in bond strength becomes progressively smaller. Table 7.3 gives *the value of bond strength corresponding to the compressive strength. The bond strength, is also a function of specific surface of gel. Cement which consists of a higher percentage of C_2S will give higher specific surface of gel, thereby giving higher bond strength. On the other hand, concrete containing more C_3S or the concrete cured at higher temperature results in smaller specific surface of gel which gives a lower bond strength. It has been already pointed out that high pressure steam cured concrete produces gel whose specific surface is about 1/20 of the specific surface of the gel produced by normal curing. Therefore, bond strength of high pressure steam cured concrete is correspondingly lower.*

Aggregate-Cement Bond Strengths

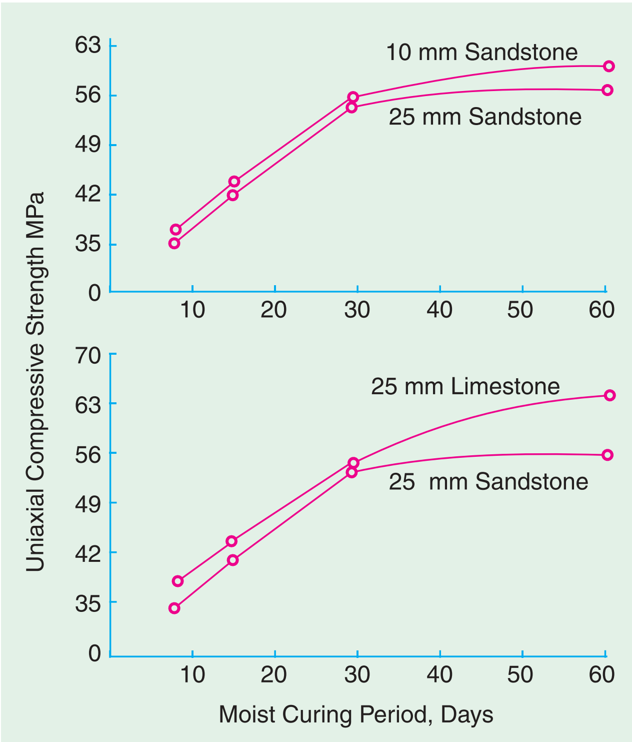
Concrete can be regarded as a chain in which aggregates are the links bonded together by cement paste. Just as the strength of a chain as a whole is depending upon the strength of welding of the individual links, the strength of concrete as a whole is depending upon the strength (bond strength) of the hydrated hardened cement paste (hcp). By and large the strength of hcp is depending upon w/c ratio which determines the quality, continuity, density, porosity of the products of hydration in particular the C-S-H gel. Stronger the gel bond stronger is the concrete. Aggregates generally being much stronger than the paste (gel bond), its strength is not of consequence in normal strength concrete. The strength of aggregate is of consideration in high strength concrete and light weight concrete.

The explanation that the strength of Concrete is limited by strength of the paste, will hold good when we consider concrete as two phase material. If we take a closer look into the structure of the concrete, a third phase comes into consideration i.e., inter-face between the paste and aggregate known as Transition Zone. In the ultimate analysis it is the integrity of the transition zone that influences the strength of concrete.

As we have seen earlier, bleeding takes place in fresh concrete. The bleeding water in the process of coming up gets intercepted by aggregates, particularly large size flaky and elongated aggregate and gets accumulated at the inter-face between paste and aggregates. The extra water remaining at the inter-face, results in poor paste structure and poor gel bond at the transition zone.

The paste shrinks while hardening. The magnitude of shrinkage is higher with higher water content, in which case, a higher shrinkage takes place at the transition zone which results in greater shrinkage cracks at the transition zone.

In case of shrinkage taking place on account of heat of

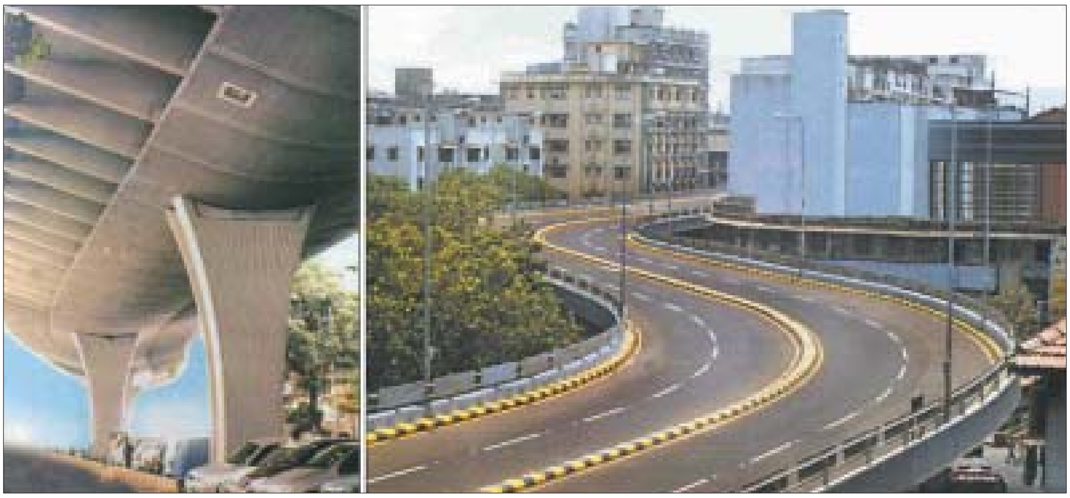


hydration, the weak gel structure at the transition zone also suffers a higher degree of shrinkage. The same situation will take place if the concrete is subjected to heat or cold during the service life.

It can be deduced that there are considerable microcracks or what you call "faults", exists in the transition zone even before the concrete structures are subjected to any load or stress. When subjected to some stress, the existing micro cracks in transition zone propagate much faster with tiny jumps and develop bigger cracks than rest of the body of concrete and structure fails much earlier than the general strength of concrete. Therefore, the transition zone is the weakest link of the chain. It is the strength limiting phase in concrete.

Point to note is that we have to come back to the basics. It is the w/c ratio that again influences the quality of transition zone in low and medium strength concrete. The w/c ratio is not exerting the same influence on high strength concrete ie., for very low w/c ratio. It has been seen that for w/c less than 0.3, disproportionately high increase in compressive strength can be achieved for very small reduction in w/c. This phenomenon is attributed mainly to a significant improvement in the strength of transition zone at very low w/c ratio.

Aggregate characteristics other than strength, such as size, shape, surface texture and grading are known to affect the strength of concrete. The increase in strength is generally attributed to indirect change in w/c ratio. Recent studies have shown that the above characteristics of aggregates have independent influence on the strength properties of concrete other than through w/c ratio by improving the quality of transition zone.



J.J Flyover at Mumbai where high strength, high performance concrete 75 MPa was used for the first time in India (2002).

Courtesy : Gammon India

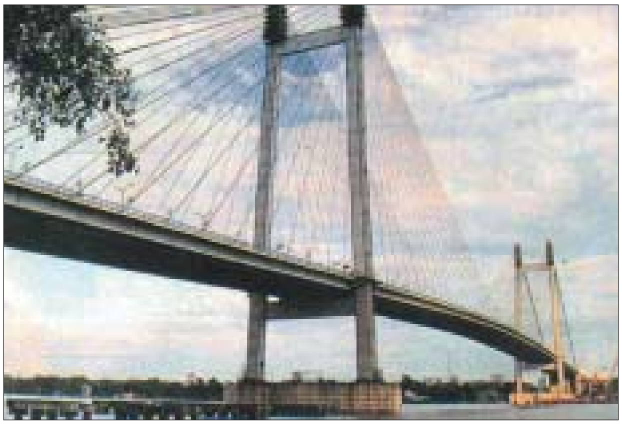
There are number of published literatures which indicate that under identical conditions, calcareous aggregates give higher strength than siliceous aggregates. The result of studies conducted at university of California is shown in Fig. 7.11.

The strength of concrete embraces so many aspects that it is difficult to describe all the factors that influences the strength of concrete. The entire book on concrete technology, in a way is dealing with the strength properties of concrete. In this book, the various aspects on strength properties of concrete is described in various chapters.

High Strength Concrete

Concrete is generally classified as Normal Strength Concrete (NSC), High Strength Concrete (HSC) and Ultra High Strength Concrete (UHSC). There are no clear cut boundary for the above classification. Indian Standard Recommended Methods of Mix Design denotes the boundary at 35 MPa between NSC and HSC. They did not talk about UHSC. But elsewhere in the international forum, about thirty years ago, the high strength lable was applied to concrete having strength above 40 MPa. More recently, the threshold rose to 50 to 60 MPa. In the world scenario, however, in the last 15 years, concrete of very high strength entered the field of construction, in particular construction of high-rise buildings and long span bridges. Concrete strengths of 90 to 120 MPa are occasionally used. Table 7.8 shows the kind of high strength produced in RMC plant.

The advent of Prestressed Concrete Technology Techniques has given impetus for making concrete of higher strength. In India, there are cases of using high strength concrete for prestressed concrete bridges. The first prestressed concrete bridge was built in 1949 for the Assam Rail Link at Siliguri. In fifty's a number of pretressed concrete structures were built using concrete of strength from 35 MPa to 45 MPa. But strength of concrete more than 35 MPa was not commonly used in general construction practices. Probably concrete of strength more than 35 MPa was used in large scale in Konkan Railway project during early 90's and concretisation of Mumbai Muncipal Corporation Roads. It is only during 90's use of high strength concrete has taken its due place in Indian construction scenario. Of late concrete of strength varying from 45 MPa to 60 MPa has been used in high rise buildings at Mumbai, Delhi and other Metropolitan cities. Similarly high strength concrete was employed in bridges and flyovers. Presently (year 2000) in India, concrete of strength 75 MPa is being used for the first time in one of the flyovers at Mumbai. Other notable example of using high strength concrete in India is in the construction of containment Dome at Kaiga Power Project. They have used High performance concrete of strength 60 MPa with silica fume as one of the constituents.



Vidya Sagar Setu at Kolkata where longest cable stayed bridge (in India) was built using high strength concrete.

Ready Mixed Concrete has taken its roots in India now. The manufacture of high strength concrete will grow to find its due place in concrete construction for all the obvious benefits. In the modern batching plants high strength concrete is produced in a mechanical manner. Of course, one has to take care about mix proportioning, shape of aggregates, use of supplementary cementitious materials, silica fume and superplasticizers. With the modern equipments, understanding of the role of the constituent materials, production of high strength concrete has become a routine matter.

There are special methods of making high strength concrete. They are given below.

(a) Seeding *(b) Revibration* *(c) High speed slurry mixing;*
(d) Use of admixtures *(e) Inhibition of cracks* *(f) Sulphur impregnation;*

(g) Use of cementitious aggregates.

Seeding: *This involves adding a small percentage of finely ground, fully hydrated Portland cement to the fresh concrete mix. The mechanism by which this is supposed to aid strength development is difficult to explain. This method may not hold much promise.*

Revibration: *Concrete undergoes plastic shrinkage. Mixing water creates continuous capillary channels, bleeding, and water accumulates at some selected places. All these reduce the strength of concrete. Controlled revibration removes all these defects and increases the strength of concrete.*

High Speed slurry mixing: *This process involves the advance preparation of cement-water mixture which is then blended with aggregate to produce concrete. Higher compressive strength obtained is attributed to more efficient hydration of cement particles and water achieved in the vigorous blending of cement paste.*

Use of Admixtures: *Use of water reducing agents are known to produce increased compressive strengths.*

Inhibition of cracks: *Concrete fails by the formation and propagation of cracks. If the propagation of cracks is inhibited, the strength will be higher. Replacement of 2– 3% of fine aggregate by polythene or polystyrene "lenticules" 0.025 mm thick and 3 to 4 mm in diameter results in higher strength. They appear to act as crack arresters without necessitating extra water for workability. Concrete cubes made in this way have yielded strength upto 105 MPa.*

Sulphur Impregnation: *Satisfactory high strength concrete have been produced by impregnating low strength porous concrete by sulphur. The process consists of moist curing the fresh concrete specimens for 24 hours, drying them at 120°C for 24 hours, immersing the specimen in molten sulphur under vacuum for 2 hours and then releasing the vacuum and soaking them for an additional ½ hour for further infiltration of sulphur. The sulphur-infiltrated concrete has given strength upto 58 MPa.*

Use of Cementitious aggregates: *It has been found that use of cementitious aggregates has yielded high strength. Cement fondu is kind of clinker. This glassy clinker when finely ground results in a kind of cement. When coarsely crushed, it makes a kind of aggregate known as ALAG. Using Alag as aggregate, strength upto 125 MPa has been obtained with water/cement ratio 0.32.*

Ultra High Strength Concrete

As technology advances, it is but natural that concrete technologists are directing their attention beyond high strength concrete to ultra high strength concrete. The following techniques are used for producing ultra high strength concrete.

(a) Compaction by pressure *(b) Helical binding;*

(c) Polymerisation in concrete *(d) Reactive powder concrete.*

Compaction by Pressure: *It has been pointed out earlier that cement paste derives strength due to the combined effect of friction and bond. In ceramic material, grain size and porosity would be the most important parameters affecting friction and bond and hence the strength. It has been attempted to reduce grain size and porosity by the application of tremendous pressure at room temperature and also at higher temperature.*

Unusually high strength have been generated in materials by employing "hot pressing" techniques and intermediate ranges of strengths have been achieved by applying high pressure at room temperature to Portland cement pastes. Strengths as high as 680 MPa *(compressive), 66 MPa (indirect tensile) have been obtained by subjecting cement pastes to 357 MPa pressure under a temperature of 250°C. The water/cement ratio used was 0.093. It was also seen that hot pressed materials are volume stable. The micro structure of such materials are very compact, consisting of intergrowth of dense hydrated cement gel surrounding residual unhydrated cement grain cores. The lowest porosity of the materials measured was approximately 1.8%.*

Table 7.8. Composition of Experimental Concretes Produced in a Ready-mix Plant[7.9] (In U.S.A.)

Concrete type	Reference	Silica fume	Fly ash	Slag + silica fume		
W/(c + m)		0.30	0.30	0.30	0.3	0.25
Water kg/m^3		127	128	129	131	128
Cement						
ASTM Type II	kg/m^3	450	425	365	228	168
Silica fume	kg/m^3	-	45	-	45	54
Fly ash	kg/m^3	-	-	95	-	-
Slag	kg/m^3	-	-	-	183	320
Dolomite limestone		1100	1110	1115	110	1100
Coarse aggregate	kg/m^3					
Fine aggregate	kg/m^3	815	810	810	800	730
Superplasticizer*	L/m^3	15.3	14	13	12	13
Slump after 45 minutes (mm)		110	180	170	220	210
Strength at 28 day	(MPa)	99	110	90	105	114
Strength at 91 day	(MPa)	109	118	111	121	126
Strength at 1 year	(MPa)	119	127	125	127	137

*Sodium salt of a naphthalin sulphonate

Helical Binding: *This is an indirect method of achieving ultra high strength in concrete. High tensile steel wire binding externally over the concrete cylinder results in good strength.*

Polymer Concrete: *Impregnation of monomer into the pores of hardened concrete and then getting it polymerised by irradiation or thermal catalytic process, results in the development of very high strength. This method of making ultra high strength concrete holds much promise. This aspect has been discussed in detail in Chapter 12 under special concrete.*

Reactive Powder Concrete: *High strength Concrete with strength of 100 – 120 MPa have been used for the construction of structural members. Concrete with 250 to 300 MPa are also used for non-structural applications such as flooring, safes and storage of nuclear wastes.*

For structural uses, high ductility is required along with high-strength. Reactive powder concrete (RPC) has been developed to have a strength from 200 to 800 MPa with required ductility.

Concrete is a heterogeneous material and strength obtained by cement paste is not fully retained when sand and aggregates are added. The Reactive Power concrete is made by replacing the convential sand and aggregate by ground quartz less than 300 micron size, silica *fume, synthesized precipitated silica, steel fibres about 1 cm in length and 180 micron in diameter.*

The typical composition and mechanical property of the RPC of 200 MPa strength and 800 MPa strength are shown in Table. 7.9. and Table. 7.10 respectively.

Table No.7.9. Typical Composition of Reactive Powder Concrete 200 [7.10]

1	Portland Cement-Type V	955 kg/m³
2	Fine Sand (150-400 micron)	1051 kg/m³
3	Silica Fume (18 m²/gram)	229 kg/m³
4	Precipitated Silica (35 m²/g)	10 kg/m³
5	Superplasticizer (Polyacrylate)	13 kg/m³
6	Steel fibres	191 kg/m³
7	Total water	153 kg/m³
8	Compressive Strength (Cylinder)	170 - 230 MPa
9	Flexural strength	25–60 MPa
10	Young's Modulus	54 - 60 GPa

Table 7.10. Typical Composition of Reactive Powder Concrete 800 [7.10]

1	Portland Cement-Type V	1000 kg/m³
2	Fine Sand (150 - 400 microns)	500 kg/m³
3	Ground quartz (4 microns)	390 kg/m³
4	Silica fume (18 m²/gram)	230 kg/m³
5	Superplasticizer (Polyacrylate)	18 kg/m³
6	Steel fibres (length 3 mm and dia. 180 μ)	630 kg/m³
7	Total water	180 kg/m³
8	Compressive Strength (cylinder)	490- 680 MPa
9	Flexural Strength	45 - 102 MPa
10	Young's Modulus	65 - 75 GPa

High-Performance concrete

Recently a new term "High performance concrete" is used for concrete mixture which possess high workability, high strength, high modulus of elasticity, high density, high dimensional stability, low permeability and resistance to chemical attack.

There is a little controversy between the terms high-strength and high-performance concrete. High-performance concrete is also, a high-strength concrete but it has a few more attributes specifically designed as mentioned above. It is, therefore, logical to describe by the more widely embracing term "High Performance Concrete" (HPC).

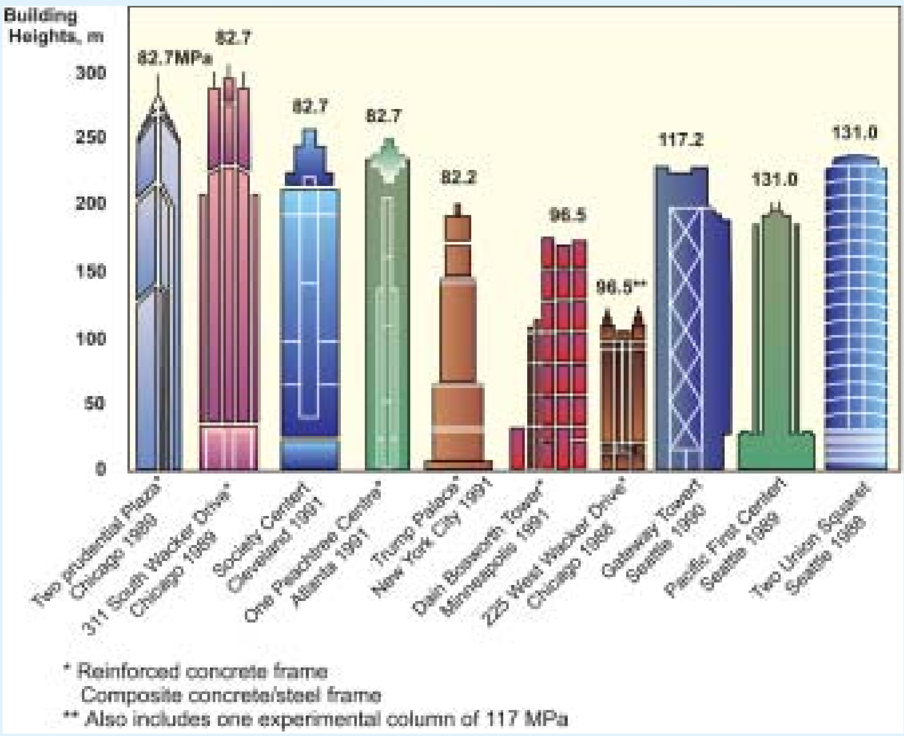
It may be recalled that in normal concrete, relatively low strength and elastic modulus are the result of high heterogeneous nature of structure of the material, particularly the porous and weak transition zone, which exists at the cement paste-aggregate interface. By densification and strengthening of the transition zone, many desirable properties can be improved many fold. This aspect has been already discussed in detail. A substantial reduction *of quantity of mixing water is the fundamental step for making HPC. Reduction of w/c ratio will result in high strength concrete. But reduction in w/c ratio to less than 0.3 will greatly improve the qualities of transition zone to give inherent qualities expected in HPC.*

To improve the qualities of transition zone, use of silica fume is also found to be necessary. Silica fumes becomes a necessary ingredient for strength above to 80 MPa. The best quality fly ash and GGBS may be used for other nominal benefits. Inspite of the fact that these pozzolanic materials increase the water demand, their benefits will out weigh the disadvantages. The crux of whole problem lies in using very low w/c ratio, consistant with high workability at the time of placing and compacting. Neville opines that the lowest w/c ratio that could be used is 0.22.[7.9]

Adopting w/c ratio in the range of 0.25 to 0.3 and getting a high slump is possible only with the use of superplasticizer. Therefore, use of appropriate superplasticizer is a key material in making HPC. The associated problem is the selection of superplasticizer and that of cement so that they are compatible and retain the slump and rheological properties for a sufficiently long time till concrete is placed and compacted.

Aggregates for HPC

In normal strength concrete, the strengths of aggregate by itself plays a minor role. Any aggregate available at the site could be used with little modification of their grading. The situation is rather different with HPC, where the bond between aggregate and hydrated cement paste is so strong that it results in significant transfer of stress across the transition zone. At the same time, the strength of the cement paste phase, on account very low w/c ratio is



Example of some well-known Structures where HPC was used. Strength of concrete is shown on the top of each building.

so high that sometimes it is higher than the strength of aggregate particles. Observation of fractured surface in HPC has shown that they pass through the coarse aggregate particles as often as, if not more often than, through the cement paste itself. Indeed in many instances, the strength of aggregate particles has been found to be the factor that limits the compressive strength of HPC.

On the basis of practical experience it is seen that for concrete strength up to 100 MPa, maximum size of 20 mm aggregate could be used. However, for concrete in excess of 100 MPa, the maximum size of coarse aggregate should be limited to 10 to 12 mm.

Table 7.11. Typical HPC mixtures used in some important buildings in USA and other countries.

Mixture Number		1	2	3	4	5
Water	kg/m³	195	165	135	145	130
Cement	kg/m³	505	451	500	315	513
Fly ash	kg/m³	60	-	-	-	-
Slag	kg/m³	-	-	-	137	-
Silica fume	kg/m³	-	-	30	36	43
Coarse aggregates	kg/m³	1030	1030	1100	1130	1080
Fine aggregate	kg/m³	630	745	700	745	685
Water reducer	ml/m³	975	-	-	900	-
Retarder	L/m³	-	4.5	1.8	-	-
Superplasticizer	L/m³	-	11.25	14	5.9	15.7
W/(c + m)		0.35	0.37	0.27	0.31	0.25
Strength at 28 day	(MPa)	65	80	93	83	119
Strength at 91 day	(MPa)	79	87	107	93	145

1- Water Tower Place, Chicago 1975

2- Joigny Bridge, France 1989

3- La Laurentienne Building, Montreal (1984)

4- Scotia Plaza, Toronto (1987)

5- Two Union square, Seattle (1988)

Regarding the shape of the aggregate, crushed aggregate can be used, but utmost care should be taken to see that aggregates are cubic in shape, with minimum amount of flaky or elongated particles. The latter would effect not only the strength but also adversely affect the workability. In one site in Mumbai even for 60 MPa concrete they had to go for well processed and well graded cubic shaped, coarse aggregate from the point of view of workability. For HPC shape and size of the aggregate becomes an important parameter. Table No. 7.11. gives the composition and stength of HPC that are used in some important buildings in USA and other countries.

In India, it is reported, that HPC of the strength 60 MPa was used for the first time for the construction of containment dome at Kaiga and Rajasthan Atomic Power Projects.

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