14 SPECIAL CONCRETES AND CONCRETING TECHNIQUES

14.1 INTRODUCTION

Notwithstanding its versatility, cement concrete suffers from several drawbacks, such as *low tensile strength, permeability to liquids* and consequent *corrosion of reinforcement,* susceptibility to *chemical attack,* and *low durability.* Modifications have been made from time to time to overcome the deficiencies of cement concrete yet retaining the other desirable characteristics. Recent developments in the material and construction technology have led to significant changes resulting in improved performance, wider and more economical use. The improvements in performance can be grouped as:

1. Better mechanical properties than that of conventional concrete, such as compressive strength, tensile strength, impact toughness, etc.,
2. Better durability attained by means of increased chemical and freeze–thaw resistances.
3. Improvements in selected properties of interest, such as impermeability, adhesion, thermal insulation, lightness, abrasion and skid resistance, etc.

The mechanical properties can be improved by using one or more of the following approaches:

1. Modifications in microstructure of the cement paste.
2. Reduction in overall porosity.
3. Improvements in the strength of aggregate-matrix interface.
4. Control of extent and propagation of cracks.

14.1.1 Modification in the Microstructure

Considerable improvements in inter-particle cohesive forces can be realized by reducing the inter-particle spacing of the hydrate phase. Perhaps the most notable attempt to modify the microstructure is the application of the *hot pressing technique.* By application of pressures of up to 350 MPa during molding at temperatures up to 150 °C, compressive strengths of the order of 520 MPa have been obtained. The electron micrographs of such *hot pressed cement plates* have revealed a marked improvement in the microstructure in comparison to those cured at ordinary temperatures in that they show dense and relatively homogeneous structures. Though not yet used in construction, this method reveals the potential of future concrete.

14.1.2 Reduction in Porosity

The *mechanical properties* and *durability* of concrete can be improved by filling the pores, voids and cracks by incorporating or impregnating the concrete with *polymers*. In *polymer-impregnated concrete* (PIC), the pores in conventional concrete after normal curing are emptied under vacuum and then a *monomer* is sucked in, which is later polymerized by the application of heat or radiation. Considerable increase in tensile and compressive strengths and modulus of elasticity and hardness results. Compressive strengths, of the order of about 280 MPa have been obtained. Commercial applications of polymer-impregnated concrete include piles, tunnel liners, precast prestressed bridge deck panels and in wide ranging repairs.

Sulfur-impregnated concretes (SIC), in a similar manner, have resulted in high strength concretes from lean conventional concrete mixes. A typical value of compressive strength of sulfur-impregnated concrete has been reported to be 55 MPa from a reference moist-cured ordinary concrete having a strength of 5.5 MPa, i.e., a ten-fold increase. In India, the applications of sulfur-impregnated concrete are limited due to high cost of sulfur.

14.1.3 Stronger Aggregate-Matrix Interface

The *mechanical properties* of cement concrete which consists of a relatively inert aggregate bounded by hydrated cement binder or *matrix*, depend upon the strength of aggregate and the stability of concrete through the matrix. In particular, the interface between the aggregate and the matrix must be capable of transferring the stresses due to loads to aggregate. This is generally achieved in cement concrete through the strong Van der-waals bonds between the micro-crystalline components of hydrated cement paste and the aggregate. However, the bonds are not so strong as to transfer tensile or shear stresses, and hence the composite, i.e., cement concrete is relatively weak in tension and shear. Only the compressive stresses are effectively transmitted. As the aggregate is usually very strong, the aggregate strength can be fully exploited by achieving greater force transfer capability. Beyond a level, the conventional cement matrix is unable to accomplish this.

It is possible to supplement the cement matrix in the composite with another matrix or, if the cement matrix is replaced by a more efficient matrix, it should be possible to obtain concrete of much higher strength. If the binder or the matrix exhibits ionic or covalent bonds with aggregate at the interface, the resulting composite will also be sufficiently strong to transmit large tensile forces. Efforts in this direction have resulted in the use of polymers, either as sole matrix or supplement to the cement matrix.

With the addition of polymers, the failure of concrete specimens does not occur through the aggregate-mortar interface, but through the aggregates themselves, thereby showing improvement in bond strength at the interface. With an improvement in bond strength at the interface, the aggregate strength can be fully exploited, i.e., the concrete strength is limited by the mechanical strength of the aggregate.

14.1.4 Control of Extent and Propagation of Cracks

The most notable development in this direction is the use of *ferrocement* and *fiber-reinforced concretes*. In ferrocements, meshes of thin steel wires of various configurations and sizes are incorporated as reinforcement in cement-mortars. However, in fiber-reinforced concrete (FRC), steel, glass or polymeric fibers of suitable mechanical and chemical properties and having optimum *aspect ratios* are incorporated with other concrete materials at the mixing stage. In a way both can be viewed as reinforced concretes. The wire-mesh or fibers hold the matrix together after *localized cracking*, and provide improved *ductility* and *post-cracking load-carrying capacity*. The compressive strength improves slightly (say by 25 per cent), but the *tensile strength, first-crack tensile strength, impact strength* and *toughness* or *shock absorption capacities* show a two-to-four fold improvement.

Ferrocement has found wide applications in boat-hull building, construction of shells, and similar structural components of thin sections. Applications of fiber-reinforced concrete include pavements and runways, industrial floors, hydraulic structures, breakwater, armour units, pile foundations, etc.

The combinations of fiber-reinforced concrete and polymer impregnation technique are seen as the potential method of utilizing the advantages of both, i.e., a ductile material of high toughness equal to 228 times that of normal mortars. Similarly, a *fibrous ferrocement* composite can be regarded as a future composite of high potential.

14.2 LIGHTWEIGHT CONCRETE

The conventional cement concrete is a heavy material having a density of 2400 kg/m^3, and high *thermal conductivity*. The dead weight of the structure made up of this concrete is large compared to the imposed load to be carried, and a relatively small reduction in dead weight, particularly for members in flexure, e.g., in highrise buildings, can save money and manpower considerably. The improvement in thermal insulation is of great significance to the conservation of energy. The reduction in dead weight is normally achieved by cellular construction, by entraining large quantities of air, by using *no-fines* concrete and lightweight aggregates which are made lighter by introducing internal voids during the manufacturing process.

The term no-fines indicates that the concrete is composed of cement and coarse aggregate (commonly 10 or 20 mm grading) only, the product has uniformly distributed voids. Suitable aggregates used are natural aggregates, blast-furnace slag, clinker, foamed slag, sintered fly ash, expanded-clay, etc.

Lightweight aggregate is a relatively new material. For the same crushing strength, the density of concrete made with such an aggregate can be as much as 35 per cent lower than the normal weight concrete. In addition to the reduced dead weight, the lower modulus of elasticity and adequate ductility of lightweight concrete may be advantageous in the seismic design of structures. Other inherent advantages of the material are its greater fire resistance, low thermal conductivity, low coefficient of thermal expansion, and lower erection and transport costs for prefabricated members. For prefabricated structures a smaller crane is required or the same crane can handle larger units due to reduction in dead weight. For cast *in-situ* structures, its smaller dead weight makes foundations less expensive.

Moreover, continued extraction of conventional dense natural aggregate from the ground is bound to be accompanied by severe environmental problems leading to deterioration of the countryside and its ecology. On the other hand, use of manufactured aggregates made of industrial wastes (slags, etc.,), preferably those containing sufficient combustible materials (pulverized fuel ash) which provide all or most of the energy for their production, may help in alleviating the problem of disposal of industrial waste.

14.2.1 Lightweight Aggregates

Lightweight aggregates may be grouped in the following categories:

1. Naturally occurring materials which require further processing, such as expanded clay, shale and slate, etc.
2. Industrial by-products, such as sintered pulverized fuel ash (fly ash), foamed or expanded-blast-furnace slag.
3. Naturally occurring materials, such as pumice, foamed lava, volcanic tuff and porous limestone.

Aggregates Manufactured from Natural Raw Material The artificial lightweight aggregates are mainly made from clay, shale, slate or pulverized fuel ash, subject to a process of either *expansion* (*bloating*) or *agglomeration*. During the process of expansion the material is heated to fusion temperature at which point pyroplasticity of material occurs simultaneously with the formation of gas. Agglomeration on the other hand occurs when some of the material fuses (melts) and various particles are bonded together. Thus to achieve proper expansion a raw material should contain sufficient gas-producing constituents, and pyroplasticity should occur simultaneously with the formation of gas. The gas may form due to decomposition and combustion of sulfide and carbon compounds; removal of CO_2 from carbonates or reduction of Fe_2O_3 causing liberation of oxygen. The common examples of *natural minerals* suitable for expansion are clay, shale, slate and perlite and exfoliated vermiculite.

1. **Expanded or bloated-clay** Bloated-clay aggregates are made from a special grade of clay suitable for expansion. The ground clay mixed with additive which encourages bloating, is passed through a rotary or vertical shaft kiln fired by a mixture of pulverized coal and oil with temperature reaching about 1200 °C. The material produced consists of hard rounded particles with a smooth dense surface texture and honeycomb interior.
2. **Expanded shale** The crushed raw material such as colliery waste, blended with ground coal is passed over a sinter strand reaching a temperature of about 1200 °C. At this temperature, the particles expand and fuse together trapping gas and air within the structure of the material with a porous surface texture.

3. **Expanded slate** The crushed raw material is fed into a rotary kiln with temperature reaching 1200 °C. The material produced is chemically inert and has a highly vitrified internal pore structure. This material is then crushed and graded.
4. **Exfoliated vermiculite** The raw material resembles mica in appearance and consists of thin flat flakes containing microscopic particles of water. On being suddenly heated to a high temperature of about 700–1000 °C, the flakes expand (exfoliate) due to steam forcing the laminates apart. The material produced consists of accordion granules containing many minute air layers.

Industrial By-product Lightweight Aggregate These include sintered-pulverized fuel ash, foamed-blast-furance slag and pelletized slag.

1. **Sintered-pulverized fuel ash** The fly ash collected from modern power stations burning pulverized fuel, is mixed with water and coal slurry in screw mixers and then fed onto rotating pans, known as pelletizers, to form spherical pellets. The *green* pellets are then fed onto a sinter strand reaching a temperature of 1400 °C. At this temperature, the fly ash particles coagulate to form hard brick-like spherical particles. The produced material is screened and graded.
2. **Foamed-blast-furnace slag** It is a by-product of iron production formed by introducing water or steam into molten material. The material produced after annealing and cooling is angular in shape with a rough and irregular glassy texture, and an internal round void system.

Naturally Occurring Lightweight Aggregates The common examples are pumice and diatomite. *Pumice* is light and strong enough to be used in its natural state, but has variable qualities depending upon its source. It is chemically inert and usually has a relatively high silica content of approximately 75 per cent. Diatomite, on the other hand, is a semiconsolidated sedimentary deposit formed in cold water environment.

Production In India, raw lightweight aggregates are produced by using any of the following:

1. Bloated-clay aggregates by bloating suitable clays with or without additives
2. Sintered-fly-ash aggregates by sintering the fly-ash.
3. Lightweight aggregate from blast-furnace slag.

In one of the processes for manufacturing lightweight concrete, the cement and pulverized sand are first mixed in a certain proportion (1 : 1 for insulation and 1:2 for partitioning purposes). The mixture so formed is then made into slurry with the addition of a predetermined quantity of water. The sand-cement slurry is next foamed to the extent of predetermined volume with the help of a foaming compound. The foam product is thereafter poured into molds. The molded blocks are finally cured under elevated *hydrothermal conditions* in autoclaves which imparts strength, reduces drying shrinkage and gives the block a creamy color.

In another product, lime and sand are used as raw materials. Both are first ground to fine powder in huge ball mills. The mixture is then made into slurry with the addition of water. Adding aluminum powder and gypsum to the slurry triggers a chemical reaction, and the hydrogen gas evolved gives the cellular concrete its lightness. After initial hardening, it is cut into convenient sizes and the molded blocks are finally cured under elevated *hydrothermal conditions* (under a pressure of 12 atmospheres and temperature of 196 °C).

The suitability of a particular lightweight aggregate is determined by the specified compressive strength and the density of concrete.

14.2.2 Properties of Lightweight Aggregates

The properties of the manufactured lightweight aggregates depend mainly on the raw material, and the process of manufacture. The properties of aggregates manufactured from materials which occur as industrial by-products can be altered to a limited extent only by the processes of bloating, foaming, sintering, agglomerating and crushing. Since the aggregate make up approximately 75 per cent of the total volume of the concrete, it influences the workability, strength, modulus of elasticity, density, durability, thermal conductivity, shrinkage, and creep properties of concrete. The structural concrete should have a high strength with low density, high modulus of elasticity, and low rate of shrinkage and creep. On the other hand, a lightweight aggregate concrete should possess low thermal conductivity. The thermal conductivity decreases with decreasing density, therefore the density of the concrete must be as low as possible. The most suitable aggregates for structural lightweight concrete are expanded-clay, shale and slate, fly ash and colliery waste. Adequate strength for structural lightweight aggregate concrete can be obtained with foamed and expanded-blast-furnace slag. For lightweight aggregate concrete for thermal insulation, the suitable aggregates are pumice, perlite, vermiculite, diatomite and expanded-polystyrene.

A surface texture with tiny and uniformly distributed pores is preferred. Particle size and shape as well as surface condition of aggregates influence properties of fresh concrete. Crushed and angular lightweight aggregate requires high mortar content resulting in a higher density than that with rounded aggregate. The strength of the lightweight aggregate particles decreases with decreasing density. The density, bulk density and water absorption capacity of some of the commonly used lightweight aggregates are given in Table 14.1. The compressive strengths and unit weights of typical concretes produced by these aggregates are also given in the table.

14.2.3 Mix Proportions

Due to large variations in the characteristics of lightweight aggregates, it is difficult to seek a single approach to mix design for structural lightweight aggregate concrete. However, following points should be considered:

Table 14.1 *Physical properties of lightweight aggregate*

Aggregate Type	Particle shape, and surface texture	Density (kg/m^3)		Bulk density (kg/m^3)	24-hour water absorption capacity (per cent)	Typical concrete	
						Compressive strength (MPa)	Unit weight (kg/m^3)
A. Aggregate for structural concrete (f_{ck} > 15 MPa)							
Expanded clay	Rounded and slightly rough particles.	Coarse	600 to 1600	300 to 900	5 to 30	10 to 60	1000 to 1700
		Fine	1300 to 1800				
Expanded shale and slate	Often angular and slightly rounded, smooth surface.	Coarse	800 to 1400	400 to 1200	5 to 15	20 to 50	1300 to 1600
		Fine	1600 to 1900				
Fly ash	Similar to expanded clay.		1300 to 2100	600 to 1100	20	30 to 60	1500 to 1600
Foamed-blast-furnace slag	Irregular angular particles with rough and open pored surface.		1000 to 2200	400 to 1100	10 to 15	10 to 45	1800 to 2000
Sintered-colliery waste	Angular with open-pored surface.		1000 to 1900	500 to 1000	15	10 to 40	1400 to 1600
B. Aggregate for low-medium strength concrete (3.5 to 15 MPa)							
Pumice	Rounded particles with open-textured but rather smooth surface.		550 to 1650	350 to 650	50	5 to 15	1200 to 1600
C. Aggregate for low strength concrete (0.5 to 3.5 MPa)							
Perlite	Rounded and of angular shape and rough surface.		100 to 400	40 to 200	—	1.2 to 3.0	400 to 500
Vermiculite	Cubical		100 to 400	60 to 200	—	1.2 to 3.0	300 to 700

As in case of normal weight concrete, the lightweight aggregate concrete can attain the strength of mortar matrix only if the strength and stiffness of the aggregate are at least as high as those of the mortar. Below this limit, internal stress transfer takes place in the same way as in normal weight concrete. In this case, concrete strength is approximately equal to the strength of mortar. The *water-cement ratio* and mix proportions applicable to ordinary concrete, can be adopted, however instead of total water only the effective water must be taken into account.

It is, of course, also possible to manufacture lightweight concretes with higher strength than the limit strength mentioned above by using a stronger mortar (having greater stiffness) with a higher density. In this concrete, the mortar matrix will transmit higher stress at the same deformation. For economic reasons, it is preferable to select a stronger aggregate such that the required concrete strength can be attained with the mortar of lower strength. For a concrete of given compressive strength, a strong aggregate requires a low mortar strength and a weak aggregate requires a high mortar strength.

Since aggregate strength and its modulus of deformation is not usually available, the suitability of a lightweight aggregate for a specific application is generally assessed by means of the particle density or bulk density. For structural lightweight concrete, the maximum nominal size of the aggregate is limited to 20 mm since the modulus of deformation, strength and density of aggregate particles decrease as particle size increases. On the other hand, a lower maximum size and a large proportion of fines may lead to higher strength but the concrete density will increase.

Natural sand is often used to improve the *workability* and reduce the *shrinkage* of fresh concrete and increase its strength, but it will increase the density of concrete.

The conventional *water-cement ratio* rule is not suitable for lightweight concrete. In lightweight concrete, the water content to be taken into account for calculation of water-cement ratio is not the total quantity of water present but only the effective or free water. The relationship between strength and water-cement ratio varies from aggregate to aggregate. The effect of cement strength on the strength of concrete is not linear.

The main problem of lightweight concrete mix design lies in the advance determination of effective water and air contents of cement matrix at the moment of completion of compaction of concrete. The prediction is difficult to make since throughout the mixing process the effective (free) water content is progressively reduced through absorption by aggregate, except when completely saturated aggregate is used. The combined free-water and air contents can be approximately estimated as the *residual absolute volume,* when the density of fresh concrete, the mix proportions and particle density are known. The residual absolute volume, V_{res}, is obtained by subtracting the volume of the solid cement and aggregates from the total volume of concrete.

$$V_{res} = V_w + V_{air} = 1000\left[1 - \left(\frac{C}{S_c} - \frac{A}{S_a}\right)\right]$$

where, V_w and V_{air} are the free-water and air contents in litre/m^3, respectively. C and A denote cement and aggregate contents in kg/m^3, respectively. S_c and S_a are the density of cement and mean particle density of aggregates in kg/m^3, respectively. In contrast to normal concrete, the relationship between *residual absolute volume-cement ratio* and the strength of lightweight concrete vary from aggregate to aggregate. As the residual absolute volume-cement ratio decreases the concrete strength increases, however the increase is less than that for normal concrete. For every type of lightweight aggregate the compressive strength of the concrete bears a definite relationship to the residual absolute volume-cement ratio and to the cement strength. This characteristic can facilitate the design of lightweight concrete mixes.

The *optimum cement content* may be determined by *trial mixes*. In general, for first trial, the cement content required for ordinary sand and gravel concrete may be used, but more cement is normally required for most lightweight aggregate concretes.

There are several methods to determine the aggregate content. In this section, a method using *effective water-cement ratio* for the calculation of aggregate content is described.

This method of lightweight aggregate concrete mix design which is based on water-cement rule and is an adaptation of the well-known British mix design method has been suggested by F.I.P. The steps involved to obtain the mix proportions for the stipulated 28-day strength of concrete are the following:

1. The target mean strength of the concrete is determined from the characteristic strength.
2. The water-cement ratio for the required target strength is read off from Fig. 14.1.

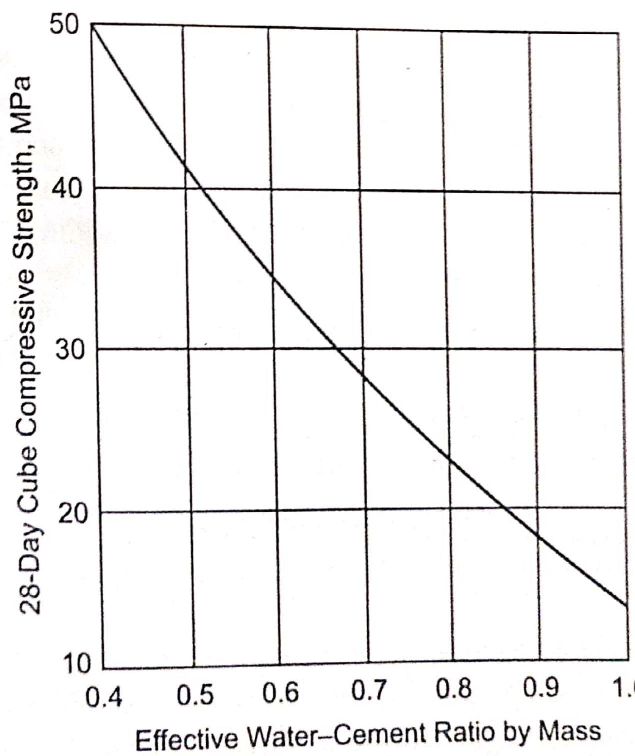
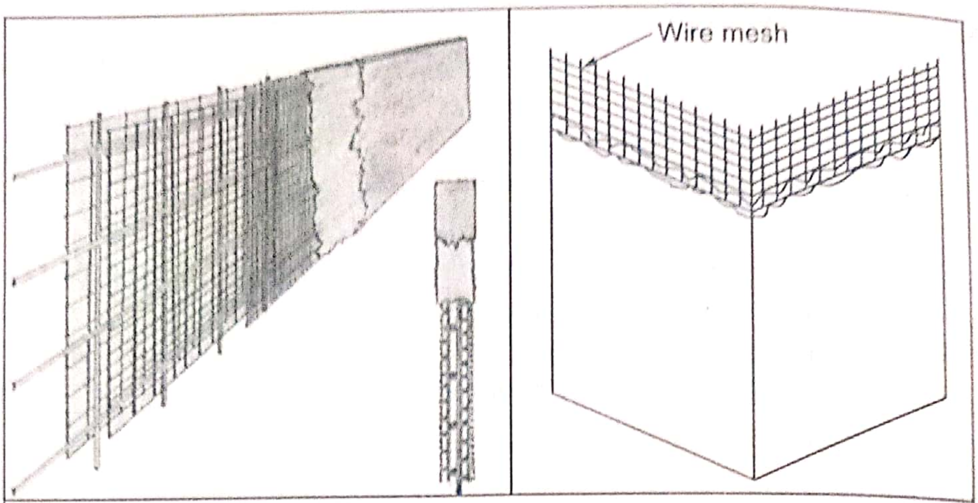


Fig. 14.1 *Typical relationship between effective water-cement ratio and compressive strength of lightweight aggregate concrete*

3. For the water-cement ratio determined in step 2. aggregate-cement ratio (by volume), cement content in kg/m^3 and optimum percentage of fine aggregate for the desired workability are selected from Table 14.2.

14.9 FERROCEMENT

The concept of use of fibers to reinforce brittle materials dates back to ancient constructions built in India using mud walls reinforced with woven bamboo mats and reeds. In the present form, ferrocement may be considered as a type of thin reinforced concrete construction where cement mortar matrix is reinforced with many layers of continuous and relatively small diameter wire meshes as shown in Fig. 14.9. While the mortar provides the mass, the wire mesh imparts tensile strength and ductility to the material. In terms of structural behavior ferrocement exhibits very high tensile strength-to-weight ratio and superior cracking performance. The distribution of a small diameter wire mesh reinforcement over the entire surface, and sometimes over the entire volume of the matrix, provides a very high *resistance against cracking*. Moreover, many other engineering properties, such as *toughness*, *fatigue resistance*, *impermeability*, etc., are considerably improved. Sometimes, conventional reinforcing bars in a skeleton form are added to thin wire meshes in order to achieve a stiff reinforcing cage. The commonly used composition and properties of ferrocement made with steel wire mesh reinforcement are summarized in Table 14.6.



Construction of typical sections of ferrocement

Fig. 14.9 *Construction of typical sections of ferrocement*

Table 14.6 *Normal ranges of composition and properties of ferrocement*

Parameter	Range
Wire mesh	
Wire diameter	$0.5 \leq \phi \leq 1.5$ mm
Type of mesh	Chicken wire or square woven- or welded-wire galvanized mesh, expanded metal
Size of mesh openings	$5 \leq s \leq 25$ mm
Distance between mesh layers	Distance between 2 layers ≥ 2 mm
Volume fraction of reinforcement	Up to 8 per cent in both directions corresponding to 650 kg/m^3 of concrete
Specific surface of reinforcement	Up to 4 cm^2/cm^3 in both directions
Skeletal reinforcement (if used)	
Type	Wires; wire fabric; rods; strands
Diameter	$3 \leq d \leq 10$ mm
Grid size	$50 \leq g \leq 100$ mm
Typical mortar composition	
Portland cement	Any type depending on application
Sand-cement ratio	$1.0 \leq S/C \leq 2.5$ (by mass)
Water-cement ratio	$0.35 \leq W/C \leq 0.6$ (by mass)
Fine aggregate (sand)	Fine sand all passing IS: 4.75 mm sieve and having 5 per cent by mass passing IS: 1.18 mm sieve, with a continuous grading curve in between
Composite properties	
Thickness	$10 \leq t \leq 60$ mm
Steel cover	$1.5 \leq c \leq 5$ mm
Ultimate tensile strength	34.5 MPa
Allowable tensile stress	10.0 MPa
Modulus of rupture	55.0 MPa
Compressive strength	27.5 to 60.0 MPa

14.9.1 Materials

Cement Mortar Matrix As described above, the ferrocement composite is a rich cement-mortar matrix of 10 to 60 mm thickness with a reinforcement volume of five to eight per cent in the form of one or more layers of very thin wire mesh and a skeleton reinforcement consisting of either welded mesh or mild steel bars.

Normally, Portland cement and fine aggregate matrix is used in ferrocement. The matrix constitutes about 95 per cent of the ferrocement and governs the behavior of the final product. This emphasises the need for proper selection of constituent materials, their mixing and placing.

The choice of cement depends on the service conditions. To maintain the quality of cement, it should be fresh, of uniform consistency and free of lumps and foreign matter. Cement should be stored under dry conditions and for as short duration as possible.

The fine aggregate (sand) which is the inert material occuping 60 to 75 per cent of the volume of mortar must be hard, strong, non-porous and chemically inert. The aggregate should be free from silt, clay and other organic impurities. The particle sizes of 2.36 mm and above, if present in substantial quantities, may cause the mortar to be porous. On the other hand, very fine particles, if present in a substantial amount, will require more water to achieve the required *workability*, thereby adversely affecting the strength and *impermeability*. The fine aggregates conforming to grading zones II and III with particles greater than 2.36 mm and smaller than 150 μm removed are suitable for ferrocement. Therefore, sands with maximum sizes of 2.36 mm and 1.18 mm with optimum grading zones II and III are recommended for ferrocement mixes. Use of fine sand in ferrocement is not recommended.

The *water content* which governs the strength and workability of mortar primarily depends upon the *maximum grain size*, the *fineness modulus*, and the *grading of the sand*. The water used for making mortar should be free from impurities such as clay, loam, acids, salts, vegetable matter, etc.

Plasticizers and other *admixtures* may also be added for achieving: (i) an improved *workability*, (ii) water reduction for increase in strength and reduction in *permeability*, (iii) *water proofing*, (iv) increase in *durability*. In addition, admixtures (containing chromium trioxide) may be used to prevent galvanic-corrosion of galvanized steel reinforcement. Pozzolanas such as fly ash may be added as cement replacement materials (up to 30 per cent) to increase the durability.

Mix Proportions The mix proportions in terms of sand-cement ratio (by mass) normally recommended are 1.5 to 2.5. The water-cement ratio (by mass) may vary between 0.35 and 0.6. In order to reduce permeability, the water-cement ratio must be kept below 0.4. The moisture content of the aggregate should be taken into account in the calculation of required water. The amount of water can be reduced by the use of appropriate admixtures.

The slump of fresh mortar should not normally exceed 50 mm, and 28-day compression strength of moist cured cubes should be around 35 MPa for most applications. Sand being the principal constituent of ferrocement, its properties have a major influence on the amount of water and hence on the mix design. Improvements in the grading composition of sand may allow considerable reduction of water requirement. Sand with maximum nominal size less than 2.36 mm or 1.18 mm should be avoided in ferrocement mixes.

The mixes should have compositions such that the total absolute volume of cement and fines is about 300 cm^3 per litre of mortar. A change in the amount of cement must be accompanied by a corresponding change in that of fines.

Reinforcement As explained earlier, the reinforcement used in ferrocement is of two types, viz. *skeleton steel* and *wire mesh.* The skeleton steel frame is made conforming exactly to the geometry and shape of structure, and is used for holding the wire meshes in position and shape of the structure.

Skeleton Steel The skeleton steel comprises relatively large diameter (about 3 to 8 mm) steel rods typically spaced at 70 to 100 mm. It may be tied-reinforcement or welded wire fabric. The welded-wire fabrics normally contain larger diameter wires spaced at 25 mm or more. Welded-wire fabrics of 3 to 4 mm diameter wires welded at 80 to 100 mm center to center have been successfully used for making skeleton frames for the cylindrical or other ferrocement surfaces where these meshes can be bent easily. They provide better and uniform distribution of steel and save time in fabrication but may cost a little more when compared to mild steel bar frames. In the case of structures where higher stresses may occur, as in case of boats, barges, etc., the mild steel bars provided to act as skeletal steel are also counted as reinforcement imparting structural strength, stiffness and durability. However, a minimum possible size of bars should be used in order to obtain the effect of wire meshes and hence the composite effect. The spacing of the skeletal transverse and longitudinal steel bars of diameter of 5 to 7 mm depends upon the type and shape of structure. In the case of boathulls, a spacing of 75 to 100 mm is adequate whereas in water tanks, bins, etc., the spacing may vary between 200 and 300 mm. The bars are mostly tied with binding wires but can also be welded.

The reinforcement should be free from dust, loose rust, coatings of paint, oil or similar undesirable substances.

Wire Mesh The wire mesh consisting of galvanized wire of diameter 0.5 to 1.5 mm spaced at 6 to 20 mm center to center, is formed by welding, twisting or weaving. Specific mesh types include woven or interlocking mesh, woven cloth, and welded mesh. The welded-wire mesh may have either hexagonal or square openings as shown in Fig. 14.10. Meshes with hexagonal openings are sometimes referred to as *chicken wire meshes.* The hexagonal wire mesh is cheaper but structurally less efficient than the mesh with square openings because the wires are not oriented in principal (maximum) stress directions. Moreover, the rectangular meshes have better rigidity when placed or tied over the skeleton frame, and do not sag during placing the mortar. Meshes with square openings are available either in the form of welded-wire mesh or in the woven form. The welded wire meshes have a higher Young's modulus and

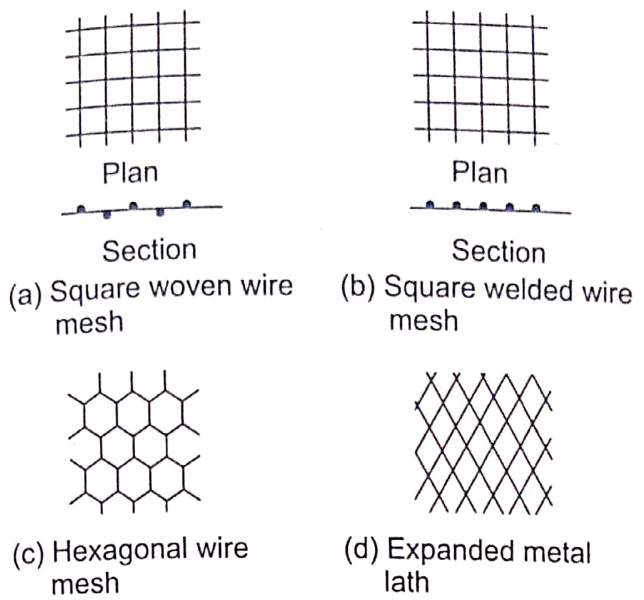


Fig. 14.10 *Different types of welded wire meshes*

hence provide a higher stiffness and less cracking in the early stages of loading. On the other hand, woven-wire meshes are a little more flexible and easy to work with than the welded meshes. In addition, welding anneals the wires and limits the tensile strength. Generally, the square woven meshes consisting of 1.0 or 1.5 mm diameter wires spaced at about 12 mm are preferable. Wire meshes are also available in the galvanized form. Galvanizing, like welding, reduces the tensile strength. However, to control cracking the welded wire fabric should be used in combination with wire meshes. The minimum yield strength of wire used in fabric should be 415 MPa for plain wires and 500 MPa for deformed wires. The wire diameter should be less than 12 mm except in case of very thick plates. Mechanical properties of steel wire meshes and reinforcing bars are given in Table 14.7.

Table 14.7 *Mechanical properties of steel wire meshes and reinforcing bars*

Property	Woven square mesh	Welded square mesh	Hexagonal mesh	Expanded metal lath	Logitudinal bars
Yield strength, f_y, MPa	450	450	310	380	410
Effective modulus, E_{RL}, GPa	140	200	100	140	200
Effective modulus E_{RT}, GPa	160	200	70	70	—

Notes

E_{RL} = *value of modulus in the longitudinal direction.*
E_{RT} = *value of modulus in the transverse direction.*

Expanded metal lath is formed by slitting thin gage sheets and expanding them in the direction perpendicular to the slits. Expanded metal offers strength approximately equal to that offered by welded-wire mesh. However, they result in a stiffer composite resulting in reduced crack widths at the early stage of loading and provide better impact resistance. It is unsuitable in the applications involving sharp curves.

Reinforcing bars may be used in combination with wire meshes for relatively thick ferrocement elements. The minimum possible size of bars should be used in order to obtain the effect of wire meshes and hence the composite effect.

Addition of steel fibers to ferrocement seems to enhance the properties considerably. They assist in distributing cracks and hence may allow the use of heavier meshes.

14.9.2 Construction in Ferrocement

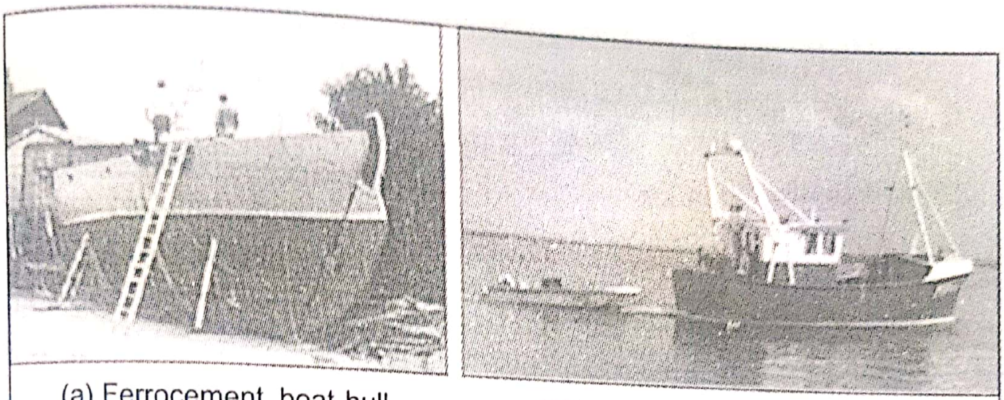
The construction in ferrocement can be divided into four phases: (i) fabrication of skeleton framing system, (ii) fixing of bars and mesh, (iii) application of mortar, and (iv) curing. The quality of mortar and its application is the most critical phase. Mortar can be applied by hand or by *shotcreting*. Since no formwork is required as in conventional reinforced concrete construction, ferrocement is suitable especially for structures with curved surfaces such as shells and other free-form shapes.

The required number of layers of wire mesh are fixed on both sides of the skeleton frame. First, the external mesh layers are fixed and tied to the frame bars. The meshes should be fixed by staggering the hold positions in such a manner that the effective hold size is reduced. A spacing of at least 1 to 3 mm is left between two mesh layers. Wherever two pieces of the mesh are joined, a minimum *overlap* of 80 mm should be provided and tied at a close interval of 80 to 100 mm center to center.

The weighed quantities of the ingredients, namely, cement, good quality graded sand, waterproofing and antishrinkage compounds are dry mixed. The liquid additives are added to the mixing water taken in the required quantity. About half of the mixing water is put in the mixer before charging the mixer with dry mixed mortar ingredients. The mixing is carried out and the remaining water is then added gradually. The cement-aggregate ratio is generally kept between 1:1.75 to 1:2.5 (by mass) and water-cement ratio may be 0.35 to 0.40 depending upon the required workability. Generally, a 3 minute mixing time is enough. The mortar should be mixed in batches of such a quantity as can be utilized in one hour of working, so that mortar can be placed before its setting starts.

The placing of the mortar is termed as the *impregnation of meshes with matrix*. This is the most critical operation in ferrocement casting. If the mortar impregnation is not proper the structure is bound to fail in its performance. A sufficient quantity of mortar is impregnated through mesh layers so that the mortar reaches the other side and there are no voids left in the surface. A wooden hammer of about 100 mm diameter with a 150 mm long wooden handle can be used for mild hammering over the temporarily held form. This will give sufficient vibrations for compacting the mortar. As soon as it is ensured that the mortar penetration through the mesh is satisfactory, the form is shifted to the next position.

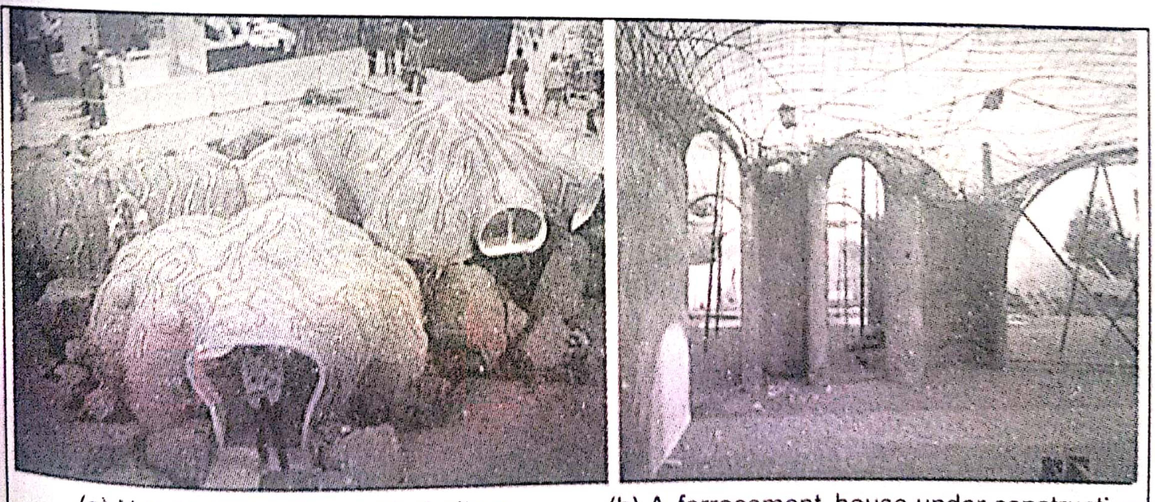
For structures like boat hulls shown in Fig. 14.11 and shells, the mortar is placed using a technique called the two-operation *mortar impregnation.* In this system, the outside of the mesh is plastered first and the inner layer left exposed. The excess mortar is scrapped using trowels and wire brushes. The mortar is left for setting till it attains enough strength for carrying the load from inside during the application of a second layer of mortar. Cement slurry is sprayed or brushed over the entire inner surface and the second layer of mortar is applied from inside.



(a) Ferrocement boat hull (b) Completed ferrocement boats

Fig. 14.11 *Construction of ferrocement boat hull*

In structures like shelters and houses shown in Fig. 14.12 where many layers are used as reinforcement and the thickness is more than 20 mm, it is advisable to do the casting in three layers. The *core* or *middle* layer is applied first covering the skeleton steel and one layer of wire mesh. This core provides a firm surface for mortar application on top and bottom. The core is cured for at least three days before the other two layers of mortar are applied. Cement slurry may be brushed over the middle layer for getting a good bond between old and new mortars.



(a) Non-toxic ferrocement shelters (b) A ferrocement house under construction

Fig. 14.12 *Construction of ferrocement shelters and houses*

For normal applications, the mortar provides adequate protection against *corrosion of reinforcement,* but where the structure is subjected to chemical attack by the environment as in sea water, it is necessary to apply suitable *protective coatings* on the exposed surface. These coatings should be such that they do not react with either the mortar or the reinforcement, and at the same time not be susceptible to the environmental attack. Vinyl and epoxy coatings have been found to be satisfactory especially on structures exposed to sea water and also in most other *corrosive environments*. For protection against a less severe environment, cheaper asphaltic and bituminous coatings are generally satisfactory.

14.9.3 Properties of Ferrocement

Though ferrocement is often considered to be just a variation of conventional reinforced concrete which may be true for the ferrocement with small quantities of reinforcement, however, it is not true for the quantity of reinforcement provided in most of the applications. Moreover, a system of construction using layers of closely spaced wire mesh separated by skeleton bars and filled with cement mortar presents all the mechanical characteristics of a *homogeneous material.*

Tensile strength of ferrocement depends mainly on the volume of reinforcement in the direction of force and the tensile strength of the mesh. The tension behavior may be divided into three regions, namely, pre-cracking stage, post-cracking stage and post-yielding stage. A ferrocement element (member) subjected to increasing tensile stresses behaves like a linear elastic material till the development of *first crack* in the matrix. Once the cracks have developed the material enters the stage of *multiple cracking* and this stage continues up to the point where wire meshes start to yield. In this stage number of cracks keep on increasing with an increase in tensile stress without any significant increase in crack width. With the yield of reinforcement, the composite enters the stage of *crack widening*. The number of cracks remains essentially constant and the crack widths keep increasing. The behavior is primarily controlled by the reinforcement bars.

In the elastic pre-cracking stage, the modulus of ferrocement composite E_c can be expressed in terms of modulii of mortar and reinforcement E_m and E_r, respectively, and volume fraction of reinforcement in longitudinal direction, V_{r1}:

$$E_c = (1 - V_r)E_m + V_r E_r \approx E_m + V_r E_r = E_m(1 + \eta V_r)$$

where $\eta = E_r/E_m$.

During the multiple cracking stage, the contribution of mortar to the stiffness of composite is negligible. Hence, the stiffness of composite is approximately represented by

$$E_c = V_r E_r$$

The value of E_r may be substantially different for woven mesh from that for a welded mesh. It has been noticed that higher the volume of reinforcement and smaller the diameter of wires, longer is multiple cracking stage with a larger number of cracks developed in the same *gage length*.

An inverse relationship between the first crack strength and average wire spacing based on linear elastic fracture mechanics has been established. The load-carrying capacity of ferrocement is correlated with the *specific surface area of reinforcement*, *S*, which is defined as the total surface area of the wires in contact with cement mortar divided by the volume of composite. However, it should be noted that some investigators have used the surface area of the wires in the load resisting direction S_L only. The specific surface area has been found to influence the *first crack load* in tension, as well as the *width* and *spacing of cracks*. For example, a 12-mm thick ferrocement section with five layers of a 12 mm square welded or woven 1.0 mm diameter wire mesh reinforcement has about 10 times as much specific surface areas as the conventional reinforcement. This results in a considerably increased load-carrying capacity. Consequently, ferrocement has tensile strength as high as its compressive strength, i.e., 27 MPa, and the widths of cracks are very small even at failure (about 0.05 mm). Ferrocement structures can be designed to be watertight at service loads.

The maximum composite stress at first crack increases in direct proportion to the *specific surface*. A specific surface area S_L equal to 1 cm^2/cm^3 has been suggested as the lower limit for a composite to be the ferrocement. The other parameter which is a direct measure of the ultimate strength of ferrocement is the percentage of reinforcement, p, defined as either the volume of wires per unit volume of composite in the loaded direction or the area of wires per unit cross-sectional area of composite in the loaded direction. There is a unique geometric relationship between S and p, but their relationships to the physical properties are quite different. S is mostly associated with the cracking behavior whereas p is a direct measure of the ultimate strength of ferrocement because the *ultimate load* is resisted entirely by the wire mesh.

Thus depending upon the cracking stage a typical *tension stress-strain curve* for ferrocement exhibits three distinct regions namely, *elastic*, *quasi-elastic* or *elasto-plastic*, and *plastic regions*. In Region I, the material is linearly elastic because both the reinforcement and matrix deform elastically. The cracking of cement mortar is the beginning of Region II and the slope of the stress-strain curve decreases. The point of decrease of the slope of the stress–strain curve indicates the first crack visible to the naked eye or with special lighting arrangement. In Region III, the wire reinforcement supports the total load and the ultimate capacity can be estimated from the maximum load capacity of the wire reinforcement alone. The boundaries of the elastoplastic region are found to shift with the specific surface of the mesh, mesh size, geometry and orientation of the mesh, yield and ultimate strengths of wire.

The behavior of thin ferrocement element under compression is primarily controlled by the properties of the cement-mortar matrix, i.e., thin ferrocement plate elements can be treated as plain mortar plates for most practical applications. Like in the reinforced and prestressed concrete beams, the *fatigue behavior* of ferrocement flexural element is governed by the tensile fatigue properties of the mesh. The ferrocement beams show poor resistance to fatigue under cyclic loading. Impact tests on ferrocement slabs show that the *impact resistance* increases almost linearly with the increase in specific surface (volume fraction) and ultimate strength of mesh reinforcement. For the same reinforcement fraction, ferrocement using welded-wire meshes offers highest impact resistance and the one reinforced by chicken-wire meshes offers the lowest. Woven mesh reinforcement provides an impact strength higher than that obtained by chicken-wire meshes but lower than that by welded-wire meshes.

14.10 FIBER-REINFORCED CONCRETE

14.10.1 Introduction

The presence of microcracks at the mortar–aggregate interface is responsible for the inherent weakness of plain concrete. The weakness can be removed by inclusion of fibers in the mix. The fibers help to transfer loads at the internal microcracks. Such a concrete is called fiber-reinforced concrete. Thus the fiber-reinforced concrete is a composite material essentially consisting of conventional concrete or mortar reinforced by fine fibers.

Discrete Fiber Reinforced Concrete In this system, the concrete is reinforced by the random dispersal of short, discontinuous, and discrete fine fibers of specific geometry. The fibers can be imagined as an aggregate with an extreme deviation in shape from the rounded smooth aggregate. The fibers interlock and entangle around aggregate particles and considerably reduce the *workability,* while the mix becomes more cohesive and less prone to *segregation.* The fibers suitable for reinforcing the concrete have been produced from steel, glass and organic polymers. Naturally occurring asbestos fibers and vegetable fibers, such as jute, are also used for reinforcement. Fibers are available in different sizes and shapes. They can be classified into two basic categories, namely, those having a higher elastic modulus than concrete matrix (called *hard intrusion*) and those with lower elastic modulus (called *soft intrusion*). Steel, carbon and glass have higher elastic moduli than cement mortar matrix, and polypropylene and vegetable fibers are the low modulus fibers. *High modulus fibers* improve both *flexural* and *impact resistances* simultaneously whereas *low modulus fibers* improve the impact resistance of concrete but do not contribute much to flexural strength.

The major factors affecting the characteristics of fiber-reinforced concrete are: water-cement ratio, percentage (volume fraction) of fibers, diameter and length of fibers. The location and extent of cracking under load will depend upon the orientation and number of fibers in the cross section. The fibers restrain the shrinkage and creep movements of unreinforced matrix. However, fibers have been found to be more effective in controlling compression creep than tensile creep of unreinforced matrix.

In contrast to reinforcing bars in reinforced concrete which are continuous and carefully placed in the structure to optimize their performance, the fibers are discontinuous and are generally randomly distributed throughout the concrete matrix. As a result, the reinforcing performance of steel fibers, for example, is inferior to that of reinforcing bars. In addition, the fibers are likely to be considerably more expensive than the conventional steel rods. Thus, fiber-reinforced concrete is not likely to replace conventional reinforced concrete. However, the addition of fibers in the *brittle cement* and *concrete matrices* can offer a convenient, practical and economical method of overcoming their inherent deficiencies of poor tensile and impact strengths, and enhances many of the structural properties of the basic materials such as fracture toughness, flexural strength and resistance to fatigue, impact, thermal shock or spalling. Thus the provision of small-size reinforcement as an integral part (or ingredient) of fresh concrete mass enhances its potential in the manufacture of thin sheet products and fabrication of structural components.

Essentially, fibers act as crack arrestor restricting the development of cracks and thus transforming an inherently brittle matrix, i.e., Portland cement with its *low tensile and impact resistances*, into a strong composite with superior *crack resistance*, improved *ductility* and distinctive *post-cracking behavior* prior to failure. Steel fibers are probably the best suited for structural applications. Due to superior properties like increased tensile and bending strengths, improved ductility, resistance to cracking, high impact strength and toughness, spalling resistance, and high energy absorption capacity, fiber-reinforced concrete (FRC) has found special application in hydraulic structures, airfield and highways pavements, bridge decks, heavy duty floors and tunnel linings.

Preplaced or Slurry Infiltrated Fiber Concretes In general, the superior *toughness* and *energy absorption properties* of FRC in comparison to conventional concrete improve as *volume fraction* of fibers increases. Techniques for achieving high fiber volumes include the strategy of pre-placing dry fibers in the framework and infiltrating the bed of fibers with a cementing slurry. This composite is called slurry infiltrated fiber concrete (SIFCON).

Recently, another form of slurry infiltrated fiber composite called slurry infiltrated mat concrete (SIMCON) has been developed. SIMCON is a new generation of high performance fiber reinforced concrete (HPFRC), made by infiltrating continuous steel fiber-mats with a specially designed cement-based slurry. Thus instead of reinforcing concrete with steel bars, it is reinforced with sheets of stainless steel fibers injected with a mixture of cement, aggregates and water, called slurry. The fiber mats (available in rolls) are shaped and wrapped around existing columns and beams, and injected with concrete slurry for repairing or strengthening existing structures. The mats are made of recycled stainless steel fibers. They add *tensile strength* and *ductility, energy absorbing properties*, to the concrete. Since continuous fiber mats are used, SIMCON differs from other high performance fiber reinforced concrete in at least two aspects: (i) it requires smaller fiber volume fraction to achieve substantial increases in mechanical properties, and (ii) it is delivered in pre-packed rolls that can be easily cut, handled, and installed in the field.

SIMCON can be used in new construction or to reinforce existing structures. Unlike conventional concrete (where reinforcement is designed to fail before the concrete and where at failure large slabs chunks of concrete break apart from the reinforcement and fall from the structure) in SIMCON at failure, the mass of fibers and concrete does not collapse. Instead of large chunks breaking and falling from a structure, the material crumbles into small harmless flakes which pose little danger to people or property below. This controlled form of failure is a key advantage of SIMCON.

In conventional concrete, the cracks are large and connected, allowing water to seep into the concrete and further compromise the integrity of the structure. On the other hand, in HPFRC the cracks are small and disconnected hairlines discounting the possibility of water seepage. As the concrete slurry uses very little water to allow it to be packed tightly into the mat, some of the cement powder remains unhydrated. With the passage of time as water seeps in through the small cracks, it mixes with the unhydrated cement and causes it to hydrate, essentially making the HPFRC system self-healing. The HPFRC system is designed to use conventional concrete construction equipment with minimal modifications, adding to the already lowered construction costs.

Process Technology Since SIMCON uses a manufactured continuous mat of interlocking discontinuous steel fibers, and flowable cement-based slurry it controls corrosion in very thin members, and permits development of high flexural strengths and very high ductility. Even with comparatively lower fiber volume fraction fiber-mats, SIMCON exhibits improved properties in tension, compression and shear. Furthermore, since fiber-mats are pre-packed in the plant, distribution and orientation of fibers can be more accurately controlled, than is the case with *short randomly distributed discrete fiber* HPFRCs. This allows the manufacture of high performance *cement-based fiber composite* that can have different yet easily *controllable properties in the longitudinal and transverse directions.* These material characteristics are desirable in the repair/retrofit of structural elements such as columns, which require a high increase in strength and toughness in the transverse direction while increasing only ductility but not strength in the longitudinal direction, i.e., *moment-carrying direction*. In a retrofit situation continuous SIMCON fiber-mats, delivered in large rolls, can be easily installed by wrapping around members to be rehabilitated. SIMCON has tremendous potential in seismic retrofit. The presence of SIMCON layer leads to both improved performance and durability of the member. The member dimensions, amount of reinforcement and weight of member can be optimized. In contrast to the behavior observed in short fibers HPFRC, SIMCON is insensitive to the angle of fiber-mat.

Properties of SIMCON The advantage of steel fiber mats over a large volume of discrete fibers is that the mat with predecided configuration provides inherent strength and can utilize fibers with much higher aspect ratios. The fiber volume is less than half that required for slurry infiltrated fiber concrete (SIFCON), while achieving similar flexural strength and energy absorption capacity. The typical aspect ratios for FRC range from 40 to 100, although special handling procedures may be required as the aspect ratio approaches 100. SIMCON utilizes fibers with *aspect ratios* exceeding 500. Since the mat is already in a pre-formed shape, handling problems are minimized and balling does not become a factor.

The superior performance of the SIMCON over SIFCON is related to the bonding of the mat fibers in the composite. In the standard SIFCON, the relatively short embedment length of 25 mm results in *fiber pullout* as the primary failure mode. In the SIMCON composites, the failure mode comprises *multiple cracks* and ultimate failure occurs through fiber breakage in the high tensile stress zones of one or more of the crack planes. In the mat reinforced composites, the yield strength of the steel is fully utilized.

The *elastic modulus, ultimate strength, strain at ultimate strength, toughness* up to 0.15 per cent strain are all increased with an increase in the *fiber volume fraction* of the composite. Apart from the elastic modulus, an increase in all the other parameters seems to be linearly related to the increase in the fiber volume fraction. The injection of the slurry from the bottom of structural member provides a better and more uniform slurry infiltration, leading to a higher density of the composite.

Simcon vs. Sifcon Compared to SIFCON, SIMCON exhibits the same or improved mechanical properties with markedly lower fiber volume fraction. SIMCON is also easier to handle and construct than with SIFCON. Hence the best design solution can be achieved only synergy of SIMCON and SIFCON. SIMCON is better suited for applications where one dimension is much smaller than the remaining two, such as in the case with bridge deck overlays. On the other hand, SIFCON is better suited for three-dimensional application, such as zones of reinforcing bar anchorage or of beam column joint.

14.10.2 Mechanism of Fiber-Matrix Interaction

In contrast to fiber composites in resin and metal matrices where the fibers are aligned and constitute to about 60 to 80 per cent of composite volume, FRC contains much less fibers which are randomly oriented. The tensile *cracking strain* of cement matrix (less than 0.02) is very much lower than the *yield* or *ultimate strain of steel* fibers. As a result, when a fiber reinforced composite is loaded, the matrix will crack long before the fibers can be fractured. Once the matrix is cracked, the composite continues to carry the increasing tensile stress; the peak stress and the peak strain of the composite are greater than those of the matrix alone. During the inelastic range between *first cracking* and the *peak*, *multiple cracking* of matrix occurs as indicated in Fig. 14.15. Until the initial cracking of the matrix, it is reasonable to assume that both the fibers and the matrix behave elastically and there is no slippage between the fibers and the matrix. After initial cracking has occurred, the composite will carry increasing load only if the *pull-out resistance of fibers* is greater than the load at the initial cracking. In the post-cracking stage, the failure of composite is generally due to fiber-pullout rather than fiber yielding or fracture.

In FRC, the fracture is a continuous process wherein the cracking occurs over a wide range of loading and the debonding of fibers occurs over several stages. The *bond* or the *pull-out resistance of* fibers depends on the average bond strength between the fibers and the matrix, the number of fibers crossing the crack, and the length and diameter of the fibers. The ratio l/d is called the *aspect ratio* where l is the length and d the diameter of the fibers.

Improvement in the structural performance of FRC depends on the strength characteristics of the fibers themselves, volume of fiber reinforcement, dispersion and orientation of fibers, and their shape and aspect ratio. Higher strength, larger volume, larger length, and smaller diameter of fibers have been found independently to improve strength of the composite. The orientation and dispersion effects may depend, among other things, on loading conditions. Unidirectional fibers uniformly distributed throughout the volume are most efficient in uniaxial tension. While flexural strength may depend on a unidirectional alignment of fibers dispersed away from the neutral plane, flexural shear strengths may call for random orientation. A proper shape and higher aspect ratio are also needed to develop adequate bond between the concrete and the fibers so that the fracture strength of fibers may be fully utilized. For steel fiber reinforced concrete (SFRC), the idealized stress-strain relation is shown in Fig. 14.15.

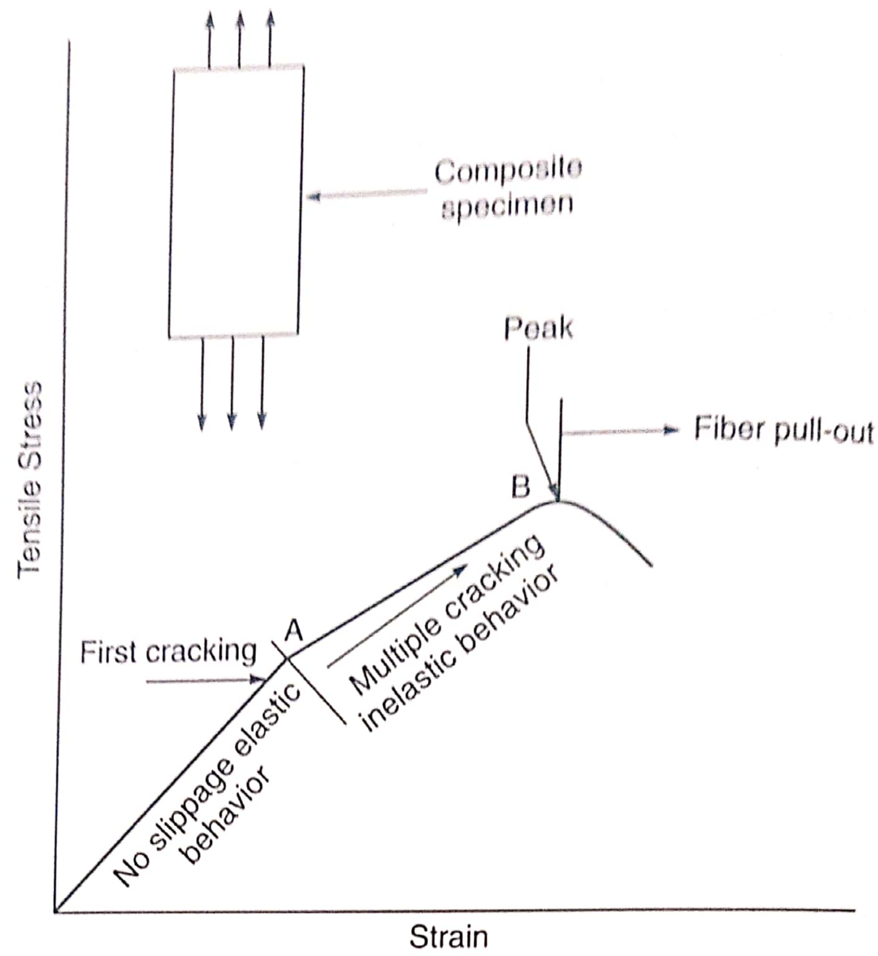


Fig. 14.15 *Behavior of fiber reinforced concrete under tensile load*

In an FRC member subjected to flexure, the load at the first crack will increase due to the crack arresting mechanism of the closely spaced fibers. After the concrete cracks in tension, the fibers continue to take the load, provided the bond is good. When the fiber strain reaches its breaking strain, the fibers fracture resulting in load transfer to the fibers of adjacent layers which on reaching their breaking strain fracture and result in the shifting of the neutral axis. Failure occurs when the concrete in compression reaches the ultimate strain. The most important factors affecting the ultimate load are the volume of fibers and their aspect ratio.

14.10.3 Concrete Matrix

The cement required is OPC or PPC conforming to IS: 269–1989 or IS: 1489–1991, respectively. The aggregates are usually crushed quartz conforming to IS: 383–1970. A fiber-reinforced concrete requires a considerably greater amount of fine material than plain concrete so that it may be conveniently handled and placed. To be fully effective, each fiber needs to be completely embedded in the matrix and this determines the proportion of fine to coarse aggregate. The effect of aggregate size on the workability is shown in Fig. 14.16. Fiber concrete, therefore, generally requires a greater proportion of cement paste than conventional concrete for handling and placing by using the equipment meant for ordinary concrete.

Normal concrete contains 25 to 35 per cent of cement paste of the total volume of concrete, and fiber-reinforced concrete requires paste content of the order of 35 to 45 per cent of the total volume of concrete, depending upon the fiber geometry and fiber volume.

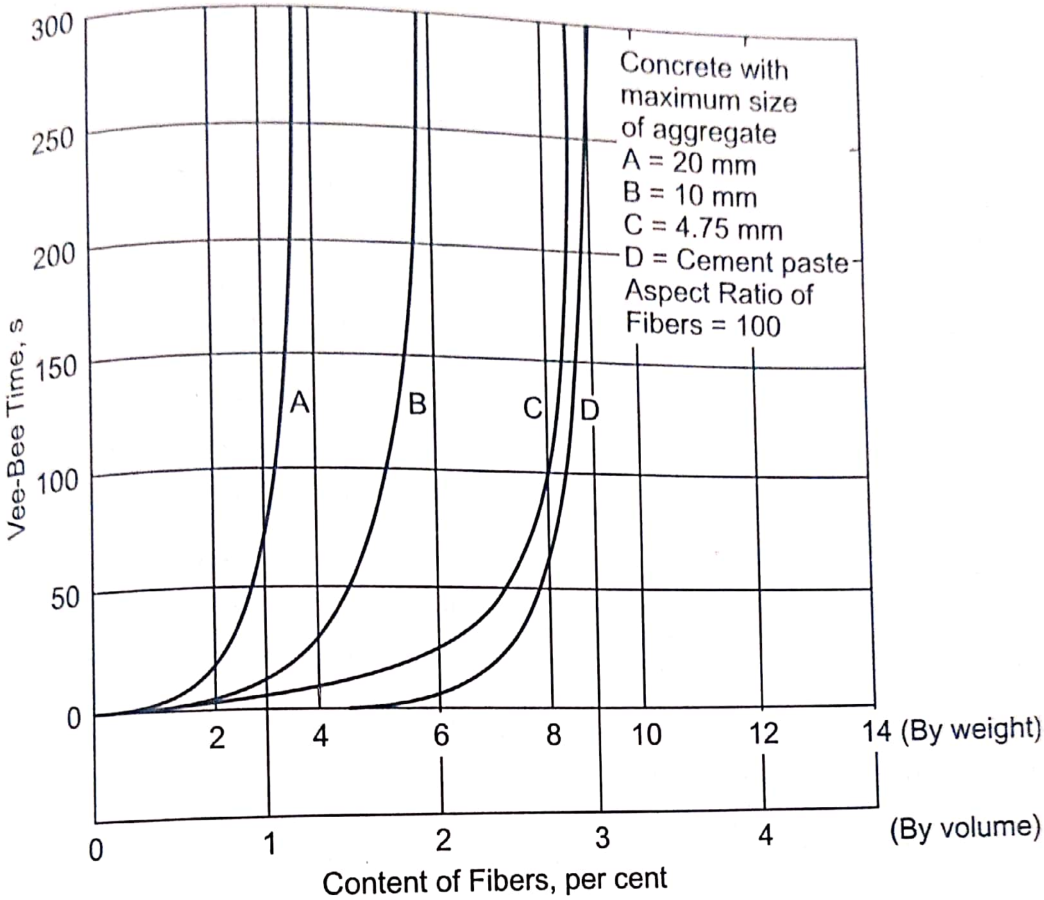


Fig. 14.16 *Effect of aggregate size on workability of fiber reinforced concrete*

14.11 DIFFERENT TYPES OF FIBERS

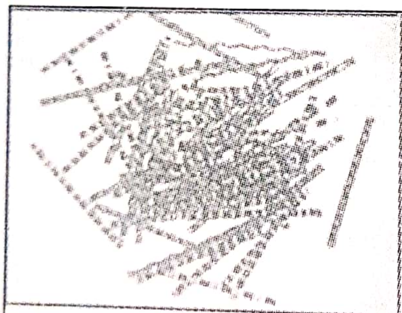
The most commonly used man-made fibers have been *steel* and *polypropylene*, principally in concrete, and glass, principally in cement mortar for thin section applications. Properties of some of the commonly used fibers are given in Table 14.8.

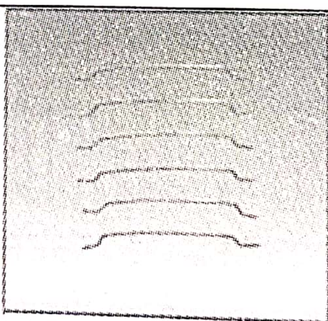
14.11.1 Steel-Fiber Reinforced Concrete

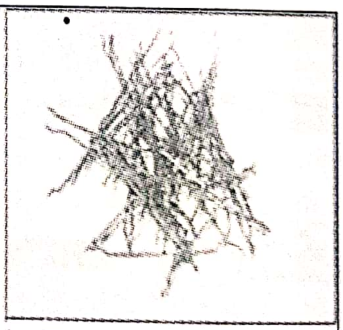
A number of steel-fiber types are available as reinforcement. Round steel fibers, the commonly used type, are produced by cutting round wires into short lengths. The typical diameters lie in the range of 0.25 to 0.75 mm. Steel fibers having a rectangular cross section are produced by slitting the sheets about 0.25 mm thick. For improving the mechanical bond between the fiber and matrix, indented, crimped, machined and hook-ended fibers are normally produced. The aspect ratio (=length/diameter) of fibers which have been employed vary from about 30 to 250. Typical examples of shape are shown in Fig. 14.17.

Table 14.8 *Physical properties of various types of fibers and matrices*

Material	Specific gravity	Effective Modulus, GPa	Tensile Strength, MPa	Elongation at breaking, point, per cent
Acrylic	1.10	2.1	210–420	25.0–45.0
Asbestos (Chrysotile) Carbon	2.55	8.4–14	200–1800	2.0–3.0
(i) high modulus	1.9	380	1800	0.5
(ii) high strength	1.9	230	2600	1.0
Cellulose	1.5	10–40	500	–
Cotton	1.5	5	420–700	3–10
Glass (Cem-FIL filament)	2.7	80	1050–3870	1.5–3.5
Nylon	1.1	4.2	780–850	16.0–20.0
Polyester	1.4	8.5	750–880	11.0–13.0
Polyethylene (high modulus)	0.96	15–40	300–700	3.0–10.0
Polypropylene	0.91	3–15	560–780	8.0
Rayon	1.50	7.3	420–630	10–25
Steel	7.86	200	280–420	3.5
OPC paste	2.0–2.2	10–20	2–6	0.01–0.05
OPC concrete	2.30	10–35	1–4	0.005–0.015


(a) Flat steel sheet fibres


(b) Two-dimensional steel fibres


(c) Three-dimensional steel fibres

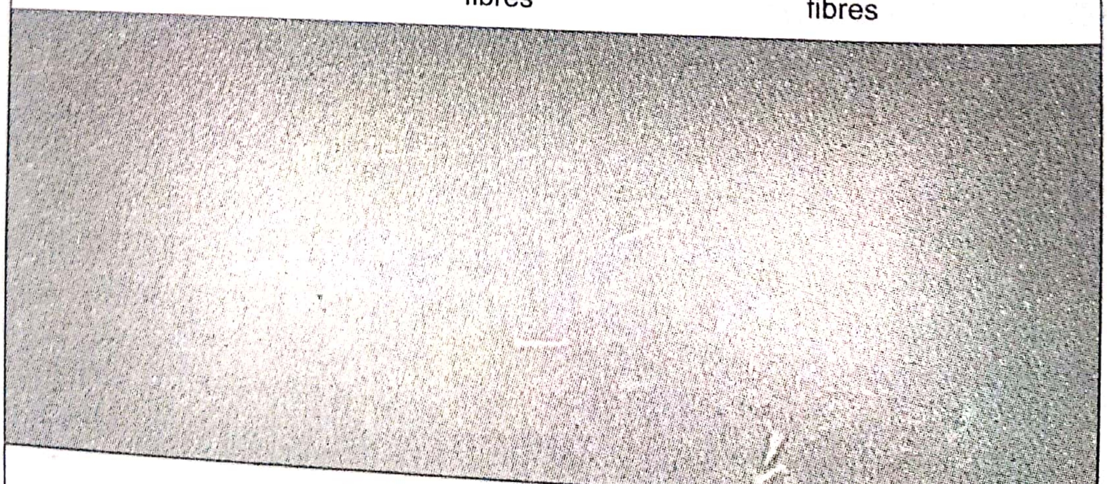

(d) Fiber reinforced concrete slab

Fig. 14.17 *Examples of steel fibers and fiber reinforced concrete slab*

Fibers made from mild steel drawn wire conforming to IS: 280–1976 with the diameter of wire varying from 0.3 to 0.5 mm have been practically used in India. *Round steel fibers* are produced by cutting or chopping the wire, *flat sheet fibers* having a typical cross section ranging from 0.15 to 0.41 mm in thickness and 0.25 to 0.90 mm in width are produced by slitting (shearing) flat sheets. *Deformed fibers* which are loosely bonded with water soluble glue in the form of a bundle are also available. Since individual fibers tend to cluster together, their uniform distribution in the matrix is often difficult. This may be avoided by adding fiber bundles which separate during the mixing process. The properties of various types of fibers are compared in Table 14.8.

Properties of Fresh Steel-Fiber Reinforced Concrete For satisfactory performance in the hardened state, fiber reinforcement should be uniformly distributed and fresh concrete be well compacted. Before adding fibers during mixing, it is essential that the clumps of tightly bound fibers be broken up. For bulk steel-fiber mixes, a mixing sequence is recommended which is to blend fiber and aggregate before charging the mixer, e.g., by combining fiber and aggregate on a conveyor belt or chute.

The ease with which the fiber concrete can be compacted during construction depends on the nature and amount of the fiber used and, most importantly for short fibers, on their *aspect ratio*. The *slump test* has been judged to be a poor indicator of relative workability of steel-fiber concretes, since the addition of fibers to the mix changes the slump out of proportion to the workability change. The Vee-Bee test which incorporates the effects of vibration has been found to give a realistic assessment of workability of fiber concretes. The unsuitability of conventional workability tests for fiber concrete is essentially because of the fact that internal structure and flow characteristics of fiber-reinforced concrete are distinctly different from those of conventional concrete due to the presence of fibers. The composite forms a relatively stable system due to the interlocking of fibers which resists the flow of fresh concrete. This makes the tests like slump and compacting factor ineffective for fiber concrete because the mobilizing force in these tests (self-weight) is inadequate to overcome the effective cohesion in the presence of fibers.

Typical relationships between Vee-Bee time, fiber content and aspect ratio for fiber-reinforced mortars are shown in Fig. 14.18 which indicate that the workability of mix decreases with an increase in fiber concentration and aspect ratio. There is a critical fiber content for each aspect ratio beyond which the response to vibration decreases rapidly. Figure 14.16 indicates that a reduction of maximum aggregate size facilitates the inclusion of fibers, although little is gained by using aggregate size smaller than 4.75 mm. Use of pulverized fuel-ash as a partial replacement of cement (30 % by mass of cement) and a water-reducing admixure may be recommended to facilitate compaction.

Measurement of Workability ACI Committee: 544 (1978) has recommended the use of inverted slump-cone test for the measurement of *workability*. The test measures the time to empty the steel-fiber concrete mix from an inverted slump-cone

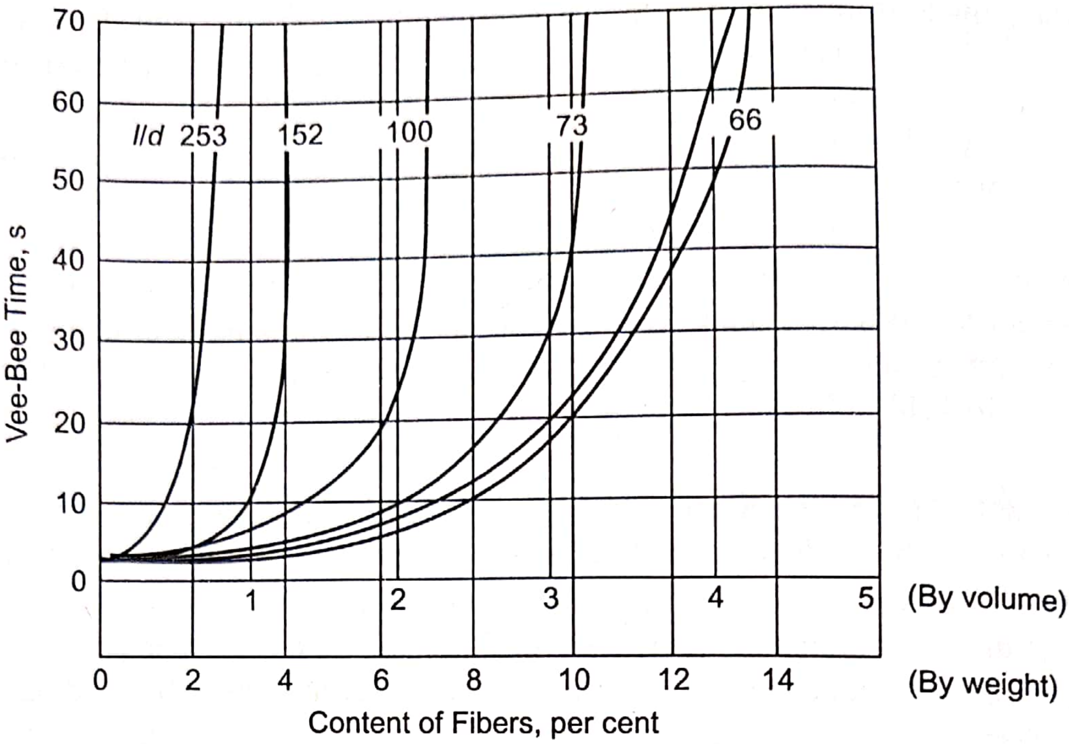


Fig. 14.18 *Effect of fiber aspect ratio on workability of fiber reinforced concrete*

resting 75 mm above the bottom of a nine-liter (yield) bucket, after a 25–30 mm diameter vibrator prob has been inserted. The prob is allowed to fall and touch the bottom of the bucket. The time recorded in the range of 11 to 28 seconds indicates a steel-fiber concrete of good workability. This test has not been fully evaluated and is somewhat cumbersome.

In the workability measurement by conventional tests it is basically the cohesion of the mix which is indirectly measured. This cohesion of mix results in shear strength of the mix in the fresh state. It has been observed that the resistance to penetration by a cone of plastic material is dependent on the shear strength of the fresh concrete. Based on this observation, a cone penetration test has been suggested to measure the workability of fiber-reinforced concrete wherein a standard cone penetrates by its own weight through a mass of fresh mix. The depth of penetration in millimetres may be taken as a measure of workability. The penetration depth of a metallic cone with an apex angle of 30° and having a weight of 40N has been reported to give the representative workability. The choice of cone with 30° apex angle and 40N weight is based on the observation that the penetration depths obtained with this cone are neither too large nor too small, and are suitable for the normal range of mixes. For normal mixes the depth of penetration has been found to vary from 200 mm to 50 mm.

The cone penetration test is easy to conduct and can be conveniently adopted in the field conditions. The test has the comparative simplicity of a slump test while being suitable even for low workability mixes for which conventional tests fail. The test data have a consistent relationship with the other measures of workability given by slump, Vee-Bee time, compacting factor and ACI inverted cone method. The relationships between workabilities measured by different methods are given in Figs. 14.19 to 14.21.

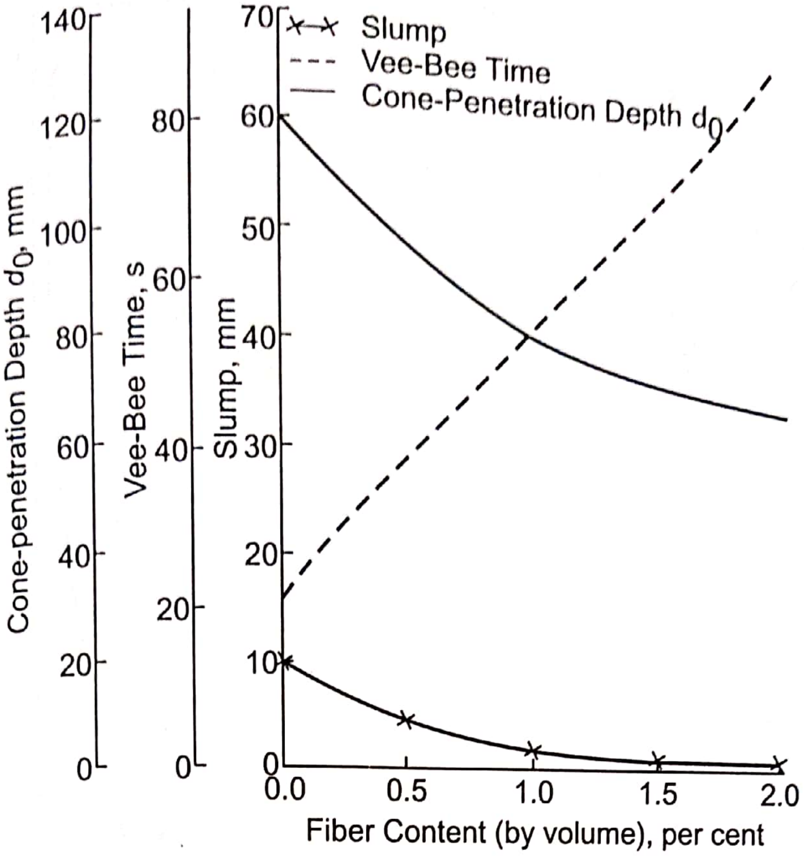


Fig. 14.19 *Variation of workability values with fiber content*

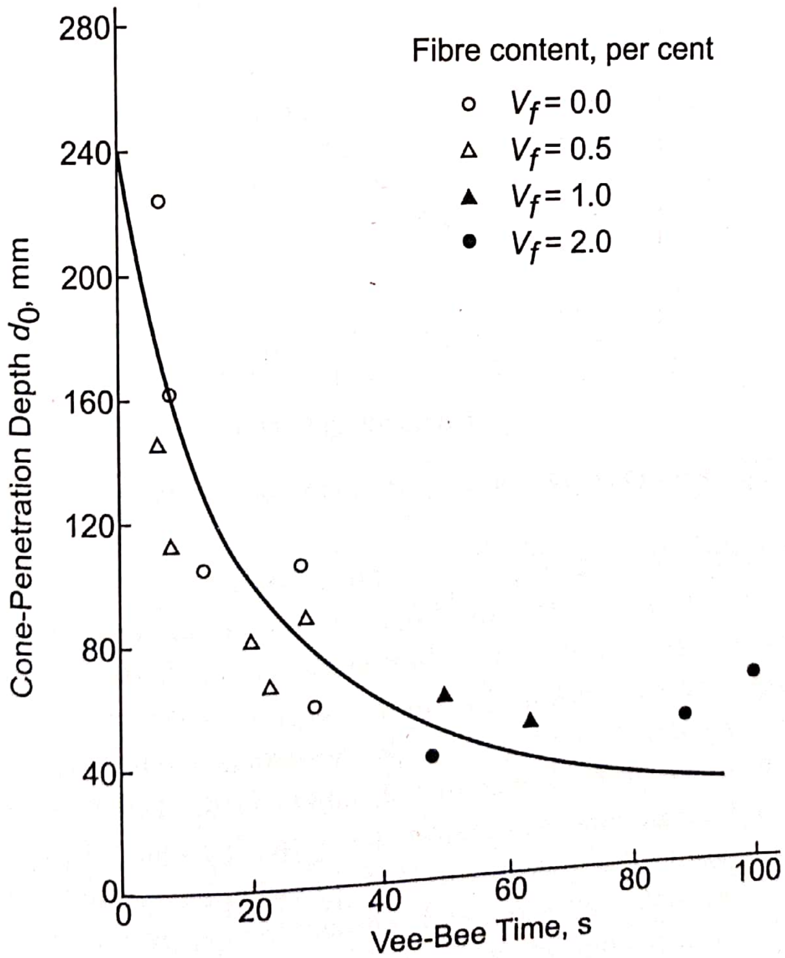


Fig. 14.20 *Relation between Vee-Bee time and cone penetration depth*

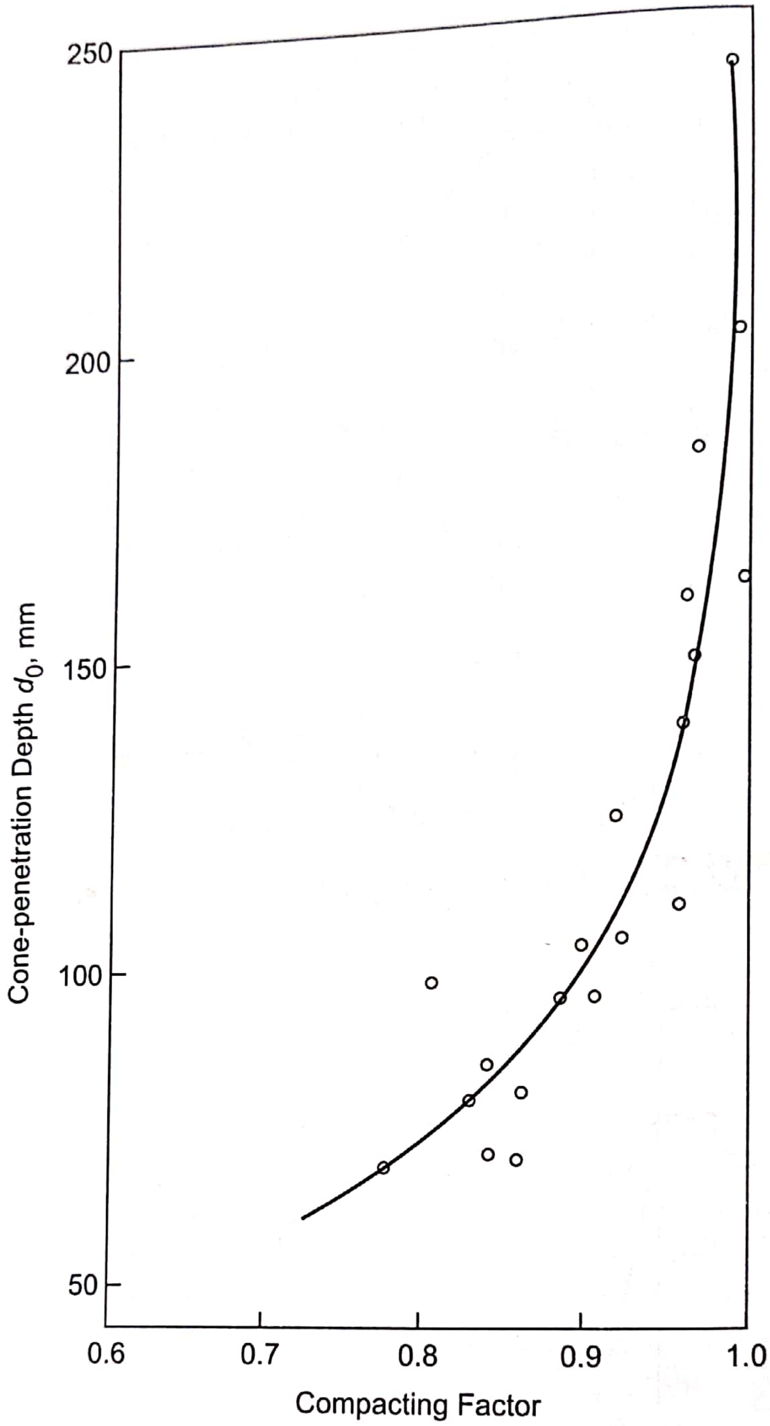


Fig. 14.21 *Relation between compaction factor and cone penetration depth*

Factors Affecting Workability The factors having a predominant effect on the workability are aspect ratio (l/d) and fiber volume concentration. Long thin fibers ($l/d > 100$) tend to mat together while short stubby fibers ($l/d < 50$) cannot interlock and can be dispersed by vibration. A *minimum fiber volume concentration* called *critical concentration* is needed to increase the strength. The critical concentration is generally inversely proportional to the aspect ratio. For l/d = 100, a volume concentration of 0.5 per cent for flexural strengthening and 1.7 per cent for tensile strengthening is required. However, for a 1.7 per cent concentration, an adequate workability can be obtained only with cement paste, and cement-sand mortar; whereas a 0.5 per cent concentration can perfectly be provided in the concrete. Thus there is a restricted range of practical fiber reinforced concrete with improved strengths. The performance of hardened concrete depends upon the *specific fiber surface* (SFS) which is defined as the total surface area of all the fibers present within the unit volume of the composite. The specific fiber surface depends upon the fiber volume concentration, fiber size and aspect ratio. For a fiber volume concentration of V_f per cent, the specific fiber surface in a unit volume of composite is given by

$$SFS = n(\pi dl)$$

where n, l and d are the number, length and diameter of the fibers, respectively, and πdl is the surface area of each fiber. The number of fibers is given by

$$n = \frac{v_f \times 100}{\pi d^2 l/4}$$

Thus,
$$SFS = \frac{400V_f}{d} = \frac{400V_f A}{l}$$

where $A = l/d$ is the aspect ratio. The above expression indicates that for the given fiber volume concentration and aspect ratio, the specific fiber surface is inversely proportional to the fiber length.

Behavior of Hardened Steel-Fiber Concrete The crack-arrest and crack-control mechanism of SFRC results in the improvement of all properties associated with cracking, such as strengths (tensile, flexural, shear, torsional, bearing strengths), stiffness, ductility, energy absorption, and the resistance to freeze–thaw damage, impact, fatigue and thermal loading. The crack controlling property of fibers has three major effects on the behavior of concrete composite:

1. Fibers delay the onset of *flexural cracking*, the increase in tensile strain at the first crack being as much as 100 per cent. The ultimate strain may be as large as 20 to 50 times that of plain concrete.
2. The fibers impart a well-defined post-cracking behavior to the composite.
3. The crack-arrest property and consequent increase in ductility imparts a greater energy absorbing capacity to the composite prior to failure. With a 2.5 per cent fiber content the energy absorbing capacity is increased by more than 10 times as compared to unreinforced concrete. The range of improvement in the mechanical properties of steel-fiber-reinforced concrete are given in Table 14.9.

The fiber concretes reinforced by conventional steel bars have substantially improved *serviceability conditions* obtained by crack and deflection control, besides increasing flexural strength marginally. These conditions are as follows.

1. **Tensile strength** The failure in tension of cement-based matrices is rather brittle and the associated strains are relatively small in magnitude. The addition of fibers to such matrices, whether in continuous or discontinuous form, leads to a substantial improvement in the tensile properties of the FRC in comparison with the properties of the unreinforced matrix.

Table 14.9 *Improvement in the properties of fiber-reinforced concrete*

Property	Maximum improvement over plain reference concrete, per cent	Optimum fiber parameters	
		Volume fraction, V_f	Aspect ratio, l/d
Compressive strength at failure (M 20 mix)	25	1.5	–
Tensile strength (direct)	45	1.0	80
Tensile strength (split cylinder)	40	1.5	80
Modulus of elasticity	15	1.5	80
Ultimate strain	300	–	–
Flexural strength			
(i) at first crack	40	1.5	80
tensile strain	100	–	–
(ii) at failure	60	1.5	80
tensile strain	20 to 50 times		
Modulus of rupture	10	–	–
Energy absorption	500	1.5	80
	1000	2.5	100
Impact resistance (due to explosive charges and dropped weight)	400–900	–	–
Flexural fatigue			
Static load	125	–	–
Endurance to 2×10^6 cycles at a strain rate equal to that in reference specimens subjected to static load			
(i) Non-reversal	90 of static	–	–
(ii) Full-reversal	70 of static	–	–
Post-flexural fatigue, flexural strength	10–30 of similar beams of non-fatigue histories	–	–

The stress-strain or load-elongation response of fiber composites in tension depends mainly on the volume fraction of fibers. In general, the response can be divided into two or three stages, respectively, depending on whether the composite is FRC (fiber volume less than about three per cent) or *Slurry Infiltrated Concrete* (SIFCON) where the volume of fibers normally varies between 5 and 25 per cent.

Before cracking, the composite (both SIFCON and FRC) can be described as an elastic material with a stress-strain response very similar to that of the unreinforced matrix. After cracking, i.e., *in the stage of bridging the cracked* *surface*, the fibers tend to pull out under load resulting in a sudden change in the load-elongation or stress-strain curve. If the *maximum post-cracking stress* is larger than the *cracking stress*, such as in SIFCON, then a second stage of behavior can be identified as the *multiple cracking stage*. This corresponds to the portion of the load-elongation curve that joins the cracking stress point to the maximum post-cracking stress point (peak point on the curve). Beyond the peak point, a third stage of behavior exists which is characterized by failure and/or pull out of the fibers across a *single critical crack. The post cracking strength increases with increasing bond strength, aspect ratio and volume fraction of fibers.*

It is now generally accepted that the type and amount of fibers currently used do not significantly enhance the first cracking tensile strength of the fiber reinforced composite. Many of the current applications of fiber-reinforced concrete involve the use of fibers ranging around 1.0 per cent by volume of concrete. In SIFCON and SIMCON with large volume of aligned fibers, there is substantial enhancement of the tensile load-carrying capacity of the matrix. This may be attributed to the fact that fibers suppress the localization of *micro-cracks* into *macro-cracks* and consequently the apparent tensile strength of the matrix increases.

2. **Compressive strength** The presence of fibers in normal strength concrete produces only modest increase in compressive strength, although the increased *ductility* resulting from the addition may be advantageous, particularly in *over-reinforced concrete beams* where a brittle failure can be changed into a ductile one. On the other hand, the use of steel fibers in *lower strength concrete* mixtures increases their compressive strength significantly compared to plain unreinforced matrices and is directly related to volume fraction of steel fiber used. fibers improve the compressive behavior by enhancing the *toughness*. The magnitude of the increase is dependent on the fiber shape and the content. This increase is more for hooked-end steel fibers in comparison with straight steel fibers, glass or polypropylene fibers.
3. **Flexure** As in the case of tension response shown in Fig. 14.8 there are three stages of the *load-deflection response in flexure*:

   (a) *A more or less linear response up to point A* The strengthening mechanism in this portion of the behavior involves a transfer of stress from the matrix to the fibers by *interfacial shear*. The imposed stress is shared between the matrix and fibers until the matrix cracks at what is termed as the *first cracking strength* or the *proportional limit*. This is called *the process zone, the distributed region in front of an advancing crack due to the stress concentration field.*

   (b) *A transition non-linear portion between point A and the maximum load capacity point B (assuming that the load at B is larger than the load at A)* In this portion (after cracking) the stress in the matrix is progressively transferred to the fibers. With increasing load, the fibers tend to gradually pull out from the matrix leading to *a non-linear load-deflection* response until the *ultimate flexural load capacity* point B is reached. This point is termed as *peak strength*. This zone is called the *pseudo-plastic zone* where matrix has cracked but fibers bridging the crack provide some resistance to pullout. The pseudo-plastic zone provides the main contribution to the *fracture energy* of fiber-reinforced cement composites.

(c) *A descending portion following the peak strength until complete failure of the composite* The load-deflection response in this portion, i.e., the degree at which loss in strength is encountered with increasing deformation is an important indication of the ability of the fiber composite to absorb large amounts of energy before failure. It is a characteristic that distinguishes fiber-reinforced concrete from plain concrete. This characteristic is referred to as *toughness*. This zone is also called *stress free zone* because the fibers have either completely pulled out or failed.

Because of the linear dependence of the ultimate flexural strength of FRC on *the volume fraction of fibers* and their *aspect ratio*, it could be stated that the ultimate flexural strength generally increases with the *fiber-reinforcing index, defined as the product of fiber volume fraction* and *aspect ratio* ($V_f L/d_f$). Based on this observation, following general equation for predicting the ultimate flexural strength of the fiber composite has been proposed.

$$f_c = C f_m (1 - V_f) + D (V_f L/d_f)$$

where

f_c is the ultimate strength of the fiber composite,
f_m is the maximum strength of the plain matrix (mortar or concrete), and
C and D are constants which can be determined experimentally.

For plain concrete $C = 1$ and $D = 0$. The constant C accounts for the *bond strength of the fibers* and *randomness of fiber distribution.* The values for the constants C and D have been proposed as 0.95 and 4.95 for the ultimate flexural strength of steel fiber-reinforced concrete and 0.85 and 4.25 for its first cracking strength.

The increasing fiber-reinforcing index ($V_f L/d_f$) has a positive influence on performance because of the improved resistance to pull-out of the fibers from the matrix. The maximum quantity of hooked-end fibers that can be added without causing balling is limited to 1.0 per cent by volume. Compared to plain concrete, the addition of fibers increase the first cracking strength by 15 to 75 per cent and static flexural strength (characterized by modulus of rupture) by 15 to 30 per cent for the values of $V_f L/d$ from 40 to 120 (a practical limit from workability consideration). Compared on equal basis of 1.0 per cent by volume, the hooked-end steel fibers contribute the highest increase, and the straight fibers provide the least increase in the above-mentioned properties.

The *ultimate load carrying capacity* of fiber-reinforced concrete beam depends mainly on the adequacy of bond. In the absence of excellent *interfacial bond*, the fibers are debonded as soon as the load is transferred to them immediately after cracking of the matrix and the ultimate load will not be greater than the ultimate load of beams without fiber reinforcement. If the bond is excellent, the fibers can withstand loads even after the cracking of the matrix, and this results in an increase in the *ultimate strength*. An improvement in bond can be achieved by the introduction of *indented, crimped*, or *bent fibers*.

The polyester and polypropylene fibers significantly increase the flexural toughness and the post-peak resistance of concrete. These improvements continue as fiber volume increases, except in ultimate strength, for which it starts to decrease beyond fiber volume of 0.35 per cent. The addition of silica fume enhances toughness and post-peak strength of plastic fiber concrete.

Slurry infiltrated concrete (SIFCON) when used over the reinforced concrete beams leads to ductility indexes exceeding three times those obtained without it. Crack widths and spacing are more than an order of magnitude smaller than in conventional reinforced concrete. There is no need for stirrups in flexural members with SIFCON matrix.

4. **Shear strength** The enhancement of shear strength of fiber reinforced high strength concrete is of the order of 60 per cent with steel and 15 per cent with polypropylene fibers, whereas fibers reinforced normal strength concrete attains an enhancement of 35 per cent with steel fibers and no increase with polypropylene fibers when compared to the strengths of their respective unreinforced plain concretes. The enhancement of performance of fibers in high strength concrete is attributed to the improved bond characteristics associated with the use of fibers in conjunction with high-strength concrete. For the concrete with steel fibers, significant increases in ultimate load and ductility is achieved. With polypropylene fibers, a lower increase in ultimate load is obtained when compared to the increase due to steel fibers. Ductility of the polypropylene fiber reinforced specimens is greater than that of steel fiber reinforced concrete. Combination of fibers and conventional stirrups, results in slight increases in the ultimate load but offers major improvements in ductility as compared to the corresponding plain concrete with conventional stirrups.
5. **Modulus of elasticity** The *dynamic modulus of elasticity* of FRC containing steel fibers up to about two per cent by volume of concrete varies within five per cent of the unreinforced matrix. Hence, the conventional solutions for the static elastic modulus can also be applied for the dynamic modulus of fiber-reinforced concrete.
6. **Creep and shrinkage** The factors that influence the shrinkage strain in plain concrete also influence the shrinkage strain in fiber reinforced concrete; namely, temperature and relative humidity, material properties, the duration of curing and the size of the structure. The addition of fibers, particularly steel, to concrete have beneficial effects in counterbalancing the movements arising from volume changes taking place in concrete, and tends to stabilize the movements earlier when compared to plain concrete.

   The primary advantage of fibers in relation to shrinkage is their effect in reducing the adverse width of shrinkage cracks. Shrinkage cracks arise when the concrete is restrained from shrinkage movements. The presence of steel fibers delays the formation of first crack, enables the concrete to accommodate more than one crack and reduces the crack width substantially. Polypropylene fibers are much less effective in reducing crack widths than steel fibers.

High strength concretes with *silica fume* undergo early cracking when deformation is restrained. This phenomenon, which occurs even when concrete is protected against any evaporation, is attributed to *autogenous shrinkage* because of the exceptionally *low water–cement ratio*. This phenomenon can be corrected by the use of fibers.

7. **Strain capacity** The ability to accomodate relatively large *strains* before failure, the superior resistance to *crack propagation*, the ability to withstand large *deformations* and the enhanced *ductility* are characteristics that distinguish fiber-reinforced concrete from plain concrete. These characteristics are generally described by *toughness,* which is the main reason for using fiber-reinforced concrete in most of its applications. Unlike plain concrete the presence of fibers imparts considerable energy absorption capacity to stretch and debond the fibers before complete fracture of the material occurs. Thus *the toughness is a measure of the ability of the material to mobilize large amounts of post-elastic strains* or *deformations prior to failure.* The area under the complete *load-deflection curve* (or under a prescribed part of the curve) can be described as a measure of *toughness* or *energy absorption capability* of the material.

   The variables that affect the ultimate flexural strength of FRC beams also influence the flexural toughness; namely, the type of fiber, volume fraction of fiber, the aspect ratio, the fiber's surface deformation, bond characteristics and orientation. The steel fibers are very effective in improving the flexural toughness of rapid-set materials. Considerable ductility and toughness can be achieved by using SIFCON and SIMCON.

   The increase in silica fume content renders the fiber-reinforced concrete more brittle as compared to concrete without silica fume.

8. **Impact resistance** Impact resistance is essential for applications such as the bridge piers. It is well recognized that the addition of fibers to concrete enhances the impact resistance. Improvements in impact strength for fiber-reinforced concretes are highly dependent on the type of fiber and the method of test. It is estimated by using falling weight method or explosives or pendulum-type impact machine. The impact strength against dynamic tensile and compressive loads due to dropped weights or explosives is 8 to 10 times that of plain concrete. The fiber-concretes incorporating hooked-end and corrugated steel fibers have excellent impact resistance.

   Furthermore, addition of silica fume at the rate of 5 to 10 per cent by mass increases the impact resistance even more due to the improvement in fiber dispersion and enhancement in bond between fibers and concrete caused by silica fume. However, it should be realized that the adverse effects on workability, caused by high contents of silica fume or fibers, results in the reduction in the impact resistance of the material.

9. **Fatigue** In many applications, particularly in pavements, bridge deck overlays, and off-shore structures, the flexural fatigue strength and endurance limit are important design parameters. Fatigue strength can be described as the maximum *flexural stress* at which FRC composites can withstand a prescribed

number of fatigue load cycles before failure. Alternatively, it can be defined as the maximum number of fatigue load cycles needed to fail a beam under a given maximum flexural stress level. However, the fatigue strength is often evaluated on the basis of endurance limit. *The endurance limit of FRC in flexural bending is defined as the maximum flexural stress at which the beam can withstand a prescribed number of loading cycles (usually two million cycles), expressed as a percentage of either:* (a) *its virgin static flexural strength (first cracking strength* or *modulus of rupture),* or (b) *the maximum static flexural strength of similar plain unreinforced matrix.* The flexural fatigue strength of steel FRC is about 80 to 90 per cent of its static flexural strength at two million cycles when non-reversed loading is applied and about 70 per cent of its static flexural strength when full reversed loading is used.

The addition of collated hooked-end steel fibers results in a considerable increase in the flexural fatigue strength of concrete. The flexural fatigue strength increases by 200 to 250 per cent, and endurance limit (to achieve two million cycles) by 90 to 95 per cent, relative to plain concrete.

The fatigue strength and endurance limit increase with the addition of fibers and increasing volume fraction of fibers. The improved bond characteristics of fibers improves the fatigue strength of fiber composites. The highest increase in fatigue strength was with hooked-end steel fibers and the lowest increase is with straight steel fibers and polypropylene fibers.

10. **Durability** As in case of conventional reinforced concrete, steel fibers will be protected from *corrosion* provided the alkalinity of the matrix is maintained in the vicinity of the fibers. *Carbonation* of concrete matrix may lead to corrosion of the fibers, and any deterioration may be accelerated if the concrete is cracked. Since fiber-concrete normally fails due to *fiber pull-out* rather than fiber fracture the uncorroded fiber strength is not fully utilized, a considerable reduction in diameter due to corrosion could be tolerated provided that corrosion does not reduce the interfacial bond strength.

The studies have indicated a greater rate and extent of chloride penetration for fiber-reinforced concrete than for conventional plain concrete. This suggests that the fibers extending from the surface may create an entry for the chlorides in addition to normal capillary system and make fiber reinforced concrete more vulnerable to *corrosion* damage than conventional steel reinforcement.

Application of Steel-fiber Reinforced Concrete Steel-fiber reinforced concrete (SFRC) provides additional strength in flexure, fatigue, impact and spalling. These properties lead to smaller concrete sections, improved surface quality and reduced maintenance. The main applications of SFRC are in highway and airfield pavements, hydraulic structures, tunnel linings, industrial floors, bridge decks, repair works, etc. SFRC can be applied in the following areas:

1. **Highway and airfield pavements** The steel-fiber concrete can be used in new pavement constructions or in the repair of existing pavements by the use of *bonded* or *unbonded overlays* to the slab beneath. The major advatages are: a higher flexural strength results in the reduction of required

pavement thickness; the resistance to impact and repeated loading is increased. The transverse and longitudinal joint spacings may be increased. Under conditions of restrained shrinkage, the greater tensile strain capacity of steel-fiber concrete results in lower maximum crack widths than in plain concrete.

SFRC gives a smooth riding surface without irregular depressions. The overlays for the rehabilitation of runways, taxiways, bridge decks, and the strengthening of existing runways and taxiways to comply with the rigid requirements of the newer generation heavy-duty jet aircrafts, are extensively used. SFRC can be advantageously used in the repair of damaged patches in existing runways, and highway pavement slabs.

The thickness of pavements constructed with concrete having a cement content of 410 kg/m^3, water–cement ratio of 0.6, maximum size of aggregates as 20 mm using 1.4 per cent (by volume, i.e., 106 kg/m^3) trough type steel-fibers could be 25 per cent less than normal concrete pavements.

2. **Hydraulic structures** The major advantage of using steel-fiber concrete in hydraulic structures is its resistance to *cavitation* or *erosion damage* by high velocity water flow. The steel-fiber concrete has been successfully used in the repair of spilling basin at Tarbela Dam in Pakistan. The fiber concrete contained about one per cent (by volume) of $25 \times 0.25 \times 0.55$ mm slit steel fibers.
3. **Fiber shotcrete** fiber shotcrete has been used in rock slope stabilization, tunnel lining and bridge repair. A thin coating of plain shotcrete applied monolithically on top of the fiber shotcrete, may be used to prevent *surface staining* due to *rusting*. The conventional sprayed concrete techniques can be used by including fiber mixing with the pneumatic conveying of fibers from a rotary fiber feeder to the nozzle via a 75 mm diameter flexible hose. In addition to usual shotcrete advantages, the fibers are aligned in two dimensions (in a plane) by the mode of application of relatively thin coating. The fiber shotcrete can be used in the protection of structural steel work particularly in the support structure.
4. **Refractory concrete** Steel-fiber reinforced refractory concretes have been reported to be more durable than their unreinforced counterpart when exposed to high thermal stress, thermal cycling, thermal shock or mechanical abuse. The increased service span is probably due to combination of crack control, enhanced toughness, and the spall and abrasion resistance imparted by the steel fibers. Through the use of shotcrete technique, the material can be used for lining ash hoppers and flame exhaust ducts.
5. **Precast applications** They include manhole covers, concrete pipes, machine bases and frames. Improved flexural and impact strengths may allow the use of steel-fiber concrete components in rough handling situations.
6. **Structural applications** Structural applications of steel-fiber concrete are rare. However, the following possibilities may be considered:

   (a) Fiber reinforcement can provide an increased impact resistance to conventionally reinforced beams, and thus an enhanced resistance to local damage and spalling.

(b) Fiber reinforcement can inhibit crack growth and crack widening, this may allow the use of high strength steel without excessive crack widths or deformations at service loads.

(c) Fiber reinforcement provides ductility to conventionally reinforced concrete structures, and hence enhances their stability and integrity under earthquake and blast loading.

(d) Fiber reinforcement increases the shear strength of concrete. As a consequence punching shear strength of slabs is increased and sudden punching failure may be transformed into gradual ductile one.

Mix Design for Steel-fiber Reinforced Concrete The mix should contain minimum fiber content and maximum aggregate for the specified strength and workability. The *cement paste content* depends upon three factors:

1. Volume fraction of fibers
2. Shape and surface characteristics of fibers, i.e., specific fiber surface
3. Water-cement ratio

For the commonly encountered SFRC mixes, the following range of parameters is associated:

Cement content	300 to 500 kg/m^3
Water–cement ratio	0.45 to 0.60
Ratio of sand to total aggregate, per cent	50 to 100
Maximum size of aggregate	10 and 20 mm
fiber content	1.0 to 2.5 per cent
fiber–aspect ratio	50 to 1000

Mix design procedure Following are the steps involved in the mix design of fiber reinforced concrete:

1. Corresponding to the required 28-day field flexural strength of steel fiber-reinforced concrete, the design strength for laboratory mix is determined.
2. For fibers of known geometry and for stipulated volume fraction, the water-cement ratio is selected between 0.45 and 0.60.
3. Depending on the maximum size of aggregate and fiber concentration, the paste content is determined by mass.
4. The fine-to-coarse aggregate ratio varies from 1:1 to 1:3, a ratio of 1:1.5 is a good start for a volume percentage of fiber up to 1.5 and length of fiber up to 40 mm.
5. For the water-cement ratio and paste content determined in Steps 2 and 3, respectively, the cement and water contents may be worked out.
6. The fiber content (by mass) is calculated by taking the density of fibers as 7850 kg/m^3.
7. The total quantity of the aggregate is determined from

$$W_A = W_{FRC} - (W_W + W_C + W_F)$$

where W_A, W_{FRC}, W_W, W_C and W_F are the masses of total aggregate, fiber reinforced concrete, water, cement and fibers, respectively.

8. The quantities of fine and coarse aggregates are worked out by using Step 4.
9. The trial mix is prepared and the paste content adjusted if the mix shows any tendency to segregate.
10. The workability of the mix is checked using appropriate test.

Example 14.2 For the illustration of the above procedure, select a fiber concentration of 1.5 per cent (by volume) of trough-shaped fibers with aspect ratio of 80 with 0.45 mm diameter.

For the maximum nominal size of aggregate of 20 mm, consider

Paste content	40 per cent
Fine-to-coarse aggregate ratio	1:1.5
Water-cement ratio	0.55

mass of fibers per cubic metre of SFRC $= 7850 \times 0.015 = 117.7$ kg (say 118 kg)

For 1 kg ($= 1/3.15 = 0.317$ litre) of cement, the water content required is 0.55 lite rgiving a total paste content of 0.867 liter. Therefore, for a cement paste content of 40 per cent, i.e., 400 liters per cubic meter of concrete, the cement and water contents are 461(=400/0.867) and 254(=0.55 × 461) kg, respectively. The total aggregate content $= 2400 - (254 + 461 + 118) = 1567$ kg. For the assumed fine-to-coarse aggregate ratio of 1:1.5, the coarse and fine aggregates are 940 and 627 kg, respectively.

Practical mix proportions Though the high fiber content brings about large improvements in mechanical properties, it makes the concrete unworkable. On the other hand, a low fiber content in workable concretes show no significant improvements in the desirable properties. Thus a practical concrete is a compromise between these situations. Typical mixes using fiber volume concentrations of 0.75 to 1.50 per cent with water-reducing admixtures and/or fly ash have been extensively used. With steel fibers, the typical mix proportions by mass are:

Cement	:	Water-cement ratio	:	Sand	:	10 mm aggregate
1	:	(0.4 to 0.6)	:	(2 to 3)	:	(0.8 to 3)

Similar mixes have also been used for polypropylene fibers.

14.11.2 Non-Steel fibers

The examples of commercilly available non-steel fibers are given in Fig. 14.22.

Polypropylene Fiber Reinforced (PFR) Cement–Mortar and Concrete Polypropylene is one of the cheapest and abundantly available polymers. Polypropylene-fibers are resistant to most chemicals and it would be the cementing matrix which would deteriorate first under aggressive chemical attack. Its melting point is high (about 165°C), so that a working temperature as high as 100°C may be sustained for short periods without detriment to the fiber properties.

Polypropylene short fibers in small volume fractions between 0.5 to 1.0 per cent have been commercially used in concrete to achieve considerable improvement in impact

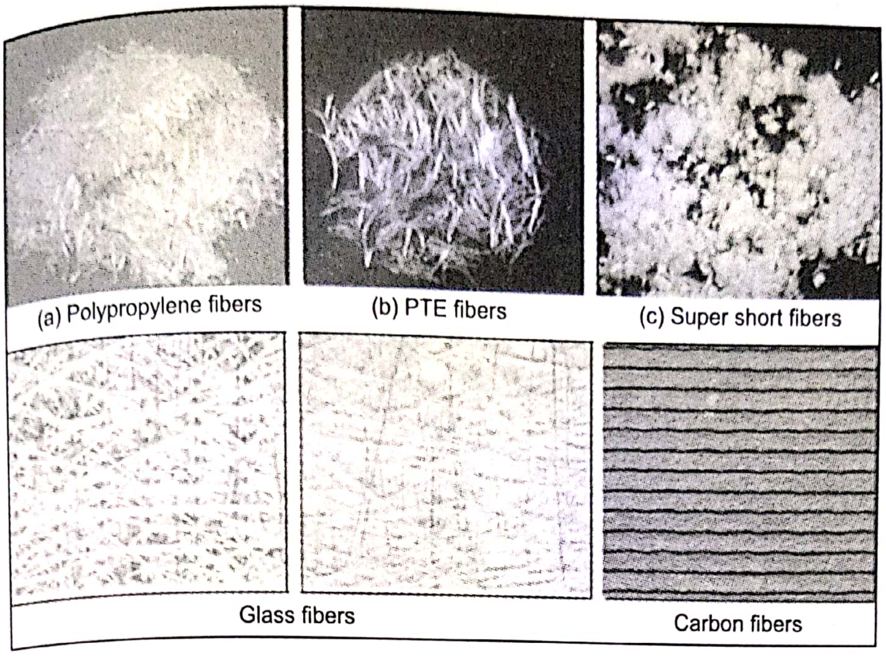


Fig. 14.22 *Examples of commercially available of non-steel fibers*

strength of the hardened concrete. They have low modulus of elasticity. Polypropylene fibers are available in two forms: monofilaments produced from spinnarets, and film fibers produced by extrusions. The film fibers are commonly used and are obtained from fibrillated film twisted into twine and chopped, usually into 25–50 mm lengths for use in concrete. The fibrillated film may also be opened to produce continuous networks for use in thin sheet manufacture. A typical machine for production of polypropylene filament is shown in Fig. 14.23. Fibrillated film may also be woven to produce flat meshes which may be used as thin cement sheet reinforcement.

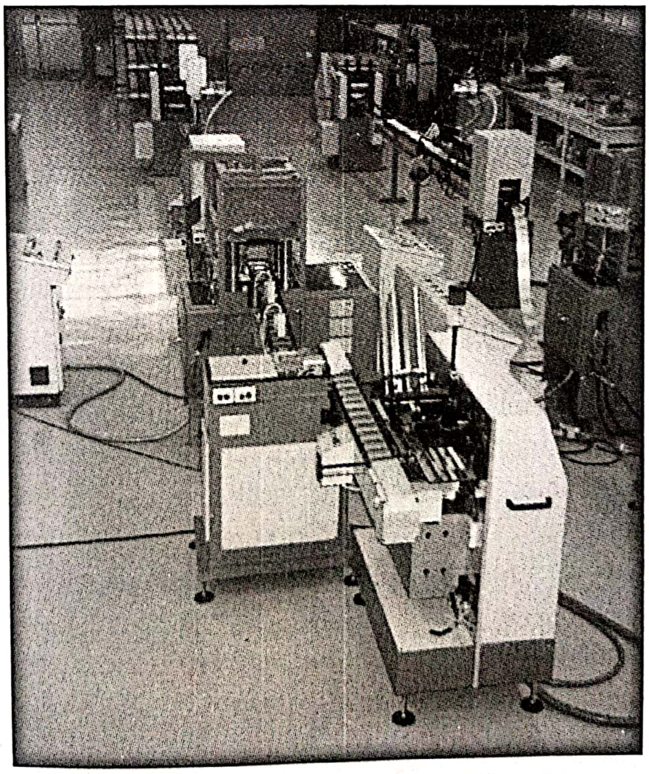


Fig. 14.23 *A typical complete line machine for production of polypropylene filament*

Polypropylene fibers being hydrophobic can be easily mixed as they do not need lengthy contact during mixing and only need to be evenly dispersed in the mix. These are therefore added shortly before the end of mixing the normal constituents. Prolonged mixing may lead to undesirable *shredding of fibers*. There is no physico-chemical bond between fiber and the matrix, only a mechanical bond is formed as cement paste penetrates the mesh structure between individual fabrics of chopped length or continuous network.

Properties of fresh PFR concrete The *compacting factor test* has been reported to be most suitable. The inclusion of polypropylene fibers reduces the workability considerably, e.g., a normal concrete mix of medium workability (CF about 0.88) may reduce to a low workability mix (CF about 0.75) following the addition of one per cent of chopped 35 mm polypropylene fibers. Polypropylene monofilaments can be used in small volume fractions of about 0.1 to 0.2 per cent to alter *rheological properties* of the material, e.g., highly *air-entrained concretes* can be stabilized by fibers.

Properties of hardened PFR concrete The tensile strength of concrete is essentially unaltered by the presence of a small volume of short polypropylene fibers. Although the change in flexural strength of polypropylene reinforced-concrete is marginal, the *post-cracking behavior* has shown its ability to continue to absorb *energy* as fibers-pullout. The energy absorbing capacity has been found to increase with the length of fibers, e.g., the 75 mm polypropylene fibers may result in an energy absorption comparable to that of the less efficient of steel fibers; and at a considerably lower cost.

Durability Polypropylene may deteriorate under attack from ultraviolet radiation or by thermal oxidation process. The cement matrix appears to prevent the former. To combat thermal oxidation, sophisticated stabilizers have been developed to delay degradation, and enhance durability.

Applications of PFR mortar and concrete

1. **Clading panels** Inclusion of polypropylene fibers instead of steel mesh reinforcement may allow reduction in panel thickness.
2. **Shotcreting** Surface coatings of polypropylene reinforced-mortar may be provided by shotcreting using normal equipment. The fibers of about 20 mm length enable smooth transport of the dry mix through air hoses and nozzles. Water is then added at the gun orifice. Shotcreting can be advantageously used in wet environments where polypropylene fibers can eliminate the need for steel (corrodable) mesh on which spray of mortar is required.
3. **Polypropylene concrete** can be advantageously used in the energy dissipating blocks.

The potential market for polypropylene reinforced-cement is principally as a substitute for absestos-cement roofing and cladding panels.

Glass-fiber Reinforced Concrete (GFR) Glass fibers are made up form 200 to 400 individual filaments which are lightly bonded to make up a strand. These stands can be chopped into various lengths or combined to make cloth, mat or tape. Using the conventional mixing technique for normal concrete, it is not possible to mix more than about two per cent (by volume) of fibers of up to a length of 25 mm.

The major application of glass fiber has been in reinforcing the cement or mortar matrices used in production of thin-sheet products. The commonly used varieties of glass-fibers are E-glass used in the reinforcement of plastics, and AR-glass. E-glass have inadequate resistance to alkalies present in Portland cements whereas AR-glass have improved alkali-resistant characteristics. Sometimes polymers are also added in the mixes to improve some physical properties such as *moisture movement.*

The process of manufacture of glass-fiber cement products may involve spraying, premixing or incorporation of continuous rovings. In the *spray-suction* process, the glass-fiber strand is chopped into lengths between 10 and 50 mm and blown in spray simultaneously with the mortar slurry on to a mold or flat bed followed by suction to remove excess water. On the other hand, in the technique involving premixing, short strands (about 25 mm in length) are mixed into mortar paste or slurry before further processing by casting into open molds, pumping into closed molds, etc. Care must be taken to avoid fiber tangling and matting together, and to minimize the fiber damage during mixing.

In the process incorporating continuous rovings, the rovings are impregnated with cement slurry by passing them through a cement bath before they are wound on to an appropriate mandrel. Additional slurry and chopped fibers can be sprayed on to the mandrel and compaction can be achieved by the application of roller pressure combined with suction.

Properties of hardened GFR concrete The behavior of glass-fiber cement sheets under tensile force is typified by *multiple cracking* of the matrix. Longer fibers improve the ultimate failure stress. In wet environments, significant reduction in strength takes place. The material may become brittle on ageing.

One of the most important improvements in the property achieved by glass fiber is the spectacular improvement in *impact strength.* With the addition of just 5 per cent glass fibers, an improvement in the impact strength of up to 1500 per cent can be registered as compared to plain concrete. With a two per cent fiber content (up to 25 mm in length), the flexural strength is almost doubled. The second important improvement is in the resistance to *thermal shock.* Ductility also improves with an increase in strength and modulus of rupture.

The flexural strength of water stored and weathered specimens reduces with time and nearly equals that of the matrix alone. The reduction in *energy absorption* is similar to that in flexural strength. The long-term *durability* of glass fiber-reinforced cement can be improved by the addition of 15 per cent polymer to the mortar matrix. The increase in matrix cost is balanced by the use of cheaper E-glass fibers.

Applications The glass fiber-reinforced cement finds its use in formwork systems, ducting, roofing elements, sewer lining, swimming pools, fire-stop partitioning, tanks and drainage elements, etc. Sometimes it is used in combination with polymer impregnated *in-situ* concrete.

Asbestos Fibers The naturally available inexpensive mineral fiber, asbestos, has been successfully combined with Portland cement paste to form a widely used product called *asbestos cement*. Asbestos fibers have thermal, mechanical and chemical resistance making them suitable for sheet products, pipes, tiles and corrugated roofing elements. Asbestos-cement products contain about 8 to 16 per cent (by volume) of asbestos-fibers. The flexural strength of asbestos cement board is approximately two to four times that of unreinforced matrix. However, due to relatively short length (10 mm), the fibers have low impact strength. There are health hazards associated with the use of asbestos cement. Its use is banned in most of countries. In the near future, it is likely that *glass fiber-reinforced concrete* will replace asbestos completely.

Carbon Fibers Carbon fibers form the most recent and probably the most spectacular addition to the range of fibers available for commercial use. Carbon fibers come under the high E-type fibers. These are expensive. Their strength and stiffness characteristics have been found to be superior even to those of steel. But they are more vulnerable to damage than even glass fibers, and hence are generally treated with resin coating.

Organic Fibers Organic fibers, such as polypropylene or natural fibers may be chemically more inert than either steel or glass fibers. They are also cheaper, especially if natural. The polypropylene-fiber concrete has been described earlier. A large volume of vegetable fibers (7 per cent, 50 mm length) may be used to obtain a multiple cracking composite. The problem of mixing and uniform dispersion may be solved by adding a superplasticizer.

Polypropylene, nylon and other organic fibers due to their low modulus of elasticity are not effective in crack control, and also the organic fibers may decay. However, these fibers improve *impact resistance*.

Vegetable Fibers The commonly used fibers are jute, coir and bamboo. They possess good tensile strength in their natural dry state. Their tensile strengths do not suffer significantly even after being immersed in 10 per cent normal solution of sodium hydroxide for up to 28 days. However, long-term *durability* is doubtful.

In contrast to glass fibers, steel and polypropylene fibers are chemically stable in a cement paste matrix. The high alkalinity of cement paste protects steel from being corroded. The corrosion of steel fibers can however become a problem when the matrix has cracked.

Irrespective of the type, size and shape of fibers to be used in a mix, the fundamental requirement of fiber-reinforced concrete is that all the individual fibers should be uniformly distributed throughout the matrix. The mix should have sufficient paste content to coat the fibers and aggregate, so that the ingredients can be placed and compacted in the final position without any *segregation*.

The mix proportions generally depend on the intended applications of the composite. The *prime considerations* are uniform *dispersion of fibers, adequate workability* for placing and compaction with the available equipment. The *workability of fiber-reinforced concrete* is influenced by *maximum size of aggregate* as can be seen in (Fig. 14.16), *volume fraction, geometry* and *aspect ratio of fibers* as shown in Fig. 14.18. As the size of aggregate increases, it becomes more difficult to achieve uniform fiber dispersion, since the fibers are bunched into mortar fraction which can move freely past the aggregate during compaction. To obtain a better dispersion the coarse aggregate content is kept lower than in a normal mix and the maximum size of aggregate is preferably limited to 10 mm. The mortar matrix (consisting of particles less than 4.75 mm) should be around 70 per cent, and aggregate–cement ratio as low as 3:1. A fine-to-coarse aggregate ratio of 1:1 is often a good starting point for a mix trial. *Water-cement* ratio between 0.4 and 0.6, *cement-content* of 250 to 430 kg/m^3 are recommended for providing adequate paste content to coat large surface of fibers. Beyond a certain optimum content of fibers the workability of the composite decreases rapidly.

14.11.3 Batching, Mixing, Placing, Compaction and Finishing

The fibers are usually added to the aggregates before the introduction of cement and water into the mixer. For laboratory testing, fibers can be added in small amounts to the rotating drum charged with cement, aggregate and water. For large batches, the fibers are blown into the previously charged rotating drum.

A fiber mix generally requires more time and vibration to move the mix and to compact it into the forms. Surface vibration of forms and exposed surface is preferable to prevent segregation. The properties of fiber reinforced concrete depend upon fiber alignment. More energy is required to compact fiber concrete than conventional concrete. Some of the precautions taken while mixing, placing and compacting fiber-reinforced concrete are as follows:

1. While mixing small quantities of fiber reinforced concrete by hand, there is a possibility of steel fibers shooting up and hitting the eyes of the worker or even pricking the hand. To avoid these hazards, the hands should be protected by gloves and the eyes with safety glasses.
2. A pan mixer of the counter-flow type should be used for mixing fiber reinforced concrete.
3. For uniform distribution of steel fibers, a dispenser should be used. While dispensing the fibers into concrete, the rate at which the fibers are fed to the mixer should be synchronized with rate of mixing.
4. Forks and rakes can prove helpful for handling low slump mixes.
5. Standard screeding methods and trowels can be used for finishing fiber concrete. A textured surface can be obtained by using a stiff brush.

Standard workability tests, such as the slump, compacting factor and Vee-Bee tests are suitable for conventional concrete but not for mixes containing fibers. For instance, the slump of a mix, even with a low fiber content, can be zero though the mix responds well when vibrated. A workability test should provide the condition of flow on vibration, because FRC responds well to conventional vibrating table as it does not easily segregate from the mix due to its low specific gravity.

14.12 POLYMER CONCRETE COMPOSITES (PCCS)

Polymer concrete composites are obtained by the combined processing of polymeric materials with some or all of the ingredients of the cement concrete composites. Depending on the process by which the polymeric materials are incorporated, polymer concrete can be classified as follows.

14.12.1 Polymer-Impregnated Concrete (PIC)

In *polymer-impregnated concrete,* low viscosity liquid *monomers* or *prepolymers* are partially or completely impregnated into the *pore systems* of hardened cement composites and are then polymerized. The partial or *surface impregnation* improves durability and chemical resistance. Overall improvements in the structural properties are modest. On the other hand, total or *in-depth impregnation* improves structural properties considerably.

The hardened concrete, after a period of moist curing, contains a considerable amount of free water in its *voids.* The water-filled voids form a significant component of the total volume of concrete ranging from five per cent in dense concrete to 15 per cent in *gap-graded concretes.* In polymer-impregnated concrete, it is these water-filled pores that are sought to be filled with polymers, i.e., the major parameters affecting monomer loading are the moisture and the air in the voids in concrete. The total or in-depth polymer impregnation of concrete, therefore, involves the following states:

1. Construction of element with well-designed cement concrete, which is adequately moist cured with optimum strength.
2. Removal of moisture by drying the concrete by heating to develop surface temperatures of the order of 120 to 150 °C. The small elements can be heated in an air oven. For large *cast–in-situ* surfaces a thick blanket of sand (usually 10 mm thick) can be used to prevent a steep *thermal gradient.* Infrared heaters may be used. About six to eight hours of heating is required to expel a large part of the free water in the concrete.
3. Cooling of concrete surfaces to safe levels (about 35 °C) to avoid flammability.
4. Removal of air by subjecting the dry concrete to vacuum. The degree of vacuum applied and the duration have significant influence on the quantity of monomer that can be impregnated and therefore, on the depth of impregnation.
5. Application of monomer by soaking the concrete surface in it for a sufficiently long time to achieve the desired depth of penetration. The soaking time depends on the viscosity of monomer, preparation of the surface prior to soaking and the characteristics of the concrete. To reduce the time required to achieve a desired depth of monomer penetration, external pressure using nitrogen gas or air is generally employed.

6. Covering the surface with a *plastic sheet* to prevent evaporation of monomer.
7. Polymerization by heating the catalyzed monomer to the required temperature levels (usually between 60 and 150 °C depending upon the type of monomer) also called thermal catalytic technique. The heating can be done, by infrared heaters or in an air oven. Depending on the polymer, two to six hours are required for this stage. The heating decomposes the catalyst and initiates the polymerization reaction. This reaction is called a *thermal catalytic reaction*. When monomer has penetrated into concrete, polymerization can also be initiated using ionizing radiation such as gamma rays. The polymers, when fully polymerized or cross-linked, are solids occupying the volume in which they have been impregnated. As such, at the impregnation stage, the polymer has to be in a prepolymer liquid form, generally called monomer. The state of polymerization of monomers, or of prepolymer resins, is brought about also by adding initiators, and cross-linking agents.

Polymers can be broadly categorized as *thermoplastics* and *thermosetting resins*. Thermoplastics soften at an elevated temperature (usually between 100 and 150 °C and called glass transition temperature), and as such the advantage of using thermoplastic impregnated concrete is lost at such temperatures. Thermoplastic monomers have a low viscosity and are able to penetrate hardened concrete well and fill a large part of the pores. Their polymerization is accomplished by addition reactions not leading to low molecular weight by-products. Thermosetting resins, on the other hand, are more viscous and difficult to impregnate into concrete. However, they can withstand higher temperatures without softening. But the condensation reactions which occur may lead to the formation of low molecular weight by-products which would occupy some of the space.

It is necessary that a monomer or its polymer is chemically compatible with the compounds of cement and the constituents of hydrated cement paste to prevent their adverse effects.

Monomer/resin systems used for polymer impregnated concrete are styrene, polyester, methylmethacrylate, butylacrylate, acrilonitrile, epoxies and their copolymer combinations. The types and strength properties of some of the commonly used systems are given in Table 14.10.

The applications of polymer impregnated concrete are as follows:

1. **Surface impregnation of bridge decks** The aim of impregnating the bridge decks is to render them impervious to the intrusion of moisture, deicing chemicals and chloride ions.
2. **Applications in irrigation structures** The effect of cavitation and erosion in dams and other hydraulic structures can be catastrophic. Conventional repairs of the damage are expensive and huge losses may be caused due to loss of benefits from irrigation, power generation, flood control, etc. In such cases, the polymer impregnated treatment may be cost effective. The concrete may be removed from the place of severe damage and the damaged area patched, dried and treated by impregnation.

Table 14.10 *Types of polymers and strength properties of polymer impregnated concrete*

Polymer type	Technique employed	Polymer loading, per cent (by mass)	Compressive strength, MPa	Strength improvement ratio	Polymeriza-tion method
Styrene	• Specimens vacuum \ and pressure impregnated	4 to 6	60–90	2.6–3.0	Thermal catalytic
	• Predried specimens just soaked in monomer	1 to 2	25–30	1.5–2.0	Thermal catalytic
60% styrene + 40% trimethol-propane trimethacrylate (TMPTMA)	• Vacuum treated and pressure impregnated	6 to 7	50–60	1.5–2.0	Thermal catalytic
Methyl-meth-acrylate (MMA)	• Vacuum treated and pressure impregnated	5 to 7	100–125	3.5–4.0	Thermal catalytic
MMA	• Vacuum treated and pressure impregnated	5 to 7	120–140	4.0–4.5	Radiation
MMA + 10% TMPTMA	• Vacuum treated and pressure impregnated	5.5 to 7.5	150	5	Radiation
	• Predried specimens just soaked with monomer from one face only	2	70	2.3	Thermal catalytic
	• High pressure steam cured concrete, dried, vacuum treated and impregnated under pressure	6 to 8	170–190	5.7–6.3	Radiation
Acrylonitrile	• Vacuum treated and pressure impregnated	3.5 to 5.5	80	2.7	Thermal catalytic
10% polyester + 90% styrene	• Vacuum treated and pressure impregnated	5 to 6.5	130	4.3	Thermal catalytic
Vinyl chloride	• Vacuum treated and pressure impregnated	3 to 5	70	2.3	Thermal catalytic
Epoxy	• Vacuum treated and pressure impregnated	–	105	3.5	Thermal catalytic

3. **Structural members** Polymer-impregnated concrete has potential as a structural material. Polymer-impregnated prestressed concrete beams have shown remarkable improvements over conventional concrete. The maximum tendon force could be enhanced to four times that in unimpregnated concrete. The creep deflection is of the order of 1/19 to 1/16 that of static deflection. Shear strength improves by the same factor as compressive strength. The stress patterns and strain curves of polymer concretes are shown in Fig. 14.24.

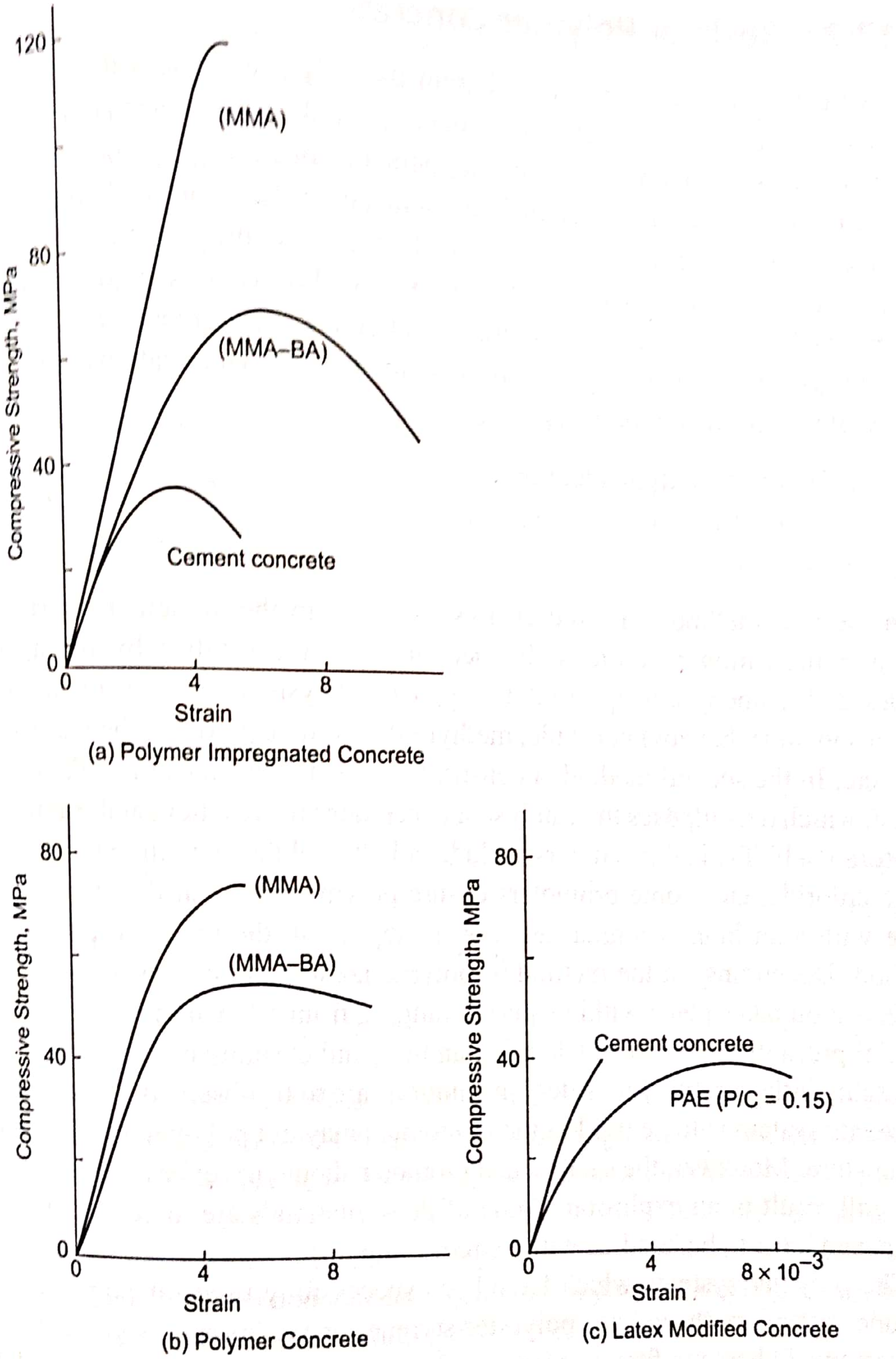


Fig. 14.24 *Stress–strain relationship for polymer concretes*

4. **Marine and underwater applications** Greatly improved structural properties and negligible water absorption and permeability make polymer-impregnated

concrete an excellent material for marine and underwater applications, such as in desalination plants and sea floor structures. Even a partial impregnation of concrete piles in sea water reduces the corrosion of reinforcing bars by 24 times.

5. **Repair of structures** Polymer impregnation has a very good potential for the repair of damaged structures. Restoration and preservation of stone monuments is an interesting application.

14.12.2 Resin or Polymer Concrete

Polymer concrete is a composite wherein the polymer replaces the cement–water matrix in the cement concrete. It is manufactured in a manner similar to that of cement concrete. Monomers or pre-polymers are added to the graded aggregate and the mixture is thoroughly mixed by hand or machine. The thoroughly mixed polymer concrete material is cast in molds of wood, steel or aluminum, etc., to the required shape or form. Mold releasing agents can be added for easy demolding. This is then polymerized either at room temperature or at an elevated temperature. The *polymer phase* binds the aggregate to give a strong composite. Polymerization can be achieved by any of the following methods:

1. Thermal-catalytic reaction
2. Catalyst-promoter reaction
3. Radiation

In the first method, only the catalyst is added to the monomer (thermoplastic) and polymerization is initiated by decomposing the catalyst by the application of elevated temperatures up to 90 °C. Typical catalysts used for different monomer systems include, benzoyl peroxide, methyl-ethyl-ketone peroxide, benzenesulphonic acid, etc. In the second method, a constituent called *promoter* or *accelerator* is also added, which decomposes the catalyst or accelerates the reaction, at the ambient temperature itself. Typical promoters include cobalt naphthanate, dimethyl-p-toluidine, ferric chloride, etc. Some promoters ensure polymerization at the ambient temperature within an hour. Gamma radiation is applied in the radiation polymerization method. Depending on the method of polymerization and the other conditions, polymerization takes place within a period ranging from a few minutes to a few hours. Special precautions are to be taken in handling and cleaning because the monomers are highly inflammable. Fire safety precautions are to be observed. A thoroughly dry aggregate system is to be used as the monomers may not polymerize in the presence of moisture. Moreover, the catalyst and promoter should never be added to each other as it will result in an explosion. Some of these materials are toxic and are carcinogenic, and have to be handled with extreme care.

The polymer systems which have been successfully used for polymer concrete include methyl-methacrylate, polyester-styrene, epoxy-styrene, styrene and furfuryl acetone. Others are furane, acrylic, polyurethane, urea formaldehyde and phenol formaldehyde, etc. The design considerations for polymer concrete are:

1. Smaller the *binder (polymer) content* to fill the voids of the aggregate system content greater is the economy.

2. *Workability* for easy mixing and placing of cement concrete without bleeding and segregation.
3. *Film forming ability* of the polymer, and *bonding* with the aggregate surface to transmit load forces.
4. *Economic curing (cross-linking) times* and temperatures.
5. *Durability* in environments to which the polymer concrete composite is exposed.

Polymer concretes can be reinforced with steel, nylon, polypropylene or glass fibers in a manner similar to cement concrete.

In general, polymer concrete exhibits a fairly linear *stress-strain curve* nearly up to failure; the failure is characterized as *brittle*. Concretes made of thermoset polymers show a decrease in strength by 30 to 40 per cent at higher temperatures, such as 90°C. The *elastic limit* may also be substantially lowered at higher temperatures. Use of *microfillers*, such as finely powdered $CaCO_3$ and silane coupling agents, improve the compressive and tensile strengths of polymer concretes. Table 14.11 shows that wide range of strengths are possible depending upon the resin system used.

Table 14.11 *Compressive and tensile strengths of polymer concrete*

Type of polymer system	Compressive strength, MPa	Tensile strength, MPa	Modulus of elasticity, ($\times 10^2$) MPa
Isophthalate or Orthophthalate polyester	50–140	7–10	9–30
Vinylester	114	7–9	–
Epoxy	45–130	6–16	7–31
Methyl-metha-acrylate + trimethol-propane trimetha-acrylate	60–80	8–9	36
Furane	70–80	5–8	20–32
Methyl-metha-acrylate (MMA)	60–120	8–9	15–18
Acrylic	130	30	–
Carbamide	40–60	25–50	10–12

Thermosetting polymers, such as polyester and epoxy exhibit significant shrinkage during the polymerization of the resin. This shrinkage can be reduced by shrinkage reducing agents, however, at some cost to the strength. Well-cured or fully cross-linked polymer concrete has excellent resistance to acids, salts, common solvents and petroleum products. *Fatigue strength* of polymer concrete, with or without fibers, is excellent. Polymer concrete having up to five per cent steel fibers has better *ductile* and *impact-resistant properties*.

While the general purpose polyester-styrene systems require an elevated temperature of about 60 to 70°C for complete polymerization; resins or monomer systems are available which can cross-link at low temperatures such as 0°C within one or two hours.

Condensation polymers which are relatively inexpensive, like phenol formaldehyde have been used successfully to develop polymer concrete.

Polymer concretes have good potential as repair material and for overlays. Thin sand-filled overlays (12 to 30 mm thick) reduce water permeability and chloride penetration. Polymer concrete can be used for rapid *repair of damaged airfield pavements* and *industrial structures*. Polymer concrete can be used for treating the sluiceways and stilling basin of the dam.

Polymer concrete pipes have been used for transporting a variety of chemicals, for carrying effluents and wastewater, etc.

Polymer concrete can be used in rock bolts. It provides necessary corrosion protection to ground anchors. Polymer concretes possess good electrical properties and can be used for high voltage insulator application. Electrical structures such as poles for electrical transmission lines have been manufactured from polymer concrete.

14.12.3 Polymer Modified Concrete

Polymer modified concrete (PMC), more specifically called *polymer cement concrete*, is a composite obtained by incorporating a polymeric material into concrete during the mixing stage. However, the polymer so added should not interfere with the hydration process. Since many polymers are insoluble in water, their addition can only be in the form of emulsion or dispersion or latex. The composite is then cast into the required shape in the conventional manner and cured in a manner similar to the curing of cement concrete. The hydrated cement and the polymer film formed due to the curing of the polymeric material constitute an interpenetrating matrix that binds the aggregate.

The polymeric materials in the form of lattices and prepolymers may be added to modify cement concretes. Depending upon the type of modifier, polymer modified cement concretes can be subdivided as:

1. Latex-modified cement concrete (LMCC)
2. Prepolymer-modified cement concrete (PMCC)

In general, the quantities of polymers required for polymer-modified cement concretes are relatively small, being in the range of one to four per cent by mass of the composite. In contrast polymer-impregnated concretes require five to eight per cent and polymer concretes 8 to 15 per cent of polymer. Polymer modified cement concretes, are therefore, the least expensive. The processing of PMCC is also simplest. Conventional plant and equipment could be adopted. However, the improvements in mechanical properties have not been as high as observed in PIC or PC.

1. **Latex-modified cement concrete** Lattices are white milk like suspension consisting of very small-sized polymer particles suspended in water with the help of emulsifiers and stabilizing agents. It contains about 50 per cent of polymer solid by mass.

   Both *elastomeric* and *glassy polymers* have been employed in lattices for modifying cement concrete. The elastomeric polymers are characterized by their rubber-like elongation and by their relatively low modulus of elasticity at ambient temperatures. Some of the commonly used elastomeric lattices are:

natural rubber latex, styrene-butadiene rubber latex, acrilonitrile-butadiene rubber latex and neoprene.

Glassy polymers are characterized by high modulus of elasticity, higher strength, and relatively brittle type of failure. Common examples are polyvinyl acetate, polyvinylidene chloride, styrene-butadiene copolymer latex, and acrylic polymers. The use of polyvinyl acetate latex due to its sensitivity to the moisture is discontinued. Polyvinylidene copolymer latex, due to its residual chloride and possible corrosion of reinforcement, is used only in unreinforced concrete applications. The latex systems for modifying cement concrete are not available in India. The optimum curing procedure involves the moist curing of composites for one to seven days, followed by dry curing at room temperature. At 28 days, the latex modified composites reach about 80 per cent their final strength.

2. **Prepolymer-modified cement concrete** Some of the prepolymer systems used are polyester-styrene-based system, epoxy systems and furane systems. With exception of epoxies, prepolymers (unlike lattices) do not improve the workability of cement concrete.

The strength improvement of PMC over conventional concrete is of the order of 50–100 per cent. Its adhesion to plain concrete is good. The ductility is significantly improved and early micro-cracking is avoided. Consequently, the tensile strength and modulus of rupture are more than twice those of control concrete. There is considerable improvement in durability over conventional concrete due to lower *water-cement ratio* and filling of pores with polymer. Further research is required since the high cost of polymer addition has not been commensurately reflected in improved strength.

The excellent bond of latex concrete to existing concrete, superior shear bond strength, good freeze–thaw resistance, resistance to the penetration of chloride ions, improved ductility, and superior tensile and flexural strengths makes latex modified concrete an eminent material for overlays and resurfacing applications for bridge decks, industrial flooring, food processing factories, fertilizer stores, damp resistant floors, for railway platforms, and nuclear processing areas.

Surface deterioration is a major problem in marine and irrigation structures. Excellent resistance to salt water makes LMCC very effective repair material. LMCC are used for fixing ceramic tiles, lining effluent ducts, reservoirs, and sewerage and industrial waste handling structures.

Latex and fiber-reinforced composites have a great potential in cement com-posites due to their synergistic behavior and improvement in matrix fiber bond.

14.12.4 Prepolymer Cement Concrete (PCC)

PCC is used for flooring in food processing and chemical industries, in wear-resistant floors, and in decks over steel bridges. Due to the early development of strengths, it is suited for repair of sea defence structures.

The development of *polymer-concrete composites* has opened up the possibility of extending the very range of applicability of concrete-like composites. It has become possible to tailor a polymer-concrete composite to meet the requirements of any given application. Polymer-concrete composites are far superior to cement concretes in their resistance to chemicals, such as acids, and salt solutions. Polymer-impregnated ferrocement, a thin, lightweight and highly durable composite has a great potential for applications in coastal, off-shore and chemical industrial structures.

Polymer-concrete composites are very cost effective in applications requiring high degrees of durability and chemical resistance and where so far, costlier materials and composites have been employed. In such situations developing nations could ill-afford either the use of inefficient material of construction or the employment of costlier conventional alternatives. The improved durability of polymer-impregnated concrete is shown in Fig. 14.25.

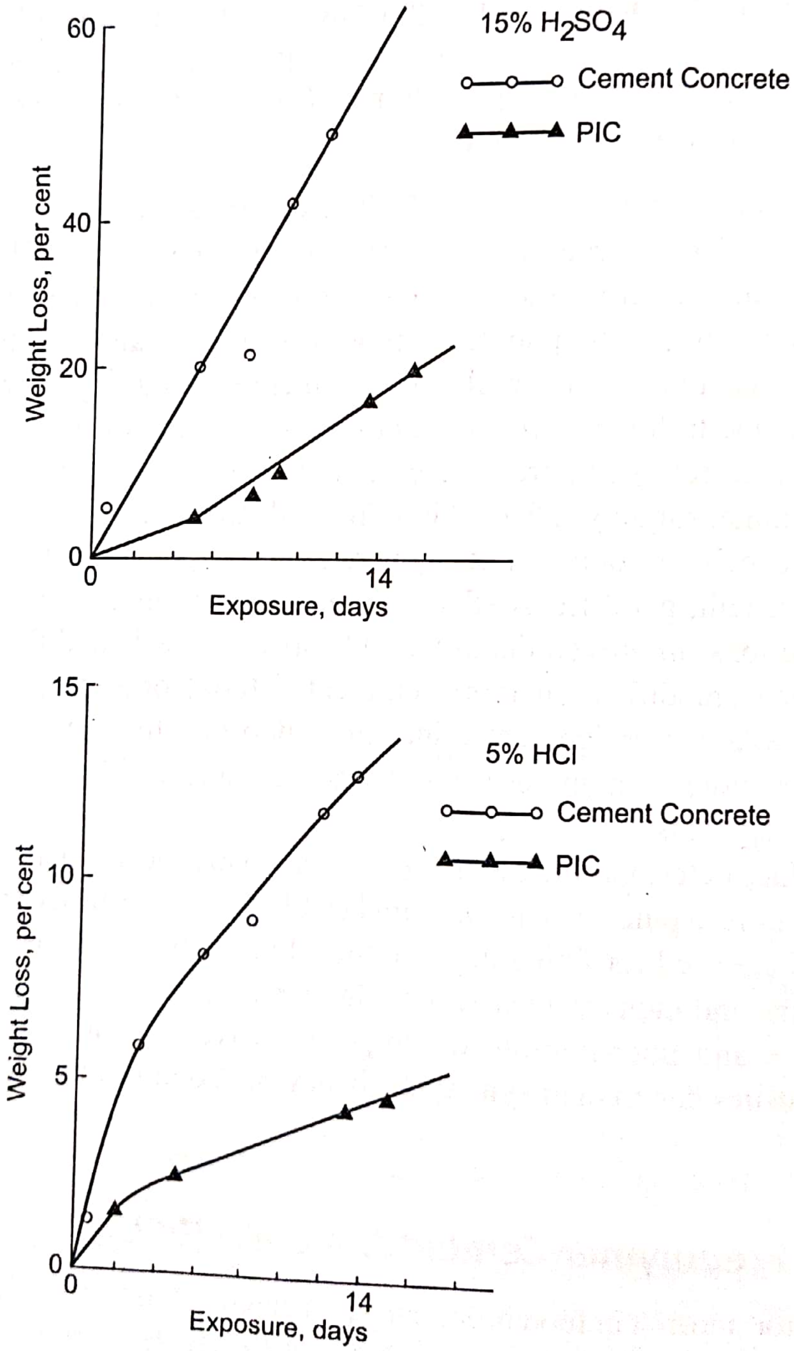


Fig. 14.25 *Durability of polymer-impregnated concrete*

14.13 JET (ULTRA-RAPID HARDENING) CEMENT CONCRETE

The jet cement which has entered the market in the early 1970s, has many characteristics superior to those of ordinary Portland cement. Due to very *short setting time*, it develops *super high initial strength* making it suitable for use in a wide range of placing and curing temperatures. The development of strength under low temperatures is excellent. Jet cement is also called *one hour cement* as it is easily possible to obtain high early strength within an hour. It contains about 20 per cent of reactive calcium fluoroaluminate which is the source of high early strength. The setting time of mortars and concretes made with jet cement can be freely controlled by adding the required amount of *retarder*. Jet cement shows stable strength development extending over a long time and has *high ultimate strength*. In contrast to aluminous cement, there is no loss of strength with age. It has *low drying shrinkage* and *low permeability*.

The jet cement is manufactured by mixing mainly specially selected anhydrite (II-$CaSO_4$) and cement clinker powder integround with sodium sulfate and calcium carbonate (about one per cent), and boric acid (about 0.2 per cent). The jet cement clinker is usually made from a ground homogenized mixture of limestone, clay, bauxite and fluorite by burning at a fairly low temperature of 1250–1350 °C in order to prevent the formation of a tricalcium aluminate phase. Clinker and anhydrite are ground to fineness 400–450 m^2/kg and 600–800 m^2/kg, respectively. The specific gravity of jet cement is about 3.03–3.05 and specific surface area is about 500–550 m^2/kg. Thus the specific gravity of this cement is lower than that of ordinary Portland cement and the specific surface area is considerably higher. The setting time of jet cement is extremely short, the final setting time being from 10 to 15 minutes. The *initial setting* time can be prolonged in proportion to the amount of retarder added. The anhydrite is usually manufactured by burning by-product gypsum and desulfurization waste from power plants.

The one day compressive and flexural strengths of jet cement mortar with cement:sand ratio of 1:2 and water–cement ratio of 0.65 are approximately equal to seven-day and three-day strengths of ordinary Portland cement mortar having the same mix proportions.

With the use of jet cement, improved *workability* of freshly mixed concrete is obtained due to *enhanced cohesiveness* and *resistance to segregation*. However, it is necessary to increase the water content by 1.25 to 1.75 per cent in order to increase the concrete slump by approximately 10 mm. The Vee-Bee time of jet cement concrete is higher than that of ordinary Portland cement concrete of same water content. There is an optimum fine aggregate percentage for each type of cement, at which the Vee-Bee time reaches a minimum value. The jet cement generally reduces the optimum value by four to five per cent because of higher *fineness* of the cement.

The *setting time* of concrete can be regulated by controlling the amount of *retarder* added. It is necessary to adopt an optimum amount of retarder based on the temperature and working conditions in order to retain sufficient handling time for the fresh concrete. At the job site having high temperature, site mixing of concrete materials is preferable to the use of *ready-mixed concrete*. The *bleeding* of fresh concrete made with jet cement is insignificant in mixes having slump values lower than 150 mm (used for normal concrete work). Consequently, concrete surface must be finished as soon as possible after placing the concrete.

The concrete made with jet cement shows good strength development at low temperature, and hence is suitable for *winter concreting*. The rate of strength development of jet cement is quite different from that of ordinary Portland cement. The moist curing of concrete at early ages is important, since the concrete cured in dry state immediately after *stripping* yields a lower strength development. The 28-day strength of jet cement concrete is about 20 per cent higher than that of ordinary Portland cement concrete at the same water-cement ratio, and a curing temperature of 20 °C. The ratio of *tensile strength* to *compressive strength* varies from 1/10 to 1/14, and the value is almost the same as that of regular concrete using ordinary Portland cement. *Bond strength* between reinforcing bars and concrete using jet cement is considerably higher than that of ordinary Portland cement concrete. The adhesive strength of concrete construction joints of jet cement concrete is 1.5 to 1.8 times higher than that of regular concrete when the concrete surface is treated carefully.

The jet cement concrete yields high *modulus of elasticity* at early ages. The relationship between the *dynamic modulus of elasticity*, E_d and *compressive strength of concrete* f_{ck} (MPa) is given by the following equations.

Jet cement concrete : $E_d = 8920\, f_{ck}^{0.376}$ MPa

Ordinary Portland cement : $E_d = 11980 f_{ck}^{0.320}$ MPa

When the concrete strengths are same the modulus of elasticity of concrete using jet cement is slightly lower than that of regular concrete because of the *lower specific gravity* of cement.

The jet cement concrete gives lower values of *drying shrinkage* than that of concrete made with ordinary Portland cement. However, the *creep* values are higher at early ages and lesser after two months. The *watertightness* at early ages is considerably higher than that of ordinary Portland cement concrete. This can further be improved by extending *curing period* and by increasing the *cement content.* The rise in the temperature of concrete, caused by hydration of cement, is considerable.

14.13.1 Application of Jet Cement Concrete

Jet cement has been found to be most suitable for urgent repair work, and winter concreting. The cost of this cement is about five times that of ordinary Portland cement.

1. **Building construction** The jet cement concrete can be used for the purpose of urgent building construction at low temperature. The surface should be finished immediately after placing, and concrete slab may be cured under canvas sheets. The column and wall forms may be removed after one day, and slab forms after two days. Since the handling time is short and the slump loss tends to be higher, quick handling is required in construction work.
2. **Concrete pavements** The jet cement concrete may enable the road to be used within hours after placing with little or no curing.

3. **Repair work** The cracks in reinforced concrete piers, and damage in expansion joints in railway or highway bridges may be repaired with jet cement concrete during the period when no train or traffic passes over the bridge. The jet concrete has been used satisfactorily in renewing the concrete pavings on an earth sub-base, repair of machine bases and concrete sleepers in Japan.
4. **Winter concreting** The jet cement has found major applications in winter concreting. At very low temperatures concrete may be cured with heaters to obtain the required strength.
5. **Concrete products** To increase production efficiency by allowing early removal of form or stripping and early transportation, the jet cement can be used for the manufacture of concrete blocks, precast concrete panels, concrete curtain walls, reinforced concrete pipes, etc.
6. **Grouting** Grouting mix consisting of jet cement, water, sand and an admixture may yield a strength of 1.5 to 2.5 MPa at one hour. The grouting may be used in stiffening the construction, consolidation of earth, etc.

14.14 GAP-GRADED CONCRETE

This type of concrete is obtained when a *gap graded aggregate* is used in the production of concrete. In case of gap grading certain undesirable sizes of aggregates are omitted from the conventional *continuous gradings*. The undesirable sizes are those which prevent the efficient packing of the other sizes. Sometimes available *single-sized aggregate* only is used.

The gap-grading is normally aimed at achieving strength from the efficient packing of the aggregate. A well-packed aggregate will require minimum cement paste to fill the *minor voids*. For discussion consider the coarse aggregate to be mathematically modeled as spheres of diameter D called *major spheres*. A multitude of these spheres will have a rhombohedral form of packing. The voids between the major spheres can be fitted with spheres of diameter 0.414 D, known as *major occupational spheres*. The fine aggregate would then mathematically consist of *minor occupational spheres* of diameter 0.225 D which would fit into the remaining voids. The remaining minor voids can now be fitted by *admittance spheres* of diameter 0.155 D, and these could also be provided by the fine aggregate. Cement paste would then occupy the remaining voids and a mathematically perfect compact mix would result. Such a mix, however, cannot be cast in practice and consequently only the major, and admittance spheres are considered to be of practical value in a mix design.

Mixes, therefore, are often designed with *single-sized* aggregate and a sand, all the particles of which can pass through the voids in the compacted coarse aggregate. However, the particles of sand must not be smaller than necessary to restrict the surface area to be coated with cement paste. Irrespective of the calculation suggested above, the sand content should be sufficient to distribute itself uniformly throughout the mix under practical conditions.

The workability can be increased be reducing the surface area of all ingredients in a unit volume. This can be achieved by using largest size aggregate consistent with other constraints.

Gap grading enables leaner and drier mixes than conventional concrete of equivalent strength to be used resulting in lesser *shrinkage*. However, a leaner mix makes the vibration almost essential. Compressive forces on gap-graded concrete are transmitted from particle to particle of the coarse aggregate and not through cement-sand matrix. Consequently the *creep* associated with such concrete is low. Due to the use of single-sized aggregate the *segregation tendency* is checked.

A number of investigators have recommended the use of two single-sized coarse aggregates with sand and cement in a gap-graded mix. Because of efficient packing of aggregates in gap-graded concrete, *vertical shuttering* can often be removed shortly after casting. However, the gap grading is very sensitive to undesirable particles and the mix obtained will be of reduced efficiency.

14.15 NO-FINES CONCRETE

As the name suggests, this concrete does not contain fine aggregate. The coarse aggregate particles have been found to possess a cement paste coating of up to 1.3 mm around them. Hence no-fines concrete contains a multitude of voids which is responsible for its low strength. However, large voids give good *thermal insulation*, and these voids being large enough prevent the movement of water through the concrete by *capillary action*.

The compressive strength of no-fines concrete is considerably lower than that of conventional concrete and depends on the cement content and grading of aggregate. The strength generally varies from 1.5 MPa to 15 MPa. In lean mixes, cement content may be as little as 70 to 130 kg per cubic meter of concrete, this is due to the absence of large surface area of fine aggregate particles which would have otherwise to be coated with cement paste. Thus the cost of no-fines concrete is lower than that of conventional concrete. It does not segregate, hence can be dropped from a considerable height. However, it should be vibrated for a very short period otherwise cement paste would run off.

The water-cement ratio does not seem to be the controlling factor in this case. It varies from 0.38 to 0.52. The density of no-fines concrete depends on grading of aggregate, and with normal aggregate it varies from 1600 to 2000 kg/m^3. *Shrinkage* is generally lower than in the ordinary concrete.

Normally no-fines concrete is not suitable for reinforced concrete work. However, due to good thermal insulation, no-fines concrete walls have been used in cold countries for housing. It has been found that rain beating on a wall penetrates only a short horizontal distance before falling down to the bottom of the wall, there being no capillary paths to conduct the water completely through it. It is, however, often desirable to paint exposed no-fines concrete walls. High absorption of water makes no-fines concrete unsuitable for use in foundation and in situations where it may be in contact with water.

14.16 HIGH DENSITY CONCRETE

Concrete having unit weight of 30 kN/m^3 to 64 kN/m^3 is called high density or heavy weight concrete. Thus the unit weight of high density concrete is more than about 25 per cent higher than that of conventional concrete which is in the range of

24kN/m³. High density concrete can be produced by using different types of *heavy weight aggregates*.

High density concrete is used for construction of nuclear radiation shield walls, ballast blocks, counterweights, sea walls and other applications where high density is important. As a shielding material, high-density concrete protects the users against the biological hazards of penetrating radiaion from nuclear reactors, production facility of radioactive materials, particle accelerator, industrial radiography, and X-ray and gamma-ray therapy. The shielding against biological hazards of radiation mainly involves protection against X- and gamma rays, and neutrons. For the shielding to be effective radiations must be attenuated sufficiently so that they do not damage the body cells of the user exposed to it. In addition to the biological hazards, nuclear reaction also generates very high temperature (resulting in cracks on outer face of concrete) necessitating shielding to protect the electronic and other sensitive equipment in the vicinity.

Selection of concrete for radiation shielding is based on space requirements, and on the type and intensity of radiation. Where there are no space restrictions, normal-density high-performance concrete will generally provide the most economical shield; where space is limited, high-density concrete will allow for reductions in shield thickness without sacrificing shielding effectiveness.

14.16.1 High-Density Aggregates

As discussed earlier in Section 3.2.4, high-density aggregates such as baryte, ferrophosphorus, goethite, hematite, limonite, magnetite, and de-greased scrap steel and steel shot having specific gravities ranging from 3.4 to 7.8 are used to produce high-density concrete with a unit weight of about 30 to 60 kN/m^3.

14.16.2 Properties of High-Density Concrete

As in the case of normal-weight concrete, the properties of high-density concrete in both the freshly mixed and hardened states can be tailored to meet the application requirements by proper selection of materials and mixture proportions. Except for density, the physical properties of high-density concrete are similar to those of normal weight concrete. As usual, strength is a function of the water-cementing materials ratio; thus, for any particular set of materials, strengths comparable to those of normal weight concretes can be achieved.

As in the case of conventional concrete, high modulus of elasticity, low thermal expansion and low elastic and creep deformations are the desirable properties high weight concrete. High-density concrete may contain higher cement content; in that case it may exhibit increased creep and shrinkage. When only smooth cubical pieces of steel or iron are used as coarse aggregate, the compressive strength may not exceed about 21 MPa, regardless of the grout mixture or water-to-cement ratio. If the pieces of sheared reinforcing bars are used as aggregate, with good grout, normal strength may be produced. The grout used in *high-density preplaced aggregate concrete* should be somewhat richer than that used in normal-density preplaced concrete. Typical densities of concretes made with some commonly used high-density aggregates are given in Table 14.12.

Table 14.12 *Densities of typical high-density aggregates and concrete (Adopted from PCA)*

Type of aggregate	Specific gravity	Bulk density, (kg/m^3)	Concrete density, (kg/m^3)
Goethite	3.4–3.7	2080–2240	2880–3200
Limonite*	3.4–4.0	2080–2400	2880–3360
Barite	4.0–4.6	2320–2560	3360–3680
Hematite	4.9–5.3	2880–3200	3850–4170
Magnetite	4.2–5.2	2400–3040	3360–4170
Ferro-phosphorus	5.8–6.8	3200–4160	4080–5290
Scrap steel	6.2–7.8	3860–4650	4650–6090

*Water retained or chemically bound in aggregates per cent (by mass): Goethite (10–11), Limonite (8–9), Ferro-phosphorus (0) and Steel scrap (0). The aggregates may be combined with limonite to produce fixed-water contents varying from about 0.5 to 5 per cent.

14.16.3 Proportioning, Mixing, and Placing

The procedures for selecting mix proportions for high-density concrete are the same as those for normal-density concrete. The cement-aggregate ratio generally varies from 1:5 to 1:9 with a *water-to-cement ratio* from 0.5 to 0.65. They produce dense and crack-free concrete. The following are the most common methods of mixing and placing high-density concrete:

Conventional concreting practice with respect to mixing, transporting, placing as adopted for normal concrete may also be adopted to heavy-weight concrete but care must be taken to avoid overloading the mixer, especially with very high-density aggregates such as scrap steel and shots. Batch sizes should be reduced to about 50 per cent of the rated mixer capacity. Because some high-density aggregates are quite friable, excessive mixing should be *avoided to* prevent aggregate breakup with resultant detrimental effects on workability and bleeding. To prevent segregation of heavier aggregates from the rest of the ingredients, a higher cement content may be required; better workability may help reducing segregation. Wear and tear of the mixer drum may be high. The formwork is required to be made stronger to withstand higher load.

Preplaced aggregate methods of concreting can be used for placing high-density concrete in confined areas and around embedded items; this will minimize segregation of heavy-density coarse aggregate, especially scrap steel. The method also reduces drying shrinkage and produces concrete of uniform density and composition. With this method, the coarse aggregates are preplaced in the forms and grout made of cementing material and sand, and water is then pumped through pipes to fill the voids aggregate.

Pumping of high-density concrete through pipelines may be advantageous in locations where space is limited, but high-density concretes cannot be pumped as far as normal-density concretes because of their higher densities.

Puddling is a method whereby a 50-mm or more layer of mortar is placed in the forms and then covered with a layer of coarse aggregate that is rodded or internally vibrated into the mortar. Care must be taken to ensure uniform-distribution of aggregate throughout the concrete.

14.17 NUCLEAR CONCRETE

Due to its excellent characteristics for neutron and gamma-ray attenuation, the ease of construction and a relatively low initial as well as maintenance costs, make concrete a most suitable material for radiation shielding. The concrete primarily used for radiation shielding may be called *nuclear concrete*. To design nuclear concrete for effective radiation shielding, it is desirable to understand the types of radiation and the resulting hazards. The general types of radiation considered in the design of biological shields are *electromagnetic waves* and *nuclear particles*. In the electromagnetic-waves category, the high-energy, high-frequency waves known, as X- and gamma-rays are the only ones that require shielding for the users. These waves are similar to light rays but have higher energy with greater penetrating power. Although both X-rays and gamma-rays are highly penetrating, they can be adequately absorbed by an appropriate thickness of specially constructed nuclear concrete shield.

Nuclear particles, on the other hand, include neutrons, protons, alpha and beta particles of the nuclei of atoms. Of all these, the neutrons are uncharged and continue unaffected by electrical fields, until they collide with a nucleus. On the other hand, protons, and alpha and beta particles carry electrical charges which interact with the electrical field surrounding the atom of the shielding material, and they lose their energy considerably. Though the accelerated protons at high energy levels are most penetrating, their energy is eventually degraded or is lost in the process that creates additional particles, and thus they do not constitute a separate shielding problem.

The type and intensity of radiation usually determine the requirements for density and water content of shielding concrete. The effectiveness of a concrete shield against gamma rays is approximately proportional to the density of the concrete, i.e., the higher the density, the more effective the shield in absorbing neutrons by inelastic collisions or scattering. On the other hand, an effective shield against neutron radiation requires both high and low atomic weight elements. The hydrogen in water provides an effective light atomic weight material in concrete shields to slow down fast neutrons. Some aggregates contain crystallized water, called fixed water, as a part of their structure. For this reason, high-density aggregates with high fixed-water contents often are used if both gamma rays and neutron radiation are to be attenuated. This can be accomplished by the use of *hydrous ores*. These materials contain a high percentage of water of hydration. On heating the concrete, some of this fixed water in the aggregate may be lost. Lemonite and goethite are reliable sources of hydrogen as long as the shield temperature does not exceed 200°C. Serpentine aggregates may be used, because of their ability to retain water of crystallization at an elevated temperature of up to about 400°C. This assures a source of hydrogen, which is not necessarily available in all heavy weight aggregates. Boron glass (boron frit) is also added to neutrons.

14.17.1 Additions

At times materials such as colemanite, boron glass (boron frits), and borocalcite are added to improve the neutron attenuation properties of concrete. However, they may adversely affect the setting and early strength of concrete; therefore, trial mixes should be made under field conditions to determine the suitability of the addition. Admixtures such as pressure-hydrated lime can be used with coarse sand sizes to minimize any retarding effect.

14.17.2 Radiation Shielding

Radiation shielding walls are constructed to prevent radiation in the user areas. As discussed above the major contribution to the environmental radiation is due to neutrons. However, neutrons can be stopped by inelastic collision or scattering and absorption in thick materials like high-density concrete composed of cement, water and typically iron ore substituting the sand and gravel. The non-magnetic coarse and fine haematite (fe_2O_3) aggregate with an iron content of more than 60 per cent and water (which is stabilized in to the mix as the cement is hydrated) are most effective in nuclear shielding. The iron nuclei lowers the neutron energy spectrum by inelastic scattering at energies above 1 m eV, while the hydrogen nuclei (from water) further degrades the energy and ultimately absorbs neutron with wall thickness that increases inversely with square root of energy below several eV. The nuclear shielding effect of the high-density concrete can be improved by using artificially enriched iron oxide pellets manufactured from haematite ore (iron content 30–35 per cent) for the steel-making industry as aggregate. The high strength and somewhat lower density (due to increased porosity with connected pores of typical size from 1–10 microns) will help improve the nuclear shielding of high-density concrete. The cured normal concrete contains about five per cent water, whereas enriched iron oxide pellets as aggregate can hold much more water which helps in neutron attenuation. The nuclear shielding of concrete mixture can further be improved by impregnating it with a good neutron absorber.

14.18 HEAT RESISTING AND REFRACTORY CONCRETES

One of the advantages of concrete is that it is non-combustibl, i.e., it neither burns nor supports combustion, so it can be used wherever non-combustible construction is permitted. Any concrete which does not disintegrate when exposed to constant or cyclic heating at the temperature below which a *ceramic bond* is formed is called *heat resistant concrete*. As Portland cement is not suitable for this application, the heat resistant concretes are normally composed of hydraulic cement (calcium aluminate cement) as a binding agent combined with heat resistant, refractory aggregates and or fillers.

There is a more or less continuous spectrum of high temperature resistant concretes, extending from 300–400 °C (the limit of concretes bound with Portland cements) to 2000 °C or more, using high range calcium aluminate cements (CAC) containing 80 per cent alumina. Somewhat arbitrarily, the boundary between *heat-resistant* and *refractory concretes* is taken as 1000 °C, although some definitions start refractory concretes from 1500 °C.

14.18.1 Fire Rating

As discussed in Section 8.11, a fire rating, or more correctly fire resistance rating as used in building codes, refers to the ability of concrete to withstand fire or to provide protection from fire. As defined in the 2000 edition of the International Building Code (IBC-2000), fire resistance rating means the period of time (in hours) a building or building component retains the ability to confine a fire or continues to perform a given structural function or both, as determined by prescribed tests.

14.18.2 Materials for Heat Resistant Concrete

Binding Material The behavior of Portland cement concretes subjected to high temperatures is complex. If the concrete is dry or the heat is applied slowly, relatively little permanent damage is done with concrete temperatures up to 200 to 250°C. At concrete temperatures of about 500°C, hydrated lime $Ca(OH)_2$ which forms a significant portion of the hydrated Portland cement loses water to form quicklime (CaO):

$$Ca(OH)_2 \Leftrightarrow CaO + H_2O$$

This reaction is reversible. At concrete temperatures of about 540°C compressive strength loss can be 55 to 80 per cent of the original strength. At the time of heating, the degree of saturation of the concrete influences the severity of strength loss; and repetitions of heating and cooling cycles further degrade the concrete. The moisture present in the atmosphere leads to rehydration of quicklime which is an expansive reaction resulting in disruption of concrete. Thus OPC is not suitable for the application which involves cyclic heating to high temperatures and then cooling to ambient temperatures.

Furthermore, near the service temperature of concrete, the silica and lime present in the Portland cement undergo a chemical change to form a low melting point compound. Thus ordinary Portland cement has limited use at high temperatures.

On the other hand, calcium aluminate cement (CAC) hydrates do not contain hydrated lime and thus are not subjected to disruption caused by rehydration of quicklime. The progressive dehydration of CAC hydrates with increasing temperatures above 300 °C forms stable compounds. These compounds at still higher temperatures (>1000 °C) react with refractory aggregates to form new stable phases.

The higher the alumina contents in CAC, the more refractory the concrete. The refractoriness can be further extended by adding free alumina to 70 per cent Al_2O_3 CAC to increase the alumina contents to 80 per cent. This is generally the upper limit of alumina contents in modern CACs.

Generally, grey CAC with 39 per cent alumina will have sufficient temperature resistance for most heat-resisting applications up to 1000 °C. In refractory concretes, the higher refractoriness of the aggregate will extend the temperature range of the CAC.

Aggregates for Heat Resistant Concrete Fire resistance of concrete is influenced by aggregate type, moisture content, density, permeability and thickness. Dolomite and limestone aggregates called *carbonate aggregates* which consist of calcium or magnesium carbonate or combinations of the two, calcine during exposure to high temperatures, i.e., carbon dioxide is driven off and calcium (or magnesium) oxide remains intact. Since calcining requires heat, the reaction absorbs some of the heat generated by the fire. The reaction begins at the fire-exposed surface and slowly progresses toward the opposite face. Thus, carbonate aggregates behave somewhat better than other normal-weight aggregates in a fire.

Moisture content has a complex influence on behavior of concrete in fire. Concrete that has not been allowed to dry may spall, particularly if the concrete is impermeable, such as concretes made with silica fume or latex, or if it has an extremely low water-cement ratio. Concretes that are more permeable will generally perform satisfactorily, particularly if they are partially dry.

In general, dried lightweight concrete performs better in fire than normal-weight concrete. The thicker or massive the concrete, the better will be its behavior when exposed to fire. lightweight concretes and carbonate aggregates are suitable for heat resisting and refractory concretes. Thus, reduction in lime content and increase alumina content in cement are the keys to high performance of concrete at high temperatures.

Thermal insulation The thermal insulating properties of the concretes are primarily associated with their density which is mainly controlled by the density of aggregate. The density of lightweight aggregates varies from extremely light, e.g., Perlite: bulk density 1.0 to 1.1 kN/m^3 to moderately light, e.g., sintered PFA or expanded clay: bulk density 6 to 8 kN/m^3. The insulating properties (thermal conductivity) of concretes made with these aggregates will be in the range 0.15–0.5 W/m°K as shown in Fig. 14.26.

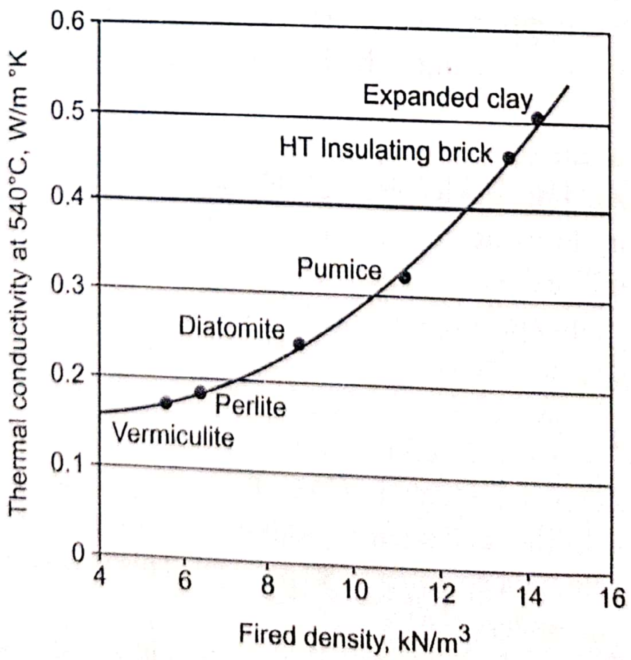


Fig. 14.26 *Relationship between fired density and thermal conductivity of heat resisting concretes at about 540°C*

Concrete Mixes for Heat Resistant Concrete Refractory concrete mixtures consist of suitably graded aggregates and hydraulic cements in proportions formulated to achieve certain desired properties for the particular end use. As explained earlier in Section 14.8.6, among the aggregates used in increasing order of service temperatures are slag, limestone, expanded-shale, calcined fireclay, perlite, vermiculite, etc.

Aluminum powder is quite often used in refractory concrete either to minimize explosive spalling during castable de-watering or to inhibit the oxidation of coke/graphite at high temperatures in carbon-containing materials. In the first case, the aluminum powder is expected to increase the permeability of castables by generating H_2 gas during reaction with H_2O and forming open porosity within the microstructure. In the latter application, on the other hand, it is desirable that a minimum amount of aluminum reacts with H_2O during castable processing, so that most of the metal remains in the microstructure to prevent carbon oxidation.

Ingredients for typical example mix River gravel or crushed fire bricks, sand, calcium aluminate cement, and water. A small amount of standard fireclay can be added.

For normal heat resistant concretes, half the cement may be replaced with the hydraulic lime and fireclay can also be added. The cement holds the mixture together when it is drying but when the heat gets into the cement and burns it out, the lime holds it all together.

A typical mixture (by volume) for heat resistant concrete is 1: 1: 1.5 + 0.25 lime + water

14.18.3 Placing and Compaction

The methods used are identical to those used for conventional concrete, thus no specialist equipment or skills are required. However, as explained in Section 14.8.6, refractory shotcreting or gunning is commonly undertaken in special circumstances.

14.18.4 Curing, Drying, and Firing

The curing is of utmost importance, and the methods of curing are similar to those for conventional concrete. However, due to rapid hardening and high heat evolution of CAC concretes, it is important to start curing three–four hours after placing and continued until at least for 24 hours to achieve complete hydration and to control drying shrinkage. The curing may be done by spraying the concrete with a fine spray of water and covering with plastic sheeting to prevent rapid loss of water on edges and the surface. After 24 hours, remove coverings and let the air dry the concrete without strong sun for 48 hours.

The free water left in green or unfired concrete after curing must be allowed to escape at the start of heating to prevent spalling. Natural or forced drying at up to 100°C is generally used to drive off as much free water as possible before exposure to higher temperatures.

After drying, the concrete is heated gradually from 100°C to 350°C, to drive off the combined water or water of hydration from the concrete. The heating cycle varies with the application, thickness and type of the concrete product. However, for conventional castables, generally the temperature may be raised at the rate not exceeding 25°C per hour to 500°C with a hold of 12 hours at this temperature. After the hold the temperature continues to be raised at a slightly higher rate to the service temperature. For thick sections (>100 mm) a hold at different temperatures is advisable. Hold at a temperature is for the period until the heat balance through the material is established to obtain the ultimate ceramic bond. Heat-up is to be continuous and uninterrupted. All temperatures are to be measured at the surface face of the refractory. Cooling should not exceed a rate of 35°C per hour.

Properties Usually refractory concretes exhibit cracks after first firing. These cracks are due to dehydration shrinkage and ceramic reaction between the cement and aggregate at high temperatures. In normal service conditions, these cracks will close down when concrete is reheated to its service temperature due to thermal expansion.

14.18.5 Applications of Heat Resisting Concrete

In addition to structural applications, heat resistant concrete is commonly used in runway pavements. Concrete pavement exposed to high temperatures from an aircraft jet blast or from auxiliary power units can suffer damage. If the concrete is wet when the heat is suddenly applied, the production of steam within the concrete can cause spalling. Typical concrete pavement damage resulting from high temperatures of jet blast includes spalling, aggregate popouts, scaling, cracking, and loss of joint sealant. The time that the concrete is exposed to the jet engine or auxiliary power unit exhaust is critical. Since there is considerable thermal lag in concrete, properly designed pavements generally do not suffer heat damage from aircraft.

14.18.6 Applications of Refractory Concretes

Refractory concretes are subjected to high temperatures, thermal and mechanical stresses, chemical and abrasive attacks. They are normally designed for specific applications predominately in the metal industry, but are also used extensively in the chemical, cement and glass industries. Refractory concretes rely on a complicated mix of aggregate and binder, the most common binder being High Alumina Cement (HAC). Aggregates used vary depending on the intended application. Refractories come in two general types: preformed and monolithics. Preformed includes bricks and large-scale monoliths shown in Fig. 14.27. Monolithics are generally obtained as shotcrete or gun mixes and castables used as linings and coatings normally fired in situ. Typical heat resistant products are shown in Fig. 14.27.

Refractory concrete sheets also have the potential for use as heat resistant wall claddings and decorations. Manufacture of thin sheets of refractory concrete may not suffer from any of the difficulties associated with fired clay thin sheets even when cast in large size with only 6 mm thickness. The fire clay thin sheets are:

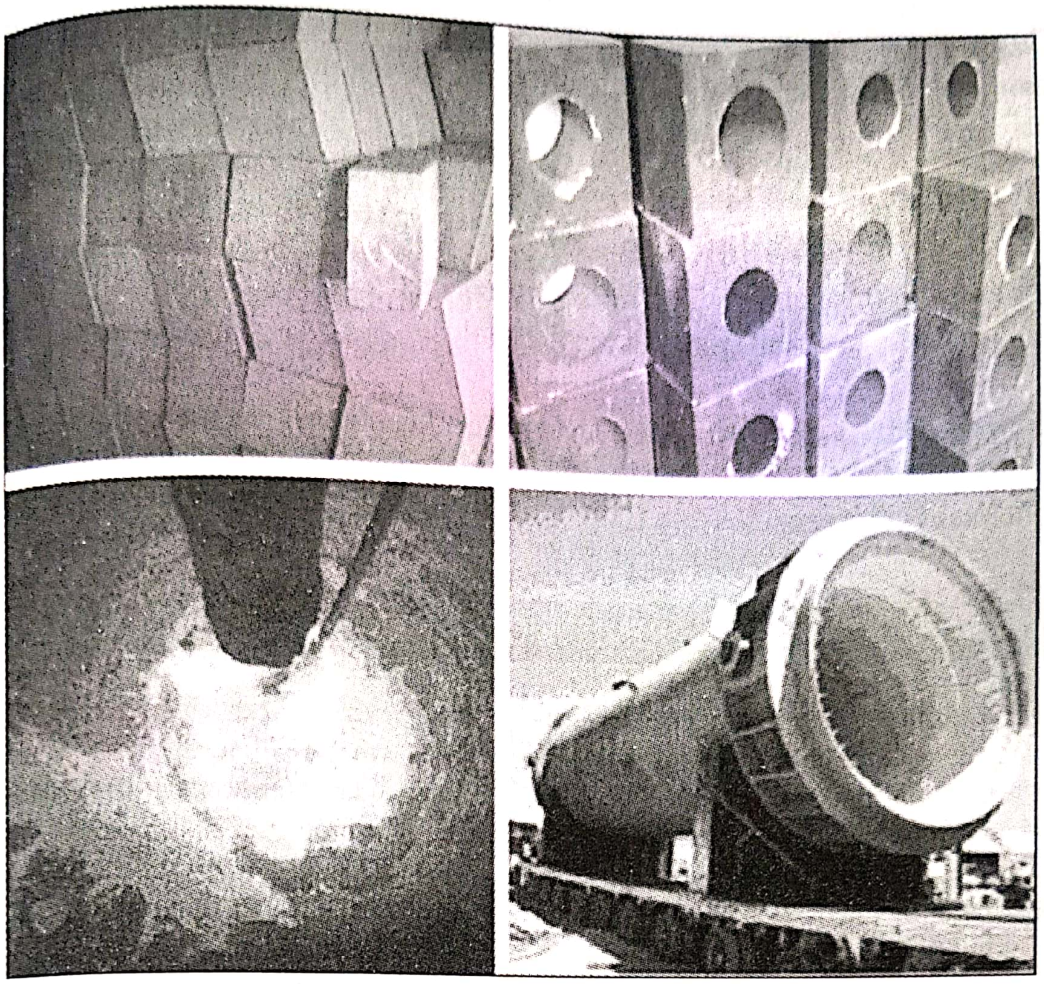


Fig. 14.27 Different refractory concretes products

1. Liable to warp during drying
2. Brittle and delicate prior to firing
3. Liable to further warping during firing and often require a support structure

14.18.7 Advantages of Heat Resistant Concretes

Shrinkage The refractory concretes do not warp during drying and firing, as they will set with a chemical reaction, which is subsequently sintered to create ceramic bonds.

Green Strength Because refractory concrete has a similar strength to conventional concrete even before it has been fired, it can be maneuvered far more easily than large fragile clay pieces.

Fired Strength and Toughness Once fired, refractory concretes are substantially harder than conventional concrete and are generally tougher than ceramics due to the aggregate's ability to arrest crack propagation.

Drying Time Once set, they require a short drying cycle to drive off any free water. In addition, the high alumina cement used as a binder in many refractory concretes has a far shorter setting time than conventional Portland cement.

Thermal Shock Refractory concretes are specifically engineered to cope with rapid and substantial changes in temperature during normal industrial application, therefore fast firing is needed.

14.18.8 Disadvantages

Reduced Workability The refractory concretes cannot be molded in the same way as plastic clay and therefore require molds.

Limited Glaze Compatibility The chemical composition of refractory concretes is different from clay bodies and therefore the interaction between glaze and refractory concretes is different.