CIVL482

ADVANCED MATERIALS OF

CONSTRUCTION

(AREA ELECTIVE)
LECTURE NOTES

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CONTENTS

1. REFRACTORIES

1.1 Refractory

Description of any material that resists heat. Refractory Concrete can withstand temperature from 300°C to 1300°C. They fail usually because they begin to shrink at some 80°C below softening point of the aggregate.

1.2 Refractory Linings

Bricks and rocks that are hard to melt and therefore used for lining furnaces. Service temperature limits are controlled more often by the aggregate than by the cement. High Alumina Cement (HAC) can withstand 1200°C (but concrete made from it with silica gravel and sand should not be used at temperatures above 300°C), limestone 500°C, and blast-furnace slag (dense or foamed) brick or calcined diatomite (B), 800°C; some igneous rocks, including basalt, dolomite and pumice, as well as expanded clay aggregate, will resist at least 1000°C, dead-burned magnesite 1400°C; bauxite 1500°C, and chromite 1600°C.

A Refractory lining material low in silica content, used for metallurgical furnace linings. It contains metal oxides like lime (CaO), magnesia (MgO), or calcined dolomite, a mixture of two.

1.2.1 Bauxite

Is the most important ore of Aluminium, $Al_2O_3.2H_2O$, named after Les Baux in Provence. It does not fuse below 1600°C. It is used as a refractory, and as the raw material for bridge decks after 1945.

1.2.2 Calcium Aluminate

The refractory part of H.A.C. consists of various calcium aluminates, some of them being even more refractory than monocalcium aluminate, which is white and melts at 1608°C.

1.2.3 Carborundum

A trade name for silicon carbide, a refractory and abrasive which is harder than quartz. It can be used at temperatures up to 2500°C.

1.3 Silica Bricks

Refractory brick which contains over 90% silica, and being bonded with lime will stand temperatures from 1650 to 1750°C before it softens.

1.4 Zirconia (ZiO$_2$)

Zirconium oxide, a refractory which can be used at very high temperatures.

2. GLASS

2.1 Introduction

Raw materials of glass are plentiful and cheap, and glass has high abrasion-resistance, light-transmission properties and resistance to weathering or chemical attack. Ordinary glass is based on silica or sand (silicon oxide (SiO_2)), which in crystalline form.

Although silica forms the basic network of glass, it is not used in the pure form because its melting point is too high (1700°C). Instead, the silica network is modified by compounds such as sodium carbonate (Na_2CO_3), which at high temperatures, decomposes to sodium oxide and then combines with part of the silica, forming sodium disilicate, thereby interrupting some of the rigid silicon-oxygen links.

Hence 'soda-glass', as the material is known, melts at a much lower temperature (800°C). Unfortunately soda-glass is water soluble and calcium carbonate ($CaCO_3$) is added to stabilize the glass.

The approximately composition of the raw materials for a typical soda-lime glass is;

SiO_2 (silicone oxide): 75%

Na_2CO_3 (sodium carbonate): 15%

$CaCO_3$ (calcium carbonate-limestone): 10%

Smaller amounts of other materials such as "Manganese dioxide", lead or borax can be added.

Manganese Dioxide: To remove coloration due to iron in the sand.

Lead: To produce high density glass resistant to X-rays.

Borax: To produce glass having low thermal movement-resistant to thermal **shocks**.

2.2 Manufacture Of Glass

The raw materials are mixed, in the correct proportions, with a quantity of scrap glass "cullet", and heated to about 1500 °C. The cullet melts first and permits reaction and fusion of the remaining ingredients at temperatures below the melting point of pure silica.

The liquid is then cooled to a temperature of 1000-1200 ^{o}C, at which its viscosity is sufficiently high for foaming. The most important processes are as follows:

1) The Flat-drawn process: The glass is drawn upwards on a metal grille known as a "BAIT", the sheet engaging with rollers which prevent its waisting.

2) Rolled Glass: The glass is drawn off in a horizontal ribbon on rollers and is then annealed (allow to cool slowly). Such glasses do not give clear vision but can be given textured or patterned finishes, allowing high transmission but giving some privacy when used in glazed doors or partitions. Wire may be incorporated against injury from impact.

3) Float Glass: This glass is optically flat and is produced by drawing it, while still soft, along the surface of molten tin in a bath. It is now used for general glazing purposes, as well as mirrors, shop windows and other situations where clear, undistorted vision is essential.

2.3 Strength Of Glass

An indication of maximun tensile strength is obtained by tests on very thin glass fibers which are sensible free of flaws and are found to withstand stresses of up to 3000 MPa. Strength reduces on aging, as surface imperfections increase, whether by chemical attack or simply mechanical abrasion; glass which has weathered for some years being much weaker than new glass.

2.4 Toughened Glass

The surface flaws in glass can be removed chemically but toughening can be carried out more simply by heat treatment. Sheet glass is heated uniformly until just plastic and then cooled by air jets. The outers layers contract and solidify and then, as inner layers try to follow, they throw the outer layers into compression, tending to close the microscopic cracks.

In this way, the overall strength of the glass can be increased several times and impact strength may increase sevenfold.

2.5 Laminated Glass

This provides a high degree of resistance to injury from flying glass in case of impact. In its simplest form, two sheets of glass are bonded with a thin film of plastic such as polyvinyl **butynate**, under pressure at a temperature of about 100°C. This glass absorbs energy in impacts but, most importantly, stops glass shattering and disintegrating. Higher levels of impact resistance can be produced by increasing the number of glass/plastic laminates; bullet-and missile-proof glazing are made in this way.

2.6 Thickness & Weight

The thickness of glass for ordinary glazing should increase with wind load and glass area. Square sheets should be thicker in general than rectangular sheets since, for a given area, there is less restraint at the center of a square sheet of glass.

In many cases, it will, nevertheless, be more economic to supply glass of uniform thickness to withstand the most demanding situation in a given building, since this simplifies supply, installation and future replacement.

2.7 Thermal Properties Of Glass

1) Solar Heat Gain

Plain glass transmits some ultraviolet, light and is quite transparent to visible and infra red light of wavelength up to about 3 μm. Hence, most energy in the sun's rays is transmitted by ordinary glass, causing warming of internal surfaces.

In order to control solar energy, the followings can be done;

a) use, tinted, heat-absorbent types of glass (colorful glasses) 50% of heat can be absorbed.

b) Heat-reflecting glass can be achieved by thin metallic surface coatings, usually applied to the inner face of the outer glass sheet in sheet double glazing, for protection, though they can also be used for single glazing about 40% of the heat is reflected in this case.

2) Heat Losses from Glass: (U value, W/m^2 ^{o}C)

When solar radiation is reduced, as in winter, the heat flow in glass can reverse quite dramatically. Double glazing operates by providing double the number of glass/air interfaces.

2.8 Fire Performance

Ordinary glass has a poor performance in fire due to its tendency to shatter when heated. A period of 60 minutes stability can be achieved by use of wired glass.

2.9 Sound Insulation

The sound-reduction properties of glazing are typical of those of a thin panel or membrane.

In double glazing the cavity size required for effective sound reduction is about 200 mm, much larger than that for best thermal insulation properties. To be satisfactory, it is extremely important that air paths through glazing should be prevented.

Table 2.1 Glazing effect on noise reduction.

Type & thickness of glazing	Reduction (dB)
3 mm single glazing	20
12 mm single glazing	22
3 mm and 4 mm double glazing window with absorbent in 200 mm cavity	31

Table 2.2 Decibel levels of common sounds

Decibels	Sound	Effect
120	Thunder, artillery	
110	Nearby riveter	Defeaning
	Elevated train	
100	Boiler factory	
	Loud street noise	
90	Noisy factory	Very loud
	Truck (unmuffled)	
80	Police siren	
	Noisy office	
70	Average street noise	Loud
	Average radio	
60	Average factory	
	Noisy home	
50	Average office	Moderate
	Average conversation	
40	Quiet radio	
	Quiet home	
30	Private office	Faint
	Average auditorium	
20	Quiet conversation	
	Rustle of leaves	
10	Whisper	Very faint
	Soundproof room	
0	Threshold of audibility	

3. LIGHTWEIGHT AGGREGATES (L.W.A.)

3.1 Introduction

The lightweight aggregate (any aggregate with bulk density less than 1120 kg/m^3) is used as a raw material in the manufacture of lightweight concrete. It is also used in the production of lightweight masonry blocks to improve thermal, insulating, and nailing characteristics of these building materials. There are two types of lightweight aggregate:

1. Natural L.W.A.
2. Manufactured L.W.A.

3.1.1 Natural L.W.A.

Consists of particles derived from natural rocks, primarily those of volcanic origin.

3.1.2 Manufactured L.W.A.

It is produced by expanding some raw materials in a rotary kiln, on a sintering grate, or by mixing them with water. The most common lightweight aggregates are pumice, scoria, expanded shale, expanded clay, expanded slate, expanded perlite, expanded slag and vermiculite.

a) *PUMICE (Volcanic glass)*

The most widely used natural L.W.A. is usually whitish gray to yellow in color but may also be brown red or black. It is porous in structure.

EXPANDING: Materials are passed through a rotary kiln at about 1090°C. Gasses within the material expand, forming thousands of tiny air cells within the mass.

b) *SCORIA*

It is also of volcanic origin, resembles industrial cinders and is usually red to black in color. (Cinders are residues from high-temperature combustion of coal in industrial furnaces). The pores in scoria are larger than those of pumice and more or less spherical shape.

c) *EXPANDED PERLITE*

It is an aggregate derived from crushing perlite and then expanding the resulting particles in a kiln by driving the water out. It is used to replace natural sand in lightweight

concrete manufacture and has very good insulating properties. Concrete made with this aggregate has limited strength as well as high shrinkage.

Perlite is also used in the manufacture of cement mortar.

d) VERMICULITE

It is a type of mica, and also used in the manufacture of lightweight concrete. It is produced by heating the raw material until it expands up to 20 times its original volume. It is too soft and weak a material to be used in concrete that requires strength, but is used in plaster as a replacement for sand. The bulk density of vermiculite is 64 to 192 kg/m^3 which is nearly same as that of perlite.

Concrete made with vermiculate or perlite has low compressive strength and high shrinkage, but excellent insulating properties.

e) BLAST FURNACE SLAG

It is a nonmetallic product consisting of (essentially) silicates and aluminates of calcium (lime) and other bases that is developed in a molten condition simultaneously with iron in a blast furnace. EXPANDED SLAG is produced by expanding blast furnace slag mixed with water while still molten. The violent reaction between the molten slag and the water creates aggregate particles that are porous in structure. They are hard and possess considerable strength, but their use in structural concrete is limited because of their high sulfur content.

f) EXPANDED SHALE, CLAY, and SLATE

These aggregates belong in the manufactured lightweight aggregate category, and are produced by crushing the raw materials and heating them to 1350ºC, when they become soft and expand (up to 600 to 700% of original volume) because of entrapped gasses.

3.2 Nailable Concrete

Some lightweight aggregates are also used to manufacture NAILABLE CONCRETE. Sawdust, expanded slag, pumice, and scoria are some of the most commonly used aggregates in the production of nailable concrete. It is made by mixing;

Cement + sand + sawdust + L.W.A. + water

When sawdust is used it should have particles of sizes 1.9 to 2.5 mm, be free of tannic acid (note that tannic acid or tannin and sugar will retard the setting of cement). Pine sawdust, which contain little or no tannin, are good aggregates.

Various methods of processing sawdust include pretreatment with lime and calcium chloride, aging for periods up to one year, and presoaking for 5 minutes to 24 hours and washing. This processing period is usually followed by a drying period.

SAWDUST concrete is used for floor finishes and in the manufacture of precast floor tiles.

Type	Bulk Density (kg/m^3)
Expanded Perlite	240
Pumice	480
Expanded Clay, Slate, Shale	800

3.3 Possible Problems Related to LWA

Some of the L.W.A., especially the fine portions of crushed aggregates, have highly angular, unfavorable particle shape. This has harmful effects on;

1. Workability
2. Finishing
3. Bleeding

on concrete.

These can be reduced by AIR-ENTRAINMENT (up to 10%), increased cement content, use of mineral admixtures, or partial substitution of fine, light particles by normal-weight concrete sand or that recommended for masonry mortar.

SEGREGATION

The lighter bulk specific gravity of the aggregate can also cause problems because it can produce segragation of the coarse particles from the concrete mass during mixing, shipping, placing, and compaction.

For instance, during the vibration of freshly mixed concrete, the coarse particles have a tendency to move upward. The danger of segregation can be reduced by careful proportioning and by proper handling of the fresh concrete.

ABSORPTION

High absorption value and the high rate of absorption of most L.W.A. can also be a problem if not checked frequently and counter balanced in the proportioning.

The high water absorption can be a problem in connection with the frost resistance of L.W.A. concretes.

4. FIBER REINFORCED CONCRETE

4.1 Introduction

Concrete made with hydraulic cement, containing fine or fine and coarse aggregate, and discontinuous discrete (seperate) fibers is called Fiber Reinforced Concrete (F.R.C.).

These fibers can be made from natural material (asbestos, sisal, cellulose) or are a manufactured product such as glass, steel, carbon, and polymer (polypropylene, kevlar).

4.2 Stress strain behavior of FRC

The purposes of reinforcing the cement-based matrix with fibers are to increase the tensile strength by delaying the growth of cracks, and to increase the toughness (total energy absorbed prior to total separation of the specimen) by transmitting stress across a cracked section so that much larger deformation is possible beyond the peak stress than without fiber reinforcement.

Figure 8.1 demonstrates the enhanced strength and toughness of F.R.C. in flexure.
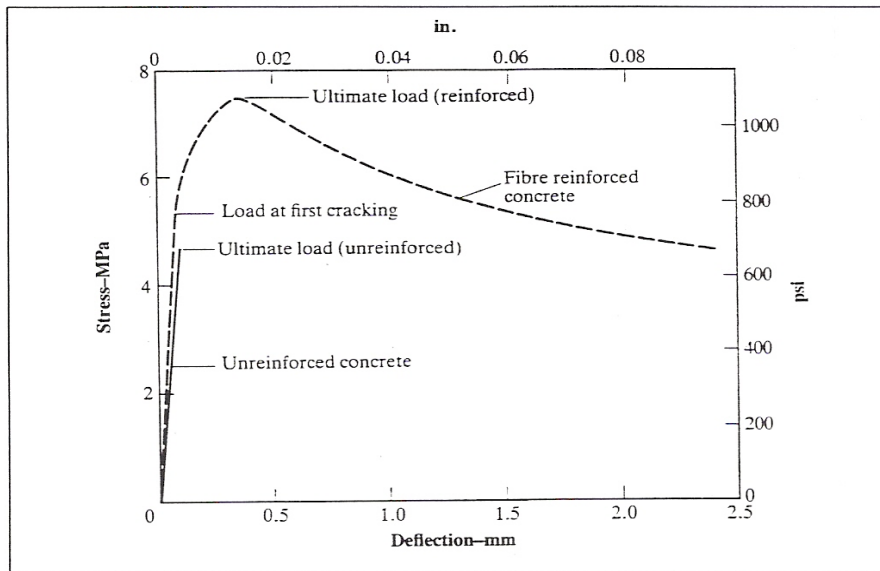
Figure 4.1 Stress-strain curves of FRC and unreinforced concrete

Figure 4.2 illustrates the enhanced toughness in compression, the compression strength not being affected.
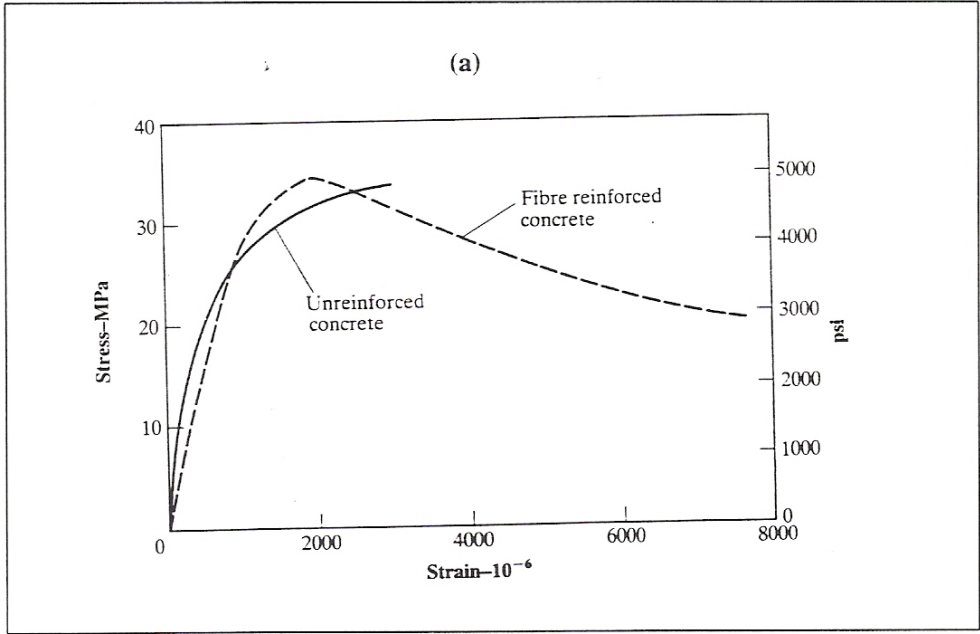
Figure 4.2 Toughness in compression.

Fiber reinforcement improves impact strength, and fatigue strength, also reduces shrinkage.

4.3 Amount of fibers in concrete

The quantity of fibers used is small, typically 1 to 5% by volume, and to render then effective as reinforcement the tensile strength, elongation at failure and modulus of elasticity of the fibers need to be substantially higher than the corresponding properties of the matrix.

Table 4.1 Typical values for fibers

Type of fiber	Specific Gravity	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at failure %	Poisson's Ratio
Asbestos	2,55	3-4,5	164	3	0,3
Alkali-resistant Glass	2,71	2-2,8	80	2-3	0,22
Fibrillated Polypropylene	0,91	0,65	8	8	0,29-0,46
Steel	7,84	1-3,2	200	3-4	0,30
Carbon	1,74-1,99	1,4-3,2	250-450	0,4-1	0,2-0,4
Kevlar	1,45	3,6	65-130	2-4	0,32

Morever, fibers should exhibit very low creep. Otherwise, stress relaxation will occur. Poisson's ratio should be similar to that of the matrix to avoid induced lateral stresses; any large lateral stress may affect the interfacial bond which must have a shear strength large enough to allow the transfer of axial stress from the matrix to the fibers.

4.4 Characteristics of FRC

Some other significant characteristics of the fibers are; Aspect Ratio (ratio of length to mean diameter: l/d), shape and surface texture, length, and structure.

The fiber can withstand a maximum stress σ_f, which depends on the aspect ratio (l/d).

$\sigma_f = \tau \ (l/d)$

where;

τ= interfacial bond strength

d= diameter of fiber

l= length of fiber

The length of fiber should be greater than the maximum size of aggregate particles.

Interfacial bond strength is improved by fibers having a deformed or roughened surface, enlarged or hooked ends, and by being crimped.

The following figure (Figure 4.3) shows different deformations of fibers:
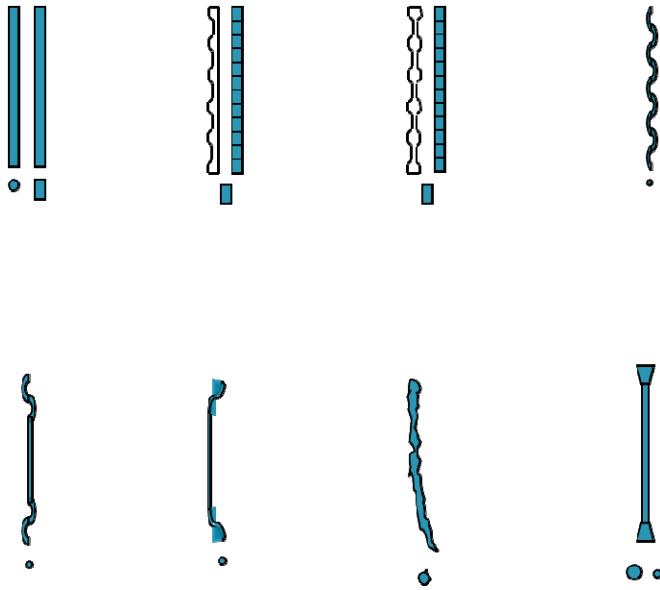
Figure 4.3 Different deformations of fibers.

The orientation of fiber relative to the plane of a crack in concrete influences the reinforcing capacity of the fiber. The maximum benefit occurs when the fiber is unidirectional and parallel to the applied tensile stress, and the fibers are of less benefit when randomly oriented in three dimensions. This statement is illustrated in Figure 4.4, which also shows that higher fiber concentrations lead to a higher strength.
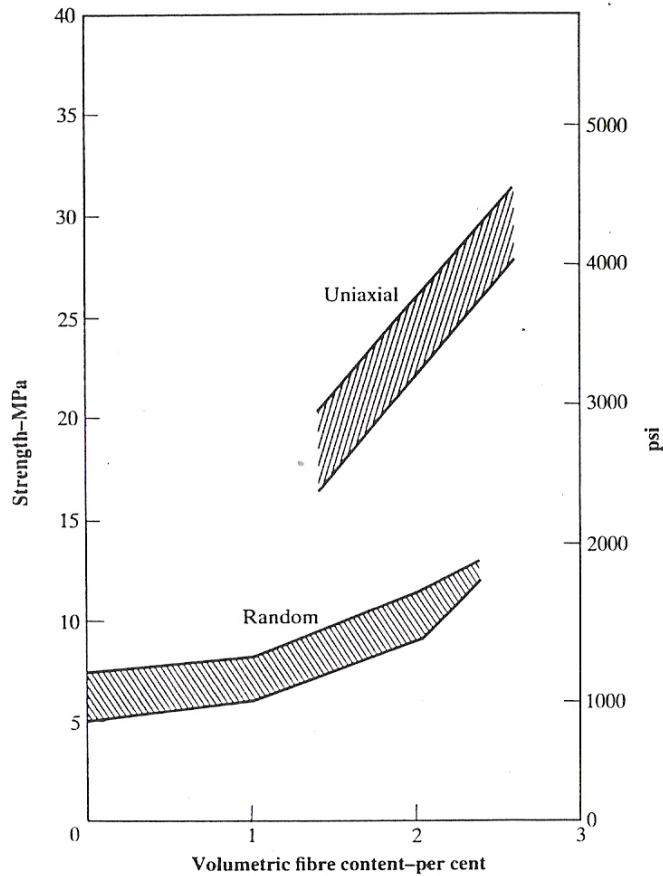
Figure 4.4 Volume of fiber versus strength varation.

The ultimate strength of the fiber reinforced composite is related to the properties of the matrix and of the fiber as follows:

$S_c = AS_m(1-V_f)+BV_f(l/d)$

Where;

S_c= ultimate strength of the composite

S_m= ultimate strength of the matrix

V_f= volume fraction of fibers

A= a constant

B= coefficient depending on interfacial bond strength and the orientation of fibers

l/d= Aspect ratio (length/diameter) of fibers

It is important that the fibers be undamaged in the process of incorporation into the matrix; otherwise the reinforcing effect will be smaller or even absent.

Compared with conventional concrete mixes, F.R.C. generally has a higher cement content, a higher fine aggregate content and a smaller size of coarse aggregate. For a particular type of fiber, the mix proportions are best determined by trial mixes and the fiber and the mix are adjusted as necessary to meet the requirements of workability, strength and durability.

workability

The workability of F.R.C. mixes decreases as the fiber content increases and as the aspect ratio increases. The usual tests are employed, **viz** slump and VeBe, but the former test is not always a good indicator of workability. For this reason, the inverted slump test has been devised for fiber reinforced concrete mixes.

Typiacal direct tensile and flexural strength of steel fiber reinforced concrete and mortar is shown in Figure 4.5.
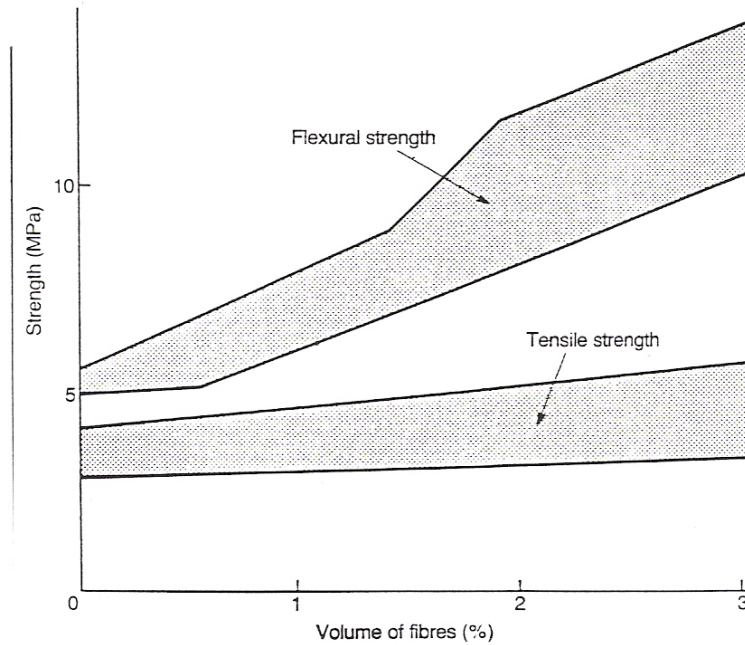
Figure 4.5 Tensile and flexural strength of FRC

Physically it is very difficult to include fibers more than 3% by volume.

4.5 Uses of Fiber Reinforced Concrete

The uses of F.R.C. and F.R. cement are widespread. Glass F.R. cement is used for precast, flat or shaped, decorative panels and facing for architectural and cladding purposes.

Asbestos cement is cheaper and can be used to produce flat sheets, fire-resistant panels, and pipes.

Polypropylene fibers have a low modulus of elasticity under normal rates of loading but the modulus increases substantially under impact loading, so that the material is used, for example, for forming the outer casing for conventional reinforced driven concrete piles.

Both steel and glass fibers are used to make overlays to concrete pavements, while steel fibers can be incorporated in shotcrete; of course, there may be a problem of corrosion of steel, especially near or at a surface exposed to weather.

Table 4.2 Typical properties of fibers and matrices.

Material or fiber	Relative density	Diameter or thickness (microns)	Length (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Failure strain (%)	Volume in composite (%)
Mortar matrix	1.8-2.0	300-5000	-	10-30	1-10	0.01-0.05	85-97
Concrete matrix	1.8-2.4	10000-20000	-	20-40	1-4	0.01-0.02	97-99.5
Aromatic Polyamides (aramids)	1.45	10-15	5-continuous	70-130	2900	2-4	1-5
Asbestos	2.55	0.02-30	5-40	164	200-1800	2-3	5-15
Carbon	1.16-1.95	7-18	3-continuous	30-390	600-2700	0.5-2.4	3-5
Cellulose	1.5	20-120	0.5-5.0	10-50	300-1000	20	5-15
Glass	2.7	12.5	10.50	70	600-2500	3.6	3-7
Polyacrylonitrile (PAN)	1.16	13-104	6	17-20	900-1000	8-11	2-10
Polyethylene							
Pulp	0.91-0.97	1-20	1	-	-	-	3-7
HDPE filament	0.96	900	3-5	5	200	-	2-4
High modulus	0.96	20-50	Continuous	10-30	>400	>4	5-10
Polypropylene							
Monofilament	0.91	20-100	5-20	4	-	-	0.1-0.2
Chopped film	0.91	20-100	5-50	5	300-500	10	0.1-1.0
Continuous nets	0.91-0.93	20-100	Continuous	5-15	300-500	10	5-10
Polyvinyl alcohol (PVA, PVOH)	1-3	3-8	2-6	12-40	700-1500	-	2-3
Steel	7.68	100-600	10-60	200	700-2000	3-5	0.5-2.0

5. FERROCEMENT

5.1 Introduction

The concept of the use of fibers to reinforce brittle materials dates back to ancient constructions built using mud walls reinforced with woven bamboo mats and reeds.

In the present form, the FERROCEMENT may be defined as a composite material obtained by reinforcing the cement mortar with steel fibers in the form of a wire mesh as shown in Figure 5.1.
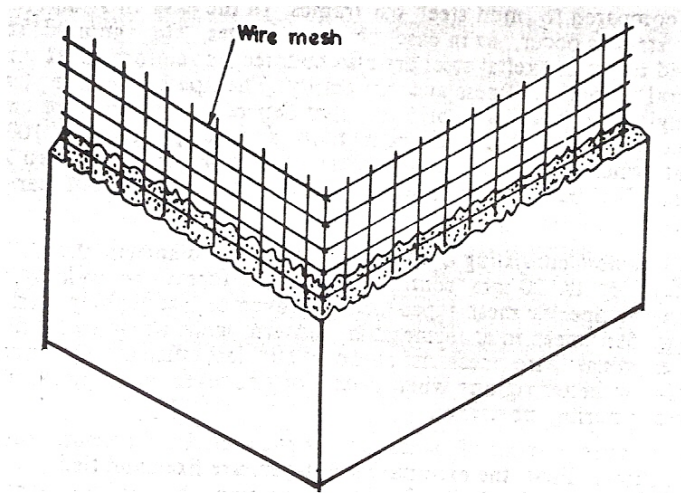
Figure 5.1 Typical section of ferrocement.

While the mortar provides the mass and steel fiber imparts tensile strength and ductility to the material. More accurately, FERROCEMENT may be considered as a special form of reinforced concrete construction with more closely layered wire meshes than a material of construction.

Due to the distribution of a small diameter wire mesh reinforcement over the entire surface, and sometimes over the entire volume of the matrix, a very high resistance to cracking is obtained. Also, toughness, fatigue resistance, impermeabilty etc. are considerably improved.

5.2 Mixture Of Ferrocement

The FC composite is a rich cement-mortar matrix of 10 to 60 mm thickness with a volume reinforcement consisting of either welded mesh or mild steel bars.
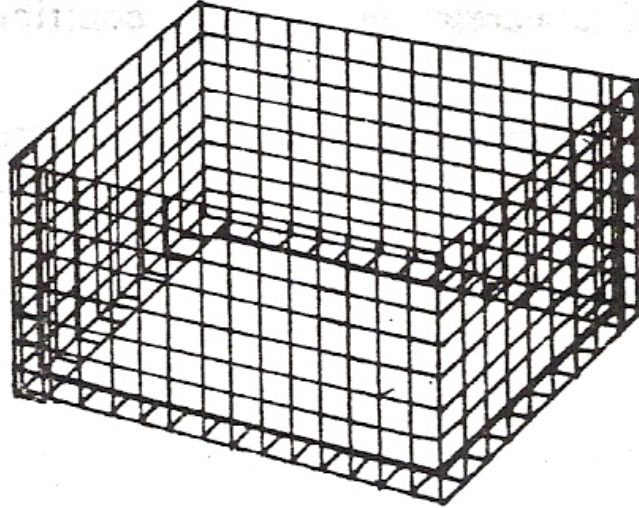
Figure 5.2 Skeleton of ferrocement

The matrix is typically rich in cement, i.e. a cement-sand ratio of 1:1.5 or 1:2 is used. Portland cement, with or without pozzolana, is generally used for FC. Plasticizers and other admixtures may also be added to improve the workability.

The fine aggregate conforming to gradings with particles greater than 2.36 mm and smaller than 150 micron removed are suitable for FC. Therefore, sands with maximum sizes of 2.36 mm and 1.18 mm (with optimum grading zones II and III) are recommended for FC mixes.

A water/cement (w/c) ratio of 0.3 to 0.4 is recommended.

5.3 Reinforcement For Ferrocement

1. <u>Skeleton Steel Frame:</u> It is made confirming exactly to the geometry and shape of the structure. It comprises relatively large diameter (about 3 to 8 mm) steel rods spaced typically 70 to 100 mm. It may be tied reinforcement or welded wire fabric. Welded wire fabric can be bent easily.

2. <u>Wiremesh:</u> Consists 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.

The required number of layers of wire mesh are fixed on both sides of the skeleton frame.

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.

5.4 Placing of Ferrocement (Impregnation of Meshes With Matrix)

This is the most critical operation in ferrocement casting. Sufficient quantity of mortar is impregnated through mesh layers so that the mortar riches the other side and there are no voids left in the surface. A wooden hammer of about 100 mm diameter with 150 mm long wooden handle can be used for 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.

In structures where many layers are used as reinforcement and the thickness is more than 20 cm, it is advisable to do the casting in 3 layers.

5.5 Corrosion Protection

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. Venyl and epoxy coatings have been found to be especially satisfactory 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.

5.6 Properties Of Ferrocement

The load carrying capacity of FC is correlated with the specific surface area of reinforcement which is defined as the total surface area of the wire in contact with cement mortar divided by the volume of the composite.

Specific Surface Area= A_{wire} / $V_{composite}$

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). FC structures can be designed to be watertight at service loads.

Impact tests on FC slabs show that damage due to impact reduces with increasing specific surface and ultimate strength of mesh.

Fatigue tests on FC beams show poor resistance of FC under cyclic loading.

5.7 Applications

FC is a popular structural composite to manufacture many precast products, such as watertanks, silos and bins, pipes, shell roofs, floor units, wind tunnel, permanent forms of concrete columns.

The major advantages are as follows;

1. FC structures are thin and light. Therefore, a considerable reduction in the self-weight of structure and hence in foundation cost can be achieved. A 30% reduction in dead weight on supporting structure, 15% saving in steel consumption and 10% in roof cost has been estimated in USSR.

2. FC is suitable for manufacturing the precast units which can be easily transported.

3. The construction technique is simple and does not require highly skilled labour.

4. Partial or complete elimination of formwork is possible.

5. FC construction can be easily repaired in case of local damage due to abnormal loads.

6. INSULATING MATERIALS

6.1 Thermal Insulation

The instability of supply of traditional energy supplies in the past few years and the high cost of alternative ones has had one positive effect on the industrial nations of the world – a realization of the importance of conservation.

heat transfer

WARM ⟶ COOL

The transfer of heat always occurs from warm to cool.

In buildings, where the ideal situation is to have a relatively stable temperature, two situations arise.

In winter; energy must be used to maintain a comfortable temperature. Without proper insulation heat is lost to the colder outside air.

In summer; temperatures are usually higher outside than inside, the building interior must be cooled to keep it comfortable. The less insulation that is used, the greater are the cost for air-conditioning.

6.2 Thermal Properties

6.2.1 Thermal Conductivity (k)

It is the term used to indicate the amount of heat that will pass through a unit of area of a material at a temperature difference of one degree.

The lower the "k" value, the better the insulation qualities of the material.

Units; US: $(Btu.in) / (h.ft^2.{}^oF)$

Metric: $W / (m.{}^oC)$

6.2.2 Conductance (c)

It indicates the amount of heat that passes through a given thickness of material;

Conductance= thermal conductivity / thickness

Units; US: Btu / (h.ft^2.^{o}F)

Metric: W/ (m^2.^{o}C)

6.2.3 Thermal Resistance (RSI for metric unit, R for US units)

It is that property of a material that resist the flow of heat through the material. It is the reciprocal of conductance;

R= 1/c

6.2.4 Thermal Transmittance (U)

It is the amount of heat that passes through all the materials in a system. It is the reciprocal of the total resistance;

U= 1/R$_t$

Table 1 lists a few of the common materials and their thermal properties;

Table 6.1 Thermal properties of materials

	Thermal Resistance		Thermal Conductivity[a]	
	RSI	R	K (SI)	K (US customary)
Brick, clay, 4 in (100 mm)	0.07	0.42	1.43	9.52
Built-up roofing	0.08	0.44		
Concrete block, 8 in (200 mm):				
Cinder	0.30	1.72	0.67	4.65
Lightweight aggregate	0.35	2.00	0.57	4.00
Glass, clear, ¼ in (6 mm)	0.16	0.91	0.04	0.27
Gypsum sheating, ½ in (12.5 mm)	0.08	0.43	0.16	1.16
Insulation, per 1 in (25 mm):				
Fiberboard	0.49	2.80	0.051	0.36
Glass Fiber	0.52	2.95	0.048	0.34
Expanded Polystyrene	0.75	4.23	0.033	0.24
Rigid urethane	1.05	6.00	0.024	0.17
Vermiculite	0.36	2.08	0.069	0.48
Wood shavings	0.42	2.44	0.060	0.41
Moving air	0.03	0.17		
Particle board, ½ in (12.5 mm)	0.11	0.62	0.114	0.81
Plywood, softwood, ¾ in (19 mm)	0.17	0.97	0.112	0.77
Stucco, ¾ in (19 mm)	0.02	0.11	0.95	6.82

[a] For SI values, thickness is in meters. For US Customary values, thickness is in inches.

6.3 Kinds of Thermal Insulation

All the materials that used to prevent heat losses are known as thermal insulation. There are 9 basics kinds;

1. Loose fill

2. Blankets

3. Batts

4. Structural insulation board

5. Slab or block insulation

6. Reflective insulation

7. Sprayed-on

8. Foamed-in place

9. Corrugated insulations

1. Loose Fill

Usually it is bulky and can be divided into two main types;

    a) Fibrous

    b) Granular

Fibrous type is made from mineral wool, rock, glass or slag wool, or vegetable fiber – usually wood fiber.

Granular insulations are made from expanded minerals such as perlite and vermicullite or from ground vegetable matter such as granulated cork.

2. Blanket Insulation

Blanket insulation is made from fibrous material, such as mineral wool, wood fiber, cotton fiber, or animal hair, manufactured in the form of a mat.

Mats are made in various thickness and cut in a variety of widths, sometimes with a paper cover.

3. Batts

They are similar in basic manufacture to blankets, but they are restricted as to length, usually being 1.2 m or less. Some are paper covered, some are made without a cover and fit between framing members by friction (see Figure 6.1).
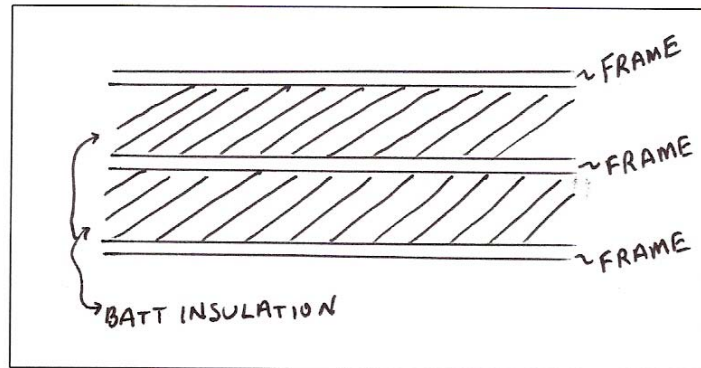
Figure 6.1 Batt Insulation

4. Structural Framing Board

It is made from a variety of substances, such as cane, wood and mineral fibers. It is used for exterior or interior sheating, insulating roof decking, roof insulating board, and interior finishing board.

5. Slab Insulation

Slab or block insulation is made in rigid units, normally smaller in area than insulation board, through some of them may be made from two or more pieces of insulation board cemented together to make a thick slab. It is made also from cork, shredded wood, and cement, mineral wool with binder, cellular glass, foamed concrete, foamed plastic, cellular hard rubber, concrete made with "perlite, vermicullite, expanded clay as aggregate".

6. Reflective Insulation

They are composed of metallic or other special surfaces with or without some type of backing.

Unlike others, reflective insulations rely on their surface characteristics, thickness of air space, temperature differences etc. for their insulating value.

7. Sprayed-On Insulation

Produced by mixing some fibrous or cellular material with an adhesive and blowing the mixture on to the surface to be insulated. Areas that are difficult to be insulated are treated in this manner (shape, location, etc.).

8. Foamed-In Place Insulation

Made from synthetic liquid resins. Two ingredients are used which, when mixed, produce a foam which solidifies to fill the space into which the mixture was introduced.

9. Corrugated Insulation

Made from paper, corrugated or cemented into multiple layers. Some types are sprayed with an adhesive which hardens to give the product extra stiffness, while others are faced with foil to provide extra insulative values.

10.4   Vapor Insulation

The dampness that sometimes occurs inside buildings can be caused by penetration of moisture from the outside or by condensation of water vapor generated on the inside.
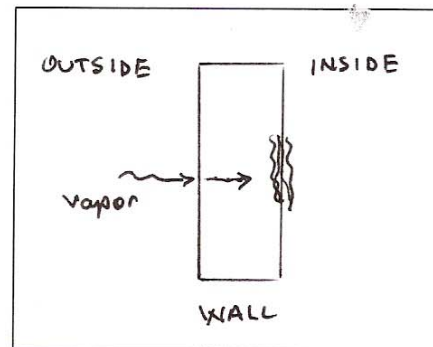
Figure 6.2 Penetration of moisture through wall.

a) Vapor Barriers:

They are materials which effectively retard or stop the flow of warm, moisture-laden air from inside a building outward through walls, ceiling, and floors to the colder, dryer outside atmosphere.
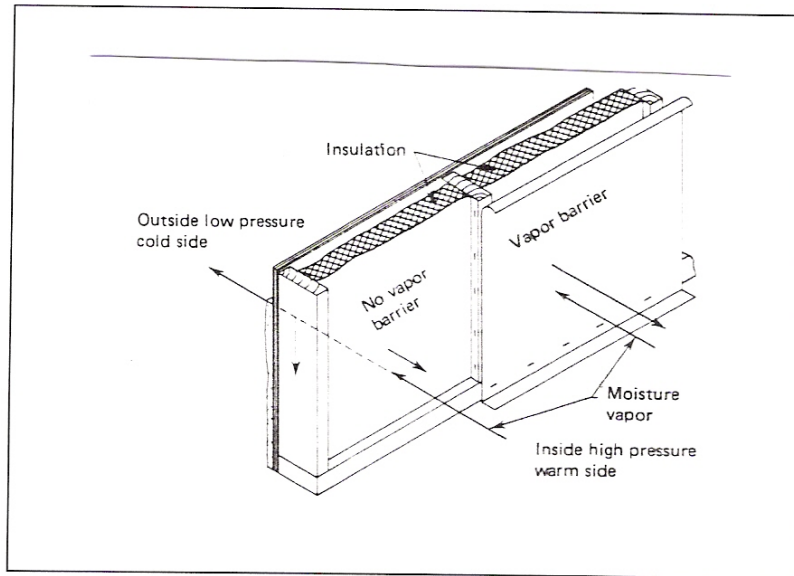
Figure 6.3 Vapor barrier on warm side of wall prevents moisture vapor from penetrating wall.

Without a vapor barrier, warm, moist air, flowing outward through a wall, ceiling or floor could cool to the extend that some of the vapor would condense out as water and collect within the wall, etc., to the eventual detriment of the material in the structure.

Vapor barriers should be installed on the warm side of the insulation and present a continuous, impervious surface to the vapor pressure from within the building.
Materials for vapor barrier include;

> 1) Polyethylene film
> 2) Asphalt coated kraft paper
> 3) Wax coated kraft paper
> 4) Aluminium metal foil sheets
> 5) Paint coatings

1) Polyethylene Film: It is chemically inert plastic, unaffected by acids, alkalis. It is produced by rolls. The film may be applied vertically in strips to stud walls, or sheets wide enough to cover the wall from top to bottom.

2) Aluminium Foil: Used as a vapor barrier in several forms. One is the foil as a single sheet. Another is a thin layer of foil laminated to a heavy backing of asphalt impregnated kraft paper. Still another consists of two layers of foil laminated with asphalt cement.

3) Coated Craft Paper: Kraft paper coated with asphalt or wax also acts as a vapor barrier. Sometimes two layers of paper are cemented with a continuous layer of asphalt. Whatever the material used, the same rule applies: the application should be continuous.

4) Vapor Barrier Paint: In situations where it is desirable to insulate an existing building but it is not possible to install a conventional vapor barrier at the same time, it is possible to use a vapor barrier paint on the inner surfaces. Paint coatings include rubber emulsion, aluminium paint, or two coats of white lead and linseed oil.

b) Moisture Barriers

These are the materials which are used to prevent the entrance of moisture into a building from the outside or from the earth below.

1) Saturated felt papers:

Such paper will shed water but will not prevent any moisture vapor which does reach the interior of a wall from escaping to the outside.

Moisture from the earth can enter a building through a concrete slab; when it reaches the warm inner surface it evaporates and becomes water vapor. To prevent this, a moisture barrier should be laid between the earth and the concrete. POLYETHYLENE FILM is an excellent material for this purpose.
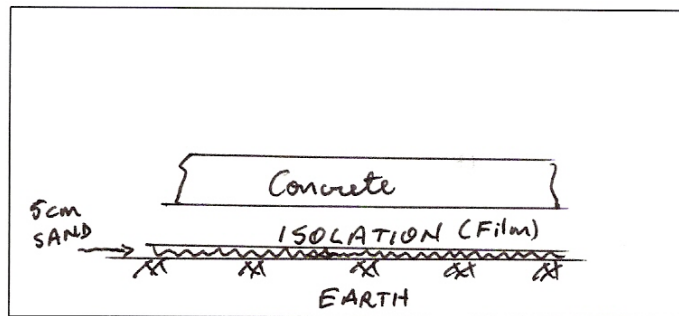
Figure 6.4 Isolation with polyethylene film.

If wire mesh reinforcement is used, it is laid over the film before the slab is poured.

In any case, great care must be taken to see that, the barrier is not broken during the preparation for the concrete pour.

6.5 Acoustical Materials

Sound control is necessary in order to;

   a) Improving hearing conditions and reduce unwanted noise in any given room
   b) To control the transmission of sound from one room to another through walls, floors, and ceilings.

Sound Mechanics:

Sound travels through the air as waves, in the form of small pressure changes occuring regularly above and below the normal atmospheric pressure.

The average variation in pressure in a sound wave, above and below the normal, is called SOUND PRESSURE. It is related to the loudness of a sound.

The loudness or strength of a sound – its intensity is measured in DECIBELS (dB).

Table 10.1 charts the decibal levels of a number of common sounds.

Table 6.1 Decibel levels of common sounds

Decibels	Sound	Effect
120	Thunder, artillery	
110	Nearby riveter	Defeaning
	Elevated train	
100	Boiler factory	
	Loud street noise	
90	Noisy factory	Very loud
	Truck (unmuffled)	
80	Police siren	
	Noisy office	
70	Average street noise	Loud
	Average radio	
60	Average factory	
	Noisy home	
50	Average office	Moderate
	Average conversation	
40	Quiet radio	
	Quiet home	
30	Private office	Faint
	Average auditorium	
20	Quiet conversation	
	Rustle of leaves	
10	Whisper	Very faint
	Soundproof room	
0	Threshold of audibility	

6.6 Sound Control

The fraction of sound energy absorbed by a material at a specific frequency, during each sound wave reflection, is called the SOUND ABSORPTION COEFFICIENT of that surface. Most sounds contain a range of frequencies, it is necessary to use an average of the absorption coefficient when considering sound absorption. To obtain that average, it has been customary to average four (4) coefficient from 250 to 2000 Hz inclusive and call the result the NOISE-REDUCTION COEFFICIENT (NRC), which is expressed as a percentage.

For example glass, concrete and masonry would have an NRC rating of 0.05 or less. Some other materials might have a rating of 0.90 or better.

Acoustical materials can be classified into 3 groups:

1. Acoustical tiles
2. Assembled accoustical units
3. Sprayed-on accoustical materials

1. Acoustıcal Tiles

They are made from wood, cane, or asbestos fibers, matted and bonded into sheets of various thickness (5-32 mm). The sheets are cut into tiles of several sizes. Edges may be square cut, or tongue-and-grooved.

These tiles are intended primarily for ceiling applications. They can be applied to solid surfaces with adhesives, nailed to strips attached to a ceiling frame or underside of a solid deck (see Figure 10.5) or installed in a suspended ceiling frame (see Figure 10.6)
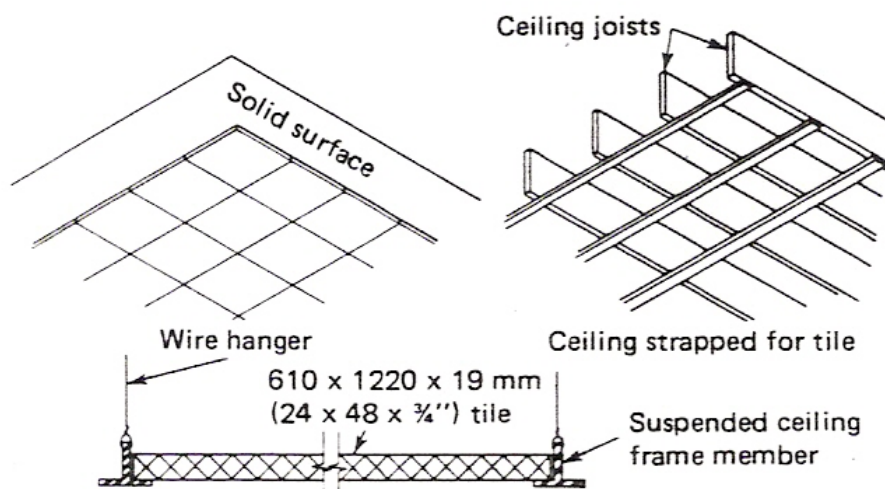
Figure 6.5 Acoustical ceiling tile application.
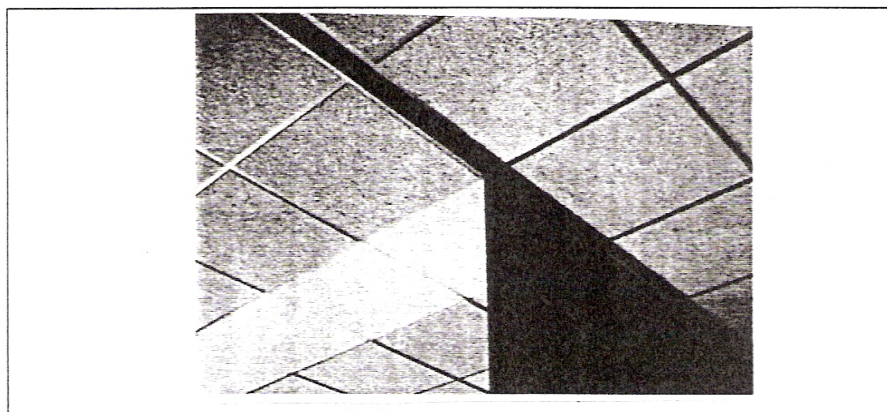
Figure 6.6 Acoustical tile in suspended ceiling.

A great variety of designs, colors, and patterns are available. The acoustic openings in the surface of the tile in themselves provide many different designs. The openings may be holes drilled in uniform or random patterns or a combination of large drilled holes and tiny punched ones (Figure 6.7).
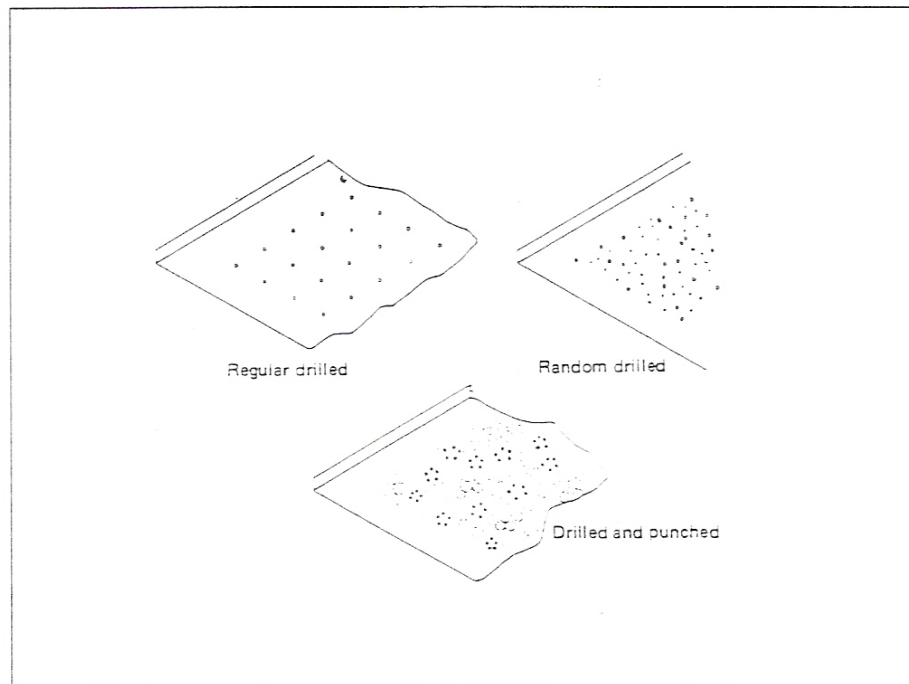
Figure 6.7 Acoustical tile hole pattern.

The openings may be slots, striations or fissures or the surface of the tile may be sculptured in various patterns (Figure 6.8)
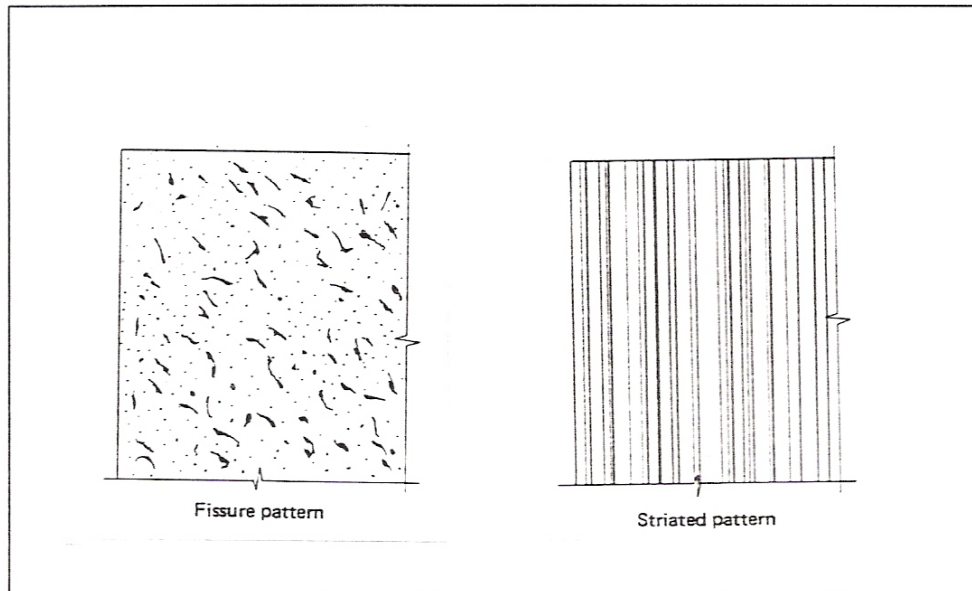
Figure 6.8 Acoustical tile surface patterns.

rockwool

Are made of several types of minerals which are fused together at high temperature and dispersed into organic fiber by a centrifugal force spin process.

- Fire safety
- Easy to handle and apply
- Thermal, acoustic insulation

2. Assembled Units

Assembled units usually consist of some type of sound-absorbing material such as a rock-wool or glass-fiber blanket fastened to an acoustically transparent facing. This facing is generally some type of rigid board, such as hardboard or asbestos board, or a metal sheet. The faces are perforated to allow the penetration of sound waves (Figure 6.10).
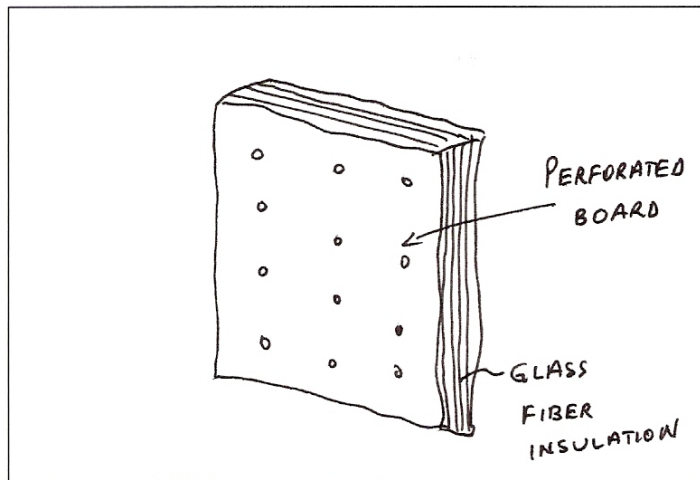
Figure 6.10 Assembled units.

3. Sprayed-On Acoustical Materials

Two type of material are used for this kind of sound control application.

   a) Plaster made with vermiculite or perlite aggregate.

   b) Coating of a mineral fiber mixed with an adhesive.

Vermiculite acoustic plaster is generally premixed product, requiring only the addition of approximately 46 lt. of water per bag of mix. This plaster can be applied by hand or by machine spraying and will bond to any clean, firm, water-resistant surface such as base plaster, concrete or steel.

Noise reduction coefficient (NRC) of vermiculite= 65%

Perlite acoustical plaster is usually mixed on the job, using calcined gypsum as the binder. It can be applied by hand or by machine. Sound reduction properties of perlite plaster are approximately same as those of vermiculite.

Acoustical treatment with mineral fiber involves the use of specially prepared mineral wool or asbestos fibers and an adhesive to hold them to the surface (In most areas,

there are **stringent** safety requirements which place restrictions on the use of such materials as asbestos fiber containing toxic dusts).

NRC= 0.85-0.90

7. ASBESTOS

7.1 Introduction

Asbestos exists in many different forms but essentially a SILICEOUS material with a FIBROUS molecular structure. It is the only naturally occurring INORGANIC FIBER.

It has extremely good durability and chemical resistance, and can be heated to high temperature without melting or burning.

In the direction of fibers, it has high strength.

7.2 Types of Fibers

There are 3 main types of fibers;

1. Chrysolite
2. Crocidolite
3. Amosite

All of them are metamorphic origin.

Properties of fibers;

1. <u>Chrysolite</u>; ($Mg_3Si_2O_5(OH)_4$) contains small amounts of aluminium, iron and sodium. It has good heat-resistance, being resistant to attack by alkalis, is very suitable for use with Portland cements, as in asbestos-cement products. The fibers are longest and have a silky white appearance. They are by far the most widely used.

2. <u>Crocidolite</u> (blue asbestos); contains more iron than chrysolite, has greater strength and acid resistance and has a characteristic blue color.

3. <u>Amosite</u>; contains relatively long, stiff but brittle fibers and is very suitable for insulating boards.

All fibers are very fine, as low as 0.1 μm diameter, hence very high aspect ratios (l/d) and bond well to most matrices.

7.3 Properties of Fibers

Embrittlement of asbestos fibers may begin at temperature as low as 300°C, due to loss of water on crystallization, decomposition into simpler products occurring progressively up to about 1000°C. Fusion is complete by about 1500°C, depending on type. Part of the fire-proofing ability of asbestos products is that, rather like wood, the decomposed material provides effective insulation to underlying layers in a fire with additional benefit of non-compustibiliy.

Milling of fibers

Asbestos fibers are milled before use to break down them into finer and hence more efficient forms. The effect of milling can be checked by measurement of specific surface, rather like cement. Values of 5000 m^2/kg are typical.

7.4 Health Hazard

It is unfortunate that asbestos particles may seriously affect the health of those who are in prolonged contact with the material. It can cause "lung cancer". This is due to inhalation of fibers. Stringent regulations now apply in areas where asbestos dust may be present. These require the provision of respirators, protective clothing and exhaust ventilation. Special storage and waste-disposal facilities are necessary in particular situations.

The most harmful type, CROCIDOLITE, may be recognized by its blue color.

CHRYSOLITE and AMOSITE are generally white and brown, respectively.

It is now also appears that there is some risk from asbestos products in use, mainly those which are not strongly bound, such as sprayed or low-density products. Fibers can be released from these materials on aging, so it is advisable to have all such materials correctly removed.

7.5 Assessment of Health Risk

The risk associated with any mineral fiber is greatly influenced by its size, fibers of diameter below 2 μm and length in the range 5-100 μm generally being considered most harmful. Larger fibers do not normally reach the sensitive lung tissues. A typical safe level is

considered to be 2 fibers/mm in working environments, with a reduction of 10 times for crocidolite.

Asbestos still has important applications in constructions where its excellent mechanical properties, combined with chemical and heat resistance, can be exploited without significant danger to health.

Safest products are those in which the fibers are tightly bound by a hard, abrasion resistance matrix.

7.6 Asbestos Cement (BS 690)

(short fibers) + (Portland cement) + (water) =

= built up layers to form sheets ⟶ moulded ⟶ cured

Silica and lime may be added during manufacture,
(short fibers) + (Portland cement) + (water) + (silica & lime)=steam autoclaved

Products are used externally; life ≥ 40 years.

During this time, impact strength decreases due to embrittlement (which also produces an increase in flexural strength).

Life can be prolonged by painting, an alkali-resistant primer being essential.

Uses of Asbestos Cement:
- Many types of pipe
- In sheet or tile form, asbestos cement is available in fully-compressed (high density (1800 kg/m^3), high bending stress (22.5 MPa) smooth surfaces on both face) or semi-compressed (density (1450 kg/m^3), bending stress (16 MPa)) states.

Flat sheets may be used for claddings, partition and ceiling linings.
Corrugated sheets have a advantage of increased rigidity for a given sheet thickness, so that they are particularly suited to roofing and cladding of larger industrial and agricultural buildings.

7.7 Low Density Insulating Boards and Wallboards

Density $\leq$ 900 kg/m^3

Thermal conductivity $\leq$ 0.175 W/ m^{o}C } Low Density Boards

Density; 900 $<$ d $\leq$ 1450 kg/m^3

Thermal conductivity $\leq$ 0.36 W/ m^{o}C } Wallboards

Low Density insulating boards; traditionally used as surface membranes in roofs, walls, ceilings, partitions or as protection to structural steels.

Wallboards are used where greater mechanical resistance was required, such as on doors or as overlays for floors. These types represent a health hazard and currently available boards now contain non-asbestos substitutes, such as glass, cellulose, or polyvinyl alcohol.

7.8 Other Products of Asbestos

Asbestos in the form of chrysolite has excellent weaving ability and has been formed into FIRE BLANKETS, GLOVES, ROPES, SLEEVING etc. for heat/fire-resisting applications.

Although non-asbestos substitutes are now available, many of these are still in use.

Further applications include vinyl floor tiles, and damp-proof membranes, the health risk from such products being generally small.

8 PAINTS

8.1 Introduction

Paints are surface coatings generally suitable for site use, marketed in liquid form. They may be used for one or more of the following purposes:

• To protect the underlying surface by exclusion of the atmosphere, moisture, fungi and insects.

• To provide a decorative easily maintained surface.

• To provide light- and heat-reflecting properties.

• To give special effects; for example, inhibitive paints for protection of metals; electrically conductive paints as a source of heat; condensation- resisting paints.

Painting constitutes a small fraction of the initial cost of a building and a much higher proportion of the maintenance cost. It is, on this basis, advisable to pay careful attention to the subject at construction stage. Furthermore, there are a number of situations in which restoration is both difficult and expensive once the original surface has failed and weather has affected the substrate; for example, clear film forming coatings on timber, and painting of steel. In other situations, access becomes more difficult later - for example, fascia boards become obscured by gutters. Such situations merit special care.

8.2 Painting systems

There are usually three stages in a painting system: primer, undercoat and finishing coat.

8.3 Primer and undercoat

The function of the primer is to grip the substrate, to provide protection against corrosion/dampness and to provide a good key for remaining coats.

The function of the undercoat is to provide good opacity (hiding power) together with a smooth surface, which provides a good key for the finishing coat. Undercoats usually contain large quantities of pigment to provide hiding power.

Undercoats and priming coats do not in themselves provide an impermeable dirt-resistant coating.

8.4 Finishing coat

This must provide a durable layer of the required colour and texture. Traditionally most finishing coats were gloss finish and these tend to have the best resistance to dirt since they provide very smooth surfaces. Silk or matt finishes can be obtained if preferred and some paint types such as emulsions will not normally give the high gloss of traditional oil paints.

8.5 Constituents of a paint

The types and proportions of paint constituents tend to be evolved by the manufacturer from experience rather than being designed from 'first principles'. Any one product will be subject to at least small modifications from time to time.
The main components of paint are the vehicle or binder, the pigment and the extender.

8.6 Vehicle or binder

This is the fluid material in the paint which must harden after application. The hardening process may be due to one of the following:

(a) Polymerisation by chemical reaction with air in the atmosphere. Such paints tend to form a film in a, part empty can. They include ordinary 'oil' paints.

(b) Coalescence of an emulsion. Emulsions are pre-polymerised into very small particles which are prevented form coalescing by an emulsifying agent. They set by water loss leading to 'breaking' of the emulsion.

(c) Evaporation of a solvent. Solvents need to be volatile, hence they are often flammable.

Paints based on types (a) and (b) are described as *convertible coatings* because once set, they cannot easily be re-softened. Once weathered, application of new coatings to these paints therefore relies on the previous paint being roughened to provide a key. Paints based on type (c) are described as non-convertible since they can be re-softened by application of a

suitable solvent. Subsequent coats also tend to fuse into previous coats and they do not form films in the can (though the paint may thicken by solvent loss due to evaporation).

The vehicle is largely responsible for the gloss and mechanical properties of the final coating. Vehicles may be blended with:

• driers, which modify hardening properties;

• plasticisers, which increase the flexibility of the hardened film;

• solvents, which adjust the viscosity of the wet paint;

• other additives - for example, with fungicidal action.

8.7 Pigments

These are fine insoluble particles which give the colouring ability and body to the paint. Primers and undercoats tend to have large proportions of pigment to produce opacity, while finish coats have low proportions, since to produce a gloss, the pigment should be beneath the surface. The particle size of pigments is very small in order that maximum colouring power is obtained by minimum thickness of material. Inorganic pigments such as titanium dioxide (white) have the best performance in respect of resistance to solvents, colour fastness and heat resistance, though organic pigments tend to produce the brightest, cleanest colours.

8.8 Extenders

These can be added to control the flow characteristics and gloss of the paint with the added advantage of reducing the cost. Because they are not involved in the colouring process they have a particle size larger than that of the pigment.

8.9 Some common types of paint

8.9.1 Oil (alkyd resin) paints and varnishes

These are well established and are still the most widely used paints for general purposes including painting of wood and metals. They were traditionally based on linseed oil but modem oil paints are manufactured from alkyd, polyurethane, or other synthetic resins, which allow greater control over flow characteristics, hardening time and hardness/flexibility of the dried film. Once hardened, alkyd resin-based paints behave as thermosetting plastics, being resistant to solution in oils from which they were formed. Unfortunately the hardening process continues slowly with time and these paints tend to become brittle over a period of years, especially if exposed to substantial levels of sunlight. This leads to cracking, especially when they are applied to substrates with high movement tendency such as timber.

Saponification of oil-based paints and varnishes

Oil- or alkyd-based paints are made by reacting organic acids with alcohols such as glycerol. If an alkali such as calcium hydroxide contacts an oil-based film, there is a tendency to revert to glycerol with the production of the corresponding salt, which in this case is a soapy material - hence the name 'saponification'.

This leads to the breakdown of films and formation of a scum. Hence, oil-containing paints (including polyurethanes) should not be used on alkaline substrates such as asbestos cement, concretes, plasters or renders based on Portland cements, especially when new or if there is a risk of dampness. Alkali-resistant primers, such as PVA emulsion paints, should be applied.

8.9.2 Emulsion paints

These are now very widely used in interior decorating. Examples are polyvinyl acetate (PVA) emulsion which are suitable for application to new cement or plaster. The molecules are very large but are dispersed in water by colloids to give particles of approximately 1 μm in size. Hence, these paints have the advantage of being water-miscible, although, on drying, coalescence of polymer particles occurs, resulting in a coherent film with moderate

resistance to water (see figure below). The film is, however, not continuous, so that the substrate can, if necessary, dry out through the film. Acrylic emulsions for painting of timber have now been produced, including a form which results in a medium gloss finish. Emulsions must have a certain amount of thermal energy to coalesce, hence, there is a 'minimum film formation temperature' (MMMF) for each type. Typical MMMF values are, for PVA 7°C and for acrylic copolymers, 9°C. They should not be used below these temperatures.
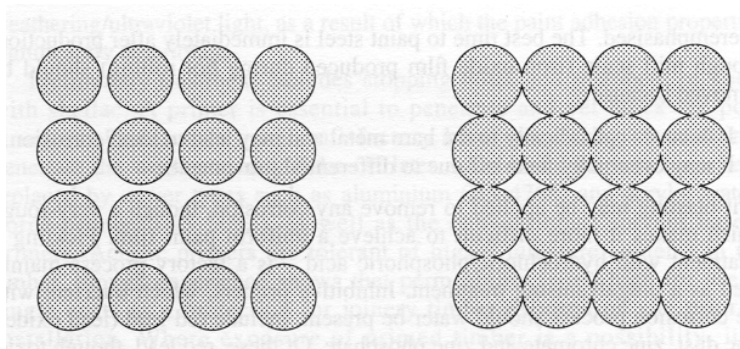
8.9.3 Cellulose paints

These are solvent-based paints. The cellulose constituent is in the form of nitrocellulose dissolved in a solvent such as acetone. Plasticisers are added to give elasticity, and synthetic resins are added to give a gloss, since pure cellulose gives little gloss.

Drying usually occurs rapidly, but well-ventilated areas are essential and the paint is highly flammable. Cellulose paints are most suited to spray application (though retarded varieties for brushing are available). These properties, together with the fact that the paints give off a penetrating odour, tend to restrict the use of cellulose paints to factory application. In these conditions, high-quality finishes can be obtained and the resulting coat has good resistance to fungal attack and to chemicals, including alkalis.

8.9.4 Bituminous paints

These are intended primarily for protection of metals used externally and have poor gloss-retention properties. They are amenable to application in thick coats which therefore give good protection, though the solvents used sometimes cause lifting if applied over oil-based paints, or bleeding in subsequent applied oil-based coats. Sunlight softens the paint, though

resistance can be improved by use of aluminium in the final coat. Chlorinated-rubber paints have similar properties. Some uses are based on their resistance to alkalis.

8.10 Painting specific materials

8.10.1 Ferrous metals

Steel forms the largest bulk of metals used in building and is one of the most difficult to maintain. The need for application to a good substrate cannot be overemphasised. The best time to paint steel is immediately after production, though mill scale (iron oxide film produced during hot rolling) should be removed because:

• It behaves cathodically to the bare metal and may lead to local corrosion.

• It may eventually flake off due to differential movement.

Grit-blasting may be applied to remove any corrosion, though a very rough finish makes it more difficult to achieve a uniform paint film. Pickling - treatment with hydrochloric/phosphoric acid - is a factory process mainly used as a pregalvanising treatment. Inhibitive primers, which interfere with the corrosion process should water be present, include red lead (lead oxide), zinc dust, zinc chromate and zinc phosphate. Of these, red lead, though toxic, is still preferred in 'safe' situations because it is fairly tolerant of poorly prepared surfaces and is amenable to application in thick coats. Metallic lead primers, though non-inhibitive, are fairly tolerant of poor surfaces and may be easier flowing and quicker drying than red lead. They also have superior chemical resistance. On account of their toxicity, lead-based primers are not recommended for use in domestic situations. Where a decorative finish is required, alkyd or aluminium paints may be used. Red oxide (micaceous iron oxide) is a moderately effective primer and is used both in undercoats and finishing coats. Special ('prefabrication') primers about 15-20 μm thick are often applied to steel soon after production to afford weather protection prior to and during fabrication. These have good weathering resistance without the need for further paint coats. They are typically based on phenolic or epoxy resins and may contain etchants and inhibitors.

Generally, the wetter the situation and the more aggressive the climate or atmosphere, the more coats should be given. In extreme situations or where extended life without

maintenance is required, protection is only likely to he achieved by impregnated wrappings, bituminous or coal-tar coatings, thick, factory-formed films or prior treatment, such as galvanising.

8.10.2 Non-ferrous metals

Zinc and aluminium are the non-ferrous metals most likely to require surface coatings and each provides a poor key for paint, unless surface treatment is first carried out. Zinc, in particular, reacts with most oil-based paints, forming soluble salts which reduce adhesion. Zinc should be degreased with white spirit, followed by roughening of unweathered surfaces with emery paper or etching treatment. Primers containing phosphoric acid are available for this; they often also contain an inhibitor, such as zinc chromate. Other suitable primers contain calcium plumbate, zinc dust or zinc oxide. For aluminium, etching is again an advantage, followed by application of zinc chromate or red-oxide primers. Lead-based primers are not suitable.

8.10.3 Wood

Wood should be protected as soon as possible after the manufacturing process is completed since the surface is quite rapidly affected by weathering/ultraviolet light, as a result of which the paint adhesion properties significantly deteriorate.

Preliminary treatment includes stopping holes and treatment of knots with shellac. A primer is essential to penetrate and yet block the pore structure. Undercoats are unsatisfactory here, since they often do not penetrate the wood and may flake off later. Lead-based primers have been replaced by newer types such as aluminium (BS 4756) and acrylic water-borne primers (BS 5082), as well as the conventional 'solvent based' primers. Acrylic primers are tolerant of higher moisture contents in the timber, though experience shows that permeability is too high for use in single coats as a protection for joinery timber exposed on site prior to installation. Where exposure of primed timber is a possibility, it is recommended that the specification should require that priming paints comply with the appropriate British Standard, since factory-based primers, in particular, often do not comply with the 'six months' exposure test requirements of current standards. Undercoats contribute to the film thickness and therefore protection, though the final coat provides the bulk of the protection. Alkyds and polyurethanes form the basis of most paints, though newer types, such as acrylic

emulsions, are now available for external use. Acrylic paints have demonstrated a number of advantages, including:

• rapid drying

• ease of application

• ease of cleaning equipment, brushes, etc.

• good durability, particularly cracking resistance

The cracking resistance is due to the fact that setting does not involve oxygen; hence embrittlement due to continued oxygen penetration does not occur. Possible problems of acrylic paints include the fact that they may inhibit hardening of fresh putty, they may be affected by rain during drying, and gloss levels are not as good as those of conventional alkyd paints.

Some paints are claimed to be microporous or to accommodate wood movement, or both. Tests on microporosity have shown that many such paints do 'breathe', though often not to a markedly greater extent than conventional paints. There is some evidence that, since cracking and blistering are less likely in such paints, they should have greater life. However, it should be appreciated that such paints would not be able to overcome high moisture contents caused by water admission at defective joints or breaks in the paint film. In some cases, there may be a possibility of higher resultant moisture contents in the wood, due to extra penetration through microporous paints during wet spells. Such porous paints produce a 'sheen' rather than the high-gloss finish which may be preferred by some clients. Hence, although there may be advantages in some situations, the need for adequate preparation for painting, together with good maintenance, still applies. The microporosity of paints is also lost if more than about three coats are applied, and this should be considered when redecorating such coatings.

8.10.4 Varnishes and wood stains

Varnishes are essentially drying oils/resins with little or no pigment, which enhance the natural colouring and grain of timber. Formulations vary greatly, some being suited to external use, though the main problem with all varnishes is that exterior surface maintenance must be meticulous. Cracking or peeling of varnish very quickly leads to bleaching or staining of underlying surfaces due to exposure to water and/or ultraviolet

light. Once affected, it is difficult to restore wood to its fomer state. The problem is especially severe on horizontal surfaces and south-facing aspects and it is not, therefore, recommended that varnishes he used in such situations. When varnishes have microporous or other properties such that they are guaranteed not to flake or peel, they can be regarded as stains and may be treated as such. The essential features of stains are:

• They penetrate the wood so that texture and grain remain, though some ('highbuild') types form a surface film in addition.

• They have a low solids content.

• The coatings breathe quite freely, though water repellents are added to reduce admission of liquid water. Fungicides are also usually added to control mould growth.

Moisture contents of stained timber may rise from time to time, such that non-corrosive metal fixings should be used. Since many forms preserve the texture and sometimes the colour of underlying wood, imperfections may be seen and putty is not recommended for glazing - gaskets of glazing beads are preferred. Stains cannot cover cracks or gaps which might be covered by a paint.

An important advantage of wood stains is that coatings generally erode rather than flake or crack, so that maintenance is confined to periodic washing and application of extra coats, though colours become progressively darker with age.

Low-build, transparent forms help retain the natural character of the wood and may leave very little surface film so that protection to wood is correspondingly less and wood may begin to weather comparatively quickly. Many types are now available with coloured pigments which are becoming aesthetically more popular. These increase protection to the wood, though there is the risk that, if a thick surface film is applied, failure characteristics of traditional timber varnishes, cracking and peeling, may occur. Higher- build varieties are recommended on 'difficult' woods, such as some hardwoods, with careful preparation, such as removal of oils, if present. Adhesion is improved on rough-sawn wood finishes, especially of difficult timbers, though these have limited acceptability aesthetically at present.

Not surprisingly, with the variety of finishes obtainable and relative ease of maintenance, the use of wood stains is rapidly increasing.

8.10.5 Plastics

Most plastics in common use do not require painting, and paint coats, once applied, cannot be removed by normal techniques. Paints, on the other hand, will reduce the rate of degradation of plastics such as polyethylene. Adhesion is poor unless the surface is first roughened to give a mechanical key. The impact strength of some plastics, such as PVC, may be adversely affected, if painted, by migration of solvent into the paint.

References

BS 4576: 1971 (1991), *Specification for ready-mixed aluminium priming paints for woodwork.*
BS 5082: 1993, *Specification for water-borne priming paints for woodwork.*

9. FIRE

9.1 Introduction

While significant improvements are constantly made in fire safety, reports on fatalities are still commonplace and major fire disasters are by no means unknown.

Many fires are associated with the use of high-risk materials and, through ongoing legislation should result in continuing improvements; it often takes several years before older, high-risk materials are replaced.

In large or tall buildings, the much higher potential risk resulting from reduced access of emergency services has long been recognized through again, fires still occur, sometimes due to failure of one or two parts of the structure to prevent fire spread. Increasing attention is now being given, for example, to fire stops in cavities, ducts and roof spaces.

9.2   Combustion
Three prequisites for a fire are;
1. Fuel
2. Oxygen
3. Heat

1. Fuel:

Almost all organic materials behave as fuels and few others.

Carbon and Hydrogen are the main constituents so that the materials rich in these will be a greater hazard and especially those rich in hydrogen, such as oil products and gas, since hydrogen generates more heat than carbon.

2. Oxygen:

This is present in the form of <u>air</u>, diluted with nitrogen which is inert. Pure oxygen, sometimes stored in cylinders is highly dangerous on account of its affinity for fuels.

3. Heat:

Heat causes;

(a) Chemical decomposition of most organic materials releasing volatile vapor. This effect is called <u>PYROLYSIS</u>.

(b) Reaction between both the solid and vapour fraction and oxygen;

$$C + O_2 \rightarrow CO_2 + heat \text{ (solid fuel)}$$

$$CH_4 + 2 O_2 \rightarrow CO + 2H_2O + Heat \text{ (hydrocarbon fuel)}$$
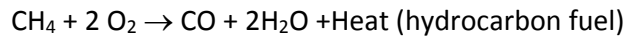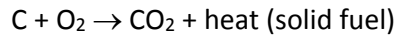
These are combustion processes though it is the reaction of vapors with oxygen together with accompanying light emission that is described as a "FLAME"

9.2 Flame

They are not necessary for fire but their pressure usually increases the severity of a fire. Because;

(a) Gases have much greater mobility than solids so that flames help spread the fire.

(b) The temperature in a flame is very high- usually $\approx 1200^0C$.

9.4 Ignition.

The application of sufficient heat will initiate the combustion process, which then generates more heat and ultimately, when the temperature is high enough, ignition or flaming will occur.

Combustion can be categorized into at least 5 types, as shown in Figure 9.1 below.

Note that in type 2 flames are not necessary and fire can travel through partition such as glass doors or walls in this way, provided they conduct or radiate heat sufficiently. <u>Type 3</u>, smouldering combustion, may occur in stored bulk materials, especially if dampness restricts the rate of temperature rise. It often makes final extinguishing of fires a time-consuming process. Spontaneous combustion (Type 4) is rare but indicates the need to take care when storing organic materials, particularly those prone to biological deterioration.

9.5   Fire and Density

The "ideal" for habitable buildings might be considered to be avoidance of all combustible materials but this normally would be totally impracticable because organic materials are

inseparably linked to human comfort furniture, furnishings, clothing- and to human activity- books paper and implements.

In many cases for reasons of economy and/ or convenience the enclosure itself will involve combustible materials, for example, wooden floors, doors, window frames and partitions. The risk presented by the combustible contents of an enclosure is defined as "FIRE LOAD", equal to the total mass of combustible contents in the enclosure, expressed as wood equivalent per unit floor area.

Fire Load = Comb.mass/(m^2 (floor))

Higher fire loads produce longer duration fires.

Structurally intact building $\Rightarrow$ higher fire resistance is necessary.

9.6   Fire Severity

Depends on the type and decomposition of combustible material and on other factors such as ventilation characteristics; good ventilation may reduce the durability of fires by venting heat.

9.7   Development of Fires

Damage of fire depends on;

- situation which give rise to it

- the way in which it develops and spreads

In the early stages of most fires, spreading is largely the result of flaming and localized heat generation, hence it requires materials which are not only combustible but in a flammable form.

9.8   Flashover

It is the most important in any fire (See Figure 9.2). This occurs when the air temperature in the enclosure reaches about 600^{0}C. At that point, pyrolysis (vaporisation) of all combustable materials takes place so that they all become involved in the fire and flaming reaches dramatic proportions, limited only by the total fuel available and/ or by the supply of air.

In many such fires, flaming occurs mainly outside windows using to lack of air internally and this helps spread the fire upwards to adjacent floors of the building. A priority in design for

fire resistance is to prevent or delay flashover since there is little change of survival in an enclosure once this has occurred.

The thermal inertia of the surfaces of an enclosure is an important factor: highly conductive, heat absorbent materials such as brick, help to delay the temperature rise as well as being non-combustible.

Flashover may be prevented in poorly ventilated closures due to lack of air for combustion, or delayed in very large ones where there are large volumes of air in relation to available fuel-they have a cooling effect. The fire than develops as if it were unenclosed. It is estimated at present that the fire services arrive before flash-over in about 90% of fires.

9.9   Fire Tests

Fire tests attempt to classify materials and components in relation to fire performance and form the basis of Building Regulations. They cover two chief areas:

1- The development and spread of fire. These tests include combustibility, ignitibility, fire propagation, spread of flame and heat emission of combustible materials.

2- Effects of fire on the structure, adjacent structures and means of escape, the first priority in any fire being the safety of the occupants. These tests are concerned with the structural performance of buildings, their ability to contain the fire and problems associated with smoke.

Many of the above aspects are covered by BS476, Figure 9.2. A brief resume of the contents of parts relating to fire spread in current Building Regulations is given in Table 9.1.

9.10 Examples on fires

1. Collapse of World Trade Centers (New York)

See below picture.

WHY THE TOWERS COLLAPSED

North Tower

South Tower

Vista Hotel

The impact of the plane crash destroyed a significant number of perimeter columns on several floors of the building, severely weakening the entire system.

As fire raged in the upper floors, the heat gradually affected the remaining structure.

The prolonged high temperatures, as the jet fuel and contents of the towers burned, reduced the strength and stiffness of the remaining steel structure.

Eventually, an entire floor collapsed, and the impact loads of the floors above created the "pancake" failure of each floor on top of each other.

Graphic adapted from Sydney Morning Herald

SMH GRAPHIC: J GAY, H EVERINGHAM 13.9.01

The **central core** is designed to carry part of the vertical loads only.

Floor trusses are supported between the perimeter columns and the central core.

The closely spaced tubular perimeter columns act like a hollow tube supporting part of the vertical loads and all the horizontal loads.

FLOOR PLAN

FLOOR PLAN OF THE WORLD TRADE CENTRE

Inside core

A hollow tube of closely spaced perimeter columns form the main structural component of the tower.

Collapse of World Trade Centers (New York) after fire.

Figure 9.1   Five ways in which fire can be initiated.

Figure 9.2   BS476 tests relating to initiation, growth, and spread of an uncontrolled fire in the compartment of origin.

Table 9.1   BS476 tests relating to fire development and spread referred to in current Building regulations.

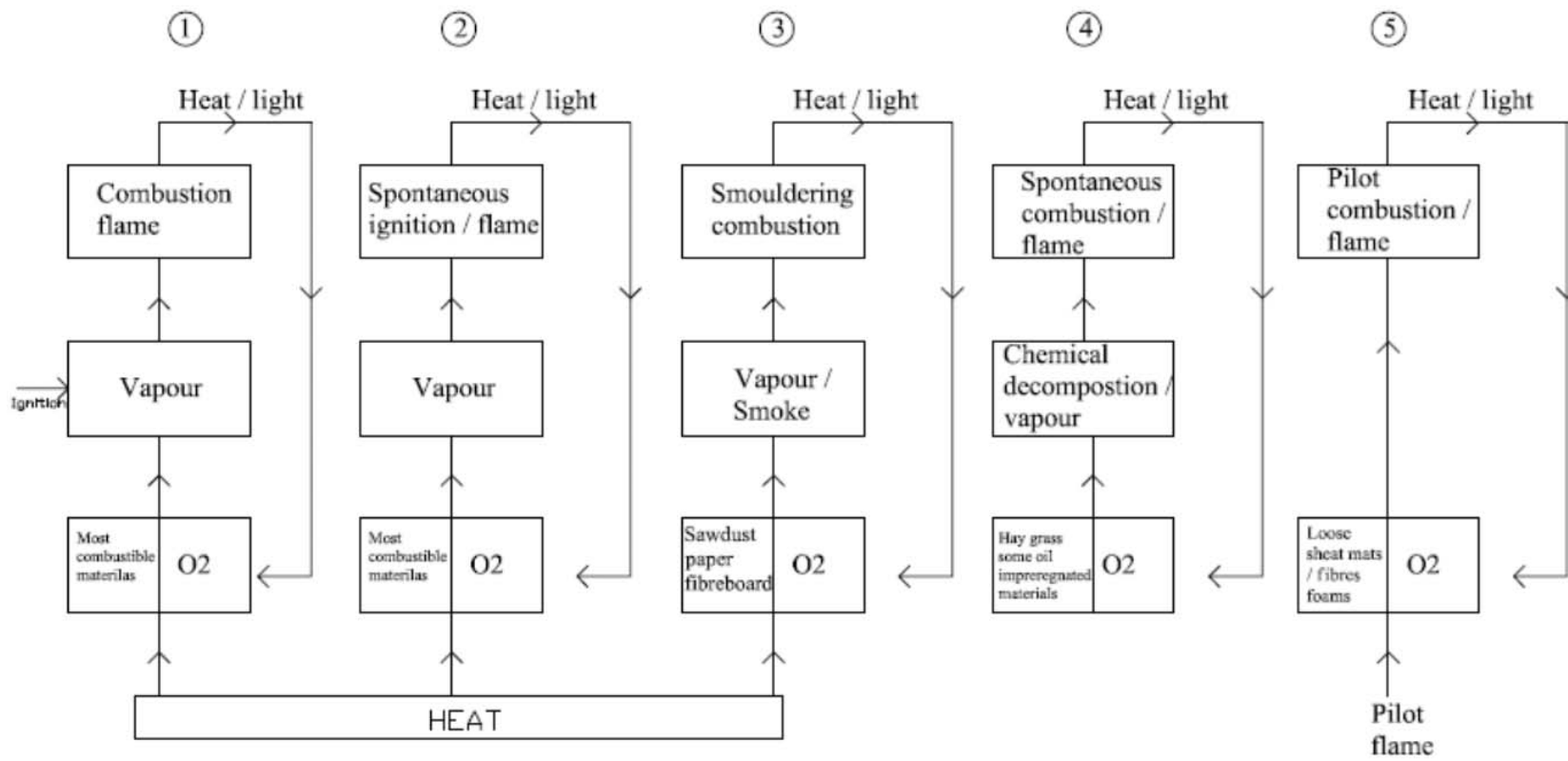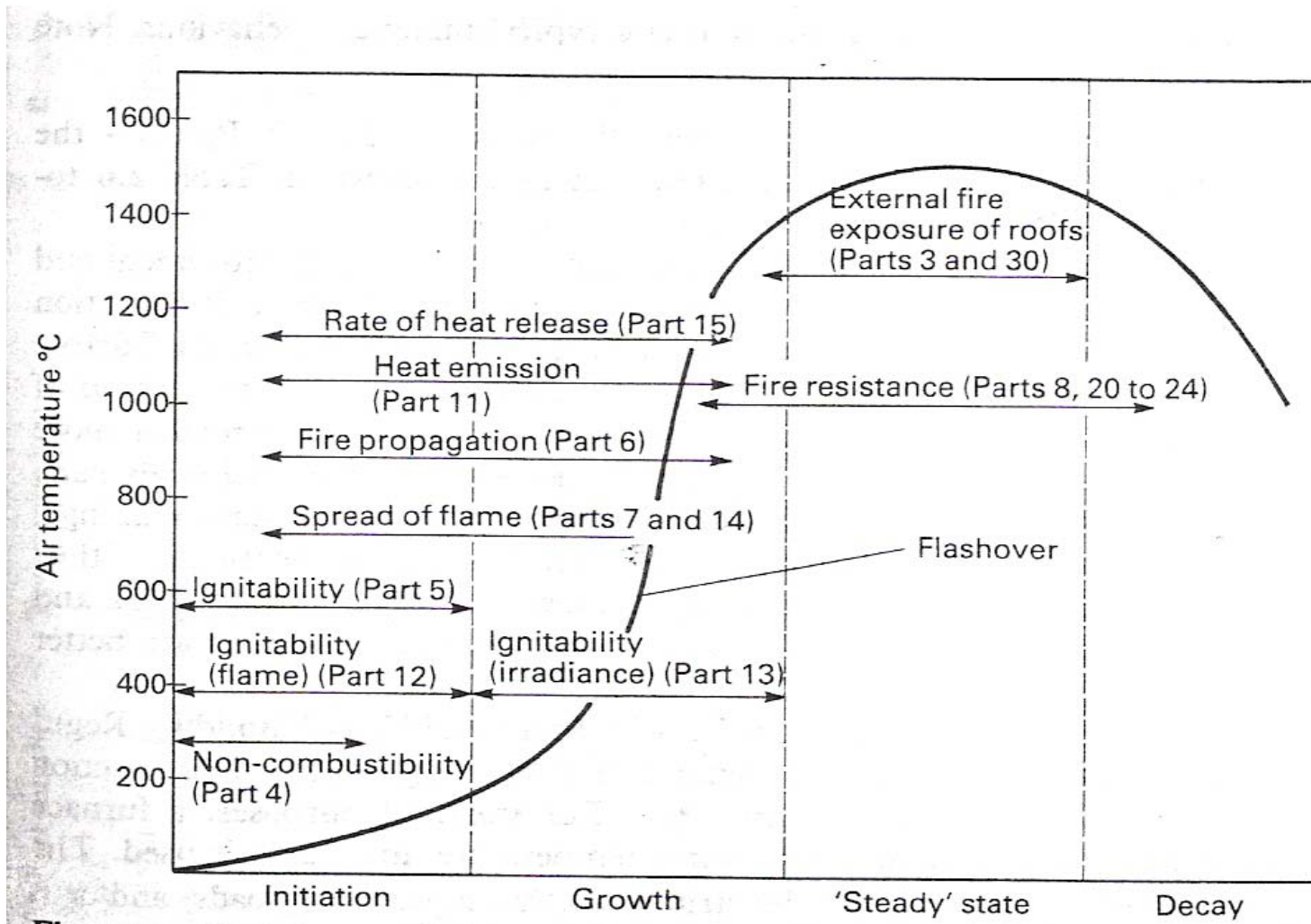| BS 476 Part number and title	Test Procedure	Results	Examples
Part 3, 1958 External fire exposure Roof test	Roof represented by panel. Preliminary ignition test, then flame/radiation	1958 Letter designation 1st letter penetration time A-D. A-1 hour; D-prelim test 2nd letter flame spread A- nil; D-sustained. Prefix F flat; S sloping	AA-best-e.g. Slates, clay or Concrete tiles on rafters. CC-bitumen felt on boarding
Part 3, (1975) As above	Similar	Prelim test: persistent or extended flaming X; Otherwise P. Penetration time. Flame spread not indicated	P60-best-as AA above
Part 4, 1970 Test for Non-combustibility	40 x 40 x 50 mm samples Heated in an electric furnace. Flaming/temp. rise observed	If no continuous flaming for 10 s and temp. rise less than 50^OC-non-ombustible	Non-organic materials usually Incombustible-exception, some Magnesium/aluminium alloys
Part 6, 1968 (1981) Fire propagation index	228 x 228 x 50 mm samples Subject to increasing heat/flame. Temperature measured at 3 min,10 min, 20 min.	Indices depend upon temperature reached i_1, i_2, i_3 at each time $I=i_1+i_2+i_3$	I and i_1 usually quoted eg. 60/40- Insulation board (unpainted) 10/5-plaster board
Part 7, 1971 Surface spread of flame	900 x 230 mm sheet not more than 50 mm thick exposed to pilot flame/radiant panel	Flame spread measured at 1½ and 10 minutes 10 min: Class I not more than 165 mm Class 2 165-455 Class 3 455-710 Class 4 more than 710 mm	Class 1 asbestos cement, fibre Insulation board + 3 coats emulsion Class 3 untreated softwood
Part 8, 1972 Fire resistance	Full size components-for example, beams, floors, walls subjected to standard temperature time curve	Stability, integrity, insulation values stated	30/20 door-stability 30 mins, integrity 20 mins
Part 11, 1982 Heat emission	45 mm diameter 50 mm thick cylinder. Method similar to Part 4	Temperature rise in furnace and in specimen measured; flaming; mass loss recorded	

9.11 Concrete (the burning issue)

After a fire, the amount of debris, blackening of the structure, peeling and loss of finishes can give the impression that the concrete elements are severely damaged. However, these first impressions may often over-estimate the extend of the destruction and its effects on the future of the structural concrete, particularly as fire-fighting often inflicts damage that may at first sight appear to have been caused by the fire itself. Alternatively, in the case of moderate heating over an extended period of time, the depth of damage may be under-estimated.

Assessing fire-damage to concrete involves an inspection of the site including limited non-destructive testing, sampling and laboratory investigation to produce a repair classification for each element. Although an experienced practitioner can obtain a significant amount of information during a site inspection, the laboratory investigation is often critical to establish the temperature achieved at different depths in the concrete and thus the condition of that element. An indispensable technique is the investigation is *petrographic* examination.

9.11.1 General considerations

Loss of strength and modulus of elasticity

Concrete loses strength on heating but, although the residual strength of a concrete element after a fire depends on several factors, for temperatures up to 300^0C the residual strength of structural-quality concrete is not severely reduced.

However, concrete is unlikely to possess any useful structural strength if it has been subjected to temperatures above 500^0C, the strength then being reduced by about 80%.

Typically, concrete made with lightweight aggregate does not lose significant strength until 500^OC.

The effects of a fire on modulus of elasticity are similar to the effects on strength. Up to 300^OC, the modulus of elasticity is not severely reduced but by 800^OC it may be as little as 15% of its original value.

Effects on reinforcement

Steel loses strength on heating but reinforcement is often protected from the effects of fire by the surrounding concrete, which is a poor thermal conductor. Steel reinforcement suffers a reduction in yield strength at temperatures above 450°C for cold-worked steel and 600°C for hot-worked steel. Prestressed steel loses tensile strength at temperatures as low as 200°C and by 400°C may be at 50% of normal strength. Buckling of reinforcement can occur at high temperatures if there is restraint, for example by adjacent elements, against thermal expansion.

Spalling

In a fire, most concrete structures spall to some extend, although lightweight aggregate concretes are usually more resistant. The surface can scale in the early stages of a fire as the near-surface aggregate splits as a result of physical or chemical changes at high temperatures. Explosive spalling also occurs in the early stages of a fire but involves larger pieces of concrete violently breaking away from the surface and may continue from areas already spalled. Such spalling usually results from high moisture content in the concrete. The thermal shock of a cold water on to hot concrete during fire-fighting can also induce spalling.

Depth of damage

Concrete is a poor thermal conductor and so high temperatures will initially be confined to the surface layer with the interior concrete remaining cooler. At corners where two surfaces are exposed to the fire, the effect will penetrate further because of the transmission of heat from the two surfaces. If concrete spalls early in a fire, the depth of effect from the original surface will be greater than if the concrete does not spall or if spalling occurs later in the fire.

9.11.2 Damage assessment

Site inspection

During the site inspection, various features of the concrete and associated materials in the fire-affected locations must be noted and from these a visual classification of the damage produced.

The Concrete Society report (TRE 33) includes a useful numerical classification and this is shown in a simplified format in Table 1.

Table 1. Classification of fire damage (Concrete Society Report TRE33).

Class of damage	Features observed						
	Plaster/finish	Colour	Crazing	Spalling	Rebars	Cracks	Deflection
0	Unaffected	Normal	None	None	None exposed	None	None
1	Some peeling	Normal	Slight	Minor	None exposed	None	None
2	Substantial loss	Pink	Moderate	Localized	Up to 25% exposed	None	None
3	Total loss	Whitish grey	Extensive	Considerable	Up to 50% exposed	Minor	None
4	Destroyed	Buff	Surface loss	Almost total	Over 50% exposed	Minor	Distorted

Firstly, the condition of any plaster or other surface finishes is noted. Surfaces may be sooty but otherwise unaffected by the fire. As the effects become more severe, the finishes start to peel until they are completely lost or destroyed. Likewise, during the fire the concrete surface will progressively craze until it is lost.

The concrete colour may also be affected during the fire, generally changing with increasing temperature from normal through pink to red, then whitish grey and finally buff. The pink and red colours relate to the presence of small amounts of iron in some aggregates, which oxidise and can be indicative of particular temperatures. It is important to note that many concreting aggregates do not change colour at temperatures normally encountered in an ordinary fire. Therefore, although colour change clearly indicates a particular temperature, the absence of colour change does not mean that the temperature was not reached.

Other site investigation requirements

Cores, or, if these are not possible, lump samples should be taken for laboratory investigation from a number of locations representing the range of damage classifications observed and should include comparable unaffected concrete as a control. Laboratory petrographic examination is necessary to support and enhance the site findings.

The depth of cover to any reinforcement must be measured during site investigation so that, once the laboratory investigation has been completed, it will be possible to determine whether the steel is likely to have been affected by the fire. It is also possible to take steel

samples for laboratory analysis, but this is usually necessary only if the visual inspection reveals a cause for concern.

Laboratory investigation: petrographic examination

Petrographic examination, which was covered in a more general article by the author, should be conducted by someone experienced in the technique and in examining fire-damaged concrete, and is best performed in accordance with ASTM C856. An initial low- to medium-power microscopic examination of all cores allows the selection of those for thin-section preparation and more detailed examination with a high- power microscope. As well as identifying physical distress such as cracking, this examination can identify features that allow temperature `contours' to be plotted on the concrete. Binocular examination allows contours to be plotted that equate to around 300°C provided the aggregate has become pink, the colour deepening to brick-red between 500°C and 600°C. Any flint in the concrete `calcines' (loses its water component, about 4 %) between 250°C and 450°C, while at similar temperatures the normally featureless cement paste begins to show patchy anisotropy with yellow-beige birefringence colours. Thus, careful and informed petrographic examination can usually reveal an approximate 500°C contour. Cracking of the surface of the concrete occurs at relatively low temperatures, but deep cracking indicates around 550°C was reached. Quartz alters structurally at 575°C resulting in a volume increase that typically causes extensive fine microcracking radiating from quartz grains. As most concrete contains quartz, an approximate 600°C contour can usually be plotted. The change in colour from brick-red to grey also begins at 600ºC. Limestone aggregate calcines at 800°C and concrete becomes a buff colour by 900°C.

Another laboratory technique sometimes used to assess the temperature reached is thermo-luminescence. This is based on the fact that quartz emits visible light when heated to 300-500°C, unless it has already been heated to that temperature. Thus, by sampling at various depths from the surface exposed to fire, it should be possible to establish the depth to which the concrete has been affected. The usefulness of this method is somewhat reduced by its limited availability and cost. However in special circumstances, thermo-luminescence is invaluable, despite the expense.

9.11.3 Overall assessment

The visual damage classification prepared on site provides the basis for a repair strategy. However the laboratory investigation - particularly the petrographic temperature contouring - provides critical information about the depth of any fire damage, and any classification of damage should be reviewed after the laboratory investigation. Critical temperatures are as follows:

Temperature >300°C: considerable loss in strength of the concrete.

Temperature: 200-400°C: considerable loss of strength of prestressed steel.

Temperature >450°C: loss of residual strength of cold-worked steel.

Temperature >600°C: loss of residual strength of hot-rolled steel.

Thus, concrete petrography can contribute significantly to the assessment of the effects of the fire on the steel reinforcement within the concrete as temperature contours can be compared with depths of cover to the reinforcement to identify areas where the steel may have lost strength.

9.11.4 Options for repair and requirements for demolition

Detailed information about repair is given in the Concrete Society Report. A brief guide to the level of repair required can be based on the final classification of damage. On the basis of practical experience, Figure 1 has been devised to illustrate the types of repair that might be appropriate for different classes of damage.
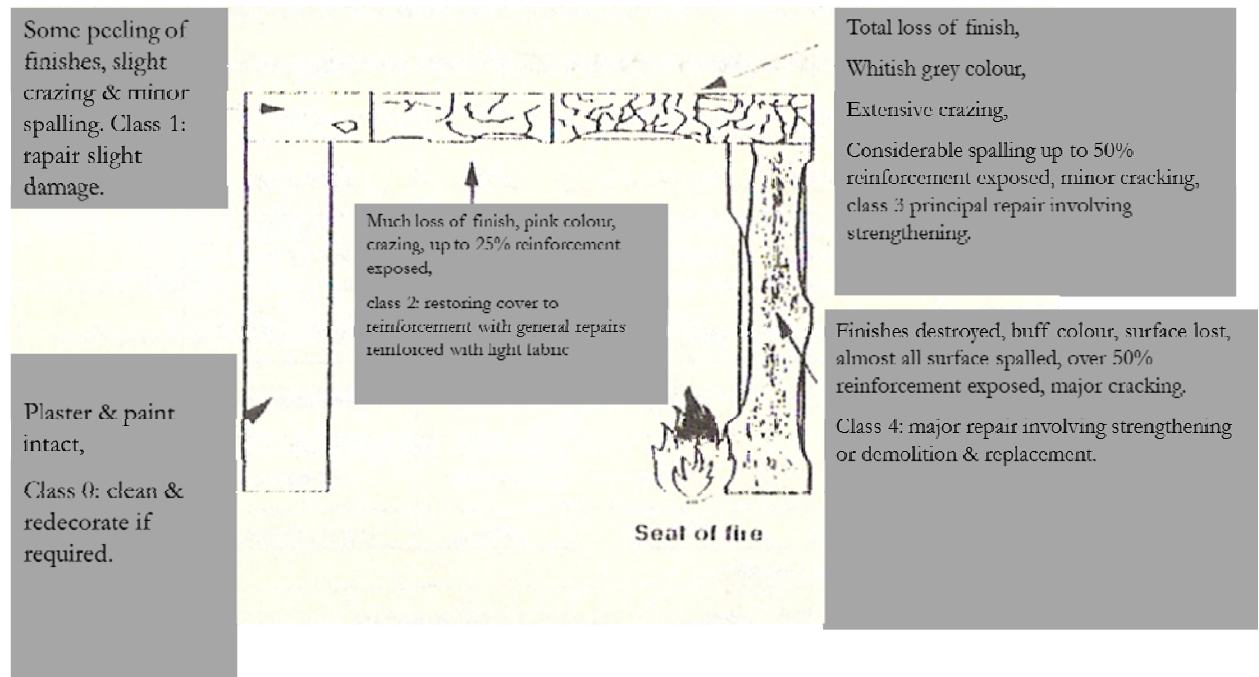
Figure 9.3 Simplified illustration of Classification and Repair.

References

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