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MATERIALS OF CONSTRUCTION

LECTURE NOTES

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The following lecture notes are based on my personal notes accumulated over the past ten years. I accept responsibility for their accuracy, and/or any mistakes which may be present. I accept any criticisms and look forwards to your suggestions for improving this lecture notes.

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1. GYPSUM

Gypsum usually is found in rock formation in nature, as $CaSO_4(2H_2O)$. It is hydrous calcium sulfate with compounds of lime, sulfur and water.

1.1 Production of Gypsum

Gypsum is rarely found in the pure state but usually contains varying amount of clay, limestone, silica, iron compound, etc. In the pure state it is white, but combined with impurities, it may be grey, brown, or reddish brown.

Some deposits of gypsum are found close to the surface of the earth; others well below the surface.

Gypsum has been recognised as a valuable building material for several thousand years.

Gypsum is a *hydrous calcium sulfate* with the chemical formula ($CaSO_4$ $(2H_2O)$, which means that it is a compound of lime, sulfur, and water.

$$CaSO_4(2H_2O) \longrightarrow \begin{array}{ll} CaSO_4 & 79,1\% \\ & \\ 2H_2O & 20.9\% \end{array} \longrightarrow \left\{ \begin{array}{ll} CaO & 32.5\% \\ SO_3 & 46.6\% \\ H_2O & 20.9\% \end{array} \right.$$

Where;

$CaSO_4$: Calcium sulfate

CaO : Lime

SO_3 : Sulfur trioxide

H_2O : Water

Natural deposits of gypsum rock are seldom pure. Usual impurities are SiO_2, Al_2O_3, Fe_2O_3, MgO, $CaCo_3$, $MgCO_3$, ...etc.

A suitable gypsum rock must contain at least 70% $CaSO_4.2H_2O$ (hydrous calcium sulfate).

The obtained gypsum stones first are crushed into (2-3) inches in diameter, then ground and then calcined. During calcinations it drives off 75% of the combined water under the temperature of 190°C.

Reaction of gypsum:

1- $CaSO_4 \,.\, 2H_2O \xrightarrow{(100\text{-}190)^\circ C} CaSO_4 \,.\, \frac{1}{2}H_2O + 1\frac{1}{2}H_2O$ (partial dehydration)

$CaSO_4 \,.\, \frac{1}{2}H_2O$: Plaster of Paris (Hemihydrate)

2- $CaSO_4 \,.\, \frac{1}{2}H_2O \longrightarrow CaSO_4 + 2H_2O$ (complete dehydration) $T > 190^\circ C$

$CaSO_4$: Anhydrate (anhydrous gypsum)

According to the temperature in the kills, one of the reactions will occur.

1.2 Hardening of Gypsum

$$CaSO_4 \,.\, \frac{1}{2}H_2O + 1\frac{1}{2}H_2O \longrightarrow CaSO_4 \,.\, 2H_2O$$

$$CaSO_4 + 2H_2O \longrightarrow CaSO_4 \,.\, 2H_2O$$

Pure gypsum sets about 10 minutes. Impure plasters set more slowly.

Retarders:

Glue, saw dust, blood, organic substances, borax and acetic acid. But they will not exceed 2 percent.

Accelerators:

Common salt, alum, sodium carbonate.

Plasticity:

To increase plasticity of gypsum plaster 15% hydrated lime or less frequently 15% clay should be added. The compressive stress of gypsum is larger than tensile stress. As the ratio of mixing water to gypsum increase, its stress decreases.

1.3 Properties of Gypsum:

1- Gypsum tends to disintegrate in damp.
2- Gypsum serves as a fireproofing material.

2. LIME

Lime was commonly used in the past as a constituent of masonry mortar; today cement has largely replaced it for this purpose.

It is still used, however in the making of the finish or putty coat for interior plaster.

Lime is obtained from LIMESTONE. Pure limestone is $CaCO_3$ (calcium carbonate). However, impurities like $MgCO_3$, Al_2O_3, SiO_2, etc may be present.

Limes can be broadly classified as non-hydraulic or hydraulic. Non-hydraulic limes do not harden without air being present (e.g. under sea).

2.1 Production of Lime

1- Excavation of limestone
2- Crushing
3- Grading
4- Calcination to obtain *quicklime*
5- Pulverize (99% smaller than 0.15 mm)
6- Mix with water under pressure
7- Dry and pulverize to obtain hydrated lime
8- Marketing

2.2 Practice of Calcination

- intermitten kiln (for small scale production)
- continuous kiln
- rotary kiln
- reactor kiln

2.3 Classification of Quicklimes (see Table 2.1)

(i) According to Particle Size:

- lump lime (10-30 cm lumps)
- pebble lime (2-5 cm)
- granular lime (0.5 cm)
- crushed lime (crushed to a specified grading)
- ground lime (passes 2 mm sieve or less than 2 mm)
- pulverized lime (less than 0.15 mm or passes 0.15 mm sieve)

(ii) According to Chemical Composition: (see Table 2.2)

- High - calcium lime : ($CaO \geq 90\%$) rich, fat, caustic lime
- Calcium lime : $75 < CaO < 90\%$
- Magnesium lime : $MgO \geq 20\%$
- High magnesian (dolomitic) lime: $MgO > 25\%$

(iii) According to Use:

- Mortar lime (used for stonework)
- Plaster lime

High Calcium Lime (fat lime):

These are produced by burning a fairly pure limestone, essentially calcium carbonate so as to drive off the carbon dioxide leaving calcium oxide or quicklime. When water is added to quicklime considerable heat is evolved, there is considerable expansion, and the resulting product is calcium hydroxide.

If the operation is carefully controlled, as it can be in a factory, so that just sufficient water is added to hydrate the quicklime, the lumps break down into a dry powder known as dry hydrate. Where lime is hydrated on the building site, or in a builders yard (which is rare today) an excess of water is added and the resulting slaked lime should be passed through a fine sieve to remove slow slaking particles and than left to mature for at least three weeks.

Although they are unlikely to be present in hydrated lime, unslaked particles tend to slake and expand after lime has been used; causing localized popping of plaster or expansion of brickwork.

The tendency of lime to expand is expressed as soundness. High calcium limes are mainly of use in building because they are fat, i.e. they are made for workable mortars, rendering and plaster mixers. Fatness improves with prolonged maturing of slaked lime (no harm is done thereby) and although “dry” hydrate can be used immediately after mixing with water, its plasticity is greatly improved by soaking overnight i.e. for at least 12 hours.

High calcium limes also retain water even when they are applied to absorptive materials such as bricks. Initial stiffening depends on loss of water-by evaporation or to absorptive materials. But hardening depends on combination with carbon dioxide from the air (carbonation) with reformation of the original calcium carbonate. Because hardening is necessarily from the outside, the interior of a mass hardens more slowly, even where a mix includes sand, which makes access of air to the interior somewhat easier.

High calcium lime is used in mortars, rendering and plasters.

High calcium limes with formulas:

Limestone: $CaCO_3$ (sometimes it is as $CaCO_3 + MgCO_3$)

Limestone under 900^{0}C gives calcium oxide + carbon dioxide. This procedure is performed in kilns.

Production of quicklime:

$$CaCO_3 \xrightarrow{900^oC} CaO + CO_2$$

Produced CaO is quicklime

Slaking of lime:

$CaO + H_2O \longrightarrow Ca(OH)_2$ (Hydrates (slaked) lime).

2.4 Hydration (Slaking)

CaO(quicklime) $+ H_2O \longrightarrow Ca(OH)_2$ + Heat

Volume expansion takes place (2.5 - 3 times).

Magnesia limes slake more slowly and heat evolution and expansion are much less than high-calcium limes. On the other hand, they harden slowly and they are more plastic. They have less sand carrying capacity.

Lime intended to be used in MORTAR is usually slaked in a box. The mixture of quicklime and water is stirred until a thin paste has been formed. This paste (putty) is then placed in a hole (or barrel) in the ground and covered with 5-10 cm thick soil to protect it from the action of air. It's kept in there for “seasoning”;

- 1 week for use in mortar
- 6 weeks for use in plaster (appearance important)

Seasoning provides homogenous mass and completion of chemical reactions. During slaking heat evolves and volume expands.

Hardening of lime:

$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$

Magnesium Lime:

These non-hydraulic limes are made from limestone, which contain about 20% of magnesium oxide. Magnesium limes slake and evolve less heat than high-calcium limes. The magnesium limes are more plastic and develops a better ultimate strength.

High Magnesium Lime:

The limestone of that kind contains more than 25% of magnesium oxide.

2.5 Hydraulic Limes

These limes which harden to some extent by an internal reaction are made by burning chalk or limestone, which contain clay, silicate and producing compounds similar to those present in Portland cement. The content of clay and silicate gives the hydraulic property; and the normal free lime slake it on the addition of water. Like all other limes, they must be thoroughly slaked, excess water would lead to premature hardening and the exact amount of water required can only be determined by experience with the particular lime concerned. Hydraulic lime cannot be soaked overnight to improve its workability. They are strong but less fat or plastic than non-hydraulic limes.

It has low strength. Therefore cannot be used as structural material. It is used for ornamental and architectural works.

Table 2.1 Classification of limes

Term	ENV 459-1*	BS 6100 Section 6.1**	ASTM C 51-98***
Air limes	Limes mainly consisting of calcium oxide or hydroxide which slowly harden in air by reacting with atmospheric carbon dioxide. Generally, they do not harden under water as they have no hydraulic properties.		
Quicklime	Air limes mainly consisting of calcium oxide and magnesium oxide produced by calcinations of limestone and/or dolomite rock. Quicklimes have an exothermic reaction when in contact with water. Quicklimes are offered in varying sizes ranging from lumps to finely ground materials.	A product obtained when calcareous material is heated at a temperature high enough to drive off carbon.	A calcined limestone, a major part of which is calcium oxide in association with magnesium oxide, capable of slaking with water.
Dolomitic lime	Quicklimes mainly consisting of calcium oxide and magnesium oxide.	Quicklime of high magnesium content.	(Dolomitic)-indicates the presence of 35-46% magnesium carbonate ($MgCO_3$) in the limestone from which the material was formed.
Grey lime		Quicklime made from grey chalk- usually having semi-hydraulic properties.	
Magnesian lime		Quicklime containing more than 5% of magnesium oxide	(Magnesian)-indicates the presence of 5-35% magnesium carbonate ($MgCO_3$) in the limestone from which the material was formed.
Hydraulic lime	Limes mainly consisting of calcium silicates, calcium aluminates and calcium hydroxide produced either by burning of argillaceous limestones and subsequent slaking and grinding and/or mixing of suitable materials with calcium hydroxide.	Quicklime containing sufficient soluble silica, aluminates, etc. to enable it to hydrate and set in the presence of water.	(Hydraulic hydrated lime) the hydrated dry cementitious product obtained by calcining a limestone containing silica and alumina to a temperature short of incipient fusion so as to form sufficient free lime (CaO) to permit hydration, and at the same time, leaving unhydrated sufficient calcium silicates to give a dry powder meeting hydraulic property requirements.
Semi-hydraulic lime		Similar to hydraulic lime but containing less soluble silica, aluminates, etc.	

		(minimum soluble silica usually 6%)	
Hydrated lime	Slaked limes mainly consisting of calcium hydroxide	Fine white dry powder, produced by mixing together quicklime and water in controlled quantities, removing gritty material from the resulting product and drying it. The main constituent is calcium hydroxide.	A dry powder obtained by treating quicklime with water enough to satisfy its chemical affinity for water under the conditions of its hydration. It consists essentially of calcium hydroxide or a mixture of calcium hydroxide and magnesium hydroxide or both.

* British Standard Institution. Building and Lime. Part 1. Definitions, specifications and conformity criteria. London: BSI, 1997; DD ENV 459-1.

**British Standard Institution. Building and Civil engineering terms. Part 6. Concrete and plaster. Section 6.1. Binders. London: BSI, 1984; BS 6100.

***American Society for Testing and Materials. Standard terminology relating to lime and limestone (as used by the industry). ASTM, 1998,; C51-98.

Table 2.2 Building limes (Lea`s book)

	ENV 459-1[1]		ASTM C 5-79[2], C 141-85[3], C 206-84[4], C 207-91[5]	
Lime type	CaO + MgO Min[a] (%)	MgO[a] (%)	CaO + MgO Min[a] (%)	MgO[a] (%)
Calcium CL 90	≥90	≤5	≥95	≤20
Calcium CL 80	≥80	≤5		
Calcium CL 70	≥70	≤5		
Magnesium			≥95	≥20
Dolomitic DL 85	≥85	≥30		
Dolomitic DL 80	≥80	>5		
Hydraulic			≥65	≤5[b]

[a] Expressed in term of quicklime.

[1] British Standard Institution. Building and Lime. Part 1. Definitions, specifications and conformity criteria. London: BSI, 1997; DD ENV 459-1.

[2] American Society for Testing and Materials. Standard Specification for quicklime for structural purposes. ASTM, 1979; C 5-79.

[3] American Society for Testing and Materials. Standard Specification for hydraulic hydrated lime for structural purposes. ASTM, 1985; C 141-85.

[4] American Society for Testing and Materials. Standard Specification for finishing hydraulic hydrated. ASTM, 1984; C 206-84.

[5] American Society for Testing and Materials. Standard Specification for hydraulic hydrated lime for masonry purposes. ASTM, 1991; C 207-91.

3. CEMENTS

3.1. Introduction

There are many different types of cements available for use in construction industry. Cements are finely ground powders and all have the important property that when mixed with water a chemical reaction (hydration) takes place. This reaction produces a very hard and strong binding medium for the aggregate particles. In its plastic stage, cement mortar gives to the fresh concrete a cohesive property. The cements have many differing properties, in terms of setting and hardening characteristics, and their resistance to chemical, temperature and other effects. These are obtained by differences in the fineness of grinding and the properties of raw materials. The cement to be used in a particular concrete or mortar will be selected on the basis of the particular properties required.

3.2 History of Cement

The cementitious properties of lime in mortars and concrete have been known since early historic times. The Romans made extensive use of lime concretes and developed pozzolanic cements of lime and certain volcanic earths. Lime mortars and concretes continued to be used in the middle Ages.

The rise of modern civil engineering in the 18th Century promoted serious efforts to develop improved cement. In 1824, the first step was made in producing the cement, which we are familiar today. The inventor of Portland cement (PC) is Joseph Aspdin from Leeds city UK. He produced a powder made from the calcined mixture of limestone and clay. He called it "Portland Cement", because when it hardened it produced a material similar to stones from the quarries near Portland in UK. Although the method of making cement has been improved, the basic process has remained same.
Cement production in Turkey was first started in Darıca Cement Factory in 1913 with a production capacity of 20,000 ton/year. Today the annual cement production in Turkey is 65 million tons (1st in EU, 8th in World) from 40 cement factories and 18 grinding mills all over the country.

3.3. Raw Materials of Portland Cement

Raw Materials: Raw materials for cement production are *calcareous rocks* (contain $CaCO_3$ > 75% such as limestone, marl, chalk), *argillaceous rocks* (contain $CaCO_3$ < 40% such as clay and shale), *argillocalcareous rocks* (contain 40-75% $CaCO_3$ such as clayey limestone, clayey marl).

Materials from any two of these groups may be used for Portland cement production providing that they must contain, in proper form and proportions of lime, silica and alumina. In the case of one of deficiency or excess of one of the ingredients supplementary materials must be used.

3.4 Chemical Composition of Portland Cements

The raw materials used in the manufacture of Portland cement consist mainly of lime, silica, alumina and iron oxide.The oxides account for over 90% of the cement. The oxide composition of (ordinary) Portland cement may be expressed as follows:

Table 3.1 The oxide composition of ordinary PC

Common Name	Oxide	Abbreviation	Approximate composition limits (%)
Lime	CaO	C	60-66
Silica	SiO_2	S	19-25
Alumina	Al_2O_3	A	3-8
İron oxide	Fe_2O_3	F	1-5
Magnesia	MgO	M	0-5
Alkalies:			
-soda	Na_2O	N	0.5-1
-potassa	K_2O	K	0.5-1
Sulfur trioxide	SO_3	$\bar{S}$	1-3

These materials (oxides) interact with each other in the kiln to form a series of more complex products (compounds). A typical chemical analysis of an ordinary Portland cement is as follows:

Table 3.2 A typical chemical analysis of ordinary PC

Item	Percentage (%)
CaO	63.6
SiO_2	20.7
Al_2O_3	6.0
Fe_2O_3	2.4
SO_3	1.4
MgO	2.4
Na_2O	0.1
K_2O	0.7
Loss on ignition	1.2
Insoluble residue	0.3
Free CaO	1.1
Total	100

It should be noted that the oxide composition varies among the different cements over a fairly narrow range. However, a relatively small change in oxide composition may result in an appreciable change in the proportions of actual compounds and on the properties of cement.

SO_3 (sulfur trioxide): Comes largely from gypsum. The amount of gypsum ($CaSO_4.2H_2O$) can be approximated by multiplying the amount of SO_3 by 2.15.

MgO (magnesia): In order to control the detrimental expansion, MgO is limited to 5% (expansion due to the hydration of free MgO in hardened concrete).

Free CaO: Same as free MgO, free CaO is undesirable. Because these oxides hydrate much later than other compounds of cement. Besides, they show a large volume expansion after hydration resulting in disintegration of hardened concrete.

$CaO + H_2O \longrightarrow Ca(OH)_2$
C H CH (1.32 times volume expansion)
$MgO + H_2O \longrightarrow Mg(OH)_2$
M H MH (1.45 times volume expansion)

Na_2O & K_2O (alkali oxides):

These may cause difficulties in the use of cement. A limiting value of alkali oxides is often specified for cements which are used with reactive aggregates to prevent alkali-aggregate reaction which results in disruptive expansion.

L.O.I. (loss on ignition):

Indicates "prehydration or carbonation" due to prolonged or improper storage. LOI is the loss of the weight of a cement sample when heated at 1000°C.

$LOI \leq 3\%$ (ASTM)

I.R. (insoluble residue):
It is that fraction of cement which is insoluble in HCl acid. It comes mainly from the silica which has not reacted to form silicate compounds in the rotary kiln. So it is a measure of the completeness of reactions in the kiln.
$IR \leq 0.75\%$ (ASTM)

3.5 Main Chemical Compounds of Portland Cement :

The oxides interact with each other to form a series of more complex compounds. The measurement of the amount of these major compounds by conventional chemical methods is not possible.

Portland cements are composed of four basic chemical compounds shown with their names, chemical formulas, and abbreviations:

1. Tricalcium silicate = $3CaO.SiO_2$ = C_3S
2. Dicalcium silicate = $2CaO.SiO_2$ = C_2S
3. Tricalcium aluminate = $3CaO.\ Al_2O_3$ = C_3A
4. Tetracalcium aluminoferrite = $4CaO.Al_2O_3.Fe_2O_3$ = C_4AF

Tricalcium silicate:

Hardens rapidly and is largely responsible for initial set and early strength. In general, the early strength of Portland cement concretes will be higher with increased percentages of C_3S.

Dicalcium silicate:

Hardens slowly and its effect on strength increases occurs at ages beyond one week.

Tricalcium aluminate:

Contributes to strength development in the first few days because it is the first compound to hydrate. It is, however, the least desirable component because of its high heat generation and its reactiveness with soils and water containing moderate to high sulfate concentrations. Cements made with low C_3A contents usually generate less heat, develop higher strengths, and show greater resistance to sulfate attacts.

Tetracalcium aluminoferrite:

It assists in the manufacture of Portland cement by allowing lower clinkering temperature. C_4AF contributes very little to strength of concrete even though it hydrates very rapidly.

Table 3.3 Main chemical compounds of PC

Name of Compounds	Chemical Composition	Usual Abbreviation	Percentage %
Tricalcium Silicate	$3CaO.SiO_2$	C_3S	51
Dicalcium Silicate	$2CaO.SiO_2$	C_2S	23
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A	8
Tetracalcium aluminoferrite	$4CaO.Al_2O_3Fe_2O_3$	C_4AF	9

C_3S and C_2S are the most stable compounds of cement. They are together form from 70 to 80 percent of the constituents in the cement. When cement comes into contact with water, C_3S begins to hydrate rapidly, generating a considerable amount of heat and making a significant contribution to the development of the early strength particularly in the first 14 days.

In contrast C_2S which hydrates slowly and is mainly responsible for the development in strength after about 7 days. The cement rich in C_2S result in a greater resistance to chemical attack and a smaller drying shrinkage than the other Portland cements.

The hydration of C_3A is extremely exothermic and takes place very quickly. It contributes to high early strength but produces little strength after about 24 hours. C_3A is the least stable and cements containing more than 10 percent of this compound produces concretes, which are susceptible to sulphate attack. The use of iron oxide in the kiln feed contributes to lower C_3A, but leads to the formation of C_4AF a product that is almost nothing but a filler that should be kept at a minimum.

3.6 Manufacturing of Portland Cement

The details of the cement making process vary widely. However, the fundamental stages in cement production are all the same and as follow. A schematic diagram of the cement manufacturing is shown in Fig.3.1.

1. The raw materials are reduced to fine particle size to be mixed intimately.
2. Raw materials are blended and mixed to produce uniform chemical composition containing calcium carbonate, silica, alumina, iron oxide etc.

3. The blended raw mix is heated to the point where all the moisture is driven off as steam or water vapor.

4. The dried mix is heated to decarbonation or calcination temperature, about 800^{o}C. At this temperature, the calcium carbonate in the mix is dissociated into calcium oxide (free lime), which remains in the mix, and carbondioxide which driven off as gas.

5. The mixture is further heated and as the temperature rises, the oxides of calcium, silicon, aluminium and iron react to form calcium silicates, calcium aluminate and calcium aluminoferrite. These are principal active compounds of Portland cement. This process is completed at a temperature of around 1400^{o}C and the resulting product is Portland cement clinker (1.8 tons of raw material produces 1 ton of clinker).

6. The clinker is cooled to a temperature at which it can be handled of about 60-150°C. Clinker may be sent directly to the finish grinding mills, but is usually stockpiled. Clinker may be stored for long periods without deterioration. When the cement is to be transported for a very far place, it may be easy to ship the clinker rather than finished cement. Of course, the grinding operation should be performed somewhere near to the point of use.

7. Clinker is ground to the specified fineness with the addition of a small proportion of gypsum to control the setting time of the finished cement. When it is required, the slag is also added during the grinding.

8. The finished cement is stored in silos for a relatively short time before being sent to the customer in bags or in bulks.

3.6.1 Production Steps of Portland Cement

The basic steps in the manufacture of Portland Cement include:

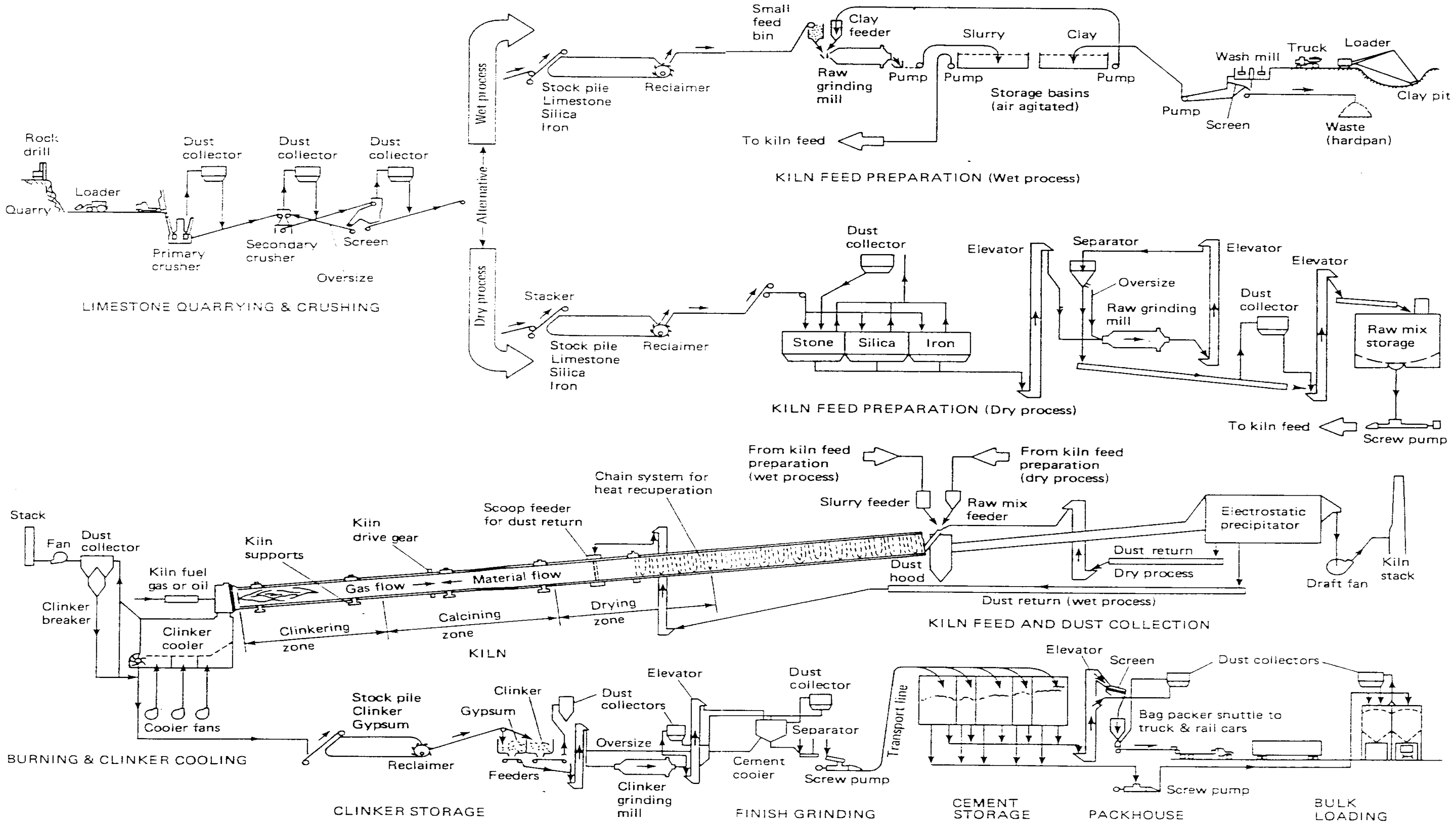
- Crushing, screwing, and stockpiling the raw materials
- Calculating the proportions of raw materials
- Preparing the raw mix by blending
- Feeding the raw mix into rotary kiln
- 100°C: Free water is evaporated.
- 150-300°C: Loosly bound water is evaporated.
- 500°C: More firmly bound water is evaporated.
- 600°C: $MgCO_3 \longrightarrow MgO + CO_2$
- 900°C: $CaCO_3 \longrightarrow CaO + CO_2$

Reaction between lime and clay starts.

- 1300°C: Major compound formation starts.
- 1400-1600°C: Output temperature.

(Around 1600°C clinker forms C_3A, C_2S, C_3S, C_4AF)

- Clinker cooled and stored.
- Clinker is ground with gypsum.
- Storing and marketing.



(Canada Cement Lafarge)

Figure 3.1 Production of Portland cement.

3.7 Physical Properties of Cement

a) Fineness:

The reaction between the water and cement starts on the surface of the cement particles. So the greater the surface area of a given volume of cement the greater the hydration. A fine cement will develop strength and generate heat more quickly than a coarse cement. It will of course cost more for grinding the clinker more finely.

Fine cement in general improve the cohesiveness of fresh concrete and can be effective in reducing the risk of bleeding but they increase the risk of being air-set before use and they increase the tendency of shrinkage cracking.

The measurement of fineness is defined as specific surface and is expressed as surface area of the grains in a sample per mass of that sample. For example, British Standard (BS12-1991) specifies the max cement fineness as 325 m^2/kg, though in practice it is usually in the range 350-380 m^2/kg.

b) Hydration:

The chemical combination of cement and water known as hydration produces a very hard and strong binding medium for the aggregate particles in the concrete. At the end of hydration normally a heat is liberated which is expressed as calories per gram. The rate of hydration depends on the relative properties of silicates and aluminate compounds, the fineness of the cement, and the ambient temperature.

Table 3.4 Time taken to achieve 80% hydration and heat of hydration of the main chemical compounds of Portland cement

Chemical compounds	Time to achieve 80% hydration (days)	Heat of hydration (J/g)
C_3S	10	502
C_2S	100	251
C_3A	6	873
C_4AF	50	419

In normal construction where the sizes of the structural members are not so large, the dissipation of this heat creates no problems. On cold weather concreting, this heat is advantageous. But in hot weather and in mass concrete construction, this generated heat may cause thermal cracks, and should be avoided.

The process of hydration in the cement can be determined by the measurement of;

a) the amount of $Ca(OH)_2$ in the paste,
b) the heat evolved by hydration,
c) the specific gravity of the unhydrated cement paste,
d) the amount of chemically combined water,
e) the amount of unhydrated cement paste.

c) Setting and Hardening:

Setting and hardening of the cement paste are the main physical characteristics associated with hydration of cement. The beginning of noticeable stiffening in the cement paste is known as the initial set. The final hardening process which is responsible for its strength known as the final set. The time from the addition of the water to the initial and final set are known as the setting times.

Setting time is affected by cement composition, cement fineness, rate of hydration, and the ambient temperature.

d) Strength:

The strength of hardened cement is its most important property. The rate of hardening of cement depends on the chemical and physical properties of the cement, the curing conditions and the water/cement ratio.

e) Soundness:

Soundness is a physical property of cement paste, which determines the ability of the cement paste to retain its volume after setting is completed.

The unsoundness is due to the presence of free CaO (lime) and free MgO (magnesia) in cement. These constituents hydrate very slowly after setting of cement. Since $Ca(OH)_2$ and $Mg(OH)_2$ occupy larger volume, expansion takes place.

The unsoundness may be reduced by;

a) limiting MgO content to less than 5%,
b) fine grinding,
c) thorough mixing,
d) Allow cement to aerate for several days (lime may have hydrated or carbonated in cement).

Tests to measure soundness are;

a) Le Chatelier test (due to free lime only)

b) Autoclave test (sensitive to free CaO and MgO)
Both measures the length change before and after the test.

3.8 Types of Cement

3.8.1 ASTM (American Society for Testing and Materials) Types

Type I:	Normal (ordinary) Portland Cement
Type I-A:	Air-entrained type-I Cement
Type II:	Modified Portland Cement
Type II-A:	Air-entrained type-II Cement
Type III:	High Early strength Portland Cement
Type III-A:	Air-entrained type-III Cement
Type IV:	Low heat Portland Cement
Type V:	Sulfate Resistant Portland Cement

3.8.2 Other Types

White Portland Cement
High Alumina Cement
Portland Pozzolan Cement
Portland Blast Furnace Slag Cement
Masonry Cement
Natural Cement
Expansive Cement

ASTM Types:

Type I (Ordinary Portland cement):

It is used for general construction work when the special properties of the other types are not required. It is normally used for reinforced concrete buildings, bridges, pavements and sidewalks when the soil conditions are normal, for concrete masonry units, and for all uses where the concrete is not subjected to special sulfate hazard, heat of hydration is not objectionable, where freezing-thawing is not expected.

Type I-A (Air-Entrained Type-I):

It is used where air entrainment is necessary.

Air-entrainment: Air intentionally incorporated by means of a suitable agent. Magnitude of these air bubbles are in the order of 0.05 mm in size. Entrained air produces separate cavities in the cement paste so that no channels for the passage of water are formed and the permeability of the concrete is not increased. The voids never become filled with the products of hydration of cement as gel can form only in water.

Type II (Modified Portland Cement):

It has better resistance to the action of sulfates than normal (ordinary) Portland cement and used where sulfate concentrations in groundwater are higher than normal but not very severe. It also generates heat at a slower rate than OPC and is used in certain concrete mass work like retaining walls. Reduced temperature rise is beneficial for hot weather concrete, too.

Type II-A (Air-Entrained Type II Cement)

Type III: (High Early Strength Cement)

It is used where high early strengths are required at early periods, usually a week or less. It is particularly usefull where it is required to remove forms as soon as possible or when the structure must be brought into service quickly. High-early strength makes it possible to reduce the period of protection for concrete during *cold* weather.

Type III-A (Air Entrained Type III)

Type IV (Low Heat Portland Cement):

It is used where the amount and rate of heat generation must be minimized. Strength is also developed at a slower rate. It is intended for use in massive concrete structures such as dams.

Type V (Sulfate Resistant Portland Cement):

It is used in structures subject to sulfate attack, chemical plants, etc. It is also resistant to the action of sea water.

OTHER CEMENTS

White Portland Cement (WPC):

It is made from raw materials containing very little iron oxide and manganese oxide. China clay is generally used together with chalk or limestone free from specified impurities (iron oxide, manganese oxide).

To avoid contamination by coal ash, oil is used as fuel in the kiln.

The cost of grinding is higher and this completed with the more expensive raw materials makes White Cement rather expensive (about 2 times).

Specific gravity and strength of White Portland Cement are less than those of OPC.

WPC is used for architectural purposes. It is not liable to cause staining, since it has a low content of soluble alkalies.

High Alumina Cement (HAC):

The raw materials of HAC are limestone or chalk and bauxite (a residual deposit formed by weathering under tropical conditions of rock containing Al_2O_3, Fe_2O_3, FeO, TiO_2) which are interground and calcined at 1600°C in the kiln. The solidified material is fragmented and ground to a fineness of 2500-3000 cm^2/gr. Its color is dark grey.

Properties are;

- It has high resistance to the action of sulfate waters (due to absence of $Ca(OH)_2$).
- Extremely high early strength (suitable for emergency repairs). 80% of the ultimate strength is achieved in 24 hours or even at 6-8 hours.
  Initial set = 4 hrs.
  Final set = 5 hrs.
  Rapid hardening is not accompanied by rapid setting.
  With special aggregates such as firebrick, it can be used to make refractory concrete that can stand high furnace temperature ($T > 1300°C$).
- It is expensive.
- Never use HAC in mass concrete.
- Never use with an admixture.
- Never mix HAC with PC (flash set and low strength).

Portland Pozzolan Cement:

Pozzolan: Volcanic dust found at Pozzuoli, Italy and used since Roman times as hydraulic cement when mixed with lime. All pozzolans contain silica and siliceous or aluminous minerals. Fly ash, slag (blast-furnace), silica fume are artificial pozzolans. Volcanic ash is natural pozzolan.

Portland Pozzolan Cement produces less heat of hydration and offers greater resistance to the sulfate attack than OPC (useful for marine and hydraulic construction and mass concrete). However, most pozzolans do not contribute to the strength at early ages, so strength gain of these cements is slow. Therefore they require larger curing period, but the ultimate strength is the same as OPC.

Portland Blast-Furnace Slag Cement:

Is made by intergrinding OPC clinker and 25-60% granulated blast-furnace slag.
Granulated blast-furnace slag is a waste product of the manufacture of iron. The amount of iron and slag being obtained is in the same order. A proper slag is a mixture of;

Lime = 40%
Silica = 30%
Alumina = 20%
Magnesia = 5%
Alkali Oxides = 1%

The slag can also be used together with limestone as a raw material for the conventional manufacture of PC clinker.
This cement is less reactive than OPC and gains strength at a slower rate during first 28 days, so adequate curing is essential.
Properties are;

- suitable for mass concrete
- unsuitable for cold weather
- has high sulfate resistance (suitable for use in sea-water construction).

Masonry Cement

Is used in mortar for brickwork. Made by intergrinding very finely ground PC, limestone and air-entraining agent, or alternatively PC and hydrated lime, granulated slag or inert filler and an air-entraining agent.
Properties are;

- It is more plastic than OPC

- Has higher water retaining power which leads lower shrinkage
- Has low strength and can not be used for structural concrete.

Natural Cement

It is obtained by calcining and grinding cement rock (which is a clayey limestone containing up to 25% argillaceous material). The resulting cement is intermediate between PC and hydraulic lime. Since Natural Cement is calcined at low temperatures, it contains practically no C_3S and is therefore slow hardening.

Expansive Cements

These are cements which upon hydration give product capable of expansion.

Expansive cements are used in special applications such as the prevention of water leakage. It has high resistance to sulfate attack.

Nomenclature for Cements

Cement is described in terms of cement type, strength class and rate of early strength development.

For example;

PC52.5R

PC: Type of cement

52.5: standard strength class

R: Sub-class: Indicated the rate of early strength development. (R: rapid, N: Normal, L: Low)

The recent standard for cement in European Norms id ENV 197-1. the standard states two additional classification, -the proportion of cement clinker and the second main constituent.

CEM II/A-S42.5N

CEMII: type of cement

A: proportion of cement clinker (A: high, B: medium, C: low)

S: Sub-type indicates the second main constituent (silica fume, GGBS, PFA)

42.5: Standard strength class

N: Sub-class indicates the rate of early strength development (R: rapid, N: normal, L: low)

Table 3.5 American (ASTM) standards[6, 7] (Lea`s book)

Cement type	Clinker and calcium sulfate (%)	Slag (%)	Pozzolan (%)	Processing additions
Portland I, IA, IIA, III, IIIA, IV, V	100	0	0	Permitted
Slag-modified Portland I (SM)	>75	<25	0	Permitted
Pozzolan-modified Portland I (PM)	>85	0	<15	Permitted
Portland blastfurnace slag IS	30-75	25-70	0	Permitted
Portland-Pozzolan IP, P	60-85	0	15-40	Permitted
Slag S	Permitted	≥70	0	Permitted

[6] American Society for Testing and Materials. Standard Specification for Portland cement. ASTM, 1995; C 150-95

[7] American Society for Testing and Materials. Standard Specification for blended hydraulic cements. ASTM, 1995;
C 595M-95

Table 3.6 European Prestandard ENV 197-1-classification of common cement types by strength

	Characteristic compressive strength (MPa)		Absolute minima (MPa)	Characteristic 28-day compressive strength (MPa)		Absolute minima (MPa)
Cement class	2 days	7 days	2/7 days	minimum	maximum	28 days
32.5	-	≥16	≥14	32.5	52.5	≥30.0
32.5 R	≥10	-	≥8	32.5	52.5	≥30.0
42.5	≥10	-	≥8	42.5	62.5	≥40.0
42.5 R	≥20	-	≥18	42.5	62.5	≥40.0
52.5	≥20	-	≥18	52.5	-	≥50.0
52.5 R	≥30	-	≥28	52.5	-	≥50.0

Table 3.7 World cement producers.

Country	**2001**	**2002**	**2003**
(By Principal Countries)	Production of Cement (tons)		
Brazil	39500	39500	40000
China	626500	705000	750000
Egypt	24500	23000	26000
France	19839	20000	20000
Germany	28034	30000	28000
India*	100000	100000	110000
Indonesia	31100	33000	34000
Iran	26650	30000	31000
Italy	39804	40000	40000
Japan	76550	71800	72000
Korea, Republic of	52012	55500	56000
Mexico	29966	31100	31500
Russia	35100	37700	40000
Saudi Arabia	20608	21000	23000
Spain	40512	42500	40000
Thailand	27913	31700	35000
Turkey	30120	32600	33000
USA	90450	91300	92600
Other Countries	361000	360000	360000
World Total	1700000	1800000	1860000

Source : *Mineral Commodity Summaries. 2003 and 2004*

Table 3.8 ENV 197-1[4] common cement types and composition: proportion by mass[a]

(Lea`s Chemistry of Cement and Concrete, 4th Ed., Edited by Peter C Hewlett, 1998.)

Cement type	Designation	Notation	Clinker K	Granulated Blastfurnace Slag S	Silica fume D[c]	Pozzolana Natural P	Pozzolana Industrial Q[d]	Fly ashes Siliceous V	Fly ashes Calcareous V	Burnt Shale T	Limestone L	Minor Additional constituents[b]
I	Portland cement	I	95-100									0-5
	Portland slag cement	II/A-S	80-94	6-20								0-5
		II/B-S	65-79	20-35								0-5
	Portland silica fume cement	II-A-D	90-94		6-10							0-5
	Portland pozzolana cement	II/A-P	80-94			6-20						0-5
		II/B-P	65-79			21-35						0-5
		II/A-Q	80-94				6-20					0-5
		II/B-Q	65-79				21-35					0-5
II	Portland fly ash cement	II/A-V	80-94					6-20				0-5
		II/B-V	65-79					21-35				0-5
		II/A-W	80-94						6-20			0-5
		II/B-W	65-79						21-35			0-5
	Portland burnt shale cement	II/A-T	80-94							6-20		0-5
		II/B-T	65-79							21-35		0-5
	Portland limestone cement	II/A-L	80-94								6-20	0-5
		II/B-L	65-79								21-35	0-5
	Portland composite cement	II/A-M	80-94	← 6-20[e] →								
		II/B-M	65-79	← 21-35[e] →								
III	Blastfurnace cement	III/A	35-64	36-65								0-5
		III/B	20-34	66-80								0-5
		III/C	5-19	81-95								0-5
IV	Pozzolanic cement	IV/A	65-89	-		11-35			-	-	-	0-5
		IV/B	45-64	-		36-55			-	-	-	0-5
V	Composite cement	V/A	40-64	18-30	-		18-30		-	-	-	0-5
		V/B	20-39	31-50	-		31-50		-	-	-	0-5

[a] The values in the table refer to the cement nucleus, excluding calcium sulfate and any additives.
[b] Minor additional constituents may be filler or may be one or more of the main constituents unless these are included as main constituents in the cement.
[c] The proportion of silica fume is limited to 10%.
[d] The proportion of non-ferrous slag is limited to 15%.
[e] The proportion of filler is limited to 5%.

4. AGGREGATES

4.1 Introduction

Aggregates occupy at least three quarters of volume of concrete. Therefore its quality is especially important. Aggregate is cheaper than the cement, and it is economical to put into the mix as much as possible. Economy is not only reason for using aggregates: but it has a higher volume stability and better durability than the cement paste alone.

4.2 General Classification of Aggregates

a) According to Production Methods:

1) Natural Aggregates:

These are taken from native deposits without any change in their natural states during production except for crushing, grading or washing.
Example: sand, gravel, crushed stone, lime rock.

2) By-Product Aggregates:

Comprise blast-furnace slags and cinders, fly ash, etc. Cinders are residue of coal or wood after burning.

3) Processed Aggregates:

These are heat treated, expanded materials with lightweight characteristics.
Example: Perlite, burnt clays, shales, processed fly ash.

4) Colored Aggregates:

Glass, ceramics, manufactured marble for decorative and architectural purposes.

b) According to Petrological Characteristics:

1) Igneous Rocks:

Solidification of molten lava forms igneous rocks. If cooling is slow crystalline structure, if cooling is rapid amorphous structure forms.

Example: Quartz, granite, basalt, obsidian, pumice, tuff.

2) Sedimentary Rocks:

Obtained by the deposition of weathered and transported pre-existing rocks.
Example: Sandstone, limestone, shale.

If these are hard and dense, OK. If not, high absorption capacity gives unsatisfactory results.

3) Metamorphic Rocks:
Formed at a depth under high heat and pressure by the alterations of either igneous rocks or sedimentary rocks.
Example: Marble, slate, schist.
If hard and dense, OK.
If laminated, undesirable.

c) According to Particle Size

In producing good quality concrete, the aggregates should be grouped at least in two groups. Therefore, according to the size of aggregate particles, it (generally) can be classified as:

1) Fine Aggregate (sand):
Fine aggregate includes the particles that all passes through 4.75 mm sieve and retain on 0.075 mm sieve.

2) Coarse Aggregate (gravel):
Coarse aggregate includes the particles that retain on 4.75 mm sieve. Aggregate particles with sizes 0.002-0.075 mm is called as silt and particles smaller than that known as clay.

d) According to Their Unit Weights:

1) Normal Weight Aggregates:
Sand, gravel, crushed stone is called as normal weight aggregates. Concrete produced by these aggregates weighs from 2160 to 2560 kg/m^3.

2) Light Weight Aggregates:
Lightweight aggregates are slag, slate and other light stones that the concrete produced by them weighs from 240 to 1440 kg/m^3. This concrete is normally used for insulation purposes.

3) Heavy Weight Aggregates:
Hemotile, barite magnetite, steel and iron punchings are used to make heavy weight concrete that weighs from 2800 to 6400 kg/m^3.

4.3 Particles Shape and Texture:

The shape and texture of the surface of aggregate particles influence the properties of fresh concrete, more than those of hardened concrete. Sharp, angular and rough aggregate particles require more paste to make good concrete, than do rounded ones.

Table 4.1 Shape Classification of Particles (BS 812 Part 1)

Classification	Description	Examples
Rounded	Fully water-worn or completed shaped by attrition	River or seashore gravel; desert, seashore and wind-blown sand
Irregular	Naturally irregular, or partly shaped by attrition and heaving rounded edges	Other gravel; land or dug flint
Flaky	Material of which the thickness is small relative to the other two dimensions	Laminated rocks
Angular	Possessing well defined edges formed at the intersection of roughly planar faces	Crushed rocks of all types
Elongated	Material, usually angular in which the length is considerably larger than the other two dimensions	
Flaky and Elongated	Material having the length considerably larger than the width and the width considerably larger than the thickness	

The classification of the surface texture is based on the degree to which the particle surfaces are polished or dull, smooth or rough. Surface texture depends on the hardness, grain size and pore characteristics of the parent material. (Hard, dense and fine-grained rocks generally having smooth fracture surfaces).

Table 4.2 Surface Texture of Aggregates (BS 812 Part 1)

Surface	Texture Characteristics	Example
Glassy	Irregular break with curved face	Black flint (chalk), vitreous slag
Smooth	Water-worn, or smooth due to fracture of laminated or fine-grained rock	Gravels, marble, slate
Granular	Fracture showing more or less uniform rounded grains	Sandstone
Rough	Rough fracture of fine or medium grained rock containing no easily visible crystalline constituents	Limestone
Crystalline	Crystalline constituents. Containing easily visible crystalline	Granite
Honeycombed	Constituents with visible pores and cavities	Brick, slag

Table 4.3 A simplified classification of artificial aggregates, based upon the type of raw materials, the degree of any treatment and the uncompacted bulk density of the aggregate product (Lea`s Chemistry of Cement and Concrete)

		Uncompacted bulk density (kg/m^3)			
		Ultra lightweight <300	**Lightweight 300-1000**	**Dense (normal) 1000-1700**	**Extra dense (high density) >1700**
Raw material	**Treatment**	**Some examples with appropriate bulk density ranges[a]**			
Natural	Untreated		Pumice 480-880	Colliery waste/spoil Slate waste China clay sand	Limonite, goethite 2100-2200 Magnetite, ilmenite 2600-2700 Barytes 2800 Haematite 3000
	Treated	Exfoliated vermiculite (micafil) 60-160 Expanded perlite 80-320	Expanded clay/shale (Leca, Fibo/Liapor/Sintag) 380-720 Diatomite 450-800 Sintered colliery waste 550-900 Expanded slate (Liapor) 560-860		
Synthetic	Untreated				Ferrosilicon , ferrophosphorus 4300 Iron or steel shot 4800 Iron or steel fragments Lead shot 8000
	Treated	Expanded polystyrene 10-20 Foamed glass 240-260			
By-product or waste	Untreated		Wood particles 320-480 Furnace clinker or ‘cinders’ (breeze) 720-1040 Furnace-bottom ash	Air-cooled blast-furnace slag 1000-1500 Steel slag 1600-1700 Non-ferrous slags Crushed concrete Crushed brick and tile Broken glass	
	Treated		Foamed slag 560-960 Sintered pfa (Lytag) 770-960 Pelletized expanded slag (pellite) 900 Sintered incinerator ash	Granulated blast-furnace slag Pulverized fuel ash Sintered incinerator ash	Iron separated from slag 3800

[a] The product names given in parenthesis are included for guidance and do not necessarily represent the only commercially available forms in which the materials may be obtained; nor do the products necessarily continue to be available.

4.4 Mechanical Properties of Aggregates

4.4.1 Bond of Aggregate

Bond between aggregate and cement paste is an important factor in the strength of concrete, especially the flexural strength (bending strength) is very related. Bond is due, in part, to the interlocking of the aggregate and the paste owing to the roughness of the surface of the former. A rough surface, such as that of crushed particles, results in a better bond; better bond is also usually obtained with softer, porous and mineralogically heterogeneous particles.

The determination of the quality of bond of aggregate is rather difficult and no accepted test exists. Generally, when bond is good, a crushed concrete specimen should contain some aggregate particles broken right through, in addition to the more numerous ones pulled out from their sockets. An excess of fractured particles, however, might suggest that the aggregate is too weak. Because it depends on the paste strength as well as on the properties of aggregate surface, bond strength increases with the age of concrete.

4.4.2 Strength of Aggregate

It is obvious that the compressive strength of concrete cannot significantly exceed the compressive strength of aggregate contained, although it is not easy to state what is the strength of the individual particles. Indeed, the crushing strength of aggregate cannot be tested with any direct test. There are some indirect tests to inform us about the crushing strength of aggregate.

One of the indirect test to have information about the crushing strength of aggregate is "crushing value test". There is no explicit relation between this crushing value and the compressive strength, but the results of the two tests are in agreement.

Other Mechanical Properties of Aggregates:

a) Impact value: Impact value of aggregates measures the toughness of particles by impact.

b) Abrasion: Abrasion of aggregates measures the resistance of aggregates against wearing.

It is an important property of concrete in roads and in floor surfaces subjected to heavy traffic. The most frequently used test method is the Los Angeles Abrasion Test.

Los Angeles Abrasion Test: The aggregate of specified grading is placed in a cylindrical drum, mounted horizontally. A charge of steel balls is added and the drum is rotated a specified number of revolutions. The tumbling and dropping of the aggregate and the balls result in abrasion and attrition of the aggregate. The resulting grading should be compared with the standard limitations.

4.5 Physical Properties

4.5.1 Specific Gravity

The specific gravity of an aggregate is a characteristic of the material, which needs to be determined in making calculations of mix design of concrete. There are several types of specific gravities:

4.5.2 Bulk Density

It is well known that in the metric system the density of a material is numerically equal to its specific gravity. Because specific gravity has to be multiplied by the unit weight of water in order to convert it into absolute density (specific weight).

Absolute density (or specific weight) refers to the volume of the individual particles only and of course it is not physically possible to pack these particles so that there are no voids between them. When aggregate is to be actually batched by volume it is necessary to know the weight of aggregate that would fill a container of unit volume. This is known as the bulk density of aggregate and this density is used to convert quantities by weight to quantities by volume.

The bulk density depends on how dense the aggregate is packed. For a coarse aggregate of given specific gravity, a higher bulk density means there are fewer voids to be filled by sand, and cement and the bulk density test has at one time been used as a basis of proportioning of mixes.

Bulk density is determined in two ways as, compacted or uncompacted. Therefore the test to which basis is applied should be given.

Empty space between the aggregate particles are termed VOIDS. It is the difference between the gross volume of aggregate mass and volume occupied by the particles alone.

$$Voids\ ratio = 1 - \frac{bulk\ density}{bulk\ sp.gr.(SSD) * unit\ weight\ of\ water}$$

Voids ratio indicates the volume of mortar required to fill the space between the coarse aggregate particles.

4.5.3 Porosity and Absorption of Aggregates

The porosity of aggregate, its permeability, and absorption influence the bonding between aggregate and cement paste, the resistance of concrete to freezing and thawing and resistance to abrasion.

When all the pores in the aggregate are full it is said to be saturated. If just the surface of aggregate is dry then it is said saturated-surface-dry. If the aggregate in saturated surface dry condition allowed to stand free in dry air, some water from pores will evaporate and it is said to be air dry condition. (See Fig. 4.1)

The water absorption of aggregate is determined by measuring the increase in weight of an oven-dried sample when immersed in water, for 24 hours. (The surface water being removed). The ratio of the increase in weight to the weight of dry sample, expressed as a percentage is termed absorption.

Although there is no clear-cut relation between the strength of concrete and the water absorption of aggregate used, the pores at the surface of the particle affect the bond between the aggregate and the cement paste, and thus may exert some influence on the strength of concrete.

Normally, it is assumed that at the time of setting of concrete the aggregate is in a saturated-surface-dry condition. If the aggregate is batched in a dry condition it is assumed that sufficient water will be absorbed from the mix to bring the aggregate to a saturated-surface-dry condition, and this absorbed water is not included in the net mixing water. It is possible, however, that, when dry aggregate is used the particles become quickly coated with cement paste which prevents further ingress of water necessary for saturation.

4.5.4 Moisture Content of Aggregate

Any water on the surface of the aggregate will contribute to the water in the mix. The surface moisture is expressed as a percentage of the weight of the saturated and surface dry aggregate, and is termed as moisture content on saturated surface dry basis.

Since absorption represents the water in aggregate in a saturated and surface dry condition, and the moisture content is the water in excess of that saturated surface dry state, the total water content of a moist aggregate is equal to the sum of absorption and moisture content.

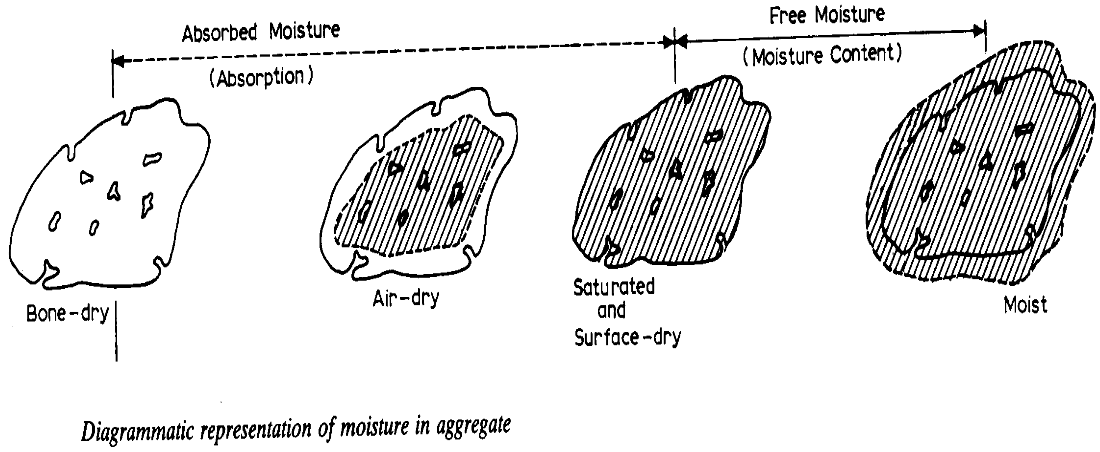


Figure 4.1 Different moisture conditions of aggregates.

If dry basis moisture content is required, the weight of total moist (in the aggregate and on the surface) should be considered.

4.5.5 Deleterious Substances in Aggregates

a) Organic Impurities:

The organic matter found in aggregate consists of products of decay of vegetable matter. The organic impurities may interfere with the process of hydration of cement. This affects the rate of gaining strength.

b) Clay and Other Fine Materials:

Clay may be present in aggregate in the form of surface coatings which interfere with the bond between aggregate and the cement paste. This is an important problem and affects the strength and durability of concrete.

Other types of fine material that can present in aggregate are silt and crusher dust. Silt and crusher dust also adversely affect the bond between cement paste and aggregates.

BS 882: 1973 limits the content of all three materials not more than the follows:

15% by weight in crushed sand
3% by weight in natural or crushed gravel
1% by weight in coarse aggregate.

c) Salt Contamination:

Aggregates obtained from the seashore contain salt and have to be washed with fresh water. The aggregate washed even with the sea water do not contain harmful quantities of salts.

If salt is not removed, it will absorb moisture from the air and cause efflorescence unsightly white deposits on the surface of the concrete. A slight corrosion of reinforcement may also result, but this is not believed to progress to a dangerous degree, especially when the concrete is of good quality and adequate cover to reinforcement is provided.

d) Alkalinity of Aggregates:

Some reactive forms of silica such as opal may occur in some types of rocks, like siliceous limestone. The reaction takes place between the siliceous minerals in the aggregate and the alkaline hydroxides derived from the alkalis (Na_2O, K_2O) in the cement. The resulting gel tends to increase in volume in a humid medium and causes cracking of concrete. In this case, it is recommended to control the limit of alkalis in the cement.

4.5.6 Soundness of Aggregate

This is the name given to the ability of aggregate to resist excessive changes in volume as a result of changes of physical conditions.

Aggregate is said to be unsound when volume changes, induced by the freezing and thawing result in deterioration of the concrete.

4.5.7 Sieve Analysis

Sieve analysis is the name of the operation of dividing a sample of aggregate into fractions, each consisting of particles of the same size. In practice each fraction contains particles between specific limits, these being the openings of standard test sieves.

Table 4.3 Sieve designations

British standards (millimeters)	***American standards***	***Nominal openings (inches)***
75	3 in	3
37.5	1 ½	1.5
20	¾	0.75
12.5	½	0.5
6.3	¼	0.25
4.75	No 4	0.187
2.36	No 8	0.0937
1.18	No 16	0.0469
0.600	No 30	0.0234
0.300	No 50	0.0117
0.150	No 100	0.0059
0.075	No 200	0.0029

Sieves are used to be described by the size of opening for larger openings and by the number of openings for smaller sizes.

All sieves are mounted in frames, which can rest. It is thus possible to place the sieves one above the other in order the size with the largest sieve at the top, and the material retained on each sieve after shaking represents the fraction of aggregate coarser than the sieve in question but finer than the sieve above.

Before the sieve analysis is performed the aggregate sample has to be air dried in order to avoid lumps of fine particles being classified as large particles and also to prevent clogging of the finer sieves.

The weights of the reduced samples for sieving are as given in Table 4.4.

Table 4.4 The weight of reduced samples for sieving.

Nominal Size of Material (mm)	Minimum weight of sample to be taken for sieving (kg)
63	50
50	35
40	15
28	5
20	2
14	1
10	0.5
6 or 5 or 3	0.2
Less than 3	0.1

The results of a sieve analysis are best reported in tabular form as below:

(1) Sieve Sizes (mm)	(2) Weight Retained (gr)	(3) Percentage Retained	(4) Cumulative Percent Retained	(5) Cumulative Percent Passing

Column 1: Sieve sizes

Column 2: The weights retained on each sieve

Column 3: Percentage of retained weights on each sieve according to the total weight of the sample.

Column 4: Cumulative percentage retained starting from largest sieve to smallest one

Column 5: Cumulative percentage passing from each sieve. It is found by subtracting Column 4 values from 100.

4.5.8 Grading Curves

The results of a sieve analysis can be graded much more easily if represented graphically, and for this reason grading charts are very extensively used. By using a chart it is possible to see at a glance whether the grading of a given sample conforms to that specified or is too coarse or too fine.

In the grading chart commonly used, the ordinates represent the cumulative percentage passing and the abscissa the sieve opening plotted to a logarithmic scale.

4.5.9 Fineness Modulus

Fineness modulus is the sum of the cumulative percentage retained on the sieves of the standard series. The value of the fineness modulus is higher the coarser the aggregate. The fineness modulus is not representative of a distribution, therefore it can be used only for measuring slight variations in the aggregate from the same source. It is used in concrete mix design especially in U.S.

Standard test sieves are as follows:
Coarse aggregate: 75mm, 38mm, 20mm, 10mm
Fine aggregate: 4.75mm, 2.36mm, 1.18mm, 0.600mm, 0.300mm, 0.150mm

Limits for FM:
Fine aggregate: 2.3-3.0
Coarse aggregate: 5.5-8.0
Combined aggregate: 4.0-7.0

Before the sieve analysis is performed, the aggregate sample has to be air dried in order to avoid lumps of fine particles being classified as large.

Example on sieve analysis:

Sieve size (mm)	Mass retained (Grams)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
10.00	0	0.0	0	100
5.00	6	2.0	2	98
2.36	31	10.1	12	88
1.18	30	9.8	22	78
0.600	59	19.2	41	59
0.300	107	34.9	76	24
0.150	53	17.3	93	7
pan	21	6.8	-	-
			Total = 246	
	Total = 307		Fineness modulus = 2.46	

4.5.10 Grading Requirements

The purpose of sieve analysis is to determine whether or not a particular grading is suitable. The related problem of grading is the combining of fine and coarse aggregates so as to produce desired grading (See Table 4.5, 4.6).

The strength of fully compacted concrete with a given water/cement ratio is independent of the grading of the aggregate. Grading in the first instance affects only the workability of fresh concrete. But however the development of strength with a given water/cement ratio requires full compaction, and this can be achieved only with a sufficient workable mix.

The main factors governing the desired aggregate grading are: the surface area of the aggregate, which determines the amount of water necessary to wet all the solids; the relative volume occupied by the aggregate; the workability of the mix; and the tendency to segregation.

The grading of aggregate is a major factor in the workability of a concrete mix. Workability, affects the water and cement requirements, controls segregation, has some effect on bleeding, and influence the placing and finishing of the concrete. These factors represent the important characteristics of fresh concrete and affect also the properties in the hardened state: strength, shrinkage and durability.

Grading is thus of vital importance in the proportioning of concrete mixes, but its exact role in mathematical terms is not fully known.

It also must be remembered that far more important than devising a good grading is ensuring that the grading is kept constant; otherwise variable workability results and as this is usually corrected at the mixer by a variation in the water content, concrete of variable strength is obtained.

4.5.11 Gap-Graded Aggregate

Aggregate particles of a given size pack so as to form voids that can be penetrated only if the next smaller size of particles is sufficiently small. This means there must be a minimum difference between the sizes of any two adjacent particle fractions.

Gap grading is a grading in which one or more intermediate size fractions are omitted. The term “continuously” is used to describe conventional grading when, it is to distinguish it from gap grading (see Figure 4.2).

Well Graded means sizes within the entire range are in approximately equal amounts (friction at many points, excellent interlocking, very few voids) (see Figure 4.2).

Uniform gradation means a large percentage of the particles are of approximately the same size (poor interlocking, high percentage of voids, friction at few points of contact) (see Figure 4.2).

Combined gradation means fine and coarse aggregates are combined (friction at many points, good interlocking, few voids, economical).

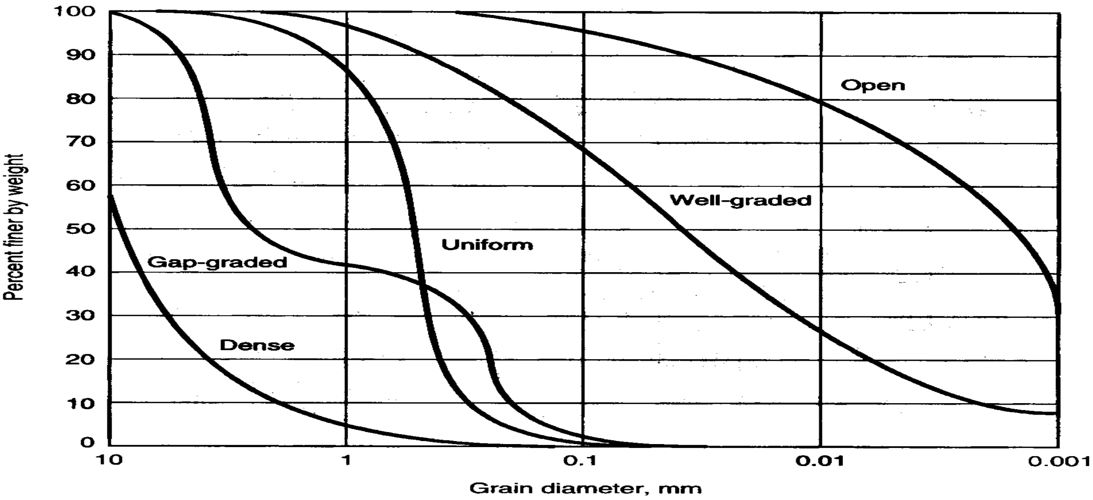


Figure 4.2 Five types of gradation.

Table 4.5: ASTM C33/C 33M Grading Requirements for Fine Aggregates

Sieve	Percent passing
9.5 mm	100
4.75 mm	95-100
2.36 mm	80-100
1.18 mm	50-85
600 µm	25-60
300 µm	5-30
150 µm	0-10

Table 4.6: ASTM C33/C 33M Grading Requirements for Coarse Aggregates

Size	**Amounts finer than each laboratory sieve, mass percent**													
mm	**100**	**90**	**75**	**63**	**50**	**37.5**	**25**	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.300**
90-37.5	100	90-100	...	25-60	...	0-15	...	0-5	...	...	...	...	...	...
63-37.5	...	...	100	90-100	35-70	0-15	...	0-5	...	...	...	...	...	...
50-25	...	...	...	100	90-100	35-70	0-15	...	0-5	...	...	...	...	...
50-4.75	...	...	...	100	95-100	...	35-70	...	10-30	...	0-5	...	...	...
37.5-19	...	...	...	...	100	90-100	20-55	0-15	...	0-5	...	...	...	...
37.5-4.75	...	...	...	...	100	95-100	...	35-70	...	10-30	0-5	...	...	...
25-12.5	...	...	...	...	...	100	90-100	20-55	0-10	0-5	...	...	...	...
25-9.5	...	...	...	...	...	100	90-100	40-85	10-40	0-15	0-5	...	...	...
25-4.95	...	...	...	...	...	100	95-100	...	25-60	...	0-10	0-5	...	...
19-9.5	...	...	...	...	...	...	100	90-100	20-55	0-15	0-5	...	...	...
19-4.75	...	...	...	...	...	...	100	90-100	...	20-55	0-10	0-5	...	...
12.5-4.75	...	...	...	...	...	...	...	100	90-100	40-70	0-15	0-5	...	...
9.5-2.36	...	...	...	...	...	...	...	...	100	85-100	10-30	0-10	0-5	...
9.5-1.18	...	...	...	...	...	...	...	...	100	90-100	20-55	5-30	0-10	0-5
4.75-1.18	...	...	...	...	...	...	...	...	...	100	85-100	10-40	0-10	0-5

On a grading curve, a horizontal line represents gap grading over the range of sizes omitted.

Gap graded aggregate can be used mostly in: Preplaced aggregate concrete; where aggregate is placed first and then mortar is pumped among those aggregate particles. Useful in mass concrete, present over heating, by cooling the aggregate with cold water.

5. FRESH CONCRETE

5.1 Introduction

The strength of concrete of a given mix proportions is very seriously affected by the degree of its compaction; it is vital, therefore, that the consistency (consistency: ability to flow) of the mix be such that, the concrete can be transported, placed and finished sufficiently easily and without segregation.

5.2 Workability

The term workability is used to describe the ease with which concrete mixes can be compacted. The highest workability must be so that concrete will be as completely compacted as possible while using the lowest possible water/cement ratio.

Workability should be obtained by the use of a well-graded aggregate and one, which has the largest maximum particle size possible. The use of smooth and rounded, rather than irregularly shaped aggregate also increase workability, but in high strength concretes, there may be no overall increase in strength, because with equal water/cement ratios irregularly shaped aggregate produce, the stronger concrete.

Air entraining admixtures improve the workability of mixes (and improve the frost resistance of hardened concrete) but reduction in density of the concrete is accompanied by a loss of strength up to about 15 percent.

Consequently we can summarize the factor of workability as:

1. **Water content of the mix:** Adding water increases workability and decreases strength.
2. **Maximum size of aggregate**: Less surface area to be wetted and more water in medium.
3. **Grading of aggregate**: Poor grading reduces the consistency.
4. **Shape and texture of aggregates**: Smooth surfaces give better workability.

In general water content and the other mix proportions are fixed. The workability is governed by the maximum size of aggregate, its grading, shape and texture.

Finer particles require more water to wet their larger specific surface. The irregular shape and rougher texture of an angular aggregate demands more water to wet their larger specific surface than rounded one.

5.2.1 Measurement of Workability

Unfortunately, there is no accepted test, which measure directly the workability. There are numerous attempts to correlate workability with some easily determinable physical measurements, but none of these is fully satisfactory, although they may provide useful information within a range of variation in workability.

Due to absorption of water by cement (and aggregates if absorbent) workability may decrease rapidly after mixing.

There are 5 types of test, which can measure workability indirectly. Unfortunately, there are no accepted tests, which can measure directly the workability.

1. *Slump Test*: Gives good results for rich mixes.
2. *Compacting Factor Test*: Used for low workable concretes.
3. *Flow Table Test*: Used for high workable concretes.
4. *VeBe Test*: Used for low workable concretes (fiber reinforced concrete).
5. *Kelly Ball Test*: It is practical in field test.

1. SLUMP TEST

This is a test used extensively in site work all over the world. The slump test does not measure the workability of concrete but is very useful in detecting variations in the uniformity of a mix of given nominal proportions.

Mixes of stiff consistence have a zero slump, so that in the rather dry range no variation can be detected between mixes of different workability. Rich mixes behave satisfactorily, their slump being sensitive to variations in workability. However in a lean mix with a tendency to harshness a true slump can easily change to the shear type or even to collapse, (Figure 5.1) and widely different values of slump can be obtained in different samples from the same mix.

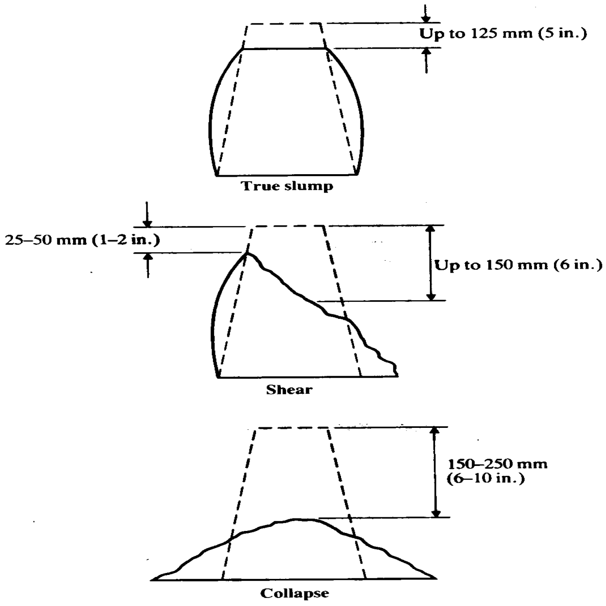


Figure 5.1 Slump: true, shear, and collapse

2. COMPACTING FACTOR TEST

There is no generally accepted method of directly measuring workability i.e. the amount of work necessary to achieve full compaction. Probably the best test yet available uses the inverse approach; the degree of compaction achieved by a standard amount of work is determined.

The degree of compaction, called compacting factor, is measured by the density ratio, i.e. the ratio of the density of actually achieved in the test to the density of the same concrete fully compacted.

Unlike the slump test variations in the workability of dry concrete are reflected in a large change in the compacting factor i.e. the test is more sensitive at the low workability. For concrete of very low workability the actual amount of work required for full compaction depends on the richness of the mix while the compacting factor does not: leaner mixes need more work than richer ones.

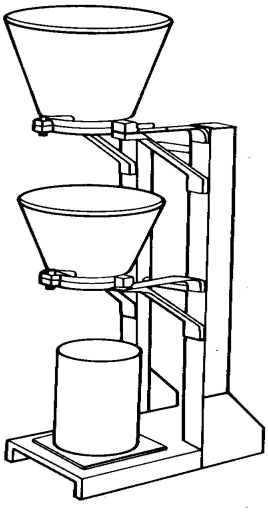


Figure 5.2 Compacting factor apparatus.

3. FLOW TEST

Measures the diameter of spread after vibration.

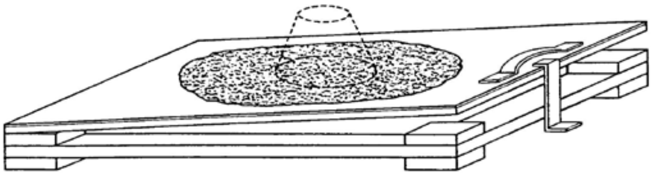


Figure 5.3 Flow table apparatus.

4. VEBE TEST

Start time after removing cone and stop counter once the transparent rider is covered with paste. Record in seconds. This is VeBe time.

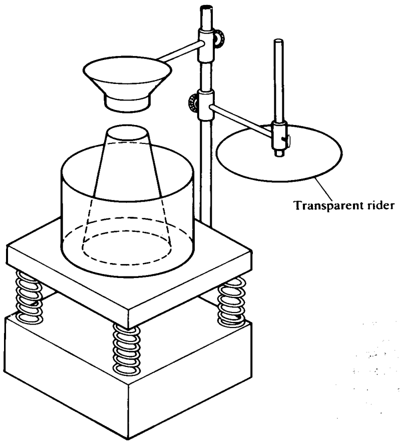


Figure 5.4 Ve-Be test apparatus.

5. KELLY BALL TEST:

Measures the depth of penetration.

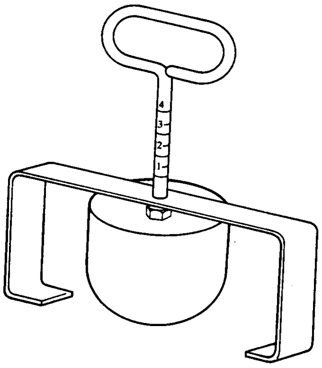


Figure 5.5 Kelly ball aparatus.

Table 5.1 gives a relation between workability, slump and compacting factor of concrete with 19 or 38 mm maximum size aggregates.

Table 5.1 Workability, slump and compacting factor of concretes with 19 or 38 mm (0.75 or 1.50 in.) maximum size of aggregate.

Degree of workability	Slump (mm)	Compacting factor	Uses for which concrete is suitable
Very low	0-25	0.78	Roads vibrated by power operated machines. At the more workable end of this group, concrete may be compacted in certain cases with hand operated machines
Low	25-50	0.85	Roads vibrated by hand operated machines. At the more workable end of this group, concrete may be manually compacted in roads using aggregate of rounded or irregular shaped. Mass concrete foundations without vibration or lightly reinforced sections with vibration.
Medium	50-100	0.92	At the less workable end of this group, manually compacted flat slabs using crushed aggregates. Normal reinforced concrete manually compacted and heavily reinforced sections with vibration.
High	100-175	0.95	For sections with congested reinforcement, not normally suitable for vibration.

Table 5.2 Range of slump and VeBe time for different construction types.

☐ **Type of Construction**	**Suitable slump**				**Suitable Vebe time**	
	mm		**In.**		**Seconds**	
	Min	**Max**	**Min**	**Max**	**Max**	**Min**
Uncongested precast concrete	0	25	0	1	-	12
Power vibrated pavements						
Mass concrete	0	50	0	2	-	4
Slabs	25	75	1	3	2	8
Footings						
Uncongested walls						
Columns	25	100	1	4	1	7
Beams						
Normally reinforced walls						
Congested narrow sections	100	175	4	7	0	2

5.3 Segregation

Segregation can be defined as separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform.

There are two forms of segregation:

1) In the **first** form, the coarse particles tend to separate out since they tend to settle more than fine particles.
2) The **second** form of segregation occurs particularly in wet mixes; it is manifested by the separation of (cement+water) from the mix.

For some gradings, when a lean mix is used, the first type of segregation may occur if the mix is too dry. Addition of water would improve the cohesion of the mix, but when the mix becomes too wet the second type of segregation would take place.

If the concrete does not have to travel and is transferred directly from the wheel-barrow to the position in the form, the danger of segregation is small.
On the other hand, dropping concrete from a considerable height, passing along a chute, particularly with changes of direction and discharging against an obstacle, all these encourage segregation, so that under such circumstances a particularly cohesive mix should be used.

It should be stressed, however that, concrete should always be placed direct in the position in which it is to remain and must not be allowed to flow or be worked along the form. This prohibition includes the use of a vibrator to spread a heap of concrete over a large area. Vibration provides a most valuable means of compacting concrete, but, because a large amount of work is being done on the concrete, the danger of segregation due to an improper use of a vibrator is increased. This is particularly so when vibration is allowed to continue too long; with many mixes, separation of coarse aggregate toward the bottom of the form and the cement paste toward the top may result. Such concrete would obviously be weak, and the scum on its surface would be too rich and too wet so that a surface with a tendency to dusting might result.

It may be noted that entrained air reduces the danger of segregation. On the other hand the use of coarse aggregate whose specific gravity differs appreciably from that of fine aggregate would lead to increased segregation.

5.4 Bleeding

Bleeding, known also as water gain, is a form of segregation, in which some of the water in the mix tends to rise to the surface of freshly placed concrete. This is caused by the inability of the solid constituents of the mix to hold all of the mixing water when they settle downwards. Bleeding can be expressed quantitatively as the total settlement per unit height of concrete.

As a result of bleeding, the top of every lift may become too wet and if the water is trapped by concrete, porous, weak, and non-durable concrete will result. If the bleeding water is remixed during finishing of the top surface a weak wearing surface will be formed. This can be avoided by delaying the finishing operations until the bleeding water has evaporated.

Some of the rising water becomes trapped on the underside of coarse aggregate particles or of reinforcement, thus creating zones of poor bond.

Bleeding need not necessarily be harmful. If it is undisturbed and the water evaporates the effective water/cement ratio may be lowered with a resulting increase in strength. On the other hand, if the rising water carries with it a considerable amount of the finer cement particles a layer of scum will be formed. At the top of a slab a porous surface will form and result with a permanently dusty surface. At the top of a lift a plane of weakness would form and the bond with the next lift would be inadequate. For this reason, scum should always be removed by brushing and washing.

The tendency to bleeding depends on the properties of cement. Bleeding is decreased by increasing the fineness of cement or adding of calciumchloride to cement. Rich mixes are less prone to bleeding than lean ones. Reduction in bleeding is obtained by the addition of pozzolans or of aluminium powder. Air entrainment effectively reduces bleeding so that finishing can follow casting without delay.

5.5 Mixing Time

On a site, there is often a tendency to mix concrete as rapidly as possible, and therefore, it is important to know what is the minimum mixing time necessary to produce a concrete uniform in composition and as result of satisfactory strength. This time varies with the type of mixer, and in fact it is not the mixing time but the number of revolutions of the mixer that is the criterion of adequate mixing. Generally about 30 revolutions are sufficient.

For a given mixer, there exists a relation between mixing time and uniformity of the mix. It is apparent that mixing for less than 1 to l ¼ minutes produces an appreciably more variably concrete, but prolonging the mixing time beyond these values results in no significant improvement in uniformity.

Table 5.3 Recommended minimum mixing times.

Capacity of mixer (m^3)	Mixing time (Minutes)
0.8	1
1.5	1 ¼
2.3	1 ½
3.1	1 ¾
3.8	2
4.6	2 ¼
7.6	3 ¼

ACI 304-73 (reaffirmed 1983) and ASTM Standard C 94-83.

5.6 Compaction of Concrete

In the process of compacting the concrete consists essentially of the elimination of entrapped air in concrete. It can be achieved either by ramming or by vibration. In any case the particles are so separated that a compact mass is obtained.

The use of vibration as a means of compaction makes it possible to use drier mixes that for a given strength concrete can be made with lower cement content. But, vibration must be applied uniformly to the entire concrete mass so that, for some parts of it will not be left without compaction while others are segregated owing to over-vibration. (Cost of labor is high for vibration)

The two basic means of compaction require mixes of different workabilities: too dry mix cannot be sufficiently worked by hand; and, conversely, too wet mix should not be vibrated as segregation may result.

A drier mix needs stronger formwork compared to wet mixes. This will increase the cost.

Types of Vibrators

a) Internal vibrator
b) External vibrators
c) Vibrating tables

5.7 Curing of Concrete

Curing means, the creation of an environment for a relatively short period, immediately after placing of concrete. The desirable conditions of that environment are suitable temperature and preventing the loss of moisture or providing moisture.

5.7.1. Common Techniques of Curing

1. Prevention of evaporation due to sun or drying wind: This is done by using polythene sheeting, tarpaulins or waterproof paper. It is better to place these materials after spraying some water on the surface.
2. Surface-spraying with a chemical composition: This chemical composition forms an impervious layer. This is applied when the concrete is still moist but not wet. The main disadvantage of this technique is that the composition layer prevents the bonding between hardened concrete and any finishes or fresh concrete, which may be applied. However, it is possible to remove that layer effectively.
3. Covering concrete surface with wet straw or hessian sacking after preliminary hardening of concrete. This material may require to be damped periodically in hot or windy conditions.
4. Flooding horizontal slabs with water.
5. The use of insulated formwork. Especially timber is a good insulated and prolonging of stripping time is a method of curing.
6. Blowing warm air around concrete or employing electrically heated insulating mats (for very cold weathers).

5.7.2. Selection of Curing Techniques

Selection of technique depends on economic consideration, which depends on labour, material and plant available. Besides, environmental conditions, structural and visual requirements affect the degree of curing to be applied.

Particular care is required when placing concrete in large pours, because of the high temperature generated in the mass during hydration. Subsequent cooling is liable to cause cracking. If it is possible applying of flooding technique is the best one for this case.

In very cold weather, insulating of both formwork and the surface may well be needed. The use of water curing is obviously unsuitable. Applying of straw is the best. When it is not very cold, polythene sheeting may be acceptable. Very low temperatures may require the use of electrically heated insulation mats or the discharge of warm air between the concrete surface and a cover. Accelerating admixtures in the concrete help generation of heat, thereby helping the curing process and shortening its duration. Curing and stripping periods must be considerably extended in very cold weather.
In very hot weather, curing membranes or polythene sheeting is particularly necessary. The use of water is also a solution if it is applicable. Retarding admixtures are particularly useful in assisting the effectiveness of curing.

5.8 Quality of Mixing Water

The quality of mixing water plays some roles for the strength of concrete. Impurities in water may interfere with the setting of the cement; may adversely affect the strength of the concrete, or cause staining on its surface; and may also lead to corrosion of the reinforcement. For these reasons, the suitability of water for mixing and curing purposes should be considered. In many specifications, the quality of water is covered by a clause saying that water should be fit for drinking.

Seawater has a total salinity of about 3-5 per cent, and produces a slightly higher early strength but a lower long-term strength; the loss of strength is usually no more than 15 percent and can therefore often be tolerated.

Water containing large quantities of chlorides (e.g. sea water) tends to cause persistent dampness and surface efflorescence. Such water should therefore, not be used where appearance of the concrete is important.

In the case of reinforced concrete, seawater is believed to increase the risk of corrosion of the reinforcement, although there is no experimental evidence that the use of sea water in mixing leads to attack on the reinforcing steel. However in practice it is generally considered inadvisable to use sea water for mixing unless this is unavoidable.

5.9 Mixing, handling, placing and compacting concrete

- Tilting drum mixers
- Non-tilting drum mixers
- Pan-type mixers
- Dual drum mixers
- Continuous mixers

5.10 Charging the Mixer

No general rule. Below steps can be followed.

- Feed small amount of water in mixer.
- Add solid materials.
- If water or cement fed too fast or is too hot, cement balls will form.

5.11 Uniformity of Mixing

Differences of two samples should not exceed any of the following:

- Density of concrete: 16 kg/m^3
- Air content: 1%
- Slump: 25 mm when average is less than 100 mm; 40 mm when average is 100 – 150 mm.
- % of aggregate retained on 5 mm sieve: 6
- Density of air free-mortar: 1.6 %

Compressive strength (average 7-day value of 3 cylinders): 7.5%

For a suitable performance test of mixers, tests are made on two samples from each quarter of a batch, and each sample is subjected to wet analysis to determine:

- Water content as % of solids (to 0.1%)
- Fine aggregate content as % of total aggregate (to 0.5%)
- Cement as % of total aggregate (to 0.01%)
- Water/cement ratio (to 0.01).

5.12 Mixing time

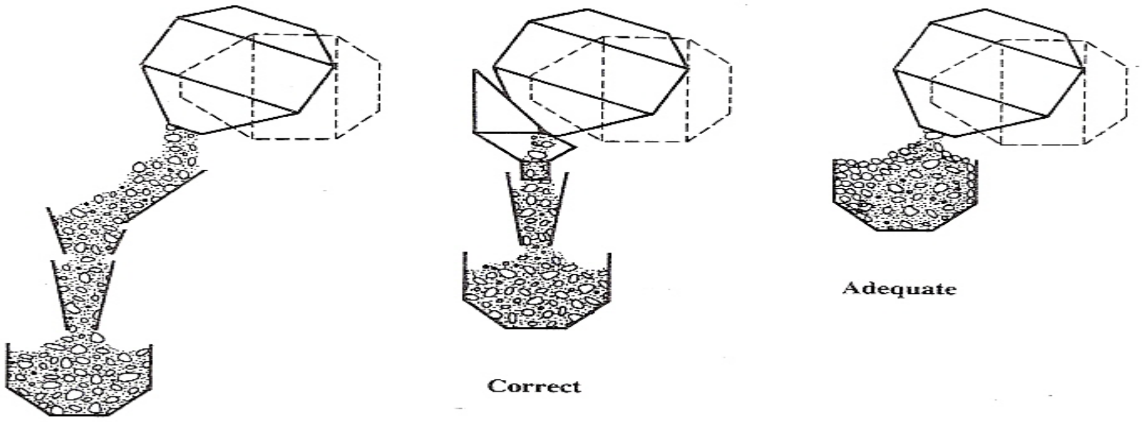
Mixing time is determined based on twenty revolutions of any mixer. Therefore, as mixer becomes bigger (in terms of capacity) the time needed for thourough mixing will be longer. Below table is prepared for different mixer capacities.

Table 5.4 Mixing times for various mixer capacities.

Capacity of mixer (m^3)	Mixing time (minutes)
0.8	1
1.5	1 ¼
2.3	1 ½
3.1	1 ¾
3.8	2
4.6	2 ¼
7.6	3 ¼

5.13 Handling

There are many methods to transport concrete from one place to another.
Methods should be economical & concrete quality should be maintained.

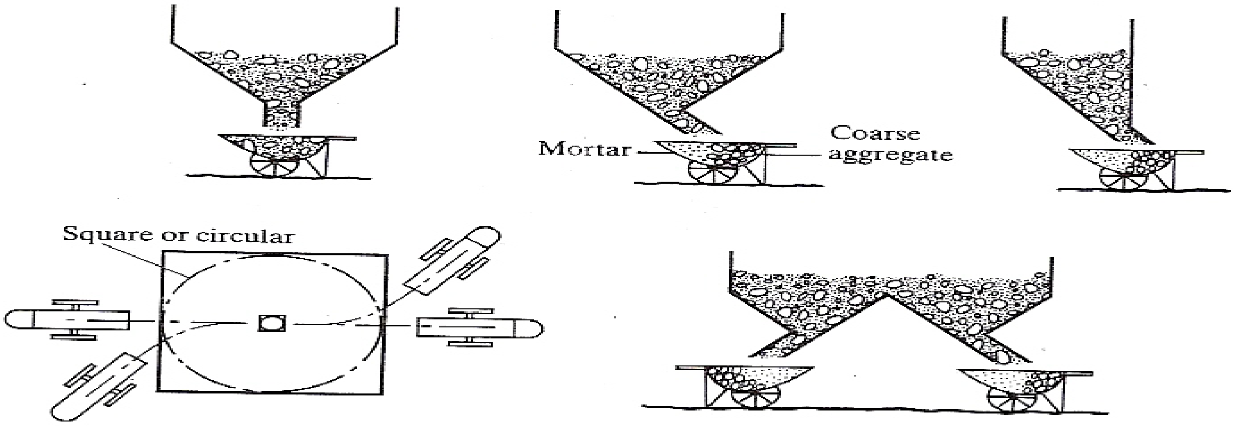


Correct

Correct

Adequate

Figure 5.6 Control of segregation on discharge of concrete from a mixer (based on ACI Manual of Concrete Practice)



Correct

Incorrect

Figure 5.7 Control of segregation on discharge of concrete from a hooper (based on ACI Manual of Concrete Practice)

5.14 Pumped concrete

- Large quantities of concrete can be transported by means of a pump to location where access is not easy.

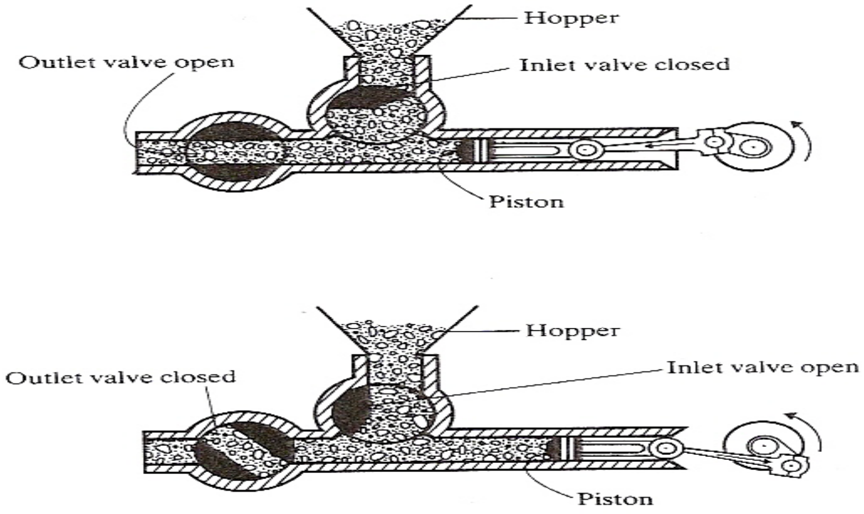


Figure 5.8 Direct-acting concrete pump

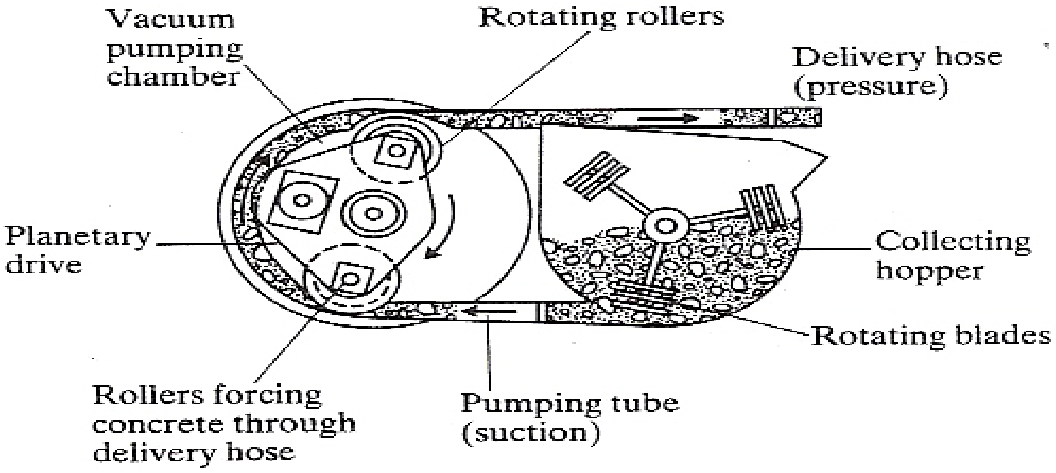
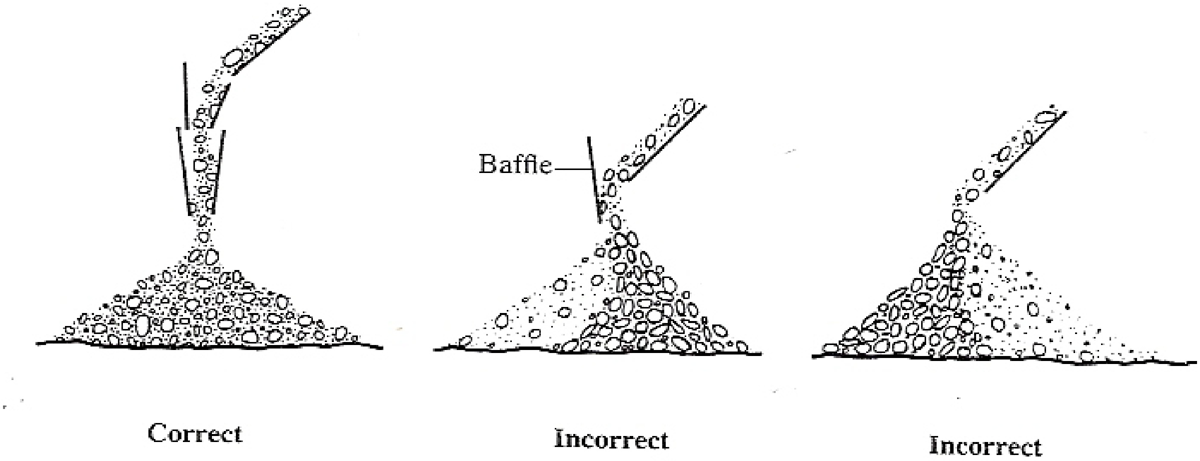


Figure 5.9 Squeeze-type concrete pump

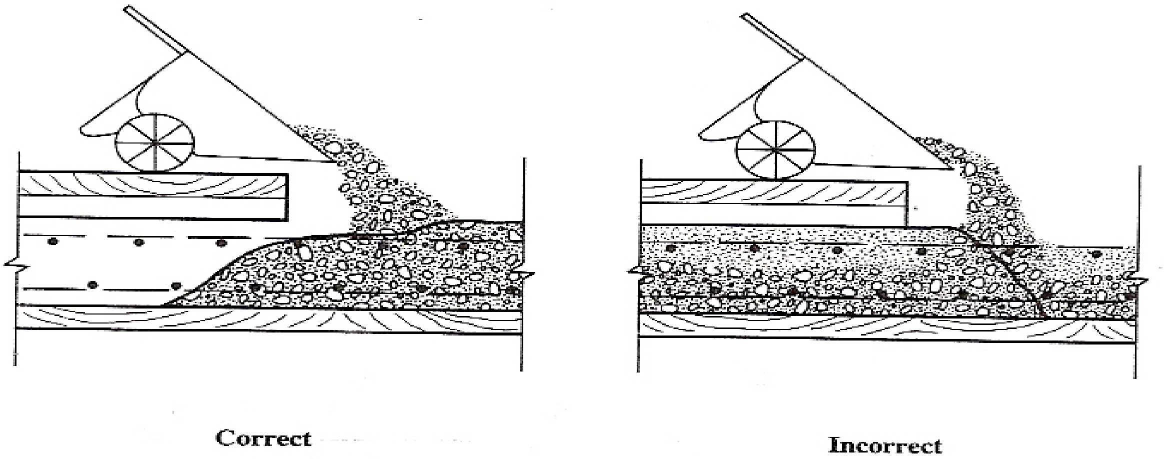


Correct

Incorrect

Incorrect

Figure 5.10 Control of segregation at the end of concrete chutes (based on ACI Manual of Concrete Practice)



Correct

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Figure 5.11 Placing concrete from bugies (based on ACI Manual of Concrete Practice)

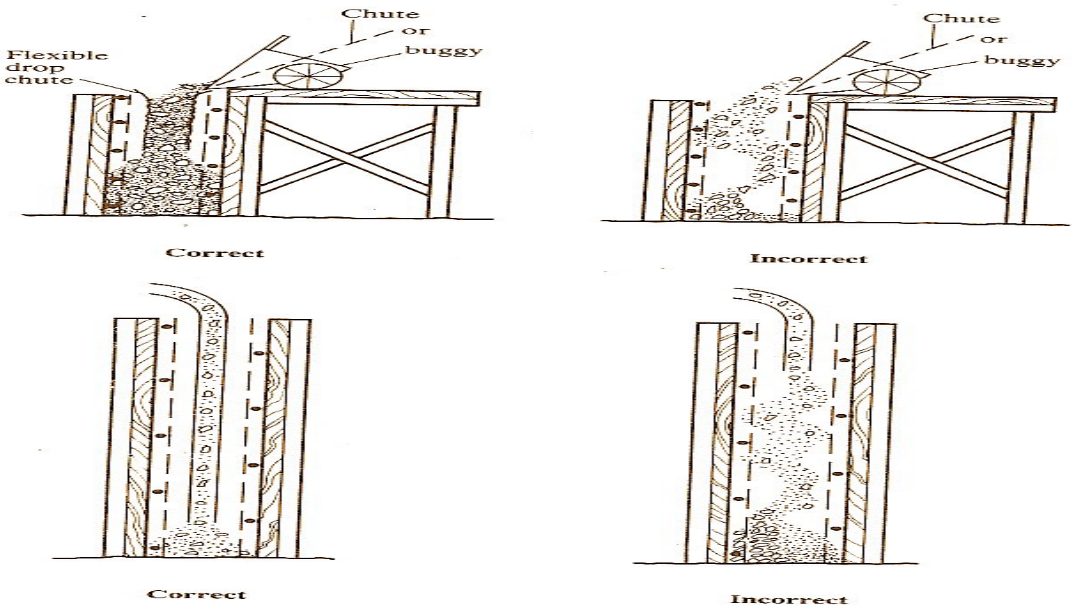


Figure 5.12 Placing concrete in a deep wall (based on ACI Manual of Concrete Practice)

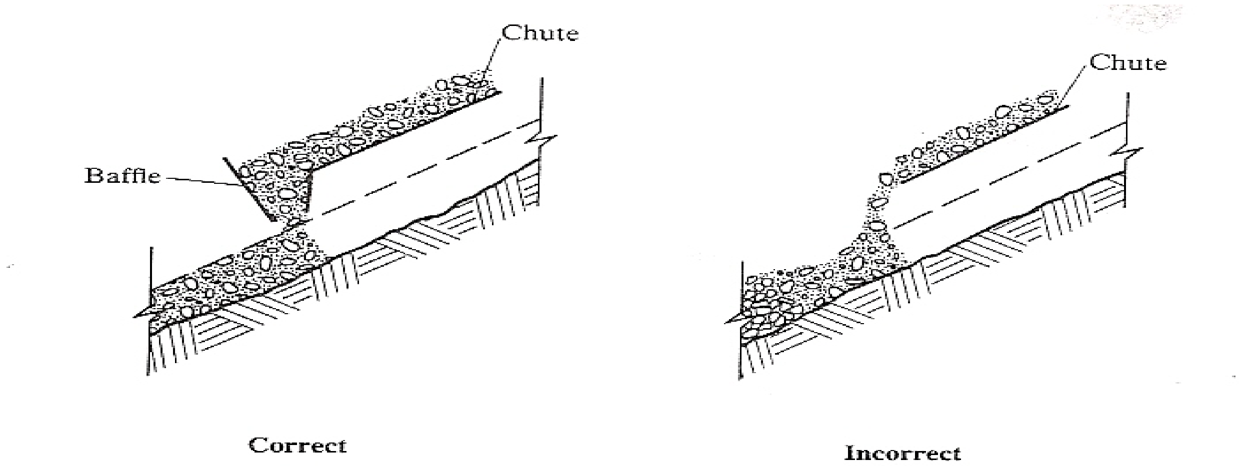


Figure 5.13 Placing on a sloping surface (based on ACI Manual of Concrete Practice)

5.15 Underwater Concreting

Underwater concreting is a special technique that is used to make concreting in water. Method is named as "tremie method" and still being used.

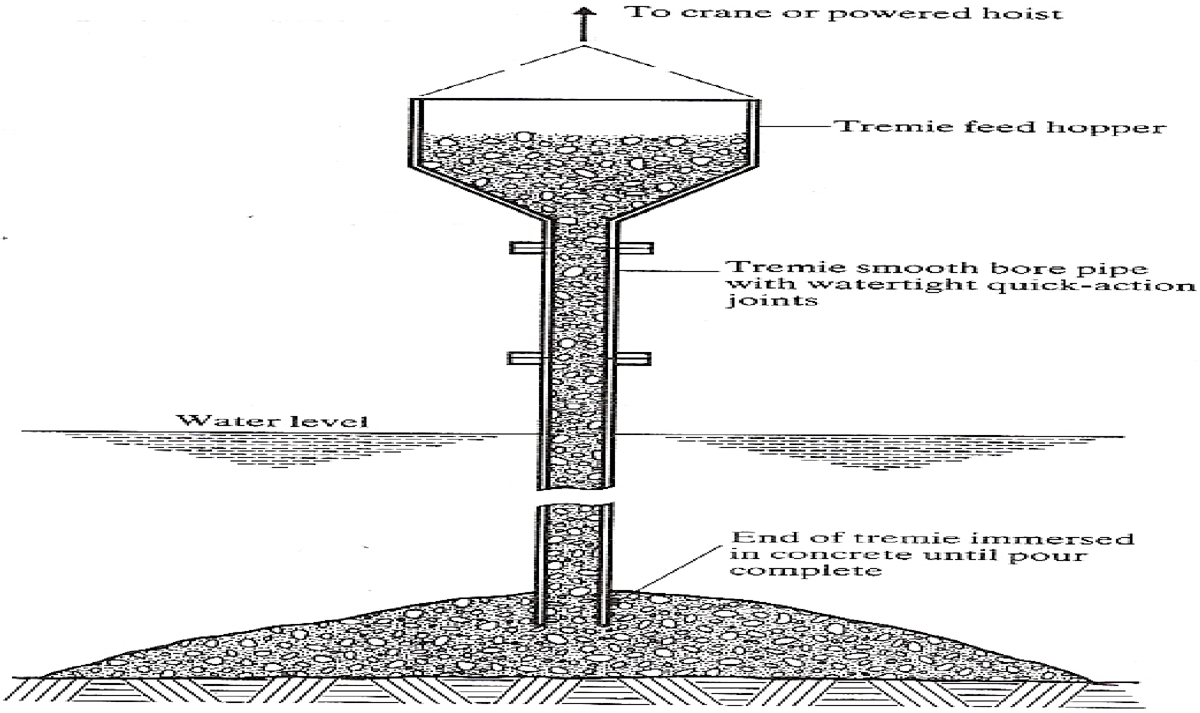


Figure 5.14 Underwater Concreting (based on Concrete Society, Underwater concreting, technical Report, No. 3, pp. 13, London, 1971)

6. HARDENED CONCRETE

6.1 Shrinkage

Shrinkage of concrete is caused by the settlement of solids and the loss of free water from the plastic concrete (plastic shrinkage), by the chemical combination of cement with water (autogenous shrinkage) and by the drying concrete (drying shrinkage). Where movement of the concrete is restrained, shrinkage will produce tensile stress within the concrete, which may cause cracking.

6.1.1 Plastic Shrinkage

Shrinkage, which takes place before concrete has set, is known as plastic shrinkage. This occurs as a result of the loss of free water and the settlement of solids in the mix. Since evaporation usually accounts for a large proportion of the water losses plastic shrinkage is most common in slab construction and is characterized by the appearance of surface cracks which can extend quite deeply into the concrete. Preventive measures are usually based on methods of reducing water loss. This can be achieved in practice by covering concrete with wet polythene sheets or by spraying it with a membrane-curing compound.

6.1.2 Autogenous Shrinkage

In a set concrete, as hydration proceeds, a net decrease in volume occurs since the hydrated cement gel has a smaller volume than the same of the cement and water constituents. As hydration continues in an environment where the water content is constant, such as inside a large mass of concrete, this decrease in volume of the cement paste results in shrinkage of the concrete. This is known as autogenous shrinkage, because as the name implies, it is self-produced by the hydration of cement. However when concrete is cured under water, the water taken up by cement during hydration is replaced from outside and furthermore the gel particles absorb more water, thus producing a net increase in volume of the cement paste and an expansion of the concrete. On the other hand, if concrete is kept in dry atmosphere water is drawn out of the hydrated gel and additional shrinkage, known as drying shrinkage occurs. Several factors influence the rate and magnitude of autogenous shrinkage. These include the chemical composition of cement, the initial water content, temperature and time.

6.1.3 Drying Shrinkage

When a hardened concrete, cured in water, is allowed to dry it first loses water from its voids and capillary pores and only starts to shrink during further drying when water is drawn, out of its cement gel. This is known as drying shrinkage. After an initial high rate of drying shrinkage concrete continues to shrink for a long period of time, but at a continuously decreasing rate. For practical purposes, it may be assumed that for small sections 50 per cent of the total shrinkage occurs in the first year.

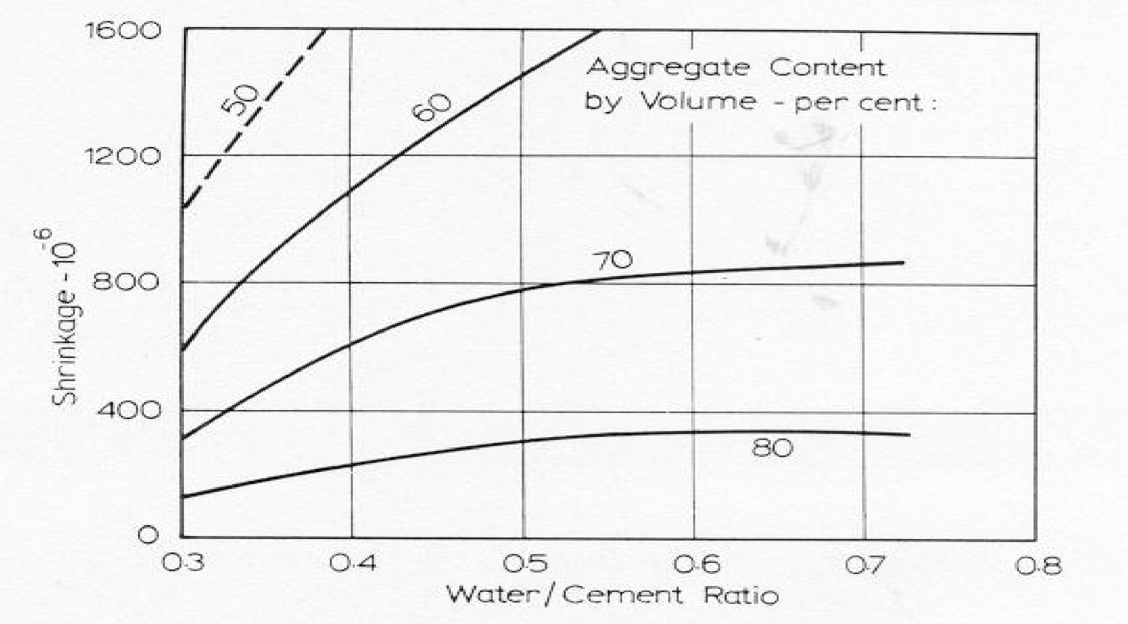


Figure 6.1 Influence of water/cement ratio and aggregate content on shrinkage.

Since the aggregate exerts a restraining influence on shrinkage, the maximum aggregate content compatible with other required properties is desirable. When the aggregate itself is susceptible to large moisture movement, this can aggravate shrinkage (or swelling) of the concrete and may result in excessive cracking and large deflection of beams and slabs.

The size and shape of a specimen affects the rate of moisture movement in concrete and this in turn influences the rate of volume change. Since drying begins from the surface, it follows that the greater the surface area per unit mass, the greater the rate of shrinkage.

The shrinkage of reinforced concrete is less than that of plain concrete owing to the restraint developed by the reinforcement. This restraint induces tensile stress in the concrete which may be large enough to cause shrinkage.

The relative humidity and temperature of the environment have a significant effect on both the rate and the magnitude of the shrinkage in as much as they affect the movement of water in concrete. The duration of initial moist curing has little effect on ultimate shrinkage although it affects the initial rate of shrinkage.

6.2 Durability

Besides its ability to sustain loads, concrete is also required to be durable. The durability of concrete can be defined as its resistance to deterioration resulting from external and internal causes. The external causes include the effects of environmental and service conditions to which concrete is subjected such as weathering, chemical actions and wear. The internal causes are the effects of interaction between the constituent material such as alkali-aggregate reaction, volume changes, absorption and permeability.

In order to produce a durable concrete care should be taken to select suitable constituent materials. It is also important that the mix contains adequate quantities of materials in proportions suitable for producing a homogeneous and fully compacted concrete mass.

6.2.1 Factors Affecting Durability

The durability of concrete is its resistance to deterioration resulting from external or internal causes.

External Causes

Physical, chemical or mechanical:

a) Leaching out of cement

b) Actions of sulphates, seawater and natural slightly acidic water. The resistance to these attacks varies with the type of cement used and increases in the order; OPC and RHC (rapid hardening cement)

Environmental such as occurrence of extreme temperatures, abrasion and electrostatic action.

Attack by natural or industrial liquids and gasses.

Internal Causes:

a) Alkali-aggregate reactions

b) Volume change due to difference in thermal properties of the aggregate and cement paste.

c) Permeability of concrete.

Alkali-Aggregate Reactions: Is the reactions between the active SILICA constituents of the aggregate, and ALKALIES in cement. As a result of these reactions expansion of cement gel causes cracks.
Reactive form of SILICA occurs in OPALINE.

Recommended Protective Treatments:
Low w/c ratios (less than 0.5)
Suitable workability
Thorough mixing
Proper placing and compaction
Adequate and timely curing.

6.3 Testing of Hardened Concrete

6.3.1 Compressive Strength

It is the most important property of hardened concrete and is generally considered in the design of concrete mixtures. It is customary to estimate the properties of concrete in the structure from compression tests on specimens made from fresh concrete as it is placed and cured in the standard manner.

Dimensions of the concrete specimens usually have the following sizes:
Cylindrical specimens of *diameters* = 7.5, 10, 15 cm
Cubes: 5, 10, 15 cm

Compressive strength is affected by many factors (environmental, curing condition). Therefore, the actual strength of concrete will not be the same as the strength of specimen.

Testing for Compressive Strength

The compressive strength of concrete is determined from compressive test on cylindrical / cube specimens.
Empty moulds are filled with fresh concrete using a standard procedure. After 24 hours the specimens are taken out of the moulds and moist cured for 28 days at the end of the curing period they are tested.

$$f_c = \frac{failure\ load}{cross - sectional\ area}$$

$$f_c = \frac{4P}{\pi D^2} \quad cylinder$$

$$f_c = \frac{P}{a^2} \quad cube$$

where P = failure load

D = diameter of cylinder

a = one side of cube

The following conversion chart can be used to convert concrete specimens from one size to another.

	divide by			
	100 mm cube	150 mm cube	200 mm cube	150x300 mm cylinder
100 mm cube	1	1.01	1.05	1.22
150 mm cube	-	1.00	1.04	1.20
200 mm cube	-	-	1.00	1.15
100x200 mm cylinder	-	-	-	1.06

The compressive strength thus determined is found to depend on the size of the specimen, the shape of the specimen, and the moisture condition. The greater the ratio of height to diameter, the lower is the measured compressive strength.

Moisture content of specimens affects the compressive strength. Air-dried specimens (at the time of testing) are shown to possess more compressive strength than that of saturated specimens, on the order of 20 to 25 %.

Speed of testing: a slower rate will show a lower strength.

In laboratory: (2-3 minutes) to reach failure.

6.3.2 Tensile Strength

The tensile strength of concrete is important to resist cracking from shrinkage and temperature changes.

a) Direct Tensile Strength:

Difficult to measure and is not usually done.

b) Splitting Tensile Strength:

The cylindrical specimens (on cube) (placed with its axis horizontal) is subjected to a line load (uniform) along the length of the specimen (Figure 6.4).

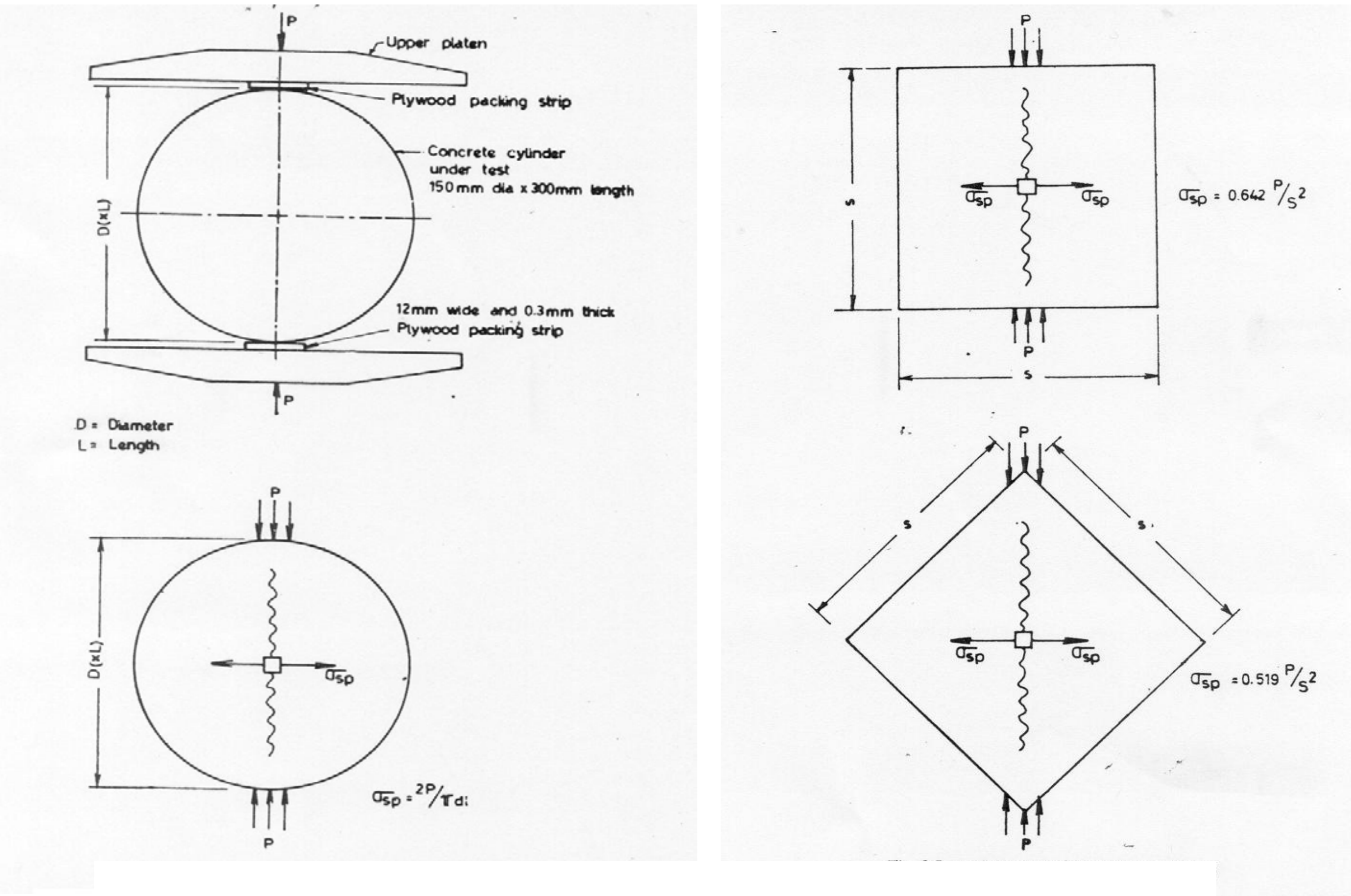


Figure 6.4 Loading arrangement of cylindrical and cubic specimens for split strength determination

Using the load (P) at which the specimens splits into two, the tensile strength can be calculated:

$$f_t = \frac{2P}{\pi l d} \quad cylinder$$

l : length of cylinder

d : diameter of cylinder

f_t : splitting tensile strength (10% of compressive strength)

7. CONCRETE MIX DESIGN CALCULATIONS

7.1 The workability of concrete

7.1.1 Measurement of workability

The word workability has been used to embrace many factors associated with the ease of placing concrete, such as its cohesiveness, mobility, compactibility and finishability. No satisfactory single test method has yet been devised to measure these combined characteristics. A workable concrete would be defined as a concrete suitable for placing and compacting under the site conditions using the plant available; thus in road construction a low-slump concrete is more suitable than one with a high slump. It is not considered practical for this publication to define the workability required for various types of construction or placing conditions since this is affected by many factors. This publication uses the slump and Vebe time tests as the means by which the workability of the concrete is specified as one of four ranges given in Table 3.

7.1.2 Water content

The water content expressed as mass per unit volume of concrete is the major factor influencing the workability of concrete. For a given type and maximum size of aggregate, the higher the water content the higher the slump and the lower the Vebe time. The free-water content required to produce concrete of a specified slump or Vebe time depends upon the characteristics of the aggregate. Research work using 24 crushed rock aggregates showed a range of water requirements from 170 kg/m^3 to 230 kg/m^3. A similar range was found during a nationwide survey of mix design data from ready-mixed concrete producers. However, as a general rule it can be assumed that uncrushed aggregates require a lower water content than crushed aggregates to make concrete of equal workability, and that the smaller the maximum size of the aggregate the higher the water content needed. Table 3 gives typical values of the free-water content for use in the mix design at four different levels of slump or Vebe time, with different types and maximum sizes of aggregate. If there is more appropriate information available related to the local materials, this can be used instead of the values given in Table 3. The grading of the coarse aggregate, provided that it complies with the requirements of BS 882, has little effect on the water requirement of a concrete mix The grading of the fine aggregate has a considerable effect on the water requirement of the concrete. Changing the grading of a sand from a coarse one, (ie say 20% by mass passing the 600 µm test sieve) to a fine one (ie say 90% by mass passing the 600 µm test sieve), can result in an increase in the water content of 25 kg/m^3 in order to maintain the required workability of the concrete. Such a change in water content would considerably reduce the compressive strength of the concrete. However, the workability can be maintained at the same water content when using finer sand by reducing the fines content. Figure 6 shows how the fines content of the mix should be reduced as the sand becomes finer, ie as the percentage passing the 600 µm test sieve increases.

7.1.3 Type and strength class of cement

Different types and strength classes of cement have different water requirements to produce pastes of standard consistence. However, for the cements covered by this publication, such differences will generally have little effect on the workability of the concrete and therefore this factor is ignored in this mix design method.

7.2 The compressive strength of concrete

7.2.1 Age at test and curing conditions

The strength developed by a concrete made with given materials and given proportions increases for many months under favorable conditions, but in the majority of specifications the strength is specified at an age of 28 days. The strength development of concrete made with all types of Portland cement depends on the temperature and humidity conditions during curing. Higher temperatures increase the speed of the chemical reaction and thus the rate of strength development, and in order to achieve higher strengths at later ages loss of water from the concrete must be prevented. For test purposes the concrete test specimens are stored in water at a constant temperature as specified in relevant standards.

7.2.2 Type and strength class of cement

Different types and strength classes of cement produce concretes having different rates of strength development. In class 52.5 Portland cements the chemical reaction initially proceeds at a faster rate than in class 42.5 Portland cements; the effect of this on typical concretes having a free-water/cement ratio of 0.5 is shown in Table 2. If there is more appropriate information available related to local materials, this can be used instead of the values given in Table 2. A class 42.5 sulfate-resisting Portland cement is assumed to have the same rate of strength development as a class 42.5 Portland cement.

7.2.3 Cement strength variation

Apart from the difference in the strength of concrete with different types and strength classes of cement described, there is inevitably some variability in the strength of concrete due to the variability of any particular type or strength class of cement. This is due to the variability of cement supplied from different works and to normal variations in production from any one works over a period of time. Typically, the standard deviation of the strength of standard concrete cubes at 28 days made with Portland cement class 42.5 from different works is about 5 N/mm^2, while the standard deviation due to the variability of the cement from a single works is about 3 N/mm^2.

7.2.4 Aggregate type and grading

The type and source of the aggregate has a considerable influence on the compressive strength of concrete. As a general rule, an uncrushed coarse aggregate (generally smooth and rounded) makes a concrete with a lower strength than one with crushed coarse aggregate. Other factors such as the type of fine aggregate, the maximum size of aggregate, the overall grading, and particle shape and surface texture, have little direct effect on the compressive strength and are ignored for the purposes of this publication. The combined effect of the aggregate characteristics does have an indirect effect on compressive strength through its influence on the water requirement to produce a workable concrete. In work on crushed rock aggregates the 28-day compressive strength varied between 29 N/mm^2 and 53 N/mm^2 depending on which of 24 different aggregates was used. In order to produce very high-strength concrete, ie concrete with a specified strength of 50 N/mm^2 or more, it is generally necessary to obtain aggregates from selected sources. Typical strength values when uncrushed or crushed coarse aggregates are used are given in Table 2. If there is more appropriate information available related to local materials this can be used instead of the values given in Table 2.

7.2.5 Relationship between compressive strength and free-water/cement ratio

One of the basic concepts of this publication is the representation in Figure 4 of the relationship between the compressive strength of concrete and the free-water/ cement ratio as defined before. It should be noted that the curves shown in Figure 4 do not indicate any age of test. It has been explained that the strength development varies for different types and strength classes of cement and that there is variation in the quality of cement, and also that the type of aggregate can affect the strength of the concrete. The curves illustrate the form of the relationships between the compressive strength and the free-water/cement ratio and are obtained from a large number of different concrete mixes using different modern Portland cements and different types of aggregate, but for any particular sources of cement and aggregates a slightly different form of relationship may be obtained. Table 2 gives typical data for a concrete having a free water/ cement ratio of 0.5 to give a datum point on Figure 4 appropriate to the age of test and materials to be used. The strength development shown in Table 2 applies to a concrete with a cement content of about 300 kg/m3 cured in water at 20°C. Such a mix made with Portland cement class 42.5 has a 7-day strength about 70% of that attained at 28 days. However, richer mixes initially gain strength more rapidly so that 7-day strength may well exceed 75% of the 28-day strength. Conversely, for lean concretes this ratio is nearer 65%.

7.2.6 Type of mixing

The compressive strength of the concrete is not directly affected by the type of mixer used. Certain types of mixer require a higher degree of workability for efficient operation and this may have an indirect effect on the proportions of the concrete required for a particular value of free-water/cement ratio. However, hand-mixing is likely to produce a lower strength concrete than machine-mixed concrete of similar proportions.

7.3 Variability of concrete strength during production

7.3.1 Factors contributing to the overall variation

The main factors influencing the workability and strength of concrete that are taken into account when designing the mix are discussed in previous sections. If these factors change during the progress of the job, the properties of the concrete must also change. The overall variation in the measured strength of concrete that is obtained during a job can be considered to be made up of three component sources which are:

- Variation in the quality of the materials used
- Variation in the mix proportions due to the batching process
- Variation due to sampling and testing

During production there are inevitable variations in the characteristics of the materials used. For example the quality of different deliveries of cement may vary, or the grading and particle shape of aggregates may vary, requiring changes of the water/cement ratio in order to maintain the specified workability. It is known that considerable variations occur in the proportions from batch to batch irrespective of whether the batching is by volume or by weight; these can be attributed partly to the plant and partly to its operation. Finally, some of the variation in the measured concrete strength arises from the processes of sampling, making, curing and testing the test specimens even though these are carried out in accordance with standards. There are few data on how these three groups contribute individually to the overall variation of concrete strength but there is considerable information on the magnitude of the overall variation.

7.4 The distribution of results

It is now generally accepted that the variation in concrete strengths follows the normal distribution such as that shown in Figure l. The area beneath the curve represents the total number of test results, and the proportion of results less than some specified value is represented by the area beneath the curve to the left-hand side of a vertical line drawn through the specified value. This normal distribution curve is symmetrical about its mean, has a precise mathematical equation and is completely specified by two parameters, its mean *m* and its standard deviation *s.* The standard deviation is a measure of the variability calculated from the equation:

$$s = \sqrt{\frac{\sum (x-m)^2}{n-1}}$$

where

x = an individual result

n = the number of results

m = the mean of the n results

It is now generally accepted that at a given level of control the standard deviation increases as the specified characteristic strength increases up to a particular level, and is independent of the specified strength above this level. This type of relationship is shown in Figure 3, the standard deviation being independent of the specified characteristic strength above 20 N/mm^2.

7.5 Characteristic strength

It has been shown that concrete cube strengths follow the normal distribution. There is therefore always the probability, however remote, that a result will be obtained less than the specified strength. It has therefore become the increasing practice to specify the quality of concrete not as a minimum strength but as a ‘characteristic strength’ below which a specified proportion of the test results, often called ‘defectives’, may be expected to fall. The characteristic strength may be defined to have any proportion of defectives; BS 5328 and BS 8110 adopt the 5% defective level in line with the CEB/FIP international recommendations for the design and construction of concrete structures. BS 5328 specifies a system for testing for compliance with a specified characteristic strength. The compliance values have been derived by making certain assumptions to give reasonable levels of risk to both producer and purchaser that concrete of the specified quality is accepted by the testing scheme. However, it may be prudent to base the initial mix design on a proportion of defectives less than 5%.

7.6 Margin for mix design

As a result of the variability of concrete in production it is necessary to design the mix to have mean strength greater than the specified characteristic strength by an amount termed the margin. Thus:

$$\boldsymbol{f_m = f_c + k_s}$$

where
f_m = the target mean strength
f_c = the specified characteristic strength
ks = the margin, which is the product of:
s = the standard deviation, and
k = a constant

The constant k is derived from the mathematics of the normal distribution and increases as the proportion of defectives is decreased, thus:

***k* for 10% defectives = 1.28**
***k* for 5% defectives = 1.64**
***k* for 2.5% defectives = 1.96**
***k* for 1% defectives = 2.33**

For the 5% defective level specified in BS 5328, $k = 1.64$
and thus $f_m = f_c + 1.64s$.

Figure 1 relates to a concrete having a specified characteristic strength of 30 N/mm^2 and a standard deviation of 6.1 N/mm^2.
Hence:
Target mean strength
$f_m = 30 + (1.64x6.1) = 30 + 10 = 40$ N/mm^2

Since the compliance rules given in BS 5328 operate on a small number of tests, producers may find that a margin based on the 5% defectives with k of 1.64 leads to an unacceptable rate of failing the compliance rules. To avoid this, it may be preferable at the mix design stage to use a greater margin by adopting a higher value for k. The standard deviation used to calculate the margin should be based either on results obtained using the same plant, materials and supervision, as for example in ready mixed concrete plants or precast concrete works, or, in the absence of such information, on a value taken from Figure 3 which should be used until adequate production data are available. It is very seldom that standard deviations less than 2.5 N/mm^2 or more than 8.5 N/mm^2 are obtained from concrete produced in the United Kingdom, and on about 60% of sites the standard deviation can be expected to be between 4.0 and 6.0 N/mm^2. The standard deviation calculated from n results is only an estimate of the standard deviation of the total population. It is therefore subject to normal probability errors which are reduced as n becomes larger . If several groups of n results are taken where n is 20, the values of the standard deviation calculated from these may vary by about ±30% without being significantly different statistically. It is thus desirable that for mix design purposes the standard deviation should be calculated from at least 20 results. If fewer results are available a standard deviation of 8 N/mm2 should be used for concrete with a characteristic strength of 20 N/mm^2 or more as shown by line A in Figure 3. When the standard deviation is calculated from a large number of results it is a much better estimate of the true standard deviation and will generally include some long term variables that might not be present with a small number of results. However, the value used for mix design should not be less than that shown by line B in Figure 3 (4 N/mm^2 for concrete with a characteristic strength of 20 N/mm^2 or more). Various Specifications and Codes of Practice may impose different limits for the standard deviation of the margin, and if relevant the mix should be designed to comply with these requirements.

7.7 The Mix Design Process

7.7.1 Flow chart of procedures

The manner in which this method links the various factors involved in the process of designing a mix is shown as a flow chart in Figure 2. Also a suitable mix design form for recording the values derived is shown in Table 1. It will be seen from the flow chart that initial information is divided into two categories:

- specified variables, the values of which are usually nominated in specifications, and
- additional information, which is normally available to the producer of the concrete.

This initial information is used in conjunction with reference data, which appear in the form of figures or tables in this publication, to evaluate a number of ‘derived values’ which are also subdivided into two categories:

- the mix parameters, several of which form an intermediate step to the derivation of the second category, and
- the final unit proportions, which are defined in terms of mass of materials required to produce one cubic metre of compacted concrete, expressed to the nearest 5 kg.

In order to clarify the sequence of operation, and for ease of reference, the flow process is divided into five stages. Each of these stages deals with a particular aspect of the design and ends with an important parameter or final unit proportions.

Stage 1 deals with strength leading to the free-water/cement ratio
Stage 2 deals with workability leading to the free-water Content
Stage 3 combines the results of Stages 1 and 2 to give the cement content
Stage 4 deals with the determination of the total aggregate content
Stage 5 deals with the selection of the fine and coarse aggregate contents

The mix design form shown in Table 1 is sub-divided into the same five stages and the separate item numbers correspond with the relevant boxes of the flow chart in Figure 2.

7.7.2 Selection of target water/cement ratio (Stage 1)

If previous information concerning the variability of strength tests comprises fewer than 20 results, the standard deviation to be adopted should be that obtained from line A in Figure 3. If previous information is available consisting of 20 or more results, the standard deviation of such results may be used provided that this value is not less than the appropriate value obtained from line B. The margin can then be derived from calculation C1:

$M = k \times s$ ...C1

where

M = the margin (Item 1.3)

k = a value appropriate to the 'percentage defectives' permitted below the characteristic strength

s = the standard deviation.

Instead of working from the standard deviation and obtaining the margin through calculation C1, the margin itself may be specified direct. Hence Item 1.3 may be a derived value or an optional specified value as indicated in Figure 2.

Calculation C2 determines the target mean strength
(expressed to two significant figures):

$f\text{m} = f_c + M$ ...C2

where

f_m = the target mean strength

f_c = the specified characteristic strength

M = the margin

Next, a value is obtained from Table 2 for the strength of a mix made with a free-water/cement ratio of 0.5 according to the specified age, the strength class of the cement and the aggregate to be used. This strength value is then plotted on Figure 4 and a curve is drawn from this point and parallel to the printed curves until it intercepts a horizontal line passing through the ordinate representing the target mean strength. The corresponding value for the free-water/cement ratio can then be read from the abscissa. This should be compared with any maximum free-water/cement ratio that may be specified and the lower of these two values used.

7.7.3 Selection of free-water content (Stage 2)

Stage 2 consists simply of determining the free-water content from Table 3 depending upon the type and maximum size of the aggregate to give a concrete of the specified slump or Vebe time.

7.7.4 Determination of cement content (Stage 3)

The cement content is determined from calculation C3:

Cement content = free-water content / free-water/cement ratio

...C3

The resulting value should be checked against any maximum or minimum value that may be specified. If the calculated cement content from C3 is below a specified minimum, this minimum value must be adopted and a modified free-water/cement ratio calculated which will be less than that determined in Stage 1. This will result in a concrete that has a mean strength somewhat higher than the target mean strength. Alternatively, the free water/cement ratio from Stage 1 is used resulting in a higher free-water content and increased workability. On the other hand, if the design method indicates a cement content that is higher than a specified maximum then it is probable that the specification cannot be met simultaneously on strength and workability requirements with the selected materials. Consideration should then be given to changing the type or strength class, or both, of cement, the type and maximum size of aggregate or the level of workability of the concrete, or to the use of a water-reducing admixture.

7.7.5 Determination of total aggregate content (Stage 4)

Stage 4 requires an estimate of the density of the fully compacted concrete which is obtained from Figure 5 depending upon the free-water content and the relative density of the combined aggregate in the saturated surface-dry condition (SSD). If no information is available regarding the relative density of the aggregate, an approximation can be made by assuming a value of 2.6 for uncrushed aggregate and 2.7 for crushed aggregate. From this estimated density of the concrete the total aggregate content is determined from calculation C4:

Total aggregate content = $D — C — W$ ...C4
(saturated and surface-dry)

where
D = the wet density of concrete (kg/m^3)
C = the cement content (kg/m^3)
W = the free-water content (kg/m^3)

7.7.6 Selection of fine and coarse aggregate contents (Stage 5)

Stage 5 involves deciding how much of the total aggregate should consist of materials smaller than 5 mm, ie the sand or fine aggregate content. Figure 6 shows recommended values for the proportion of fine aggregate depending on the maximum size of aggregate, the workability level, the grading of the fine aggregate (defined by its percentage passing a 600 µm sieve) and the free-water/cement ratio. The best proportion of fines to use in a given mix will depend on the shape of the particular aggregate, the actual grading of shape of the particular aggregate, the actual grading of the fine aggregate and the use to which the concrete is to be put. However, adoption of a proportion obtained from Figure 6 will generally give a satisfactory concrete in the first trial mix which can then be adjusted as required for the exact conditions prevailing. The final calculation, C5, to determine the fine and coarse aggregate contents, is made using the proportion of fine aggregate obtained from Figure 6 and the total aggregate content derived in Stage 4:

Fine aggregate content = (total aggregate content) x (proportion of fines)
Coarse aggregate content = (total aggregate content) – (fine aggregate content)

The coarse aggregate content itself can be subdivided if single sized 10, 20 and 40 mm materials are to be combined. Again, the best proportions will depend on aggregate shape and concrete usage but the following ratios are suggested as a general guide:

1:2 for combination of 10 and 20 mm material
1:1.5:3 for combination of 10, 20 and 40 mm material.

7.8 Trial mixes

The preceding design method determines a set of mix proportions for producing a concrete that has approximately the required properties of strength and workability. The method, however, is based on simplified classifications for type and quality of the materials and it still remains to check whether or not the particular aggregates and cement selected for use in a given case will behave as anticipated. This is the object of making the trial mix, and the subsequent feedback of information from the trial mix is an essential part of the mix design
process. In order to avoid the possible delay caused by a need to prepare a second trial mix as a result of strength tests, it may be expedient to prepare two or more initial trial mixes with the same water content but with different water/cement ratios. Normally, when typical materials are to be used, a single trial mix would be sufficient although some Codes of Practice may stipulate not only the number of trial mixes to be made but also requirements for accepting them as suitable. Adjustments to be made to the original mix proportions, if necessary, will differ according to how much the results of the trial mixes differ from the designed values which will depend partly upon how typical the materials are of their classifications. Depending on these, there are three courses of action open:

- To use the trial mix proportions in the production mixes
- To modify the trial mix proportions slightly in the production mixes
- To prepare further trial mixes incorporating major changes to the mix proportions

7.8.1 Production of trial mixes

The design method gives the mass in kilograms of the different materials required to produce one cubic metre of compacted concrete. The batch quantities for the trial mix can be obtained directly, therefore, by multiplying each of the constituent contents by the volume of the mix required. Typically, a 50 litre (0.05 m^3) mix is sufficient to make six cubes of 150 mm side and to carry out, separately, measurements of slump, Vebe time and density. The individual batch quantities (in kg) would then be equal to the appropriate contents, multiplied by 0.05. Trial mixes should be prepared in accordance with the requirements of BS 1881:Part 125. This British Standard allows the use of aggregates in any one of four moisture conditions, ie

(a) oven-dry,
(b) air-dried,
(c) saturated surface-dry, or
(d) saturated by soaking in water for at least 24 hours.

The batch quantities determined in the mix design process are based on saturated surface-dry aggregates as in (c) above. If the aggregates are surface-wet or saturated as in (d) above, the amount of free-water that is present should be determined so that adjustments can be made to the mass of aggregate and water added at the mixer. When aggregates are to be batched in a dry condition as in (a) or (b) above, the batch quantities of the aggregate should be reduced and the mass of mixing water increased to allow for the absorption of some of the mixing water by the dry aggregate. The mass of the fine and coarse aggregate required for the trial mix should be calculated by multiplying the batch quantities derived from calculation C5 by 100/(100 + A) where A is the percentage by mass of water needed to bring the dry aggregate to the saturated surface-dry condition. The mass of the mixing water should be increased by the amount required for absorption by the aggregates. When dry aggregates are used they should be allowed to soak with some of the mixing water before other materials are added, to avoid obtaining false values for the workability and possibly for the strength of the concrete. This is achieved, in accordance with BS 1881:Part 125, by mixing the aggregate with about half of the total water and allowing it to stand for a period so that the aggregate takes up most of the water it will ultimately absorb, before adding the cement, the rest of the water and continuing to mix for the periods specified.

7.8.2 Tests on trial mixes

Tests on the fresh concrete, the making of test specimens, the curing of the specimens and their method of test should be in accordance with the relevant part of BS EN.

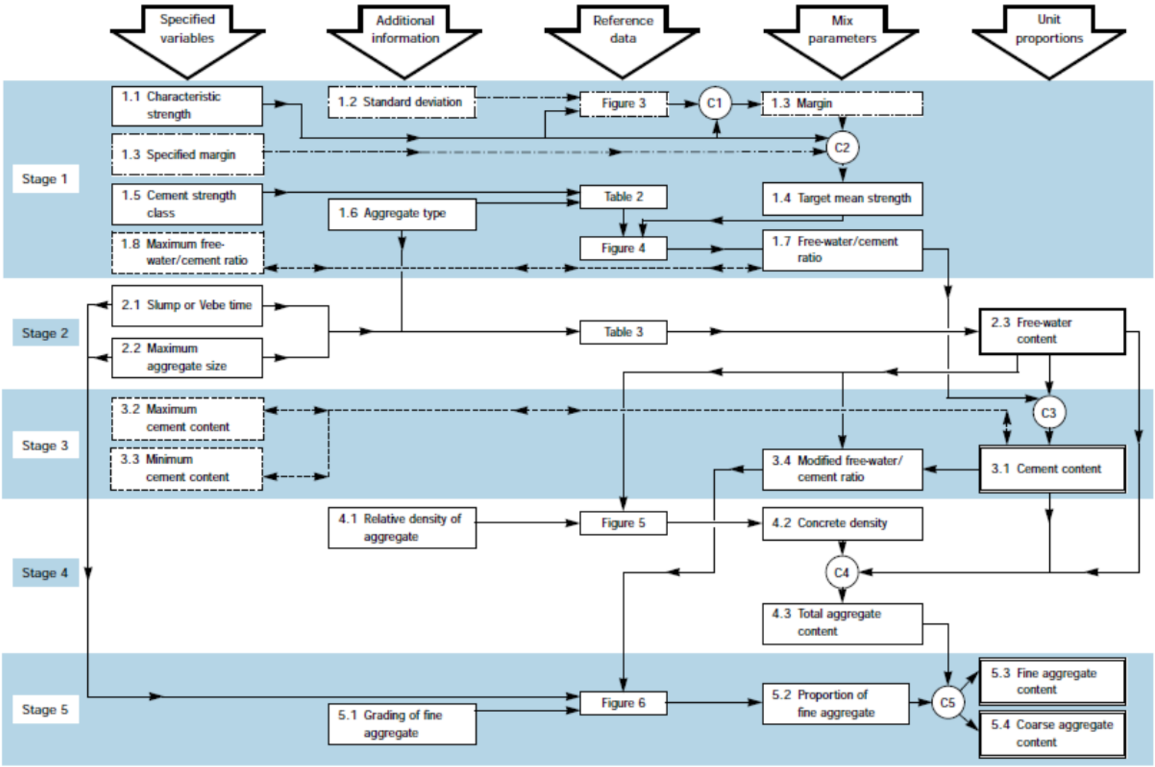


Figure 2. Flow chart of mix design procedure.

7.8.3 Adjustments to mix proportions

Workability

During the mixing of the trial mix an experienced technician is able to adjust the water content by inspection if the workability of the mix is much outside the specified range. It is thus useful, initially, to withhold a small proportion, say 10%, of the mix water until the technician has assessed visually that its addition is needed to achieve the required workability. Furthermore, if at the designed water content the workability of the trial mix appears below that required, additional water should be added to obtain the required workability. After completion of the mixing cycle and workability measurements a change of water content may still be needed, either for use in the production mix or for a further trial mix, and this can be estimated by reference to Table 3. During the measurement of workability the concrete should also be assessed subjectively for its other rheological properties; this may indicate a need to change the relative aggregate proportions.

Density

After the density of the fresh concrete is measured, the resultant value is compared with the density value used during the design. If there is an appreciable difference, the constituent contents per cubic metre, referred to as the unit proportions of the trial mix, will differ from those intended in the initial design. In this case, the initial design values should be corrected by the ratio of measured density to assumed density in order to determine the actual masses per cubic metre in the trial mix.

Strength

When results of the strength tests become available they are compared with the target mean strength (and any other existing requirements or guides in other Specifications or Codes). If necessary an adjustment is made to the water/cement ratio by using the curves of Figure 4. Two examples of this adjustment are shown in Figure 7, where:

A represents the reference data given in Table 2 for the particular types of aggregate and cement to be used and the appropriate age of test

B represents the free-water/cement ratio estimated for the trial mix

B' represents the actual free-water/cement ratio used in the trial mix when different from B. (This situation arises if the water content of the concrete is adjusted during the manufacture of the trial mix as in example 2)

C represents the strength result of the test specimens made from the trial mix

D represents the new estimate of the free-water/cement ratio required to give the target mean strength Minor adjustments may be made to the mix proportions for use in production mixes without the need to carry out further trials. Exceptionally, when large adjustments seem to be necessary to the water/cement ratio it is advisable to make a second trial mix using the revised proportions and recalculated batch quantities based on the updated value for density of the mix.

7.9 Examples of mix design

The following examples are given to illustrate the use of this mix design procedure. The relevant details and calculations are entered on the standard mix design form (shown in Table 1) and the examples are chosen to illustrate the various options that may arise. Although there are eight items listed in the specified variables (see Figure 2), ie 1.1, 1.3, 1.5, 1.8, 2.1, 2.2, 3.2 and 3.3, only four of them are essential for the process. Three are optional limiting values that may be specified: Item 1.8 maximum free-water/cement ratio; Item 3.2 maximum cement content; Item 3.3 minimum cement content. These are therefore shown in italics on the standard mix design form

(Table 1) and by two-way arrows in Figure 2. The final specified variable is Item 1.3 specified margin. This is an alternative method for dealing with the margin required to determine the target mean strength. The other method is to use the permitted percentage of defectives in Item 1.1 so that the appropriate constant *k* can be used in Item 1.3 (mix parameter) to calculate the margin using Item 1.2, standard deviation.

Example 1: unrestricted design

The following requirements are specified and thus entered under the relevant item on the mix design form, as shown in Table 4.

Characteristic compressive strength, 30 N/mm^2 at 28 days, with a 2.5% defective rate (k = 1.96)
Portland cement class 42.5
Slump required, 10–30 mm
Maximum aggregate size, 20 mm
Maximum free-water/cement ratio, 0.55
Minimum cement content, 290 kg/m^3
A maximum cement content is not specified.

There are no previous control data and thus a standard deviation of 8 N/mm^2 obtained from Figure 3 is used in Item 1.2. The fine and coarse aggregates to be used are uncrushed, the relative density is unknown and is assumed to be 2.6, and the fine aggregate has 70% passing a 600 µm sieve. These details are entered in Table 4 under Items 1.6, 4.1 and 5.1 respectively.

The target mean strength is obtained by performing calculations C1 and C2 and found to be 46 N/mm^2. Table 2 shows that for the materials being used, the estimated 28-day strength at a free-water/cement ratio of 0.5 is 42 N/mm^2. This value is then applied to Figure 4, and for the target mean strength of 46 N/mm2 it is found that a free-water/cement ratio of 0.47 (Item 1.7) is required. This is less than the specified maximum value of 0.55 and is thus suitable for the design. This completes Stage 1. Stage 2 is completed by obtaining the required freewater content of 160 kg/m^3 (Item 2.3) from Table 3 appropriate to the specified requirements. The cement content of 340 kg/m^3 (Item 3.1) is obtained from calculation of C3 and, since this is greater than the specified minimum of 290 kg/m^3, it is suitable for the design. This completes Stage 3. Using the assumed relative density of 2.6 and the freewater content of 160 kg/m3, a wet density of concrete of 2400 kg/m^3 (Item 4.2) is obtained from Figure 5, and calculation C4 gives a total aggregate content of 1900 kg/m^3 (Item 4.3) completing Stage 4. Finally the fine and coarse aggregate contents are obtained in

Stage 5 by selecting the proportion of fine aggregate of 27% (Item 5.2) from Figure 6 for the given maximum aggregate size, required slump and derived free-water/cement ratio. The fine and coarse aggregate contents (Items 5.3 and 5.4) are obtained through calculations C5. If single-sized 10 mm and 20 mm coarse aggregates are used the coarse aggregate content is proportioned 1:2 as described in 7.7.6.

Thus the quantities of the constituent materials per m^3 are:

Cement 340 kg
Water 160 kg
Fine aggregate 515 kg (saturated surface-dry)
Coarse aggregate 1385 kg (saturated surface-dry) consisting of 460 kg 10 mm single-size and 925 kg 20 mm single-size

Assuming that the aggregates are used in a saturated surface-dry condition, the quantities for a 50 litre (0.05 m^3) trial mix are therefore:

Cement 17.0 kg
Water 8.0 kg
Fine aggregate 25.7 kg (satuated surface-dry)
Coarse aggregate 69.2 kg (satuated surface-dry) consisting of 23.0 kg 10 mm single-size and 46.2 kg 20 mm single-size.

To obtain the mass of the oven-dry aggregates when aggregates are to be batched in an oven-dry condition, the masses of the saturated surface-dry aggregates derived from calculations C5 are multiplied by $100/(100 + A)$ where A is the percentage by mass of water needed to bring the dry aggregates to a saturated surface-dry condition. The amount of the mixing water should be increased by the mass of water absorbed by the aggregates to reach the saturated surface-dry condition. Thus if the absorption of the fine aggregate is 2% and of the coarse aggregate is 1%, then in the above trial mix:

Mass of oven-dry fine aggregate = 25.7 x 100/102 = 25.2 kg
Mass of oven-dry coarse aggregate = 69.2 x 100/101 = 68.5 kg
Water required for absorption = (25.7 – 25.2) + (69.2 – 68.5) = 0.5 + 0.7 = 1.2 kg

The quantities for the trial mix are:

Cement 17.0 kg
Water 9.2 kg
Fine aggregate 25.2 kg (oven-dry)
Coarse aggregate 68.5 kg (oven-dry) consisting of 22.8 kg 10 mm single-size and 45.7 kg 20 mm single-size

Example 2: mix restricted by maximum water/cement ratio

The following requirements are specified and thus entered under the relevant item on the mix design form, as shown in Table 5:

Characteristic compressive strength, 25 N/mm^2 at 28 days

Portland cement class 42.5

Slump required, 30–60 mm

Maximum aggregate size, 40 mm

Maximum free-water/cement ratio, 0.50

Minimum cement content, 290 kg/m^3

There are no previous control data but a margin of 10 N/mm2 is specified and is used in Item 1.3.

The following information is known concerning the aggregates to be used and the data are entered under the relevant items on the mix design form, as shown in Table 5:

Aggregate type, uncrushed Item 1.6

Aggregate relative density, 2.5 Item 4.1

Fine aggregate, 90% passing a 600µm sieve Item 5.1

The design process continues as in the previous example but under Item 1.7 it is found that the free-water/cement ratio for the required strength is 0.57; this is higher than the specified maximum value of 0.50, so this latter value is used in the rest of the mix design but Figure 4 indicates a mean strength of 42 N/mm^2 instead of 35 N/mm^2. The remaining stages of the mix design are completed as in the previous example.

Example 3: mix restricted by minimum cement content

In this example the same requirements and materials are specified as in Example 2 but the workability required is reduced to a slump of 0–10 mm. The mix design proceeds as before and is shown on the mix design form in Table 6. Owing to the lowered workability requirement, the free-water content is reduced to 115 kg/m^3 (Item 2.3) and this results in a reduced cement content of 230 kg/m^3 (Item 3.1) which is less than the specified minimum of 290 kg/m^3 (Item 3.3). This higher value must be used and Item 3.4 calculated to give a modified free-water/cement ratio of 0.40 which supersedes the value chosen in Stage 1 (Item 1.8). At this lower water/cement ratio Figure 4 indicates a strength of 55 N/mm^2. This is an example of the required strength being very low in relation to the other specified parameters of low workability, maximum free-water/cement ratio and minimum cement content.

Example 4: mix restricted by maximum cement content

The following requirements are specified and thus entered under the relevant item in the mix design form, as shown in Table 7:

Characteristic compressive strength, 50 N/mm^2 at 7 days, defective rate 1%

(k = 2.33)

Portland cement class 52.5 Item 1.5

Slump required, 30–60 mm Item 2.1

Maximum aggregate size, 10 mm Item 2.2

Maximum cement content, 550 kg/m^3 Item 3.2

Previous control data indicated an expected standard deviation of 5 N/mm2 and this is used in Item 1.2.

The following information is known concerning the aggregates to be used and the data are entered under the relevant item on the mix design form (Table 7):

Aggregate type: coarse, crushed fine, uncrushed Item 1.6

Aggregate relative density, unknown, assume 2.7 Item 4.1

Fine aggregate, 45% passing a 600 µm sieve Item 5.1

The mix design continues as in the previous examples giving a free-water/cement ratio of 0.37 (Item 1.7) at the end of Stage 1 and a free-water content of 215 kg/m^3 (Item 2.3) at the end of Stage 2. The free-water content is calculated as described in the Note to Table 3. In Stage 3 the cement content required is found to be 580 kg/m^3 (Item 3.1) compared with the specified maximum of 550 kg/m^3. It is thus not possible to proceed further with the mix design for the original specified requirements and changes should be considered.

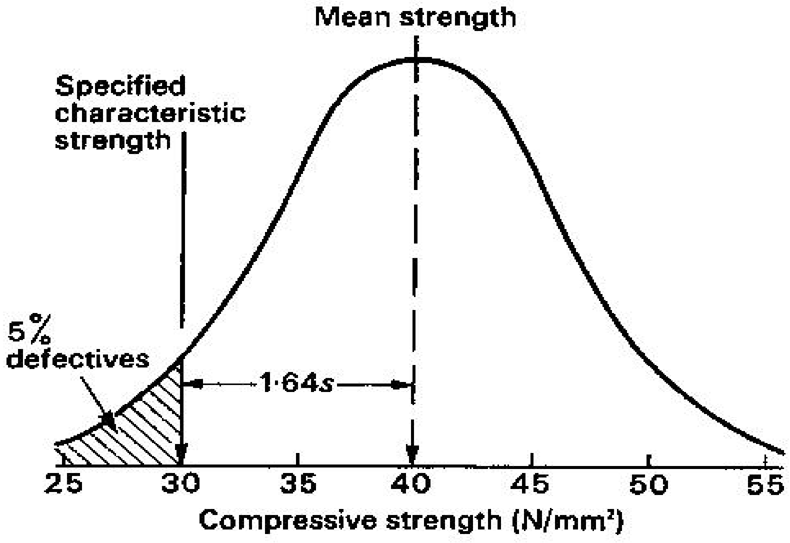


Figure 1 Normal distribution of concrete strengths

Table 2. Approximate compressive strengths (N/mm^2) of concrete mixes made with a free-water/cement ratio of 0.5

Cement Strength Class	***Type of Coarse aggregate***	***Compressive strengths (N/mm^2) (age in days)***			
		3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

1 N/mm^2 = 1 MN/mm^2 = 1 MPa

Table 3 Approximate free-water contents (kg/m^3) required to give various levels of workability

Slump (mm)		0-10	10-30	30-60	60-180
V-B (s)		>12	6-12	3-6	0-3
Maximum size of aggregate(mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water content is estimated by the expression

$$\frac{2}{3}W_f + \frac{1}{3}W_c$$

where W_f = free-water content appropriate to type of fine aggregate

and W_c = free-water content appropriate to type of coarse aggregate.

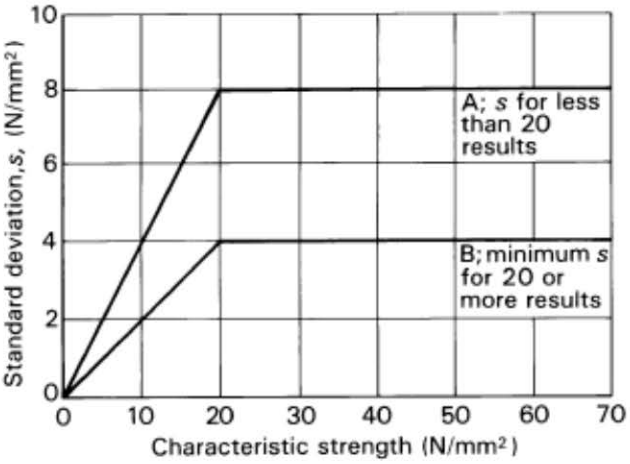


Figure 3
Relationship between standard deviation and characteristic strength

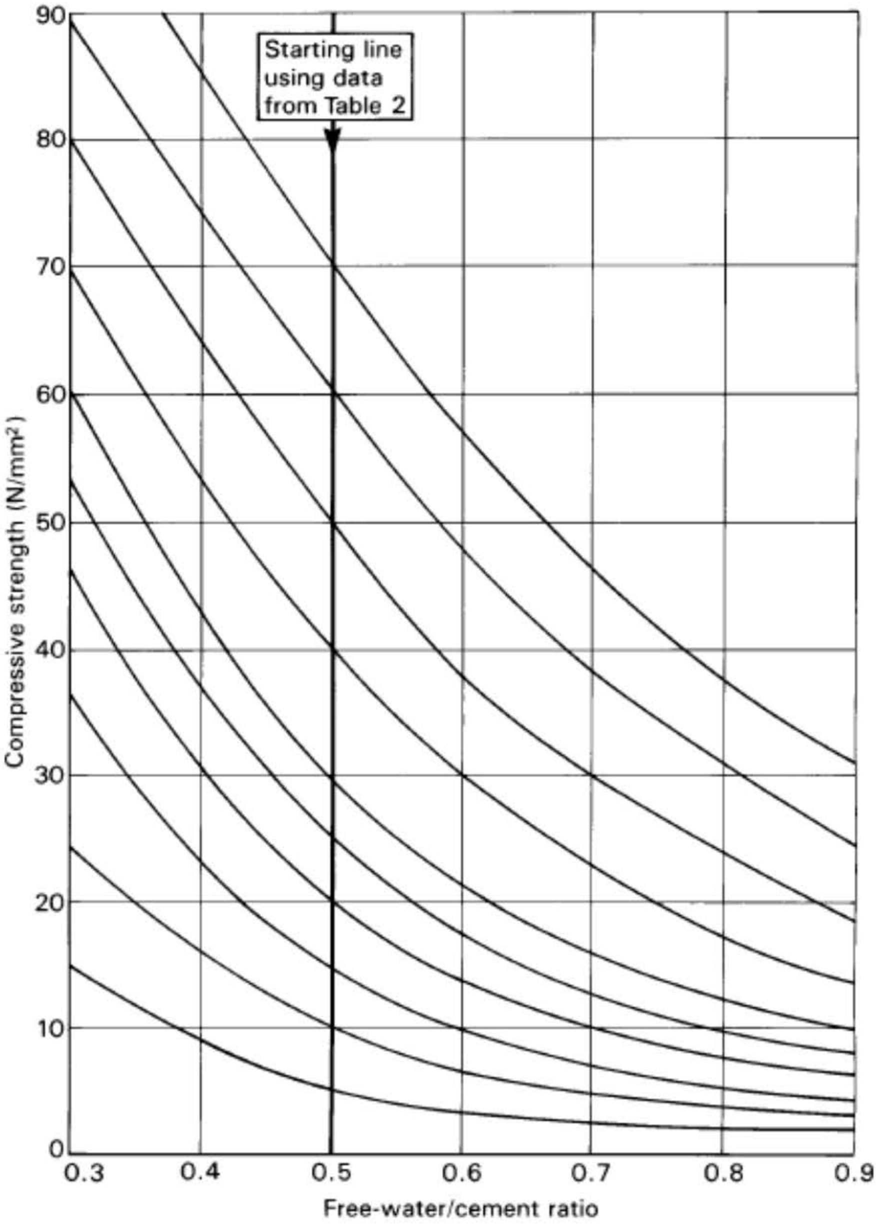


Figure 4
Relationship between compressive strength and free-water/cement ratio

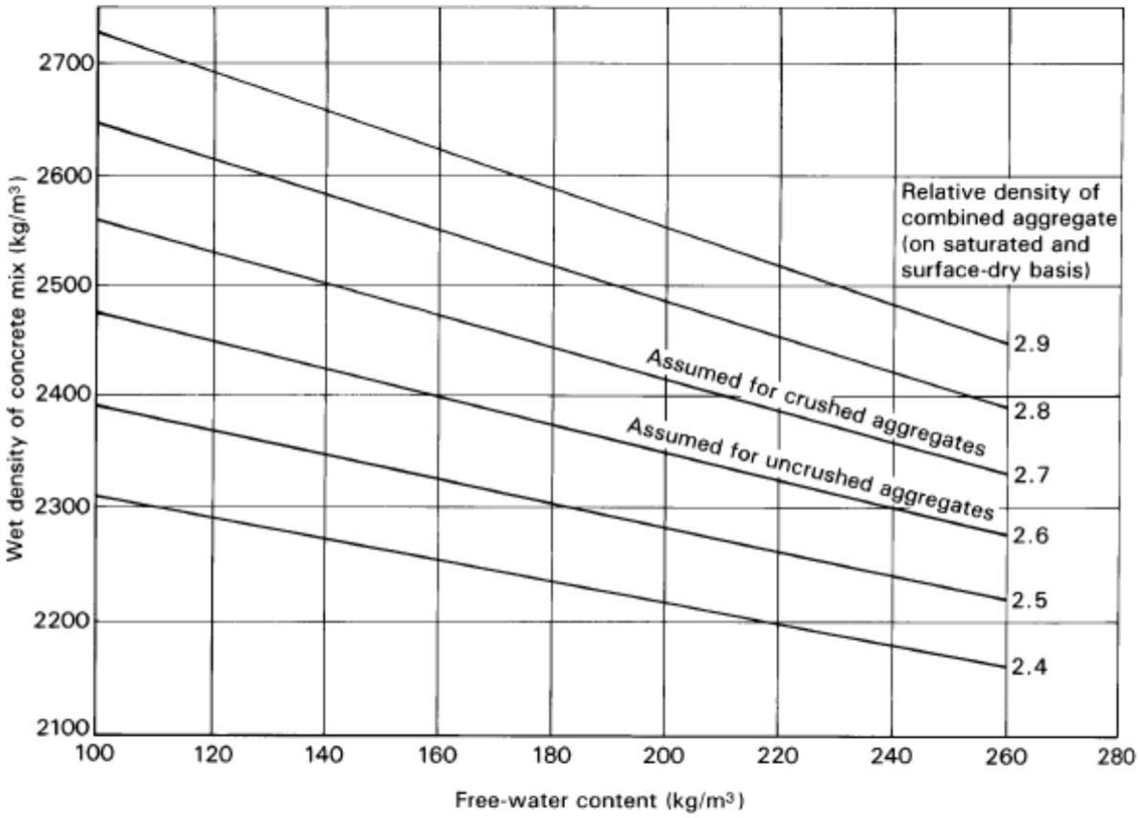


Figure 5 Estimated wet density of fully compacted concrete

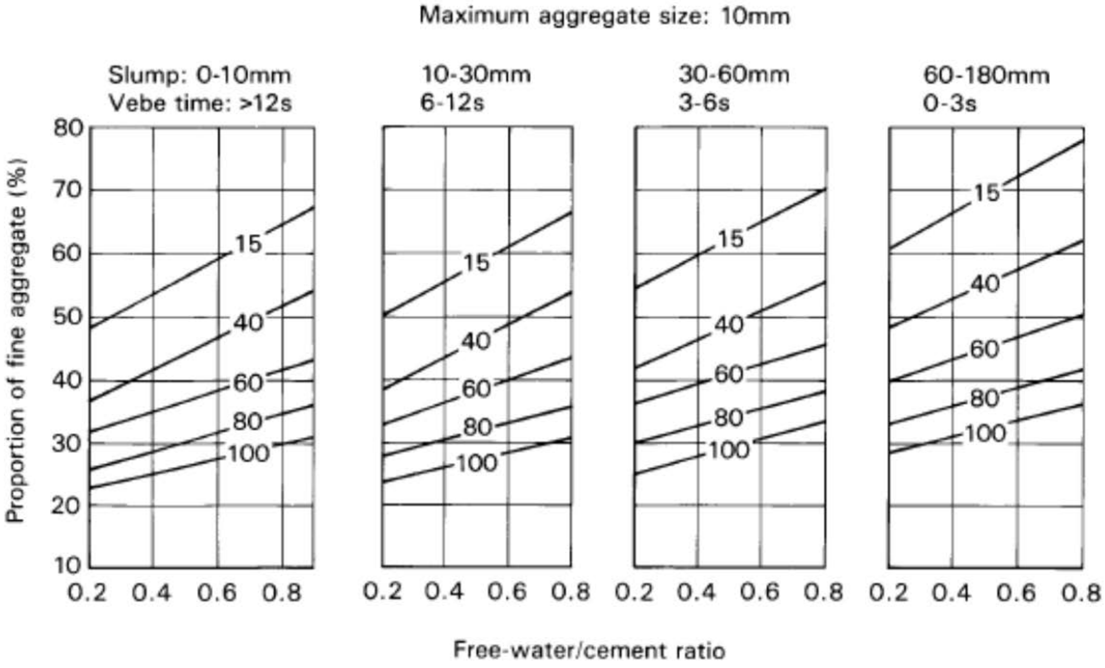


Figure 6 Recommended proportions of fine aggregate according to percentage passing a 600 µm sieve

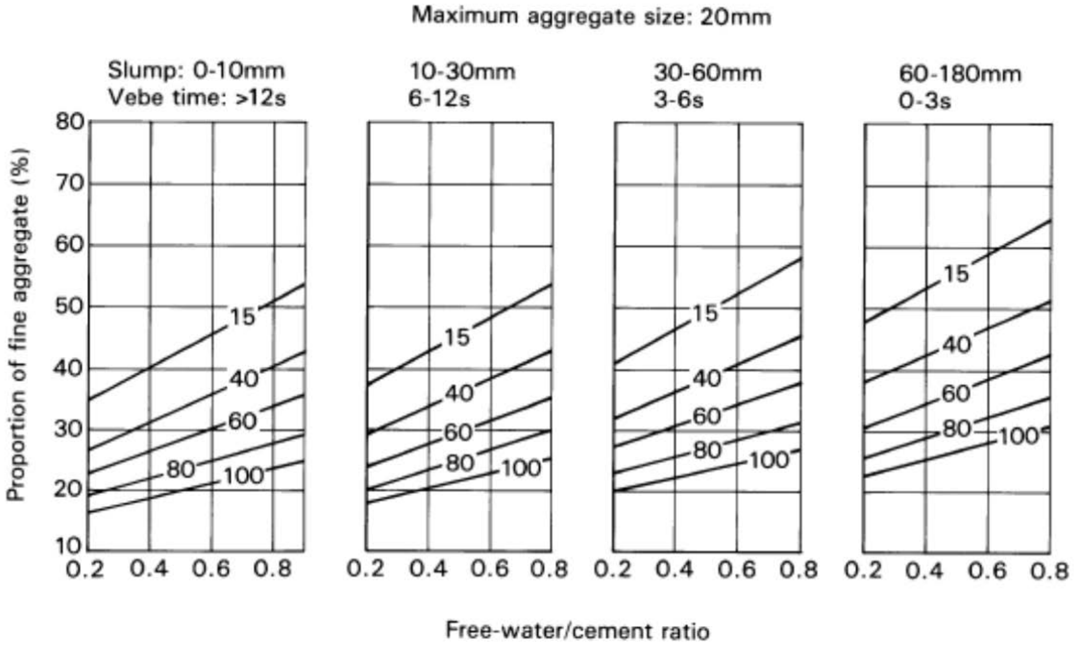


Figure 6 (continued)

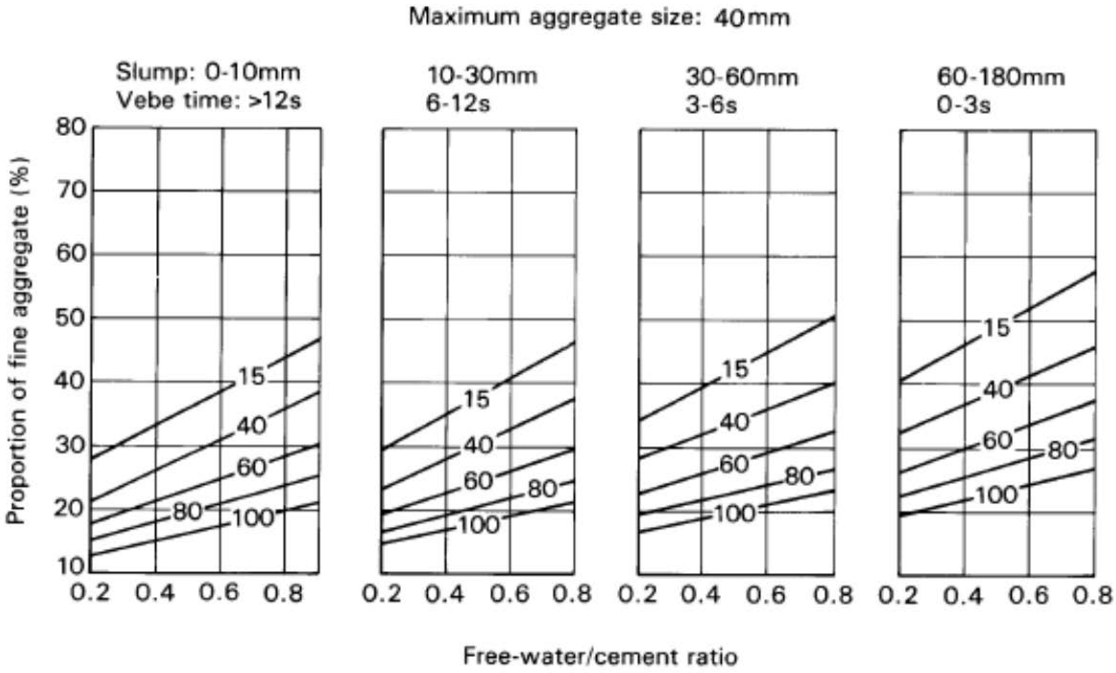


Figure 6 (continued)

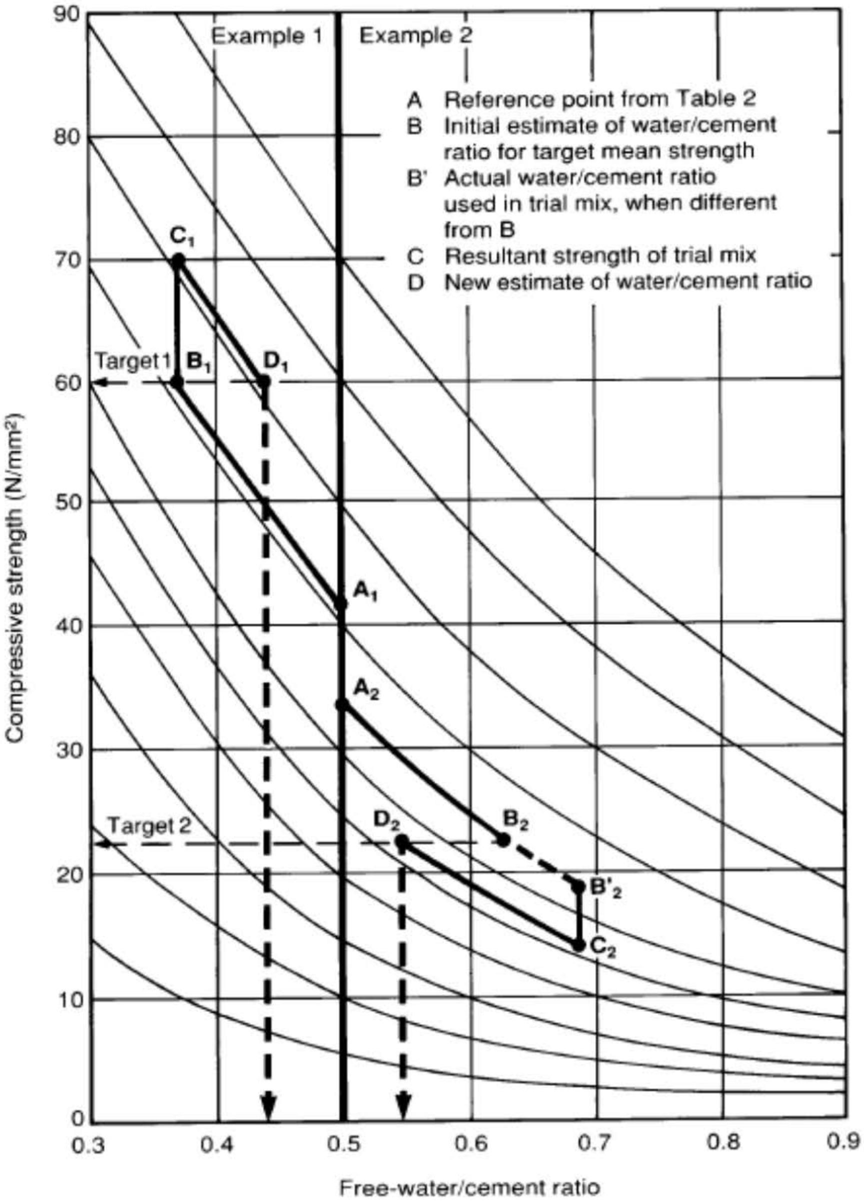


Figure 7 Two examples of the process for adjusting a water/cement ratio using the results of a trial mix

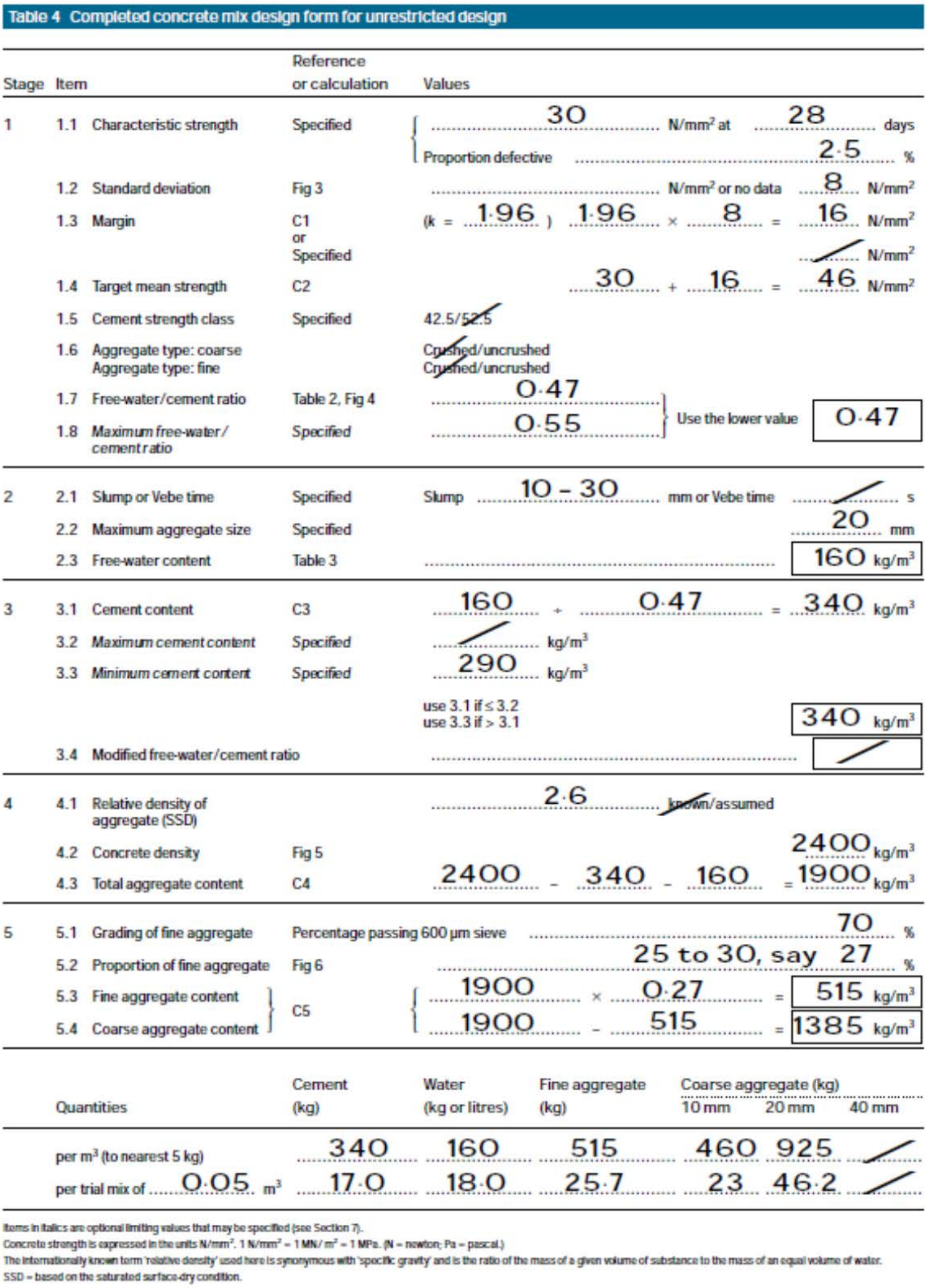


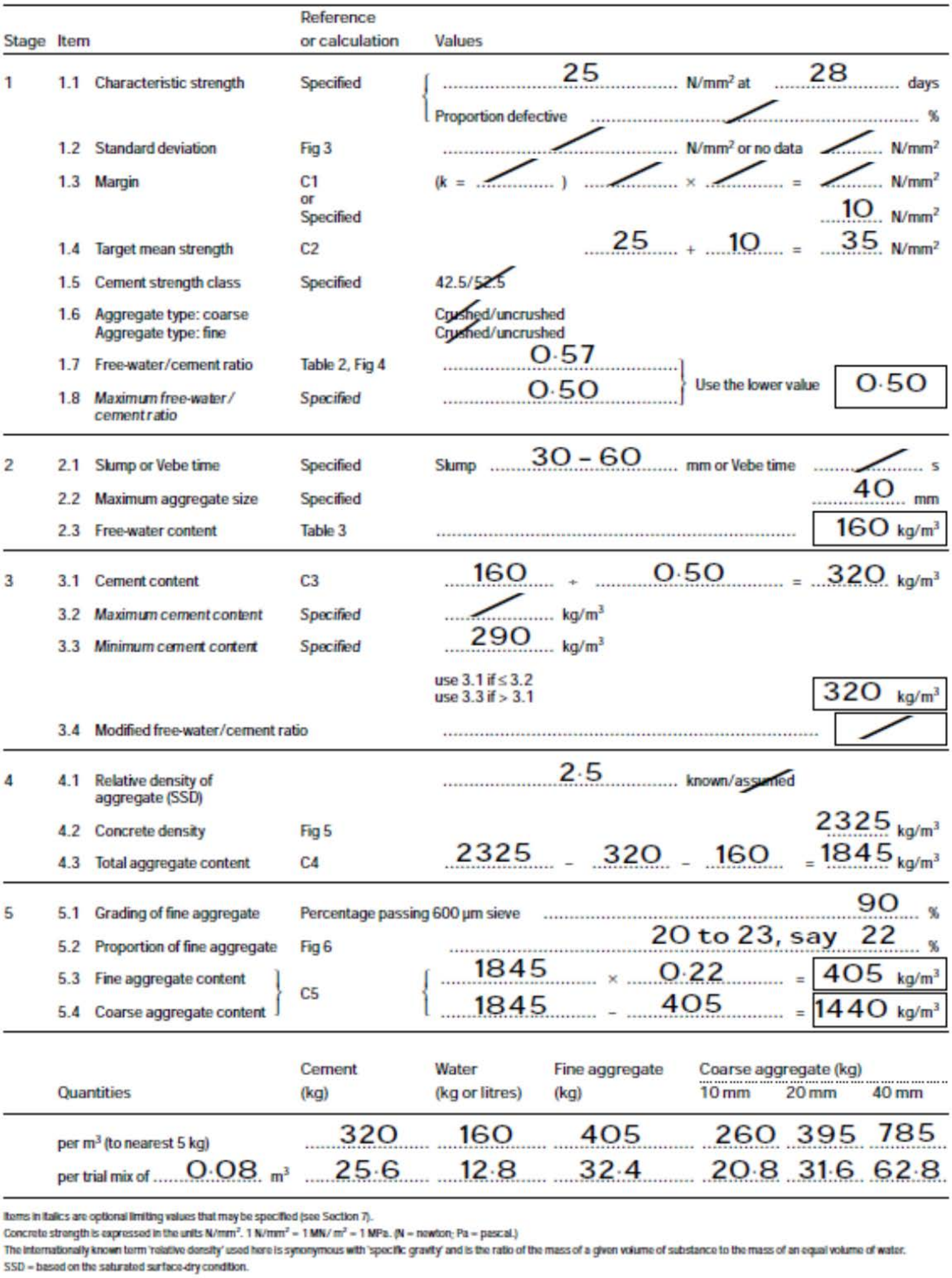
Table 4 Completed concrete mix design form for unrestricted design

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	30 N/mm² at 28 days Proportion defective 2·5 %
	1.2 Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3 Margin	C1 or Specified	(k = 1·96) 1·96 × 8 = 16 N/mm² / N/mm²
	1.4 Target mean strength	C2	30 + 16 = 46 N/mm²
	1.5 Cement strength class	Specified	42.5/~~52.5~~
	1.6 Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0·47 } Use the lower value 0·47
	1.8 *Maximum free-water/cement ratio*	*Specified*	0·55 }
2	2.1 Slump or Vebe time	Specified	Slump 10 – 30 mm or Vebe time / s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	160 kg/m³
3	3.1 Cement content	C3	160 ÷ 0·47 = 340 kg/m³
	3.2 *Maximum cement content*	*Specified*	/ kg/m³
	3.3 *Minimum cement content*	*Specified*	290 kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 340 kg/m³
	3.4 Modified free-water/cement ratio		/
4	4.1 Relative density of aggregate (SSD)		2·6 ~~known~~/assumed
	4.2 Concrete density	Fig 5	2400 kg/m³
	4.3 Total aggregate content	C4	2400 − 340 − 160 = 1900 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	70 %
	5.2 Proportion of fine aggregate	Fig 6	25 to 30, say 27 %
	5.3 Fine aggregate content	C5	1900 × 0·27 = 515 kg/m³
	5.4 Coarse aggregate content	C5	1900 − 515 = 1385 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	340	160	515	460	925	/
per trial mix of 0·05 m³	17·0	18·0	25·7	23	46·2	/

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Table 5 Completed concrete mix design form for a mix restricted by maximum water/cement ratio

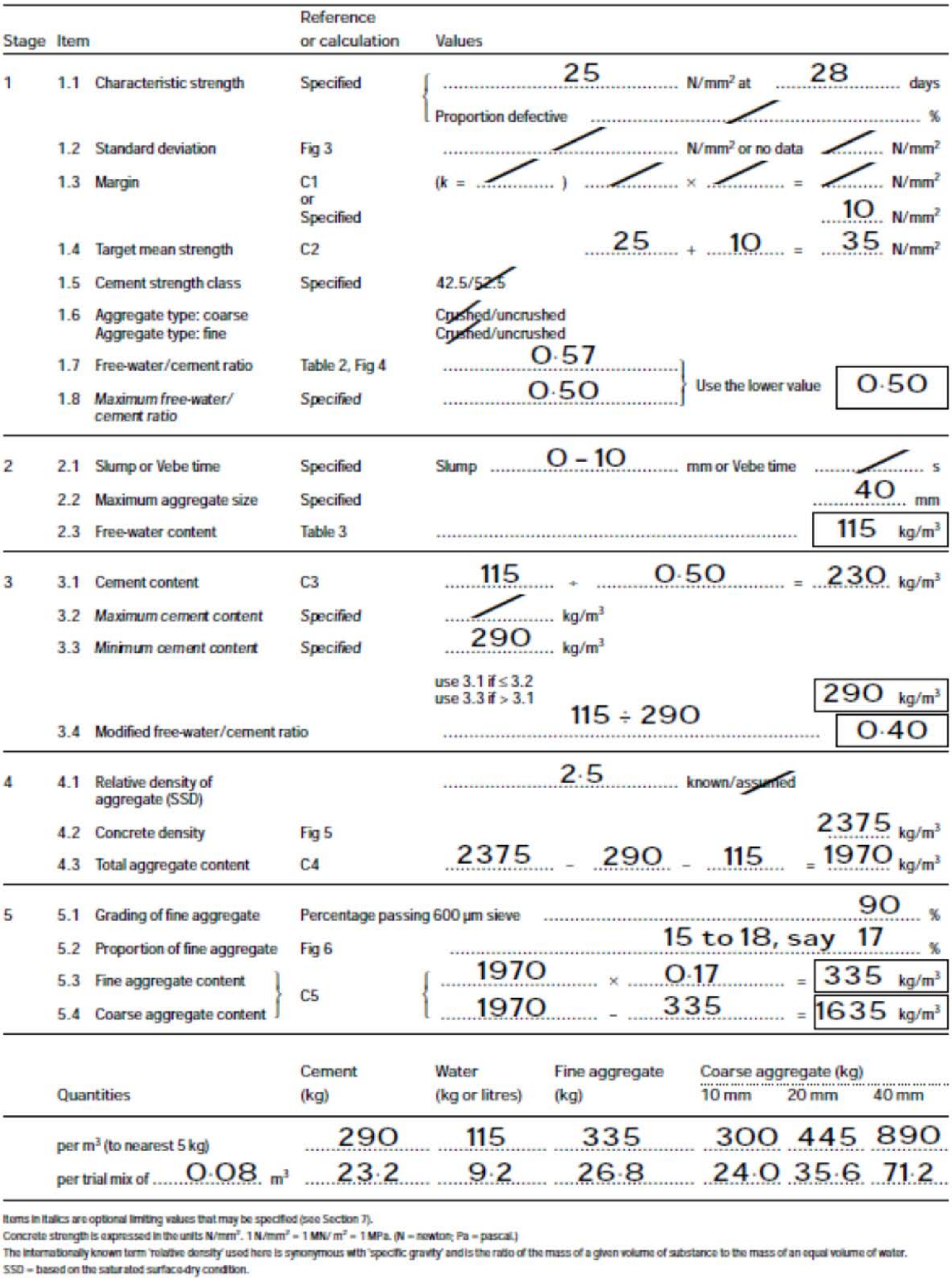


Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	25 N/mm² at 28 days Proportion defective / %
	1.2	Standard deviation	Fig 3	/ N/mm² or no data / N/mm²
	1.3	Margin	C1 or Specified	(k = /) / × / = / N/mm² 10 N/mm²
	1.4	Target mean strength	C2	25 + 10 = 35 N/mm²
	1.5	Cement strength class	Specified	42.5/~~52.5~~
	1.6	Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0·57 } Use the lower value 0·50
	1.8	*Maximum free-water/ cement ratio*	*Specified*	0·50
2	2.1	Slump or Vebe time	Specified	Slump 30 - 60 mm or Vebe time / s
	2.2	Maximum aggregate size	Specified	40 mm
	2.3	Free-water content	Table 3	160 kg/m³
3	3.1	Cement content	C3	160 ÷ 0·50 = 320 kg/m³
	3.2	*Maximum cement content*	*Specified*	/ kg/m³
	3.3	*Minimum cement content*	*Specified*	290 kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 320 kg/m³
	3.4	Modified free-water/cement ratio		/
4	4.1	Relative density of aggregate (SSD)		2·5 known/~~assumed~~
	4.2	Concrete density	Fig 5	2325 kg/m³
	4.3	Total aggregate content	C4	2325 - 320 - 160 = 1845 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	90 %
	5.2	Proportion of fine aggregate	Fig 6	20 to 23, say 22 %
	5.3	Fine aggregate content	C5	1845 × 0·22 = 405 kg/m³
	5.4	Coarse aggregate content		1845 - 405 = 1440 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	320	160	405	260	395	785
per trial mix of 0·08 m³	25·6	12·8	32·4	20·8	31·6	62·8

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Table 6 Completed concrete mix design form for a mix restricted by minimum cement content



Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	25 N/mm^2 at 28 days Proportion defective .... %
	1.2 Standard deviation	Fig 3	.... N/mm^2 or no data .... N/mm^2
	1.3 Margin	C1 or Specified	(k = ...) .... × .... = ... N/mm^2 10 N/mm^2
	1.4 Target mean strength	C2	25 + 10 = 35 N/mm^2
	1.5 Cement strength class	Specified	42.5/~~52.5~~
	1.6 Aggregate type: coarse Aggregate type: fine		~~Crushed~~/uncrushed ~~Crushed~~/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0·57 } Use the lower value 0·50
	1.8 *Maximum free-water/cement ratio*	*Specified*	0·50
2	2.1 Slump or Vebe time	Specified	Slump 0 – 10 mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	40 mm
	2.3 Free-water content	Table 3	115 kg/m^3
3	3.1 Cement content	C3	115 ÷ 0·50 = 230 kg/m^3
	3.2 *Maximum cement content*	*Specified*	.... kg/m^3
	3.3 *Minimum cement content*	*Specified*	290 kg/m^3
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 290 kg/m^3
	3.4 Modified free-water/cement ratio		115 ÷ 290 0·40
4	4.1 Relative density of aggregate (SSD)		2·5 known/~~assumed~~
	4.2 Concrete density	Fig 5	2375 kg/m^3
	4.3 Total aggregate content	C4	2375 – 290 – 115 = 1970 kg/m^3
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	90 %
	5.2 Proportion of fine aggregate	Fig 6	15 to 18, say 17 %
	5.3 Fine aggregate content	C5	1970 × 0·17 = 335 kg/m^3
	5.4 Coarse aggregate content	C5	1970 – 335 = 1635 kg/m^3

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	290	115	335	300	445	890
per trial mix of 0·08 m^3	23·2	9·2	26·8	24·0	35·6	71·2

Items in italics are optional limiting values that may be specified (see Section 7).

Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)

The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

SSD = based on the saturated surface-dry condition.

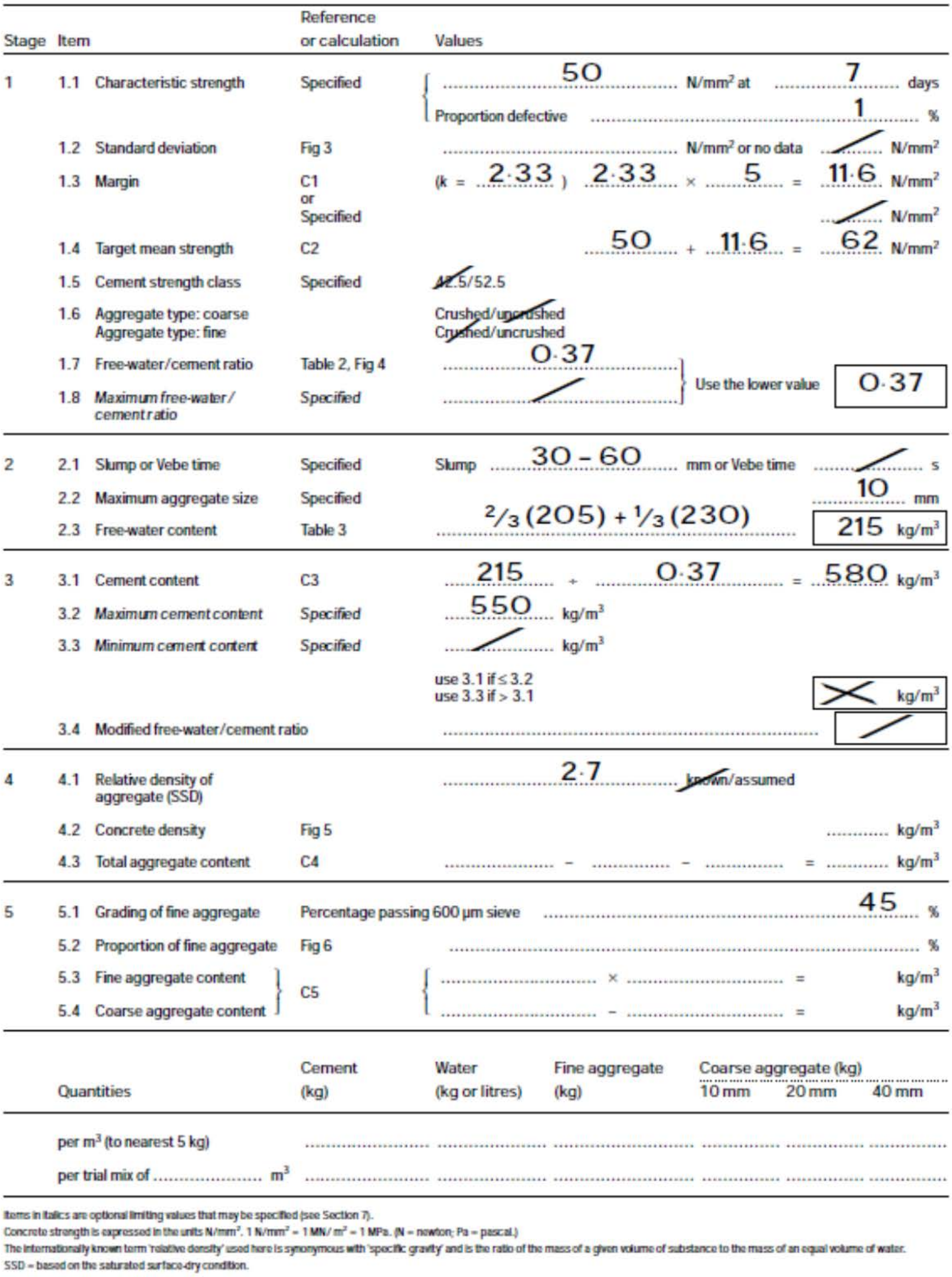


Table 7 Completed concrete mix design form for a mix restricted by maximum cement content

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	50 N/mm² at 7 days Proportion defective 1 %
	1.2 Standard deviation	Fig 3	.... N/mm² or no data .... N/mm²
	1.3 Margin	C1 or Specified	(k = 2.33) 2.33 × 5 = 11.6 N/mm² .... N/mm²
	1.4 Target mean strength	C2	50 + 11.6 = 62 N/mm²
	1.5 Cement strength class	Specified	~~42.5~~/52.5
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/~~uncrushed~~ ~~Crushed~~/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.37 } Use the lower value 0.37
	1.8 *Maximum free-water/ cement ratio*	*Specified*	....
2	2.1 Slump or Vebe time	Specified	Slump 30 - 60 mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	10 mm
	2.3 Free-water content	Table 3	⅔ (205) + ⅓ (230) 215 kg/m³
3	3.1 Cement content	C3	215 ÷ 0.37 = 580 kg/m³
	3.2 *Maximum cement content*	*Specified*	550 kg/m³
	3.3 *Minimum cement content*	*Specified*	.... kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 .... kg/m³
	3.4 Modified free-water/cement ratio		....
4	4.1 Relative density of aggregate (SSD)		2.7 ~~known~~/assumed
	4.2 Concrete density	Fig 5	.... kg/m³
	4.3 Total aggregate content	C4	.... − .... − .... = ... kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	45 %
	5.2 Proportion of fine aggregate	Fig 6	.... %
	5.3 Fine aggregate content	C5	.... × .... = ... kg/m³
	5.4 Coarse aggregate content	C5	.... − .... = ... kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	....	....	....	....	....	....
per trial mix of .... m³	....	....	....	....	....	....

Items in italics are optional limiting values that may be specified (see Section 7).

Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)

The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.

SSD = based on the saturated surface-dry condition.

8. BRICKS

8.1 Introduction

Bricks may be broadly described as building units which are easily handled with one hand. By far the most widely used size at present is the brick of 300 mm x 200 mm x 100 mm (length, width, depth).

The basic ingredient of brick is clay, which has specific properties. It must have plasticity when mixed with water, so that it can be molded or shaped; it must have sufficient tensile strength to keep its shape after forming; and clay particles must fuse together when subjected to sufficiently high temperatures.

Clay occurs in three principal forms, all of which have similar chemical compositions but different physical characteristics:

1. **Surface Clay:** As the name implies, they are found near the surface of the earth.
2. **Shales:** They are clays, which have been subjected to high pressure until they have become relatively hard.
3. **Fireclay:** Fireclays are found at deeper levels than the other types and usually have more uniform physical and chemical qualities. Their most important characteristics is their ability to withstand high temperatures.

Clays are complex materials, but basically they are compounds of silica, and alumina with varying amounts of metallic oxides and other-ingredients. They may be divided into two classes, depending on basic composition:

a) Calcereous clays: They contain about 15% calcium carbonate and burn to a yellowish color.

b) Noncalcerous clays: They are composed of silicate of alumina and iron oxide. These clays burn to red or salmon (yellowish-pink), the color depending largely on the iron oxide content (2-10%).

8.2 Manufacturing of Bricks

Manufacturing of bricks has seven phases.

1-) Mining and storage of raw materials

2-) Preparing raw materials

3-) Forming units

4-) Drying
5-) Glazing
6-) Burning and cooling
7-) Drawing and storing the finished product.

8.2.1 Mining And Storage

Most clays are mined from open pits, although some fireclays are obtained by underground mining. The material is transported to the plant site, if the clay is in large lumps, it first undergoes preliminary crushing. Care must be paid to minimize the variations in chemical composition and physical properties.

8.2.2 Preparing Raw Materials

From the storage bins, clay passes to crushers, where stones are removed and the material is reduced to relatively small pieces, no larger than 5 cm in diameter. Then the crushed materials are transmitted to grinders, where it is reduced to a very fine flour. The ground clay passes over a vibrating screen which passes only the material which has been ground finely enough.

8.2.3 Forming

The first step in forming process is tempering (softening), the mixing of clay with water in a mill (mixer). The amount of water used depends on the method being used to form the units. There are three principal methods in use.

a-) The stiff-mud process:

Only enough water is used to produce plasticity, usually from 12 to 15 percent by weight. The plastic clays go through a machine to remove air pockets and bubbles. This also increase workability and strength. The clay is then forced by an auger through a die, which produces a continuous column of clay of the proper size and shape, and at the same time imparts the desired texture to the surface. The clay column passes through an automatic cutter which cuts of the proper lengths. These are carried by belt to an inspection area, where good units are unloaded onto drier cars, and imperfect ones are returned to the mill for reprocessing.

b-) Soft-mud process:

This is used for making brick only with clays, which contain too much natural water for the stiff-mud process. Twenty to thirty percent water is used in tempering and the bricks are formed in molds. Molds are lubricated by sand or water.

c-) Dry-press process:

This is a process using the least water in tempering (softening), the maximum being about 10 percent. The relative dry mix is fed to machines which form the bricks in steel molds under high pressure, much the same way which concrete blocks are produced.

8.2.4 Drying

When the units come from the forming machines, they contain from 7 to 30 percent moisture (Green Bricks). Most of that moisture is removed in drying process. Drying may be in natural or kiln driers. Natural drying is very rare today. Today's system of drying is by drier kilns. Drier kiln temperatures range from 38 to 204 ^{o}C, and the drying time varies from 24 to 48 hours, depending on the type of clay. Drying causes shrinkage, which must be allowed for when the bricks are being formed so that the finished product will be the proper size. Heat in kilns is usually provided by the exhaust heat from the burning kilns. In all cases the heat and humudity are carefully regulated to avoid too-rapid shrinkage, which causes excessive cracking.

8.2.5 Glazing

When bricks are to be glazed, it is usually done at the end of the drying period, although low fire glazes can be applied after the brick has been burned. Ceramic glazing consist of spraying a coating of a mineral ingredients on one or more surfaces of brick. The glaze melts and fuses to the brick at a temperature, producing a glasslike coating which is available in almost any color.

8.2.6 Burning & Cooling

Burning is a very important step in the manufacture of brick. The time required varies from 40 to 150 hours, depending on the type of kiln, the type of clay, the type of glaze if any. Kiln types are tunnel kilns and periodic kilns. In the tunnel kiln, dried bricks pass through various temperature zones on special cars. In periodic kilns the temperature is varied periodically until the burning is completed. Fuel may be natural gas, oil, or coal.

Burning may be divided into six general steps; water-smoking, dehydration, oxidation, vitrification, flashing and cooling. Water-smoking (evaporation of free water) takes place at temperatures up to about 204°C; dehydration at temperature from about 149°C to 982°C; oxidation from 538 to 982°C and vitrification from 871 to 1315°C.

Near the end of the burning process, the bricks may be flashed to produce color variation. This is done by injecting natural gas at the appropriate time or place. When extra fuel burns, variations in color are formed throughout the stack of bricks.
Cooling takes from 48 to 72 hours, depending on the type of kiln; it must be carefully controlled because the rate of cooling has a direct effect on color and because too-rapid cooling will cause cracking in the bricks.

8.2.7 Drawing & Storing

Drawing is the process of unloading a kiln after the bricks are cool. At this time they are normally stored, graded, packed and taken to storage yards or loaded on trucks for shipment.

8.3 Types of Bricks

There is a wide range of bricks available, varying in the materials used, method of manufacture and form of brick and these are also changes from country to country. Bricks can be classified in three different ways.

8.3.1 Varieties and Functions

1-) Common:
Suitable for general building work but generally of poor appearance.

2-) Facing:
Specially made or selected to give an alternative appearance.

3-) Engineering:
Dense and strong semi-vitreous(nature) to defined limits for absorption and strength.

8.3.2 Qualities

1-) Internal:
Suitable for internal use only.

2-) Ordinary:
Normally sufficiently durable for external use.

3-) Special:
Durable in situations of extreme purposes.

8.3.3 Types

1-) Solid:
Not more than 25% small holes of volume of brick.

2-) Perforated (making holes):
Small holes exceeding 25% of volume.

3-) Hollow(big holes):
Larger holes, exceeding 25%.

4-) Cellular:
Holes closed at one end, exceeding 20%.

8.4 Mortars

Bricks are bedded in and jointed with mortar. A good mortar spreads easily, remains plastic while bricks are being laid to provide a good bond between bricks and mortar, resists frost and acquires early strength, particularly in winter. Mortars should not be stronger than necessary, as an excessive strong mortar concentrates the effects of any differential movements in fewer and wider cracks.
The types of mortars are as listed below:

8.4.1 Lime Mortar

This mortar was used in part. It composed of one part of lime to three parts of sand (1:3). With the advent of cement its use diminished.

8.4.2 Cement Mortar

A mix of (1:3) cement to sand is workable but too strong for or every day use. It would be suitable for heavily loaded brickwork in extremely wet situations. The sand should be clean and well graded.

8.4.3 Cement Lime Mortar

This is the most useful for general purposes. The best properties of both cement and lime are utilized to produce a mortar which has good working, water retaining and bonding qualities, and also develop early strength without an excessive high mature strength.

8.4.4 Air Entrained Mortar

Mortar plasticisers, which entrain air in the mix, provide an alternative to lime for improving the working qualities of lean cement-sand mixes. Hence, a 1:6 cement-sand mortar gauged with plasticiser is a good alternative to a 1:1:6 cement-lime-sand mix.

8.5 Properties of Brick and Brickwalls

All properties of brick are affected by the composition of raw material used and the manufacturing processes involved. Those properties include color, texture, size, strength, and absorption.

8.5.1 Color

The color of a burned brick depends on its chemical composition, the heat of the kiln and the method used to control the burning. All clays containing iron will burn red if exposed to an oxidizing fire. If it is burned in a reducing atmosphere the same clay will take purple color. If the same clay is underburned salmon (orange-pink) colors are produced. Overburning produces dark red bricks.

8.5.2 Texture

Texture is produced by the surface treatment of clay and is given as it leaves the die (forming unit).

8.5.3 Size

Most clays shrink during drying and burning, from 4.5 to 15 percent, and allowances are made for this when the units are molded. Shrinkage will vary, depending on the composition of the clay, its fineness, the amount of water added, and the kiln temperature. As a result, absolute size uniformity is possible, and consequently specifications normally include permissible variations in size.

8.5.4 Strength of Bricks

The strength characteristics of brick also vary with the raw materials and the manufacturing process involved. The considered strength of bricks are compression, tensions and shear, traverse strength. In different standards, they are given.

8.5.5 Water Absorption Of Brick

The water absorption of brick is defined as the weight of water, expressed as a percentage of the dry weight, which is taken up under a given test method. The water is taken in through the pores which act as capillaries to suck water into the unit. This initial rate of absorption or suction, of a brick has an important effect on the bonding between brick and mortar. Test indicate that maximum bond strength is obtained when suction rate at the time of laying is about 20 g/min. The method of determining the suction rate of brick consists of partially immersion the unit to a depth of 3 mm in water for 1 minute. It is then removed and weighed, and the final weight is compared to the dry weight.

Table 1: TS 705 Specification Requirements for Factory Bricks

Classes of Bricks		Types of Bricks		Type No	Symbols of Bricks(1)	Highest Average Bulk Weight (kg/dm^3)	Average Compressive Strength(3) (kgf/cm^2)	Lowest Compressive Strength(3) (kgf/cm^2)	Highest Total Hole Area (%)	Marks on the Brick
Unvetrified Bricks	Solid Brick	Solid Brick		1	DOT 1.8/200	1.8	200	160	15	1
				2	DOT 1.8/120	1.80	120	95	15	2
				3	DOT 1.8/80	1.80	80	65	15	3
	Hollowed Bricks With Vertical Cells	Percentage of Holes in the Cross Section	Low	4	SDT 1.4/200	1.40	200	160	25	4
				5	SDT 1.40/120	1.40	120	95	25	5
				6	SDT 1.40/80	1.40	80	65	25	6
			Med.	7	ADT 1.20/150	1.20	150	120	35	7
				8	ADT 1.20/100	1.20	100	80	35	8
				9	ADT 1.20/60	1.20	60	45	35	9
			High	10	ÇDT 1.0/80	1.00	80	65	45	10
				11	ÇDT 1.0/50	1.00	50	40	45	11
	Hollowed Brick With Horizontal Holes	Hollowed Brick With Horizontal Holes		12	YDT 0.80/36	0.80	36	30	No Limit	12
				13	YDT 0.50/24	0.50	24	20	No Limit	13
Vetrified Bricks		Solid		14	DOK 1.80/300	1.80(2)	300	250	-	14
		Hollowed		15	DEK 1.80/300	1.80(2)	300	250	No Limit	15

Notes:

(1) Bricks required to show resistance to freezing and thawing

(2) Lowest unit weight

(3) Lowest average compressive strength and lowest compressive strength values are valid for normal bricks only. They should be reduced by 25 % for block-bric

9. BUILDING STONE & MASONRY

9.1 Introduction

Natural stone is obtained from rocks that constitute the earth's crust. Rock and stone are essentially the same materials, except that after the rock has been quarried, it is called stone.

The term dimension stone refers to stone that has been fabricated to required dimensions, texture, surface finish, and so on, and meets the requirements for durability, strength water absorption and the like. The term includes stone cladding panels, veneer stone, counter- and tabletops, wall copings, stair treads and rises. It specifically excludes broken or crushed stone.

Stone is a natural material, so its characteristics (properties and appearence) are inconsistent.

9.2 Types of Natural Building Stones

Granite

It is igneous rock. It is the strongest and densest of building stones. It weathers far more slowly than other stones and takes an extremely good polish. Therefore it is commonly used in the exterior cladding of significant buildings.

Generally it contains 25% to 40% quartz and 3% to 10% mica; the remainder (50% or more) is feldspar. Quartz is the srtongest and more durable of the three minerals. Therefore, it is more difficult to process (sawing, profiling, grinding) granite.

A granite low in quartz is generally darker in color. Black granite (basalt) which has a handsome finish, is commonly used as table or countertops. It is not used where hidh strength or abrasion resistance is necessary, such as floors and stair treads.

Quartzite is a stone that is almost 100% quartz. It is commonly used as an aggregate to produce ultra-high-strength concretes.

Limestone

It is a sedimentary rock, consisting primarily of the carbonates of calcium and magnesium, with small amounts of clay, sand, and organic material such as seashells and other fossils. Limestone is generally nongranular, with a relatively uniform surface appearence. It is softer than both marble and granite hence easier to quarry, saw and shape. Color may vary from white to gray. Calcium carbonate reacts with acids. Most foods contain acids therefore, limestone is not used for kitchens or tabletops.

Several historic buildings with limestone facades have performed quite well in the absence of reactive atmosphere. Limestone is also used commonly for concrete aggregate (like in Cyprus).

Marble

Geologically marble is different from limestone because it is metamorphic rock. Chemically it is similar to limestone. In facti marble is limestone, which under centuries of high pressure and heat in the earth's crust changed from a sedimentary rock to metamorphic rock. Because of pressure and heat, marble is stronger and denser than the original limestone. It takes a good polish. Marbles vary from white to black, pink, and so on. It is vulnerable to acid attack.

Travertine

It is a sedimentary rock obtained from the sediments of limestone dissolved in spring-water. Springwater (particularly hot springs) running over limestone deposits dissolved the limestone, which subsequently sedimented (deposited) in a nearby location.Travertine is a porous stone and slabs are pitted with voids.

They are softer. Therefore, they do not take polish. Denser varieties are referred as *travertine marble*.

They are used is building exteriors as masonry walls. When used as flooring material, surface can collect dirt which requires greater maintenance.

Sandstone

It is a sedimentary rock formed by layers of sand (quartz) particles with oxides of calcium, silicon and iron as cementing agents. If cemented primarily of oxide of silicon, sandstone is light in colour and strong. If cemented by iron oxide sandstone is brown or red in colour and softer. Large amount of calcium oxide makes sandstone more vulnerable to disintegration.

9.3 Production of Finished Stone

Natural stone is produced by stone fabricators from quarries in the form of large blocks. Blocks are of irregular sizes (see **figure 9.1**). These blocks are converted into slabs and other cross-sectional profiles in stone fabrication plants. The conversion is done by sawing the blocks-a process similar to sawing lumber, except that water is used continuously during the sawing process to keep the saw blades cool (see **Figure**

9.2). The saw uses a blade that can move in horizonlar and vertical direction. Complex ornamental work requires hand tools (see **figure 9.3**).

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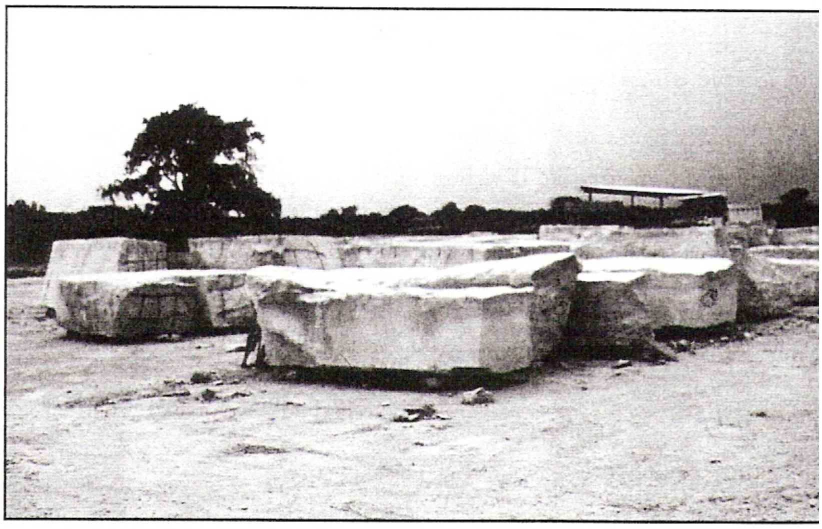

Figure 9.1 Natural building blocks of irregular sizes.

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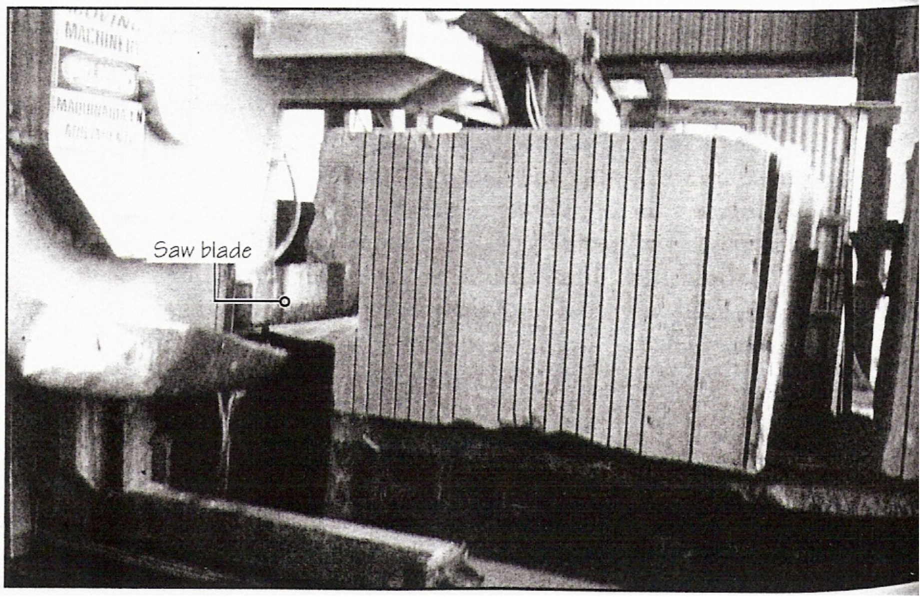


Figure 9.2 Sawing process of natural building blocks.

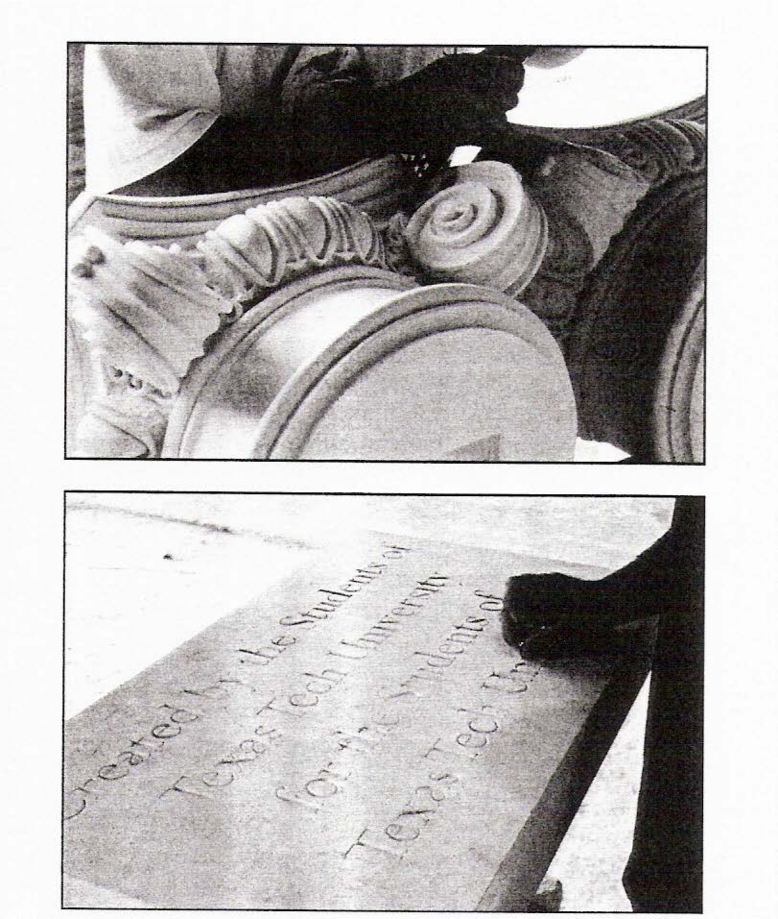


Figure 9.3 Ornamental works with natural building stones.

9.4 Finishes on Stone Slabs & Panels

The surface of stone slabs and panels can be finished in several ways. This finish also effects the durability of stone. The following are some of the commonly used finishes on stone slabs and panels:

Sawn finish: If stone is not finished after sawing, it is called sawn finish. Saw marks are visible.

Honed finish: When a sawn finish is ground smooth with an abrasive material, a honed finish is obtained. It requires repeated honing (grinding) with increasingly finer abrasives. Water is used continiously during the process to control dust (see **Figure 9.4**).

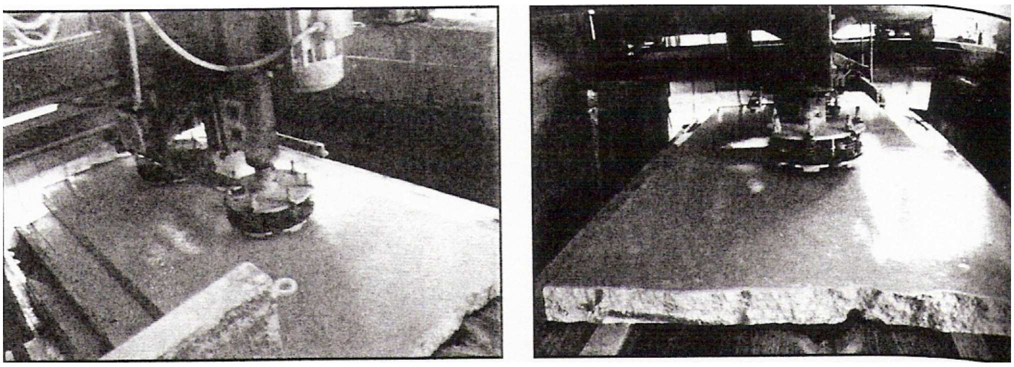


Figure 9.4 Polishing of surfaces.

Polished finish: Polish finish is also honed but with a matt appearence. It is obtained by grinding the stone surface beyond the honed finish with finer abrasives and finally buffing it with felt until the surface develops a sheen. It brings out the colour of stone to its fullest extend by reflecting like a mirror.

Flame-cut finish: Also known as “thermal finish”. It is a rough finish obtained by torching the stone surface with a natural gas or oxyacetylene torch. Before torching, the stone is wetted. The heat from the torch expands the absorbed water into stream, which breaks loose surface particles in the stone, leaving behind a rough surface. These finishes are paticularly ideal for floors subject to frequent wetting.

Bush hammered finish: It is also a rough finish and is obtained by hammering off the surface of stone with picks.

Split-face (cleft) finish: Stone is split through one of its faces.

Sandblasted finish: This process yields a rough surface.

9.5 Stone Selection

The selection of stone for a particular use is a function of several factors. Budget and aesthetics (color, pattern and surface appearence) are the two most important factors to be considered for stone used in building interiors.

For exterior use, the history of performance of a stone in the local environment (durability) is obviously another important factor.

Generally the following properties are important:

- Density
- Water absorption
- Compressive strength

- Flexural strength (modulus of rupture)
- Abrasion resistance

Table 9.1 below, based on common uses of various stones, provides a rough guide in stone selection.

Table 9.1 Common applications of selected stones.

Application	***Commonly used stones***
Exterior wall cladding	Granite, marble, limestone
Interior wall cladding	Granite, marble, limestone
Interior flooring	Granite, marble, slate
Stair treads and risers	Granite
Kitchen counter top	Granite
Bathroom counter top	Granite, marble
Wall copings and balusters	Granite, marble, limestone
Roofing	Slate

9.6 Bond Patterns in Stone Masonry Walls

In contemporary buildings, natural stone is generally used as thin slabs. For exterior or interior wall cladding, slabs vary in thickness from 20 mm to 50 mm. For flooring, slab thickness can be as low as 9.5 mm. The thinner the stone, the smaller the size of slab in which it is available.

Stones used in exterior-wall veneers are generally 75 mm to 100 mm thick. Those used in load bearing stone walls are thicker. In some cases, stones are so large and thick that they can not be laid by hand bu require mechanical hoists.

Stone veneer and load-bearing stone walls are referred to as ***stone masonry*** to distinguish them from thin stone cladding. These walls are laid with mortar, stone by stone, in the same way as bricks.

Because natural stone is not available in uniform sizes as are bricks, the bond patterns in stone masonry walls are different from those used in bricks. Two basic patterns used in stone masonry walls are

- Rubble masonry
- Ashlar masonry

Rubble masonry:

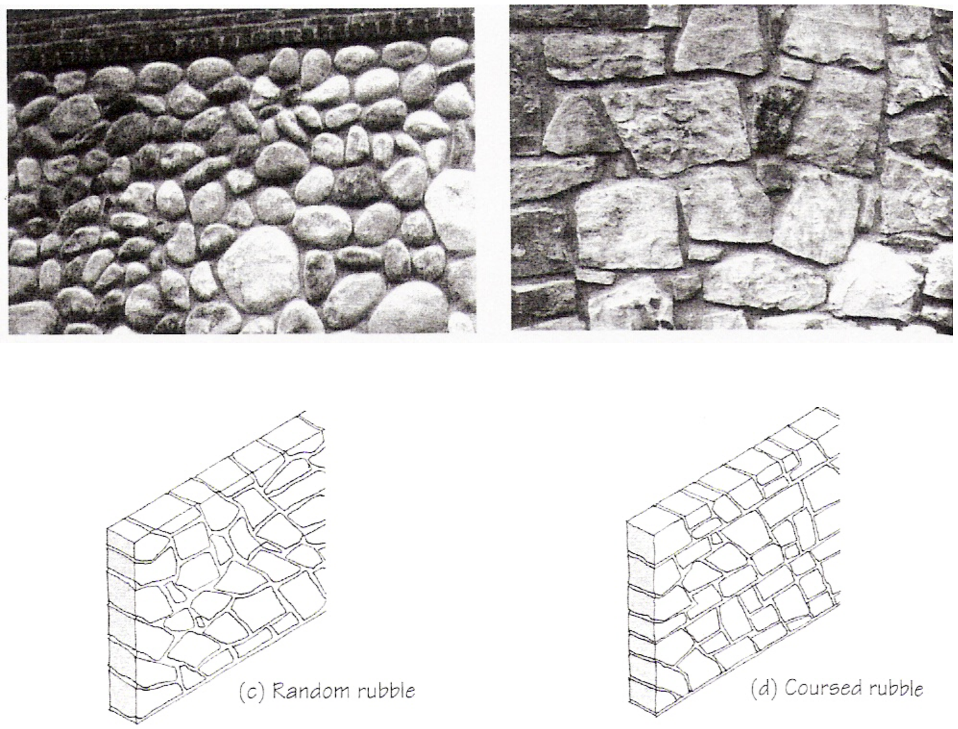
These walls are made from stones whose sides are irregular (not at right angles to each other). Rubble masonry is further subdivided as “random rubble” and “coursed rubble”.

Random rubble: The mortar joints are irregular. A random rubble wall may consist either of stones obtained from the quarries or rounded riverbed boulders.

Coursed rubble: The bed joints line up after every few pieces of stone (see **figure 9.5**). Therefore, the mason has to select the stones in the field (or shape them using a pointed hammer) so that they fit in the available spaces.

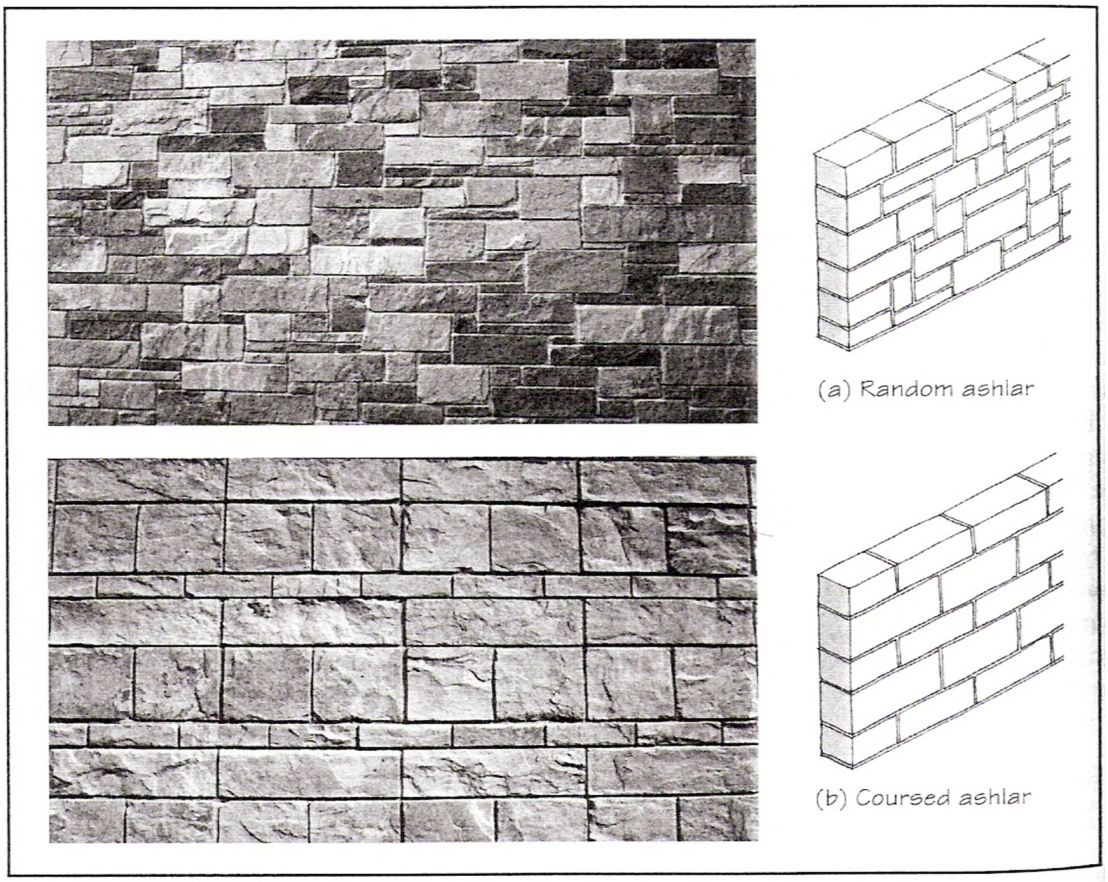
Ashlar masonry:

The sides of the stones are dressed square (at right angles to each other). The front and back faces of the stone may, however, be dressed or undressed. Like rubble masonry, ashlar masonry is also divided into “random ashlar” and “coursed ashlar” (**see figure 9.6**).


(c) Random rubble

(d) Coursed rubble

Figure 9.5 Random rubble and coursed rubble masonry walls.



(a) Random ashlar

(b) Coursed ashlar

Figure 9.6 Random ashlar and coursed ashlar masonry walls.

9.7 Glass Masonry Units

Glass masonry units (glass blocks) are used as non-load bearing walls in virtually all types of projects-commercial and residential-on the exterior as well as in the interior of buildings. By conbining the modularity of masonry units and the transparency of glass, glass masonry units give designers a means of expression that is not available in other materials (**see figure 9.7**).

Figure 9.7 A typical glass masonry unit.

These units are manufactured in several sizes (typical 190 mm x 190 mm x 80 mm). The units are generally hollow with air trapped within, although solid units are also available. Glass blocks are generally translucent. Thus a glass block wall provides light similar to a frosted window glass. However, a glass block wall gives greater privacy, more security and greater sound insulation as compared with a glass window or a glass curtain wall. Where greater transparency is needed, transparent units are used.

Glass masonry walls also have a higher fire-resistance rating than conventional glas walls. A 45-min rating is easily achievable, and a higher rating is available.

Construction of a glass masonry wall

The construction of a glass masonry wall is similar to other masonry walls. The units are generally laid in stack bond with Portland cement-lime mortar. The joints are fully mortared as with clay bricks.

Glass masonry units are non-structural. Therefore, a glass masonry wall must be treated as a non-load bearing wall. It should not be designated to support any gravity load except its self-load. However, it must resist lateral (wind and earthquake) loads and be able to transfer them to the structural frame.

A large glass masonry panel is treated as a combination of panels held between structural steel or reinforced-concrete framing members (**see figure 8.8**). Manufacturers provide the data to facilitate the structural design of a panel, in addition to some engineering support.

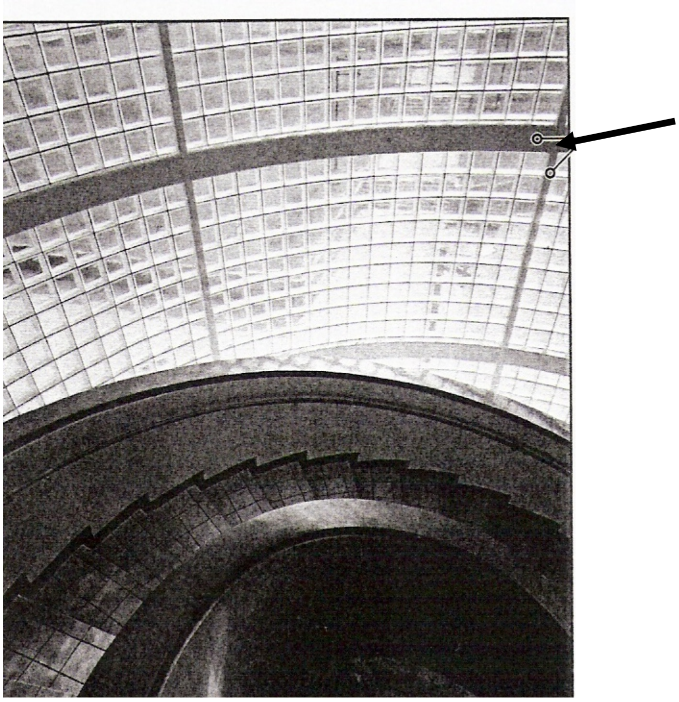


Figure 9.8 Staircase enclosure built with glass masonry units.

Figure 9.9 shows a detail commonly used for the construction af a glass masonry panel. Steel anchors are used at the top and the sides (jambs) to transfer the lateral load from the panel to the supporting members. The long leg of an anchor is embedded in the mortar joint, and the short leg is fastened to the jamb or the head of the supporting frame.

Joint reinforcement is needed to stiffen the panel so that the panel as a whole is able to transfer the lateral load to the structure. Generally, the joint reinforcement is placed in the same course as the horizontal anchors.

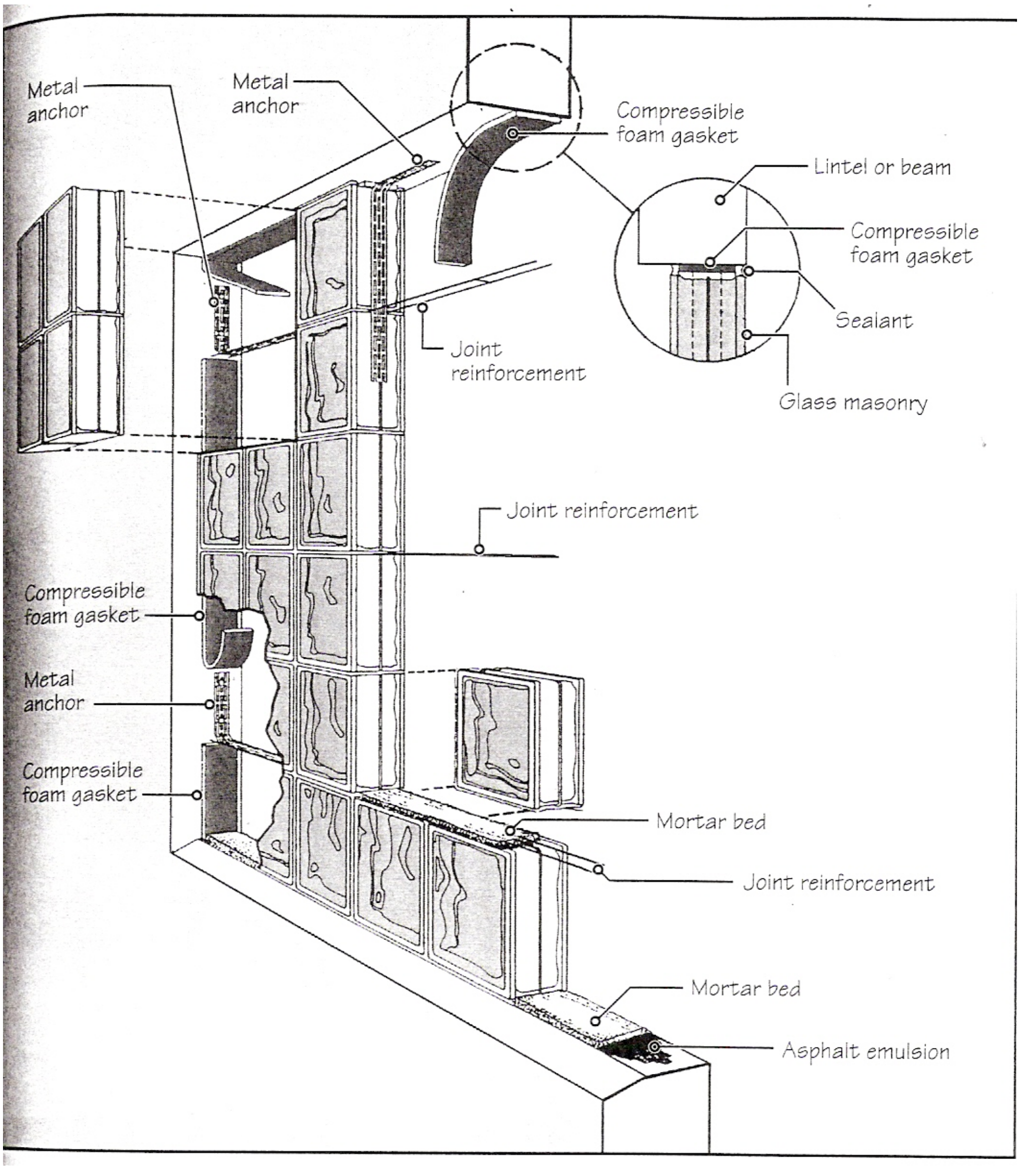


Figure 9.9 A typical detail used for the construction of a glass masonry panel.

9.8 Fire Resistance of Masonry Walls

Fired clay, concrete and stone are noncombustible and inherently fire enduring. Therefore, the fire-resistance ratings of masonry assemblies is generally high. One of the important factors that affects the fire-reistance rating of a masonry wall is the amount od solid content in them. The greater the solid content, the greater the fire-resistance rating of a wall. Therefore, a grouted wall has a higher fire-resistance rating than an ungrouted wall.

Because concrete masonry units are generally hollow, the fire resistance rating of a concrete masonry units wall is given in terms of the wall's equivalent (solid) thickness. Equivalent thickness is the thickness of the wall excluding the cells (voids). The equivalent thickness of a fully grouted wall is the thickness of the wall itself.

Another factor that influences the fire resistance rating of a concrete masonry unit wall is the type of aggregate used in the concrete masonry units. A wall made with concrete masonry units containing lightweight aggregate gives a higher fire-resistance rating for the same equivalent thickness than a wall with concrete masonry units containing normal-weight aggregate.

Figure 8.10 gives the approximate fire-resistance ratings of selected masonry assemblies.

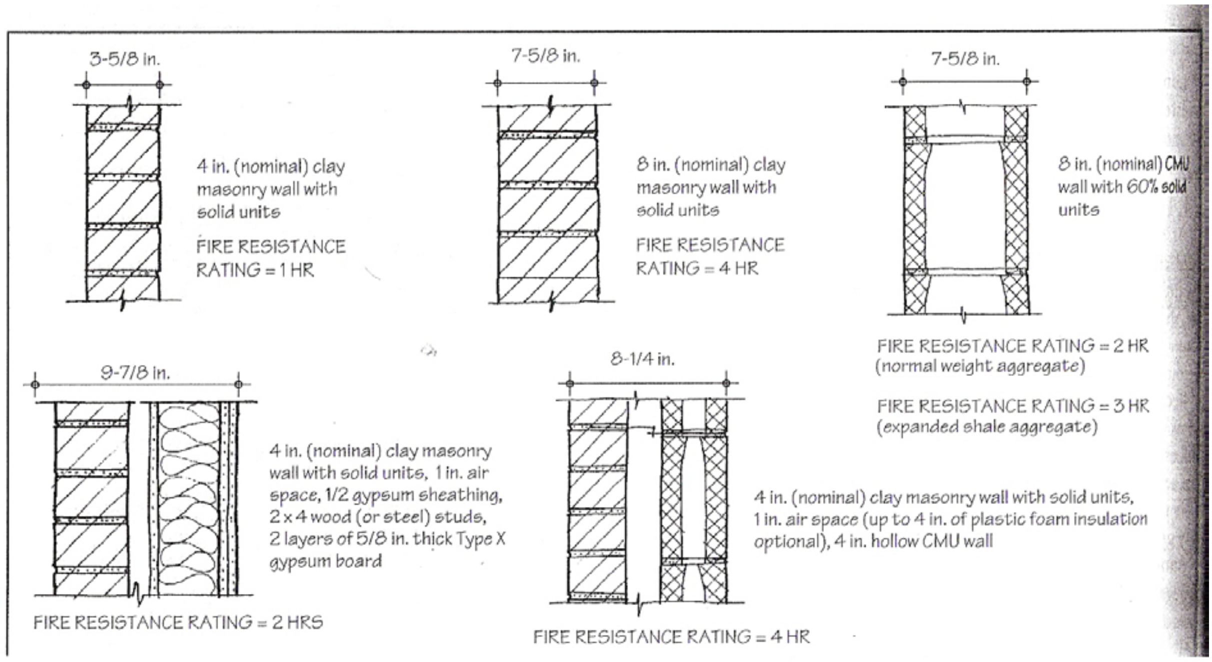


Figure 9.10 Approximate fire-resistance ratings of selected masonry assemblies.

10. PLASTERS

10.1 Introduction

Plasters may be defined as materials designed to provide a durable, flat, smooth, easily decorated finish to internal walls or ceilings. Traditionally they are based on lime or cement but in the last 40 years gypsum has become the most important binder. Some of the advantages of gypsum plasters are as follows:

- Their setting time can be controlled.
- Time delay between successive coats may be very small.
- Various surface textures and surface hardness can be obtained.
- If plastering technique is correct they will not shrink like cement based plasters.
- Excellent fire-resistance. Contains 21% water of crystallisation which absorbs heat and minimises the rate of temperature rise in behind the plaster.

Gypsum plasters are not suitable for exterior uses except very effective permanent protection is provided.

10.2 The Plastering Process:

Maximum 3 coats may be used.

1. Render coat- levels the background.
2. Floating coat- produces flat surface of uniform suction
3. Finishing coat- provides a smooth, hard finish.

10.3 Classes of Gypsum Plasters:

Class A-Hemihydrate ($CaSO_4 1/2\ H_2O$: Plaster of Paris)

Produced by heating to a temperature not in excess of 200°C. Sets within 5-10 minutes of adding water, which is far too rapid to permit use in ordinary trowel trades. It is useful for decorative plasterwork.

Class B- Retarded hemihydrate ($CaSO_4 1/2\ H_2O$)

Produced by adding set retarded (keratin) to Class A plaster. The amount of retarder can be changed.

These plasters are normally designed to be used with sand in ratios of up to 3:1 sand : plaster. Setting times are in the range of 2-3 hours.

Addition of hydrated lime accelerates the set (1-1.5 hours) of plaster. This is normally 25% by weight of hydrated lime.

Premixed plasters containing lightweight aggregates are now widely used. Board finish plasters are in this class.

Class C-Anhydrate

Obtained by heating the raw material to a higher temperature than class B plasters. Therefore, anhydrous calcium sulphate forms and some hemihydrate also remains. Slow setting is accelerated by adding alum. Initial set is fast and final set is slow. This plaster is used as finishing coat on a sand/cement backing (trade name is Sirapite).

Class D- Anhydrate (Keens's cement)

This is burnt harder than class C. There is higher proportion of anhydrate. The product has very high strength with superior smoothness and hardness. Applied on squash court walls where a durable finish is required. It is also an ideal base for gloss finish.

10.4 Lightweight Aggregates

Low-density aggregates, such as expanded perlite (produced from siliceous volcanic glass) and exfoliated vermiculite (produced from mica) are a most important ingredient of modern plasters, which are now almost always premixed. Some advantages of these plasters are as follows:

- Transporting and handling costs of the plaster are reduced.
- The low-density fresh material requires less effort to mix and apply and can be used in thicker coats without sagging.
- The thermal insulation of walls or ceilings is improved and the internal surface temperature increased, thereby improving U values and reducing the risk of surface condensation and pattern staining.
- Fire performance of structures is improved.

10.5 Lime

Lime may be used in quantities up to 5 per cent of gypsum in finishing coat of ordinary class B and C plasters. It improves the working properties ("fattiness") of the fresh material and in class C plasters counteracts acidity due to accelerators, hence it may help reduce corrosion of embedded metals. Non-hydraulic limes must be used and should be soaked in water for one day before use.

10.6 Factors affecting the choice of plaster

These may be conveniently described under the headings undercoat and finishing coat, although the two components are not completely independent – for example, strong , hard finishing coats also require a reasonably strong undercoat.

10.6.1 Undercoat

The most important factor affecting choice of undercoat is background suction – that is, the tendency of the background to absorb water from the plaster coating.

Some suction is desirable, since it removes excess water from the plaster and therefore initiates stiffening. The pores which are responsible for suction also increase adhesion of the plaster by a mechanical keying effect.

Excess suction is a disadvantage because it results in premature stiffening of the paster, giving too little time for levelling and may lead to poor adhesion.

Very low suction is equally a problem, owing to lack of pores which improve adhesion.

Table 10.1 indicates plasters which may be used for backgrounds of varying types. The properties of premixed lightweight undercoat plaster can be varied according to function – for example, “bonding” plaster contains vermiculite aggregate and produces a relatively dense plaster with good adhesion; “browning” plaster contains perlite; while “high-suction background” plaster contains, in addition, cellulose additives to improve water retention.

Table 10.1 Undercoat plasters and their applications.

Suction	*Examples*	*Lightweight Gypsum plaster*
Low	Dense concrete. No-fines concrete. Engineering bricks.	Bonding
Medium	Ordinary clay bricks	Browning
High	Some stock bricks. Aerated autoclaved concrete blocks.	High suction background browning.

Raking of joints in low-suction brickwork or hacking of dense concrete will improve adhesion to backgrounds in the low-suction group. Treatment with PVA-bonding agents both reduces water absorption of high-suction backgrounds and improves adhesion of low-suction backgrounds such as high-strength concrete. Cement/sand/lime plasters form an alternative group of undercoat materials, though these have the disadvantage that the finishing coat application must be delayed for some days to allow curing and shrinkage of the undercoat. One possible advantage of cement based plasters is that they form a barrier to efflioresecent salts if these are present in substantial quantities in the background. It is important, when using cement-based undercoats, that their strength does not exceed that of the background, otherwise shrinkage may result in breakdown of the background surface.

10.6.2 Finishing coat

This will be selected primarily according to the surface hardness requirement, which will in turn depend on the situation within the building and the function of the building. The most demanding situations are projections in corridors and doorways of pubic buildings for which the hardest plasters are required. Table 9.2 indicates the gypsum plaster type most appropriate to various situations. Of the plasters listed, the lightweight variety form the largest part of the current market. These do not have the hardness of dense plasters but are nevertherless quite resilient, since impacts are absorbed by localized indentation of the lightweight undercoat.

10.6.3 One-coat plasters

Plasters are now available which serve as both undercoat and finishing coat. A typical product consists of a white, high-purity Class B gypsum plaster combined with perlite and other additives. The material is best machine mixed. After application, the material is straightened and then left for about 1 hour to stiffen. The surface is then wetted and trowelled with a wooden float to bring fine material (fat) to the surface. After a further delay, the plaster can then be trowelled to a smooth finish with a metal float. The cost of the material is considerably higher than that of the more common gypsum plasters but a saving in time can be achieved since \`float\` and \`set\` functions are obtained in a single coat. The background should be of uniform suction (that is, of the same material type) to avoid the difficulty of different areas of the material stiffening at different rates.

Table 10.2 Finishing coat plasters and their applications.

Function	*Plaster type*	*Comments*
Very hard smooth surface	Class D (anhydrate) finish plaster	Strong undercoat needed. Lightweight types not suitable.
Hard surface	Class C (anhydrate) finish plaster	Normally on cement/sand or class B/sand backing.
Ordinary purposes. Maximum fire resistance and insulation	Lightweight class B olaster	Used on lightweight undercoat.

10.7 Plasterboards

These consist of an aerated gypsum core sandwiched between and bonded to strong paper liners. Most boards have one ivory-coloured surface for direct decoration and one grey-cloloured surface, which has better adhesion properties for plastering. Plaserboards with a foil backing for improved thermal insulation or with a polythene backinfor improved vapour resistance are also obtainable.

Plasterboard can be easily fixed to timber studding by nails or special screws the latter being more satisfactory where the timber frame is of low stiffness. It can also be fixed to masonry, using dabs of special plaster-based adhesives, provided the background is sufficiently straight. In such applications it offers the advantage of requiring only a very small quantity of water; hence it could be used in situations where it is important to keep the relative humidity of the atmosphere to reasonably low levels, where rapid drying is required, or where poor drying conditions prevail. Plasterboard is also available with polystyrene or glass fibre insulation bonded to it, for application either to timber frames or masonry.

A variety of sizes is obtainable (Table 9.3). Laths and baseboards are specifically designed for a plastered finish and provided joints are staggered, they are less likely to result in cracks at joints than wallboards. Planks are intended primarily for fire-resistance applications. Various edges are obtainable according to function – for example, tapered edges are suitable for smooth seamless joints on boards to be decorated direct (dry lining), square edges are suitable for plastering and rounded edges as in laths give a good bond to the filler which is used between adjacent pieces. For plastered finishes, all joints except those in laths must be reinforced with some form of scrim tape to prevent cracking. Correct procedure is essential in respect of joint treatment to obtain the best finished effect and to avoid cracking.

Where plastering is to be carried out, this may be in one or two coats and a neat class B board finish plaster is normally used. The thickness applied is quite small – in the region of 5 mm – and it is important that drying out is prevented until setting is complete, otherwise a soft powdery surface will result.

Table 10.3 Examples of thickness and sizes obtainable in gypsum plasterboards.

Type	*Length (mm)*	*Width (mm)*	*Thickness (mm)*
Laths	1200	406	9.5 or 12.7
Baseboards	1200	914	9.5
Wallboard	2400	1200	9.5 or 12.7
Plank	2400	600	19.0

In spite of their paper surfaces, plasterboards provide good fire protection, being designed as `**class O**` on Building Regulations.

In terms of impact resistance, plasterboards are not as good as traditional in-situ plasters, especially if thin sheets are employed on hollow backgrounds. Thicker sheets or more frequent fixings at least partly overcome such problems. Care is also necessary when making fixing to the materials though reasonably large loads can be carried using special metal or plastic inserts in conjuction whit timber battens which spread the load.

10.7.1 Dry Lining

In this technique, the ivory face of plasterboard is used as the finished surface, the only "wet" trade involved being treatment of joints, nail indentations and any small defects. This offers a further advantage in terms of moisture input into the building. The process cannot however, be "rushed"; to obtain a good result, joints must be taped in the same way as when skimming the whole surface and filling must be carried out in several coats, since the filler material can only be applied in small thicknesses. The final finish is also not as hard as that obtained by application of a thin layer of plaster to the entire surface.

10.8 Common defects in plastering

These may be associated with background problems, inadequate or incorrect surface preparation, incorrect use of materials or incorrect plastering technique. The main problems are listed below.

10.8.1 Cracking

Cracks occur when the plaster is subjected to movement in excess of its strain capacity. Gypsum plasters are non-shrinking but may sill be subject to tensile stress if the background moves.

Examples are:

1. *Background shrinkage*: This may result if the background is very wet when the plaster is applied. The plaster then cracks at concave corners or following a definite line of cracks in the background. The only practicable remedy is to fill the cracks and disguise with a suitable decorative finish.
2. *Undercoat shrinkage*. Cement-based undercoats may form numerous hairline cracks if not given sufficient time to shrink before the finishing coat is applied. An excess of lime in the finishing coat may have the same effect. These cracks maybe filled or simply obscured using a suitable wallpaper.
3. *Plasterboard finishes*. This type of cracking is widespread, usually following plasterboard joints. The extent of cracking is reduced by use of laths or baseboard, movement then being spread over more joints than in large sheets. Causes include undersized joists, inadequately fixed or restrained joists, poor nailing technique, omission of scrim tape, inadequate joint filling or simply severe impact or vibration of the structure. Fine cracks can be covered by

textured finish but deeper cracks should be cut out and filled. Where background movement is the cause of the cracking, it will be likely to recur.

4. *Structural movement*. This leads to well-defined cracks which follow a continuous line through the structure, plaster cracking in the same position on each side of solid walls. Cracks tend to be concentrated at weak points such as above doorways or windows. Before cutting out and filling, it is essential to establish and rectify the cause of the movement.

10.8.2 Loss of adhesion

This results when a strong finishing coat especially if the backing is inadequately scratched to form a mechanical key of if it is still green. The problem is uncommon, except with sand/cement backings. Both coats must be replaced unless the problem is caused by a green backing; if this is the case it should be allowed to harden loose material removed and then the finishing coat reapplied.

The problem will occur with plasterboard if too much lime is added, or in two-coat work if too much sand is used in the undercoat. The plaster must be stripped off and replaced. If the exposed surface is damaged or uneven, the plasterboard must also be replaced.

10.8.3 Dry out

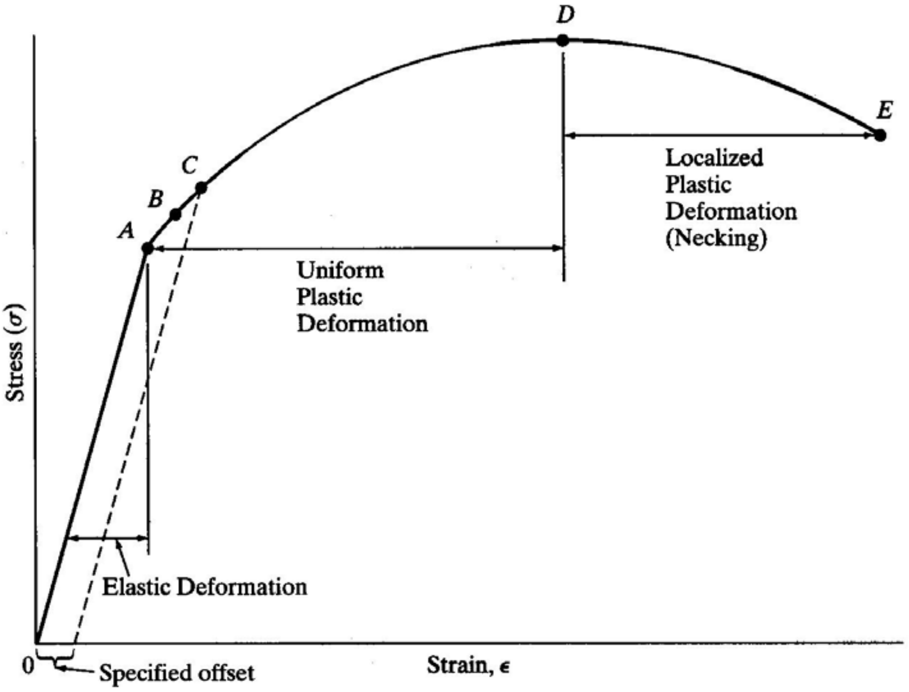
This occurs if plaster dries before the water becomes chemically bound by setting. It occurs if thin coats are applied to dry backgrounds such as plasterboard, especially in hot, dry weather. The result is a soft powdery surface which may be difficult to paint or paper. Defective plasters but salts maybe present in the background or in sand (when used) if not clean. Salt deposits may appear on drying of plaster, especially if the background is wet during plastering. Deposition may also result subsequently if a plastered are becomes wet due to a leak. The salts crystallize below the surface of emulsion paints, causing loss of adhesion. They can be removed by brushing one plaster is dry and will not recur provided the plaster does not become rewetted.

11. METALS

Metals display a number of properties not found in other materials; for example, high tensile and compressive strength, the ability to deform plastically without damage, rapid surface oxidation in the atmosphere; good heat and electrical conduction properties.

11.1 Mechanical properties of Metals

a- Tensile Strength

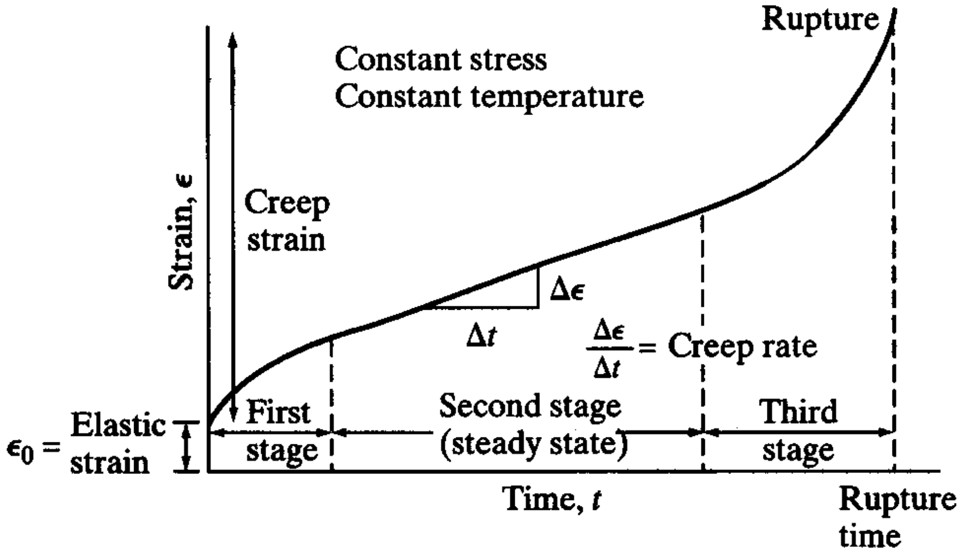


In the tensile test of a metal, a suitable specimen is extended until fracture occurs while measuring the applied loads and extension.

On loading mild steel it behaves elastically showing a straight-line relationship between load and extension from the origin 0 until the yield point “A”. At “A” sudden extension or discontinuous yielding occurs, followed by permanent or plastic deformation. This is from point B to point D where D is the ultimate load or tensile strength reached. From C to E plastic deformation continues but localized reduction in diameter of the specimen (known on necking) causes a reduction in the load required to cause extension although the true stress on the reduced cross-section is increasing. At point E fracture occurs.

b- Creep

Creep is defined as time-dependent strains, which occur when steady stresses are maintained. The phenomenon has been described in concrete, but the same effect occurs in metals,



In the first stage, primary stage, strain increases rapidly from the initial point. During the secondary stage, the strain is less in duration of time. Finally, in the third stage necking occurs with eventual failure.

c- Impact strength

Impact testing measures the toughness of metals. It is the ability of metals to absorb energy quickly. There are many causes of shock loading in a structure, such as slamming of a door, using a heavy loading equipment etc.

d- Fatigue

This is defined as a reduction in strength caused by continued variations in loading. It is quite possible for fatique to occur in bridges where, due to traffic movement, stresses are continually fluctuating.

Fatique damages normally starts at a fault in the metal, such as a weld fault. When the stress fluctuates, plastic movement, which would be possible in the case of static stresses, cannot take place, since there is insufficient time. This may be regarded as equivalent to the increase of yield stress, which occurs on rapid loading. Eventually crack occurs at the stressed point.

e- Hardness

Hardness is not normally an important criterion for metals used in construction. But this test is used for quality control purposes during the manufacturing. “Brinell hardness” is measured by pressing a hardened steel ball into the surface of the metal. In the case of steel, the load is normally about 30 kN with a 10 mm diameter ball. The Brinell hardness is equal to:

$$\frac{\text{Load}}{\text{Surface area of the indentation}}$$

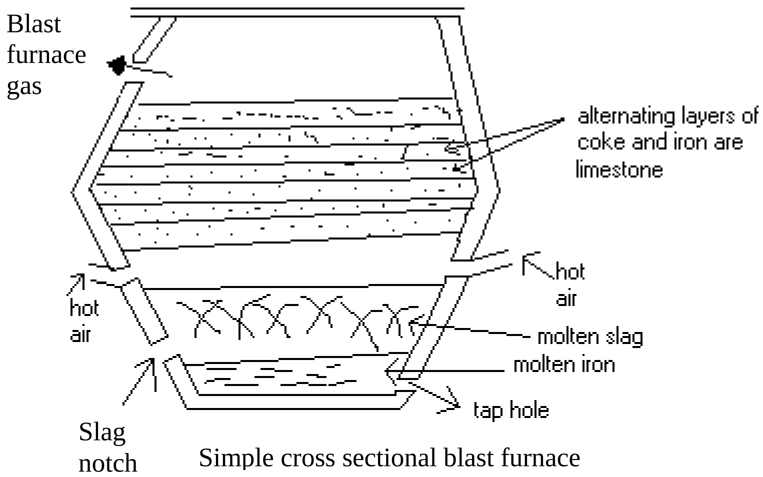
In some metals, hardness may be limited to a maximum value since it is indicative of a brittle structure.

11.2 Extraction of metals

Most of commercial metals are extracted from their ores by reduction process in which, the ores are reduced to the metallic state and any impurities present are separated and removed as slag. The extracted metal still contains appreciable amounts of dissolved impurities, which are further removed by refining processes.

Iron is extracted from its chief ores hematite (Fe_20_3) and magnetite (Fe_30_4). The process is called as reduction and is carried out in the blast furnace into which alternate layers of coke and iron are together with limestone are fed and preheated air is blown in at the bottom. The limestone reacts with such impurities in the ore as alumina and silica to form a low-melting slag. The oxygen in the air burns the coke, and this reaction provides heat and carbon monoxide for reducing the iron oxide.

The molten iron and slag are drawn off separately at the bottom, whereas flue gases and dust escape at the top.



Simple cross sectional blast furnace

The product of the blast furnace is called pig iron, it contains many dissolved impurities and large amount of carbon. Pig iron is not used as an engineering material, because of its brittleness and non-uniform composition, and it has to be further relined to produce cast iron, steel and wrought iron.

Cast iron is generally made by remelting pig iron in a cupola similar in shape to the blast furnace. The cupola is charged with pig iron, scrap iron, coke and some limestone, whereas air is blown upward through the charge. Second melting causes partial refining and the molten cast iron and slag are removed separately at the bottom of the cupola.

Steel is made from pig iron in a furnace. The molten pig iron, scrap iron and steel, limestone is all charged into the furnace (open-hearth furnace). For the melting process, fuel oil or natural gas serves as fuel; it is injected along with hot air. Refining takes from 3.5 to 7 hr at temperatures up to 1650^{o}C.

Ingots

When it is ready the molten steel is drawn from the furnace in giant ladles, from which it is poured into ingots molds. This pouring into molds is known as teeming. The moulds are cooled and then removed, and the ingots placed in seaking pits, where they are reheated to a uniform temperature high enough for rolling.

A great variety of products used in construction industry are made from these ingots. They include rolled structural shapes, rods, bars, plates, pipe, wire, bolts, rivets, nails, sheet steel and many others.

Shaping of Ingots

Ingots may be shape as;

Rolling

Hot rolling: Long length of sections has produced. Rolled at above 700 ^{0}C. Heavy rollers are used to reduce the section size and extend its length.

Cold rolling: It is process after hot rolling, gives clean surfaces and also increases the strength of the metal. Again heavy rollers are used.

Forging: Hammering into complex shape when it is hot.

Casting: Only high carbon steels are suitable and metals poured into moulds tend to be more brittle than those shaped by pressure.

11.3 Carbon Content of Steel

Low Carbon Steels: (up to 0.15 percent carbon) are soft and suitable for iron wire and thin sheet for thin plate.

Mild Steels: (0.15 to 0.25 percent carbon) are strong, ductile, and suitable for rolling into sections, strip and sheet but not usually for casting. They are easily worked and welded.

Medium Carbon Steel: (0/25-0/50 percent carbon) are suitable for forging and for general engineering purposes.

High Carbon Steel: (0.50-1.50 percent carbon) Tensile strength increases to about 725 N/mm^2 as the carbon content increases to about 1 percent. Hardness increases up to about 1.5 percent carbon content, but ductility decreases and high carbon steels are too brittle for structural work. They are also difficult to weld.

High carbon steels can be hardened for use as files and cutting tools, and they can be treated to the springy condition without loss of hardness.

11.4 Types of Steels

Structural Steels
Sheet Steels
Alloy Steels

Structural Steels

They are weldable steels. Generally four different types of them are produced. Each type has different tensile strength ranges. Under these topics we can write all steel bars as reinforcement, steel profiles and all steel tubes for general engineering purposes.

Sheet Steel

Sheet steel is described as not more than 3 mm thick and is used for roof decking, furniture, curtain wall panels etc. But sheets exceptionally sometimes obtained from mild steel up to 6.3 mm.

Alloy Steel (Mixture of metals is called Alloy)

Alloy steel contains more than 5 percent of alloying elements to provide special properties such as ultra high strength, high corrosion resistance. For example a stainless steel is obtained by alloying chromium. (Aluminum, Manganese, Tungsten etc.)

11.5 Corrosion Protection

The atmospheric corrosion of steel structure can be minimized as follows:

Protective coatings of paint, aluminum and zinc may be applied. The metal coatings are more resistant to corrosion than steel in all but the most severe environment and are more abrasion-resistant than painted coatings.

Some steels contain copper, chromium and phoqphorus. They improve resistance to atmospheric corrosion, but still need to be protected.

Concrete Reinforcement

Concrete has low tensile and bending strengths and a high compressive strength. Steel reinforcement overcomes the deficiencies in the tensile and bending strengths.

The reinforcing steel must have adequate tensile properties and form a strong bond with the concrete since the concrete transmits load to the steel by shearing stress. The bond arises from surface roughness and friction. Mild steel with a maximum carbon content of 0.25-0.40 percent is suitable and is supplied in two conditions. These are hot rolled and cold rolled. Their yield strengths changes between 2200-5000 kg/cm^2. Reinforcing steels are supplied as plain or twisted round bars or square bars in a variety of sectional shapes in straight lengths or bent shapes. Protection against corrosion is provided by high alkaline environment of the Portland cement hydrates within the concrete.

Prestressing Steels

With pretension concrete the strained steel member attempt to shorten when the straining device is removed. The shortening is resisted by the concrete and a condition is established of compressive stress in the concrete balanced by tensile stress in the steel. When the composite is stressed in service the compressive stress in the concrete must be overcome before the concrete is subjected to a damaging tensile stress.

Prestressing steels must have high yield strength in tension so that a high elastic strain can be induced in them. A stress approaching the yield strength must be supported at an elongation of 1.5-2.0 percent without the steel suffering creep relaxation. In addition pretensioning steels must form a good bond with the concrete. 0.6-0.9 percent carbons, 0.5-0.9 percent manganese steel is suitable for pretensioning.

11.6 Nonferrous Metals

Because the initial cost of nonferrous metals is generally greater than that of ordinary ferrous alloys they are only selected when utilization of their special properties reduces the cost difference or the properties are essential to the application. Cost difference may be reduced by the utilization of superior working properties, low specific gravity or corrosion resistance. Nonferrous metals are, aluminum, copper, zinc and lead.

a) Aluminum

The useful engineering properties of aluminum are low specific gravity, resistance to corrosion, high electrical conductivity and excellent forming properties. The low strength of aluminum is a disadvantage and for satisfactory service it must be supported or alloyed. The alloying elements added to aluminum are copper, manganese, magnesium, silicon, nickel and iron.

b) Copper

Copper is of interest to engineers because of its case of working, high electrical conductivity and resistance to corrosive attacks by the atmosphere. The main alloying elements of copper are brasses and bronzes where increase the corrosion resistance and strength and decrease the conductivity.

c) Zinc

The main uses for zinc in building construction are:

Protective coating, on steel (galvanizing).

An alloying ingredient in copper/zinc alloys.

In the form of sheet or strip for roof coverings, wall cladding and gutters.

d) Lead

Ductility of lead is very high and can be cold worked into complex shapes. It is used in building construction as pipes, roof coverings and wall cladding, weathering and flashing, sheets (damp proof course)

Table 11.1 Properties of non-ferrous metals. Iron is shown for comparison.

metal	Relative density	Melting point (°C)	Elastic modulus (kN/mm^2)	Ultimate tensile strength (N/mm^2)	Coeff. of thermal expansion (x10^{-6}per °C)
Lead	11.3	327	16.2	18 (short term)	29.5
Zinc	7.1	419	90	37	Up to 40
Aluminium	2.7	659	70.5	45	24.0
Copper	8.7	1083	130	210	16.7
iron	7.8	1537	210	540	11.6

12. WOOD

The principle characteristics of timber are strength, durability and finished appearance. All of these are derived from natural characteristics present in the growing tree.

12.1 Strength

Strength of timber is affected by the following factors; density, moisture content and grain structure as well as by the various defects.

The more dense the stronger it is. So density is almost an indication of strength. All timber is made up of much the same chemical constituents, but dense timber has thicker cells walls, which contribute to the strength of the timber.

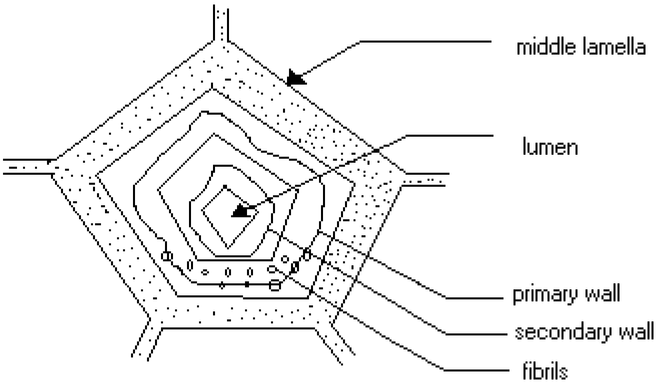


Figure 12.1 Cell Structure

Strength however decreases with the increase of moisture content. A side aspect of moisture content is to cause flourishing fungal growth or the attraction of insects, which indirectly decreases the strength of timber.

Grain structure and continuity are of significance in strength context and any disruptions due to growth defects will induce a reduction in strength from the clear specimens of the same timber.

12.2 Stress Grading

In order to design a timber structure properly, the following properties of the timber should be known:

Permissible bending stress

Permissible shear stress

Permissible compressive stress perpendicular to grain

Permissible compressive stress parallel to the grain
Modulus of elasticity.

Factors affecting the strength of clear timber such as moisture content, size and shape of specimen and sustained loading have also been investigated and estimates of their effect on strength made. These factors together with a general factor of safety are all incorporated in reduction factors which when multiplied by the statistical minimum strength give basic stress which are permissible for clear timber.

Grading of timber can be determined in two ways.

Visual stress grading:

This take into account the size of defects, knots, slopes of grains etc.

While visual stress grading can be carried out rapidly by ran experienced grader, where is a weakness of the method which is factor of density, that influence strength is completely disregarded.

Mechanical stress grading:

The strength of timber can directly obtainable from the mechanical stress grading. Also the modulus of elasticity can be found out from bending test, by measuring deflection of a timber under a bending loading.

12.3 Moisture Content

The moisture content of timber is the quantity of moisture contained by it expressed as a percentage of the dry weight.

Moisture Content % = 100 x (Weight of specimen – dry weight of specimen) / Dry weight of specimen

In green timber, moisture is contained within cells and the cell walls. The moisture may be removed from the cells without any effect other than a reduction in bulk density. The condition when all the cells are empty but the cell walls are still saturated is referred to as the fibre saturated point, usually between 23 and 27 percent moisture content. Any further reduction in moisture content results in shrinkage of timber.

12.4 Timber Seasoning

12.4.1 Air Seasoning

The timber is stacked in open-sided sheds in such a way as to promote drying without artificial assistance. The timber stack is supported about 45 cm clear of the ground and adjacent boards in each layer are kept separate; layers are provided with air space by means of spacers or sticks about 25mm square. Hardwoods and some softwoods which dry out slowly are usually stacked in winter so that the timber will not be affected by summer heat until its moisture content has been reduced; quick drying softwoods may be stacked in spring or early summer. The advantages of air seasoning are that, it is a cheaper method with very little loss in quality of timber if done properly. The disadvantages are that both timber and space are immobilized for a long period.

12.4.2 Kiln Drying

This method of seasoning employs a heated ventilated and humidified oven. Kiln drying must be used to reduce the moisture content below 17 percent; temperature much greater than atmospheric shade temperature are used, which cause the moisture in the wood to move more rapidly to the surface, when it is removed by the circulating air. If this air were merely heated, excessive evaporation of moisture from the surface would take place faster than moisture could move out to the surface. The outer parts of the timber would than tend to shrink peripherally so that splitting might occur. It is therefore necessary to humidity the circulating air in order to control the rate of evaporation, and this humidity is reduced as the drying proceeds. Different species of timber withstand different initial kiln temperatures and as drying proceeds this temperatures can be raised as the humidity is lowered.

Air circulating should be uniform over the face of the timber pile at which it centers, and the velocity of the air through the pile should be sufficiently high to be consistent as an economic operation.

The essential of a kiln are:

a) Heat, under proper control and sufficient to raise the temperature to the maximum required.
b) Humidification, also under proper control and sufficient to meet all requirements.
c) Air circulation, uniform and of sufficient velocity and,
d) Air interchange, in order to assist in controlling the humidity of the circulating air, it is found expedient to exhaust some of the air from the system from time to time and replace it with fresh air from outside. Any deficient in water vapor being supplied by means of carefully regulated spray.

12.5 Classification of Trees

Trees generally are divided into two groups:

Hardwoods, and softwoods. The term ‘hardwood’ or ‘softwood’ applied to a particular species does not necessarily indicate the relative hardness of that particular kind of wood. Some trees in the relative hardness of that particular kind of wood. Some trees in the hardwood class, such as poplar are softer than the average softwood. Douglas fir, on the other hand in the softwood group, is harder than several of the hardwoods:

Softwoods:

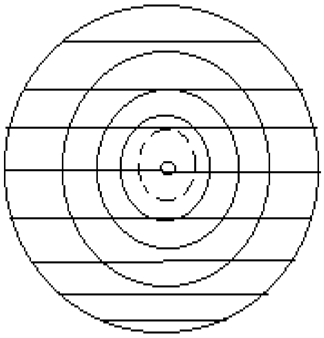
These trees have needles rather than leaves and needles stay green through the winter and remain on the tree for two or more years. They are cheaper than hardwoods.

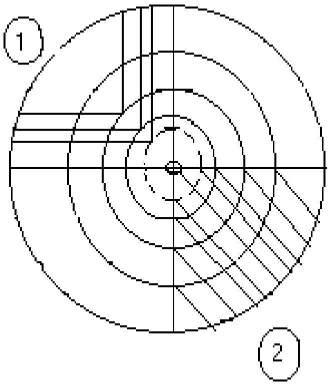
Hardwoods:

These trees have broad leaves, which are normally shed in the fall. Hardwoods include the densest, strongest and most durable timber. Some hardwoods contain resins and/or oils, which interfere with the hardening of paints such as teak.

12.6 Manufacturing of Lumber

In the sawmill logs may be quarter sawed or slash sawed.





1 or 2

The obtained lumbers will be preceded either as kiln drying or air-drying.

To manufacture kiln-dried lumber, logs are sawed into rough lumber, which is first kiln dried and then surfaced (planed or dressed) to final finished size. Lumber to be air dried is sawed and dressed oversize while green, so that after drying it will be equivalent in size to lumber which has been surfaced dry.

12.7 Softwood Lumber Classification

Standard softwood lumber is classified according to species, use, extent of manufacturing and size.

The species commonly used for softwood lumber include different kinds of fir, spruce pine, and cedar. Softwood lumber is classified by use into three groups:

Yard lumber:

Lumber of those grades, sizes and patterns, which are generally intended for use in ordinary construction or generally building purposes.

Structural lumber:

Lumber, which is at least 5 cm in nominal width and thickness, to be used where working stresses, are required.

Factory and shop lumber:

Lumber that is produced or selected preliminary for remanufacturing purposes. Softwood lumber is classified according to the manufacture as follows:

i) Rough lumber:

Lumber, which has not been dressed but has been sawed, edged and trimmed.

ii) Dressed (surfaced) lumber:

Lumber, which has been dressed by a planar in order to obtain a smooth surface and uniform of size. It may be dressed on one side (S1S), on two sides (S2S), (S3S), (S4S).

iii) Worked lumber:

Lumber, which in addition to being dressed, has been further shaped as follows:

Matched lumber:

Lumber, which has a tongue on one edge and a matching groove on the opposite edge, to provide a close-fitting joint between two pieces.

Shaped lumber:

Lumber, which has been rebated on both edges of each pieces, so that two pieces will fit together with a close-lapped joint.

Pattern lumber:

Lumber, which has been shaped to a pattern or molded form, in addition to being dressed, matched or shiplaped or any combination of these.

Softwood lumber is classified according to size by nominal size and by dressed size. Nominal sizes include the following:

Board: Lumber less than 5 cm in nominal thickness and 5 cm or more in nominal width.

Dimension: lumber from 5 cm to but not including 12.7 cm in nominal thickness and 5 cm or more in nominal width. Dimension lumber may be further classified as framing, studs, rafters, planks and joists.

Timber: Lumber, which is 12.7 cm or more nominally in least dimension. Timber may be further classified as girder, stringers, beams, posts and purlins.

12.8 Hardwood Lumber

Hardwood lumber is produced from trees, those that drop their leaves each year including ash, beech, cherry, elm, magnolia, marble, bak, poplar, and walnut.

Hardwood lumber is produced in a variety of categories, including boards, dimensions lumber, finishing lumber, and structural timbers, which are used for many purposes, such as flooring, wall pancling, furniture, plywood etc.

12.8.1 Plywood

Plywood is made by bonding together thin layers of wood-veneers-in pairs about a central core. The outside veneers are called the faces or backs; the center layer, the core, and where more than three plies are used, those in between crossbands. Generally, in the manufacture of softwood plywood, the same species or species group is used throughout, whereas, in hardwood plywood, a less expensive core and crossbands may be used with the hardwood face and back. The veneers are united high pressure and temperature with a high strength glue to produce panels of various sizes and thickness.

12.8.2 Manufacturing of Plywood

Selected logs are cut into 2.6 m or 3.2 m lengths, called blocks. Blocks are placed in a lathe and rotated at a constant surface speed against a long steel blade, which peels the veneer from the block in a continuous thin sheet. Then a veneer goes to a clipper, which cut the strip into various widths. The material is then dried to approximately 5 percent moisture content and graded into three grades, A, B, and C, based on the presence of defects, knots etc. The strips are then glued. The cross band veneers are coated with a water proof phenol formaldehyde resin glue and laid at right angles to the adjacent sheets on either side.

The veneer sandwiches then go to a hot press, where they are subjected to a pressure 200 psi at a temperature of 149^oC. When the glue is cured, panels are cut usually (120×240)cm.

13. POLYMERS

13.1 Introduction

In general, plastics exhibit a number of outstanding characteristics;

1) Lightness in weight (generally half as light as aluminium) (Specific gravity=2,7/2=1,35)
2) High dielastic strength (electrical insulation)
3) Low heat conductivity (heat insulation)
4) Special properties towards lights (colorability)
5) Extremely resistant towards chemicals
6) Metals inserts may be molded into the plastic (since plastics are inert toward such materials)
7) Many high-quality products can be developed (using sawing, punching, and drilling)

13.2 Classificatıon

A plastic is a polymeric material (usually organic) of high molecular weight which can be shaped by flow (see Table 13.1).

In general, organic plastic can be divided into three general classification:

Thermoplastics
Thermosetting plastics
Chemically setting plastics

13.2.1 Thermoplastics (see Table 13.1, 13.2)

They are organic plastics, either natural or synthetic, which remain permanently soft at elevated temperatures. Upon cooling, they again become hard. These materials can be shaped and reshaped any number of times by repeated heating and cooling. Natural thermoplastics include asphalt, bitimens, pitches and resins (sticky liquid), to name some of the most familiar.

They are divided into 2 groups;

1) Natural: Resin and asphaltic binders
2) Synthetic: a- Cellulose derivatives
    b- Addition polymerides
    c- Condensation polymerides

Cellulose plastics are true thermoplastics and exhibit the greatest toughness and resilience (elastic) of any of the plastics. They are used for objects having thin-walled sections where other plastics may be too brittle.

Addition and condensation polymerides (noncellulose plastics) are strong, tough, and chemically inert with little water absorption. They are odorless, tasteless, nontoxic and transparent. They are suited for electrical insulation or cable coatings, safety glass, nylon, and **saran** (covering to prevent corrosion and chemical attack on pipes and tubing).

13.2.2. Thermosetting Plastics (see Table 13.1, 13.3)

They are organic plastics that were originally soft or soften once upon heating, but upon further heating, they harden permanently. They remain hardened without cooling and do not soften appreciably when reheated. The most common thermosetting plastic is polyester.

They can be divided into 2 groups;

a) Addition polymerides
b) Condensation polymerides

Plastics of thermosetting group have excellent mechanical and electrical properties and are highly resistant to heat. They also have resistant to water, oil, alkalies and acids. They also exhibit very little shrinkage.

13.2.3. Chemically Setting Plastics (see Table 13.1)

They are those that harden by the addition of a suitable chemical to the composition just before molding or by subsequent chemical treatment following fabrication.
They are generally used where resistance to heat and arcing are of primary importance. Thus, they are utilized for electrical insulating parts.

13.3 Types Of Plastics

Polymerization and Condensation

Polymerization involves unsaturated molecules that contain double or triple bonds between carbon atoms that are weaker than single bonds. Unsaturated molecules are unstable and they react in such a way as to break the multiple bond.
Polymerization is grouped into 2 catagories:

1. Addition polymerides
2. Condensation polymerides
3. Addition polymerides:

They are mixtures of polymers that have been formed by addition of like molecules. The molecules are added to increase the average molecular size and weight.

1) Condensation polymerides:

They are formed by chemical reactions in which two or more different molecules combine with the seperation of water or other simple substances in the forming of resins.

Table 13.1 Classification Of Organic Plastics

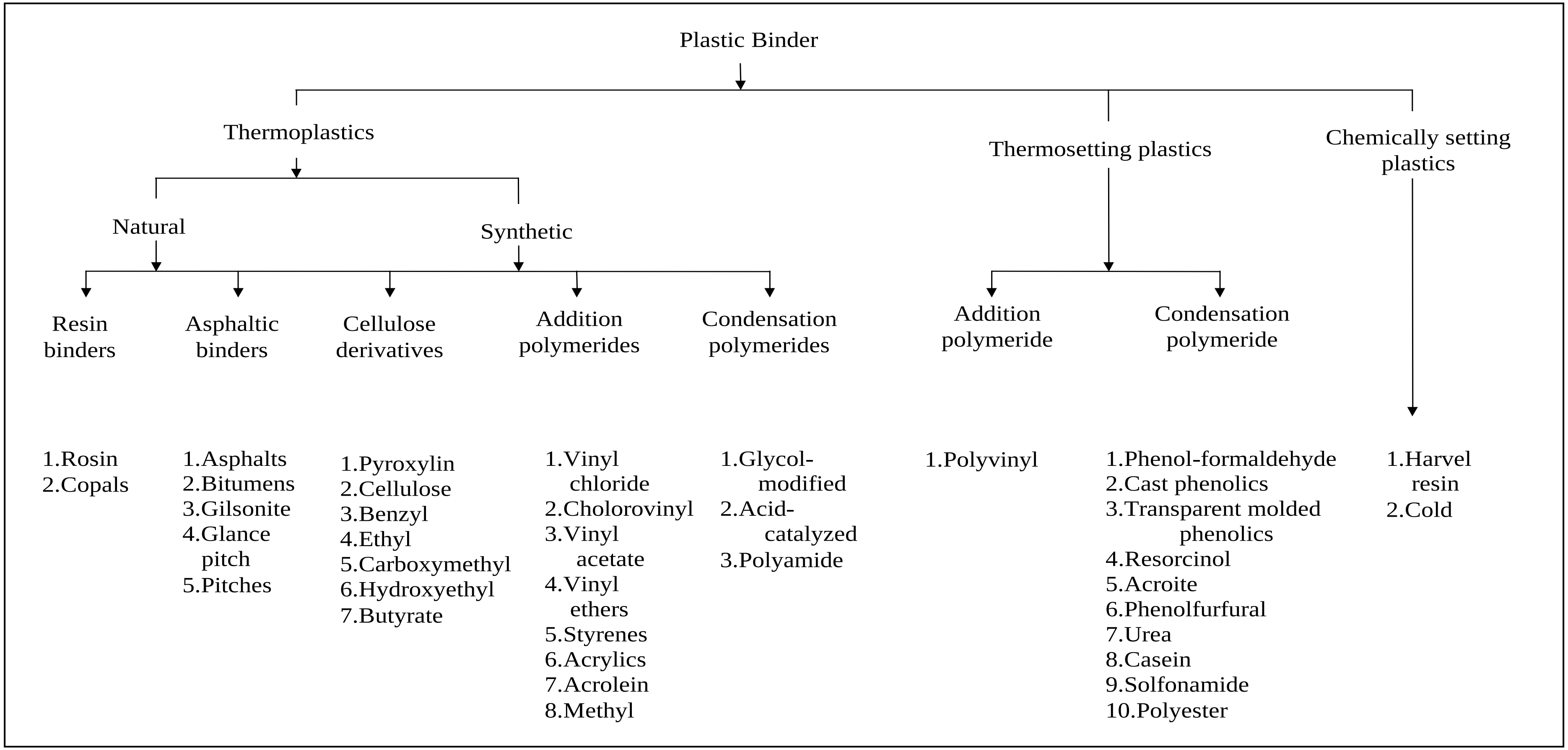


Table 13.2 Properties And Uses Of Common Plastics (Thermoplastics)

Property	Shellac	Polyethylene	Polymonochlorotrifluroethylene	Vinylidene Chloride Molding	Poly-styrene	Methyl methacrylate, Cast	Polyamide (Nylon) Molding	Cellulose Acetate Molding	Cellulose Nitrate (Pyroxylin)
Injection molding pressure(1000psi)	1.0-1.2	8-15	20-60	10-30	10-30	—	10-25	8-32	
Specific gravity	1.1-2.7	0.92	2.10	1.65-1.72	1.05-1.07	1.18-1.20	1.14	1.27-1.37	1.35-1.40
Tensile stregth (1000psi)	0.9-2.0	1.5-1.8	5.7	3-5	5-9	6-7	7-9	1.9-8.5	7-8
Elongation (% in 2 in.)	—	50-400	28-36	20-250	0.1-3.6	2-7	40-100	6-50	40-45
Modulus of elasticity in tension (100,000psi)	5-6	0.19	1.9	0.5-0.8	4-6	3.5-5	2.6-4.0	0.86-4.0	1.9-2.2
Compressive strength, (1000 psi)	10-17	—	32-80	7.5-8.5	11.5-16.0	11-19	7.2-13	13-36	22-35
Impacts strength, Izod test on 1/2*1/2-in. notched bar (ft-lb./in. width of notch)	2.6-2.9	Less than 16	3.6	0.3-1.0	0.26-0.50	0.4-0.5	1.0	0.4-5.2	5-7
Hardness, Rockwell[a]	—	R11	R110-115	M50-65	M65-90	M90-100	M111-118	P85-125	R95-115
Highest usable temperature continuous(^{0}F)	150-190	212	390	160-200	150-205	140-200	270-300	140-220	140
Thermal conductivity 10^{-4} cal / (sec)(cm^3)(^{0}C)	—	8	1.4	3	2.4-3.3	4-6	5.2-5.5	4-8	3.1-5.5
Thermal expansion (10^{-5} in./in. ^{0}C)	—	16-18	4.5-7.0	19	6-8	9	10-15	8-16	8-12

Dielectric strength, Short time, 1/8 in. thickness (V/mil)	200-600	400	2500	350	500-700	450-500	385-470	250-365	300-600
Water absorption 24 hr,1/8 in. thick (%)	0-0.1	Less than 0.01	0.00	0-0.1	0.03-0.05	0.3-0.4	0.4-1.5	1.9-6.5	1.0-2.0
Effect of strong acids	Deteriorated	Attacked by oxidizing acids	None	Highly Resistant acids	Attacked by oxidizing acids	Attacked by oxidizing	Attacked	Decomposed	Depomposed
Color possibilities	Limited	Unlimited	Unlimited	Extensive	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
Common uses	Phonograph records, electrical insulation	Bottle stoppers, flexible bottles, wire insulation, textiles, tablewear	Filter disks, insulators, gaskets	Screening, chemical tubing, auto seat coves	Electrical insulators, battery boxes, lenses, toys, boxes	Windows, furniture, dentures, picture frames	Bearings, cups, fabrics, bristles	Fountain pens, tools, toys, spectacle Packaging	Packaging foils, glazing materials, photographic film

[a] Rockwell scales: M, ¼-in.-diameter ball, 100-kg major load; R, ½-in.diameter ball: 60-kg major load.

Table 13.3 Properties and Uses of Common Plastics (THERMOSETTING)

	Phenol-Formaldehyde Resin							
Property	Macerated Cotton Fabric or Cord Filler, Molded	Mechanical Grade, No Filler, Cast	Urea-Form-aldehyde α-Cellulose, Molded	Melamine-Formaldehyde Asbestos, Paper or Fabric Laminate	Polyester, Glass Fiber, Mat, Laminate	Silicone Glass Fabric Laminate	Cold-Molded[a] Cement Binder Asbestos-filled	Hard Rubber[b] No Filler
Compression molding pressure(1000psi)	2.00-8.00	0	2.00-8.00	1.00-1.80	0.01-0.15	1.00-2.00	1.00-10.00	1.20-1.80
Specific gravity	1.34-1.47	1.25-1.30	1.45-1.55	1.75-1.85	1.5-1.8	1.6-1.8	1.6-2.2	1.4
Tensile strength (1000psi)	2-9	4-7	6-13	6.5-12.	10-20	10-25	1.6-25	8-10
Elongation (% in 2 in.)	0.4-0.6	Very small	0.5-1.0	Very small	Very small	Very small	Very small	5-7.5
Modulus of elasticity in tension (100,000psi)	9-13	5-7	12-15	16-39	10-19	20	—	3.0
Compressive strength, (1000 psi)	15-30	15-20	25-35	27-50	30-50	35-46	16	8-12
Impacts strength, Izod test on 1/2*1/2-in. notched bar (ft-lb./in. width of notch)	1-8	0.3-0.4	0.24-0.36	0.7-5.0	11-25	5-22	0.4	0.5
Hardness, Rockwell[c]	M110-120	M70-110	M115-120	M110-115	M90-100	M100	M75-95	HR95
Highest usable temperature continuous(^{0}F)	250	250	170	225-245	300-400	400-480	900-1300	—
Thermal conductivity 10^{-4}cal / (sec)(cm^3)(^{0}C)	4-7	3-5	7-10	10-17	8-12	305	—	2.9
Thermal expansion (10^{-5} in./in. ^{0}C)	1-4	8-11	2.5-4.5	2.0-4.8	1.0-3.0	0.5	—	7.7
Dielectric strength, Short time, 1/8 in. thickness (V/mil)	200-400	—	300-400	40-150	250-400	200-480	45	470
Water absorption 24 hr,1/8 in. thick (%)	0.04-1.8	0.2-0.4	0.4-0.8	1-5	0.3-1.0	0.2-0.7	0.5-15	0.02
Effect of strong acids	Decomposed by oxidizing acids	Decomposed by oxidizing acids	Decomposed	Decomposed	Some attack	Very slight	Decomposed	Attacked by oxidizing acids
Color possibilities	Limited	Limited	Unlimited	Limited	Unlimited	Limited	Gray and Black	Limited
Common uses	Serving trays, radio cabinets, electrical parts	Punches and dies	Tableware, electrical controls, housings	Aircraft Structural parts, hight-strength electrical parts, stove swithes	Aviation and automotive structures, decorative application	High-temp. resisting electrical insulation	Arc-shield terminal insulators, electric heater elements	Beakers, funnels, etc., for chemicals combs

[a] The cement binder is not strictly a thermosetting material but is set by chemical combination with water from steam (hydration)

[b] Hard rubber is not usually classified as thermosetting but as vulcanizing.

[a] Rockwell scales: M, ¼-in.-diameter ball, 100-kg major load; R, ½-in.diameter ball: 60-kg major load.

13.4 Manufacture Of Organic Plastics

In general, four main steps are required in the manufacturing of articles made from organic plastics;

1) The production of intermediate materials (chemical) from the raw materials of coal, petroleum, and cotton.
2) The manufacture of synthetic resins from the above.
3) The preparation of molding powders, fillers, rods, and sheets from step 2.
4) Molding the articles from the powders, fillers, rods, and sheets.

Methods of Forming and Fabricating Plastics

1) Casting
2) Compression molding
3) Injection molding
4) Transfer molding
5) Extruding
6) Blowing
7) Laminating

1) Casting

Is the simplest molding method available. Both thermoplastics and thermosetting plastics may be cast.

2) compression molding

Is the most widespread molding operation for thermosetting plastics. Thermoplastics may be molded by compression molding, but the mold must be cooled after each molding before the article is removed from the press. This is time consuming.

3) injection molding

Is one of the most widely used and most rapid methods of production articles of intricate (complex) shape. This method is widely used for thermoplastic materials. It consists of forcing softened plastic materials into a closed mold maintained at a temperature below the softening point of the compression. The plastic is cooled, the mold is opened, and the part removed.

4) transfer molding

Used for thermosetting materials when the article is to include delicate metal inserts for any reasons.

5) extruding

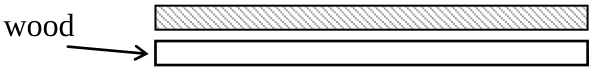
Basically it is the opposite of injection molding. Extruding of **thermoplast** plastics is a widely used practice for producing rods, tubes, and other cylindrical shapes.

6) blowing

It is a process by which hollow objects are made. It is like blowing of glass.

7) laminating

Used to produce hard boards or sheets or resin-impregnated papers, wood veneers, or fabrics. Laminates are made into stock sizes of flat sheets under medium to high pressure in a press.



13.5 Plastics in Construction

Plastics, with their wide range of properties; light-weight, strong, durable, corrosion-resistant, and weatherproof, to list a few are ideal for construction applications. With the perfection of manufacturing processes, any size and shape can be produced quicly and accurately. Plastics are now being used as structural and nonstructural components, in composite applications, and as auxiliary materials.

Structural Applications

For structural purposes, a family of plastic materials produced by reinforcing the plastic with a fibrous mat are commonly used. About 90 percent of all reinforced plastics use glass fiber, cotton, sisal, asbestos, synthetic and metallic fibers.

1) corrugated panels

One of the more common structural products is the glass-fiber-reinforced acrylic corrugated panel, which is not only transparent or translucent but also highly resistant to discoloration. Panels are available in a variety of colors.

Because these panels have good dimensional stability, as well as being strong and corrosion- resistant, their applications are many. They are used as roof panels, skylights, wall cladding, room dividers,and carport and patio covers.

2) flat sheets

Flat sheets of clear acrylic and polycarbonate plastic are used extensively as glazing material. They are available in a variety of thicknesses, sizes, and finishes. Because of their light weight, high impact strenght, and high light transmission values, these sheets are used in skylights, curtain walls, passive solar applications, pool enclosures, and greenhouses.

3) thermoformed shapes

Sheets may also be molded by the thermoform process into roof shapes. Tinted acrylic sheets may be used as suncsreens to reduce solar heat, or the material may be used to make light control lenses for glare-free lighting. Transparent or translucent sheets may also be used for dome sky-lights.

Plastic materials are widely used in the manufacture of sandwich panels used in curtain-wall construction. In some cases only the sandwich core is a plastic material, while in others both the core and one or both faces are of plastic. Some sandwich panels are made by bonding plastic sheets to an aluminum grid core. Plastics used for such panels include acrylics, polypropylene, polycarbonates, and polyesters because of their dimensional stability, high impact resistance, ability to withstand weathering, corrosion resistance, and, in the case of colored products, their ability to resist fading.

4) glass-fiber structural shapes

A relatively new use for fiber-reinforced plastic is in the manufacture of structural shapes. These shapes come in a wide variety of standard sizes, and nonstandard sizes and shapes are produced upon special request. Nonstandard thicknesses and sizes can be made to order.

5) plastic foam boards

Rigid slabs of foamed plastic are finding increasing use for structural purposes. Expanded polystyrene are used to form the roof deck for a hyperbolic paraboloid roof. Because of their flexibility, the slabs can be readily fitted to the contours of the roof. Later, the deck will be covered with a layer of concrete.

Polystyrene has rigidity, lightness, good impact resistance, and structural strenght. Structural polystyrene items are stronger than comparable wood or metal ones. Like most plastics, it has the added advantage of being able to be molded into almost any desired shape. This could mean a reduction in the number of component parts required to form a given structure. Also, like many other plastics, polystyrene is resistant to shattering, is weather- and corrosion-resistant, and is dimensionally stable.

6) fabics

Polyester and nylon fabrics, coated with PVC, provide an alternate method for enclosing large open areas. These fabrics, a result of spaceage technology, are light, strong, durable, and remain pliable over large temperaturu changes.

A combination of glass-fiber fabric and a teflon fluerocarbon resin has been used in fabric roof applications with much success. The glass-fiber fabric provides the strength for sustaining the necessary design loads, while the Teflon provides the flexibility, durability, and weather resistance. This type of coated fabric has been given a life expectancy of more than 20 years.

7) foamed insulated

One of the most important uses of plastics in the construction industry is as insulation. Polystyrene, polyurethane, phenolic resin, and vinyl resins are the most common materials used in the manufacture of insulating materials.

Polystyrene and polyurethane are foamed by a patented process to about 40 times their original volume. Slabs are formed either by extrusion or by the molding process and a variety of sizes are manufactured. Both materials have extremely good insulation qualities and relatively high compressive strength and are flexible enough to be formed around curved surfaces.

REFERENCES

1. CE282 Materials of Construction, Lecture Notes prepared by Özgür Eren, Eastern Mediterranean University Press, Gazimağusa, 2004.

2. CE482 Advanced Materials of Construction, Lecture Notes prepared by Özgür Eren, Eastern Mediterranean University Press, Gazimağusa, 2003.

3. Concrete Technology, A.M. Neville & J.J. Brooks, Longman Scientific and Technical, 1994.

4. Construction Materials, G.D. Taylor, Longman Scientific and Technical, 1991.

5. Construction Materials, Their Nature and Behaviour, Ed. J.M. Illston, E & FN Spon, 1998.

6. Materials of Construction, R.C. Smith, C.K. Andres, McGraw-Hill, 1989.

7. Properties of Concrete, A.M. Neville, Longman Scientific and Technical, 1990.

8. Properties of Materials, C.V.Y. Chong, MacDonald & Evans, UK, 1981.

9. The Science and Technology of Civil Engineering Materials, J.F. Young, S. Mindess, R.J. Gray, A. Bentur, Prentice Hall, 1998.