

9. Construction materials

SUMMARY

Construction materials for port and coastal structures may be classified into five general categories: steel, timber, concrete, stone and synthetics. However, subject of materials and their suitability for application within a port facility is very wide and, for this reason, the intention is to condense the subject into a single chapter covering the basic principles while eliminating superfluous coverage. The chapter is confined to the properties of those materials and treatments or variations thereof that are applicable to port structures. Nevertheless, emphasis is duly placed on full coverage of the basic materials that have proved most durable in the highly aggressive marine environment inside port structures. The overall objective being the provision of sound advice to the reader regarding the selection of materials for port structures and acceptable practices as well as other less suitable materials and practices that should be avoided.

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9.1. METALS

9.1.1 Ferrous metals

Many ferrous (iron) alloys are used for engineering purposes. Despite this, iron alloys are used in larger quantities than the alloys of any other metal. This arises from the relative cheapness with which steels (an iron alloy) and cast iron can be produced with a variety of useful properties, by variations of composition, heat treatment and heat working. Steel is an alloy of iron and carbon, silicon, phosphorus, manganese and sulphur. Inclusion of nickel and chromium produces stainless steel.

Wrought steel components are produced by hot- or cold-working processes, although some machining may be involved. In civil engineering, the largest use of wrought steels goes into making reinforcement steel and structural sections such as beams and channels, sheet piles and pipes.

Forged steel involves hot shaping between dies and the deformation sequence is chosen so that adequate deformation is given to all parts of the component and the metal flow direction is controlled to give optimum fibre structure and properties. A limitation on the shape of forgings arises from the need to remove them from the dies. Forged steel is used in making chains, shackles, boat moorings, as well as other products.

Cast iron provides an alternative to forging for the production of complex shapes. Instead of working the metal in a die, casting is achieved by pouring molten metal into a recyclable sand mould. In general, forgings have better properties than castings because the properties of castings are determined by the solidification characteristics of casting alloys. Typical products in cast iron are manhole covers and bollards.

9.1.2 Non-ferrous materials

Non-ferrous metals and alloys are available for engineering and building purposes. Pure non-ferrous metals (like aluminium) have properties that make them suitable for engineering applications and as a building material.

However, care must be taken when, for example, aluminium is to be used in conjunction with steel in order to ensure that cathodic action will not take place.

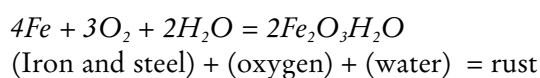
9.2 CORROSION

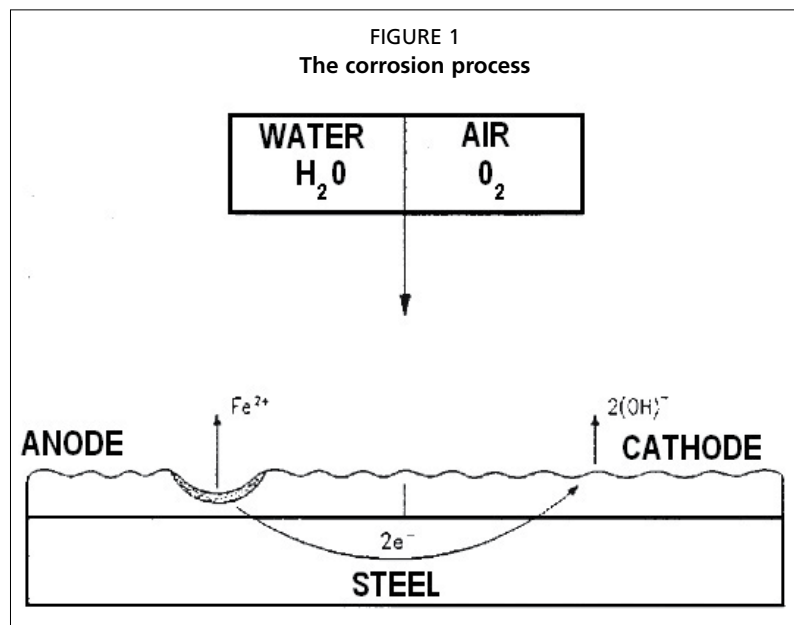
9.2.1 Introduction

Corrosion is the destructive attack on a metal by chemical or electrochemical reaction with its environment (Figure 1). Rusting applies to the corrosion of iron or iron-base alloys with formation of corrosion products consisting mainly of hydrous ferric oxides. Non-ferrous metals, therefore, corrode as well but do not rust.

Most corrosion of steel can be considered as an electrochemical process which occurs in stages. Initial attack occurs at anodic areas on the surface, where ferrous ions go into solution. Electrons are released from the anode and move through the metallic structure to the adjacent cathodic sites on the surface where they combine with oxygen and water to form hydroxyl ions. These react with the ferrous ions from the anode to produce ferrous hydroxide which itself is further oxidized in air to produce hydrated ferric oxide: red rust.

The sum of these reactions is described by the following equation:





Two important points emerge:

- For iron or steel to corrode it is necessary to have the simultaneous presence of water and oxygen; in the absence of either, corrosion does not occur.
- All corrosion occurs at the anode; no corrosion occurs at the cathode.

However, after a period of time, polarization effects such as the growth of corrosion products on the surface cause the corrosion process to be stifled. New, reactive anodic sites may then be formed thereby allowing further corrosion. Over long periods the loss of metal is reasonably uniform over the surface and so this case is usually described as “general corrosion”. Nevertheless, various types of localized corrosion can also occur such as:

Pitting corrosion occurs in some circumstances where the attack on the original anodic area is not stifled and continues deep into the metal, forming a corrosion pit. Pitting more often occurs with mild steels immersed in water or buried in soil rather than those exposed in air. Pitting can also occur on stainless steels in certain environments.

Crevice corrosion leads to crevices that can be formed by design-detailing, welding, surface debris, etc. Available oxygen in the crevice is quickly used by the corrosion process and, because of limited access, cannot be replaced. The entrance to the crevice becomes cathodic since it can satisfy the oxygen-demanding cathode reaction. The tip of the crevice becomes a localized anode and high corrosion rates occur at this point.

Bi-metallic corrosion occurs when two dissimilar metals are joined together in an electrolyte, like seawater, an electrical current passes between them and corrosion occurs on the anoxic metal. Some metals (e.g. nickel and copper) corrode preferentially themselves, thereby protecting the steel. The tendency of dissimilar metals to bi-metallic corrosion is partly dependent upon their respective positions in the galvanic series (in descending order, the galvanic series for seawater lists magnesium – zinc – aluminium – cadmium – mild steel – wrought iron – cast iron – stainless steel – lead/tin solder). The further apart the two metals are in the series, the greater the tendency. In the presence of seawater, cadmium, aluminium, zinc and magnesium all corrode preferentially to mild steel, with magnesium corroding the fastest and cadmium the slowest. Other aspects which influence bi-metallic corrosion are the nature of the

electrolyte and the respective surface areas of the anodic and cathodic metals. Bi-metallic corrosion is most serious for immersed or buried structures but should also be considered for steel in the atmosphere.

Stress-corrosion cracking occurs under the simultaneous influence of a static tensile stress (the metallic element is under load), which may be well below the yield strength of the steel and a specific corrosive environment. This type of corrosion is not common with ferrous metals, though some stainless steels are susceptible in chloride environments and mild steels can exhibit stress-corrosion cracking in the presence of nitrates or in highly alkaline solutions.

Bacterial corrosion can occur in soils and water as a result of microbiological activity. The most commonly encountered is that arising from the presence of sulphate-reducing bacteria. These reduce sulphates in the soil to sulphides and cause corrosion under anaerobic conditions (i.e. in the absence of oxygen). They are characterized by black corrosion products having the distinctive “rotten-egg” smell of sulphide. Bacterial corrosion is most commonly encountered in pipelines, sheet piles and other buried structures.

9.2.2 Corrosion and steel

The principal factors that determine the rate of corrosion of steel in air are:

- type and amount of pollution;
- “time of wetness”, i.e. the proportion of total time during which the surface is wet; and
- temperature.

Within a given local environment corrosion rates can vary markedly. For example, steel may corrode more on a particular side of a building because it is in the shade and so remains wet for longer periods. Prevailing winds may carry airborne contaminants (e.g. exhaust from a power station or sea spray from the coast) predominantly on to one face of a structure. It is therefore the “microclimate” immediately surrounding the structure which determines corrosion rates for practical purposes. Steel is most commonly used in the following environments:

- rural atmospheric – essentially inland, unpolluted environments;
- industrial atmospheric – inland polluted environments;
- marine atmospheric – the 2 kilometre strip around the coast is broadly considered as being a marine environment;
- marine/industrial atmospheric – polluted coastal environments;
- seawater immersion:
 - (i) the splash zone, immediately above high-tide level, is usually the most corrosive zone;
 - (ii) the tidal zone, between high tide and low tide, often covered with marine growth; and
 - (iii) the low-water zone, a narrow band just below the low-water level;
- the permanent immersion zone, from low-water level down to the sea bed;
- freshwater immersion – corrosion rates are lower in freshwater than in saltwater;
- soils – the corrosion process is complex and very variable; various methods are used to assess the corrosivity of soils, such as resistivity (generally high-resistance soils are least corrosive), redox potential (to assess the soil’s capability of anaerobic bacterial corrosion), pH (highly acidic soils, e.g. pH less than 3.0, can be corrosive), water content (corrosion depends upon the presence of moisture in the soil and the position of the water table has an important bearing).

Long-buried steel structures, e.g. pipelines, are most susceptible to corrosion. Steel piles driven into undisturbed soils are much less susceptible due to the low availability of oxygen.

9.2.3 Influence of design on corrosion

Design can have an important bearing on the corrosion of steel structures. The prevention of corrosion should therefore be taken into account during the design stage of a project. The main design points to be considered are:

Entrapment of moisture and dirt:

- avoid sharp edges, sharp corners, cavities, crevices;
- welded joints are preferable to bolted joints;
- avoid or seal lap joints;
- provide drainage holes for water, where necessary;
- seal the ends of hollow sections, such as pipe piles, box sections, etc.; and
- provide free circulation of air around the structure.

Contact with other materials:

- avoid bi-metallic connections or insulate the contact surfaces;
- provide adequate depth of cover and quality of concrete; and
- separate steel and timber by the use of coatings or sheet plastics.

Coatings application:

- design should ensure that the selected protective coatings can be applied efficiently;
- radius all edges and corners;
- provide vent-holes and drain-holes for items to be hot-dip galvanized;
- do not drill or cut through items that have already been galvanized; and
- provide adequate access for metal spraying, paint spraying, etc.

In general:

- large flat surfaces are easier to protect than more complicated shapes;
- ideally, locate load-bearing members in the least corrosive locations;
- provide access for subsequent maintenance; and
- provide lifting lugs in the design to reduce damage during handling and erection.

9.3 ANTI-CORROSION METALLIC COATINGS

9.3.1 Introduction

Anti-corrosion coatings for steel fall into two broad categories:

- metallic coatings, and
- paint coatings.

Due to their very thin nature, the coating thickness is measured in microns:

- 1 000 microns = 1.0 millimetre or 1 micron is equivalent to one thousandth of a millimetre.

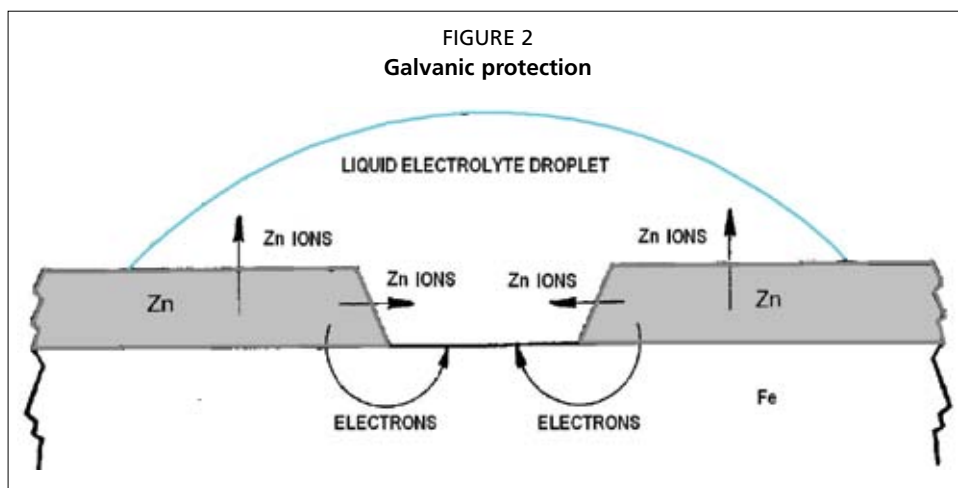
The term galvanizing has its origin with the concept of galvanic or electrochemical corrosion, which is demonstrated by placing two dissimilar metals in contact with each other in an electrolyte, such as seawater.

The principle is the same as that in an electrochemical cell or battery of cells, corrosion being the chemical attack that occurs at the anode. Conversely, batteries make use of the electrical energy produced by such a reaction. Applying this principle to galvanic protection, metals have individual electrical characteristics known as

electrode potentials. The difference between these potentials is the driving force for electrochemical action such as corrosion. When dissimilar metals are connected in the presence of an electrolyte, the driving force for the corrosion reaction is released and electronic conduction (with no mass transfer) occurs by the route of least resistance through the metals from the electropositive to the most electronegative. To satisfy the requirement for more electrons at the electronegative metal interface with the electrolyte mass transfer occurs by dissolution of the metal of most electropositive potential, creating ions in the solution.

The main advantages of using zinc are the low melting point (around 420 °C) and the fact that zinc is anodic to steel: that is, when in contact with iron or steel in the presence of an electrolyte, zinc will corrode in preference to the iron or steel. The zinc acts as a “sacrificial anode”, Figure 2, and corrodes by the mass transfer of zinc ions into the electrolytic solution, releasing electrons to travel the electrically conducting path through the metals to the steel/electrolyte interface where they are consumed in a reverse cathodic reaction, forming compounds with the positively charged ions from the solution. In some instances these deposit as a chemically stable film on the exposed steel surface, thereby protecting it from further corrosion and limiting reaction.

There is another factor of importance when considering the corrosion activity of zinc. The inherent corrosion resistance of zinc relies mainly on the formation on its surface of insoluble carbonates, which act as a protective film against further corrosion activity.



There are four commonly used methods of applying metal coatings to steel surfaces:

- hot-dip galvanizing;
- metal spraying;
- electroplating; and
- sherardizing.

Hot-dip galvanizing and metal spraying are best suited for large items, whereas the latter two processes are used for fittings, fasteners and other small items.

9.3.2 Hot-dip galvanizing

The most common method of applying a metal coating to structural steel is by galvanizing. The galvanizing process involves the following stages:

- The steel is cleaned properly; surface preparation of steels is described in detail further on in this text.

- The cleaned steel is dipped into a bath of molten zinc at a temperature of about 450 °C at which the steel reacts with the molten zinc to form a series of zinc/iron alloys on its surface, Figure 3.
- As the steel item is removed from the bath a layer of relatively pure zinc is deposited on top of the alloy layers.

As the zinc solidifies it assumes a crystalline metallic lustre, usually referred to as “spangling”. The thickness of the galvanized coating is influenced by three major factors:

- size of the component;
- surface roughness of the steel; and
- chemical composition of the steel.

In general, thicker, heavier sections tend to produce heavier coatings.

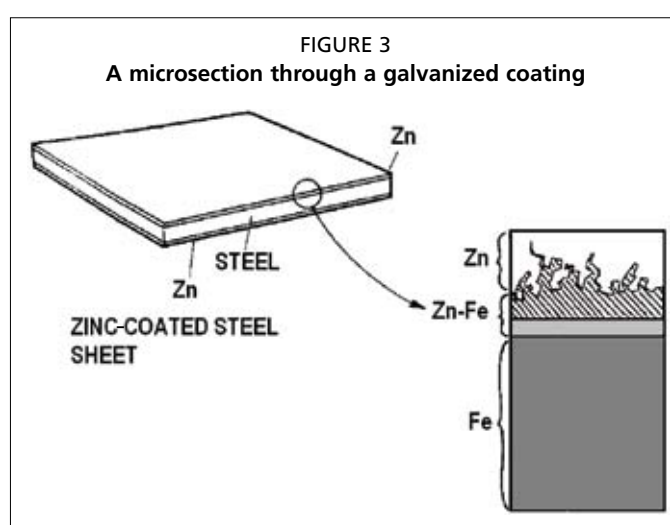


TABLE 1
Zinc coatings

Base sheet thickness (mm)	Minimum average coating (grams/mm ²)	Coating thickness (microns)
Over 5 mm	610	85
Between 2 and 5 mm	460	65
Between 1 and 2 mm	335	47
Cast iron	610	85
Centrifuged components	305	43

The greater the surface roughness of the steel, the heavier the coatings (Table 1). The surface of a component may be purposely abraded by different means such as grit or shot blast to increase the surface area of the component by as much as 50 percent.

Silicon, a major chemical component of steel, can have a marked effect on the coating weight deposited. The thickness of the coating varies with an increase in the silicon content of the steel and, sometimes, these coatings may have a dull dark-grey appearance and can be brittle and less adherent.

Since this is a bath-dipping process there is obviously some limitation on the size of the components which can be galvanized. Generally, filling, venting and draining holes, with a diameter of at least 10 mm, must be provided in hollow items such as tubes to allow rapid access for the molten zinc, venting of hot gases and subsequent draining of the zinc.

For most applications, galvanized articles do not need to be painted. Where, for reasons of decorative effect, there is a need to paint, then special etch primers are normally required.

In seawater immersion, zinc coatings are effectively resistant for protecting steel against rusting, with each 0.03 mm of zinc roughly equivalent to about one year of useful life.

9.3.3 Metal spray coatings

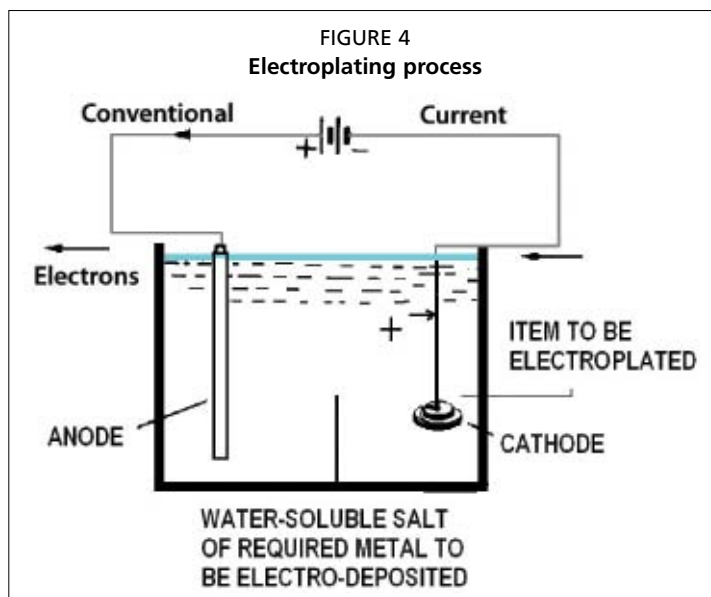
An alternative method of applying a metallic coating to structural steelwork is by metal spraying of either zinc or aluminium. The metal, in powder or wire form, is fed through a special spray gun containing a heat source which can be either an oxy-gas flame or an electric-arc. Molten globules of the metal are blown by a compressed air jet on to the previously blast-cleaned steel surface. No alloying occurs and the coating which is produced consists of overlapping platelets of metal and is porous. The pores are subsequently sealed, either by applying a thin organic coating which soaks into the surface, or by allowing the metal coating to weather, when corrosion products block the pores. The adhesion of sprayed metal coatings to steel surfaces is considered to be essentially mechanical in nature.

It is therefore necessary to apply the coating to a clean roughened surface for which blast cleaning with a coarse grit abrasive is normally specified, usually chilled-iron grit. Coating thickness varies from 100–250 microns for aluminium to 75–400 microns for zinc. The metals perform similarly in most environments but aluminium is more durable in highly industrial environments.

Metal spray coatings can be applied in workshops or at site and there is no limitation on the size of the component, as there is with hot-dip galvanizing. Since the steel surface remains cool there are no distortion problems. However, metal spraying is considerably more expensive than hot-dip galvanizing. For many applications metal-spray coatings are further protected by the subsequent application of paint coatings. A sealer is first applied which fills the pores in the metal-spray coating and provides a smooth surface for application of the paint coating.

9.3.4 Electroplated coatings

Together with galvanizing, electroplating is the second most important method of applying a metal coating to a steel item (Figure 4). The method consists in suspending steel articles from a cathode in an aqueous electrolyte of the metal to be plated to



the article. A current is then passed through the solution and the positive metal ions migrate to the cathode and hence the article in steel to be plated. Physically, a very thin layer a few microns thick is deposited; thicker layers are obtained by prolonging the electrolyte bath. Due to its simplicity, this method can also be utilized to electrodeposit a number of noble metals such as tin, nickel, chromium and gold. This system, however, is best suited to small engineering components where precision in film thickness is of the utmost importance.

9.3.5 Sherardizing

A sherardized coating is produced by a process called sublimation. In this process, heat is applied to steel components in contact with zinc powder, which then deposits itself on the steel. Sherardizing gives a hard and wear resistant surface and is generally reserved for small components like nuts and bolts.

9.3.6 Stainless steel

Stainless steels are alloys of iron, chromium and other elements that resist corrosion from many environments. In general, steel cannot qualify for a stainless prefix unless it has at least 10 percent chromium. Stainless steels can be very complicated from the metallurgical standpoint because they can contain significant concentrations of eight or more elements and the properties of the various alloys vary from alloy to alloy.

The most popular stainless steel used in marine applications is the 316 series, known as AISI 316 (American Iron and Steel Institute).

The basic AISI 316 has extra molybdenum added to the basic alloy to improve its corrosion resistance, whereas the AISI 316L has a lower carbon content to improve its welding characteristics (Table 2). AISI 316 LN has less carbon and more nitrogen to improve its strength.

Wrought stainless steel components for the fabrication of mooring rings, step ladders and railings should be specified in AISI 316L. Fittings may be in AISI 316.

Stainless steel reinforcement is also commercially available. Stainless steels in the series AISI 304 and AISI 308 are not suitable for a marine environment and should be avoided.

TABLE 2
Properties of some stainless steels

Steel types	C max	Si max	Mn max	S max	Cr	Ni	Mo	P max	N
AISI 304L	0.07	1.0	2.0	0.03	17.0/19.5	8.0/10.5	-	0.045	≤0.11
AISI 316L	0.05	1.0	2.0	0.015	16.5/18.5	10.5/13.0	2.5/3.0	0.045	≤0.11
AISI 316LN	0.03	1.0	2.0	0.015	16.5/18.5	11.0/14.0	2.5/3.0	0.045	0.12/0.22

9.4 PAINT COATINGS

9.4.1 Introduction

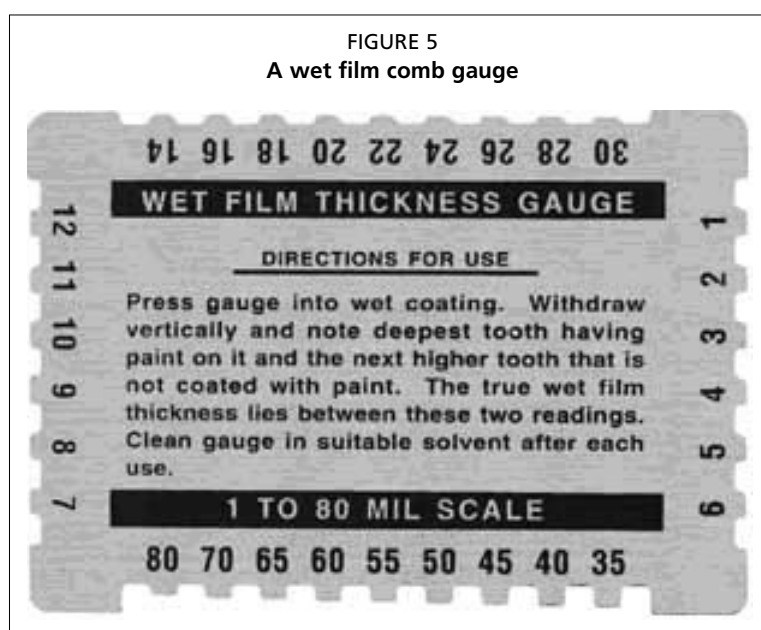
Paints are made by mixing and blending three main components:

- *Pigments*: finely ground inorganic or organic powders which provide colour opacity, film cohesion and sometimes corrosion inhibition;
- *Binders*: usually resins or oils but can be inorganic compounds such as soluble silicates. The binder is the film-forming component in the paint; and
- *Solvents*: used to dissolve the binder and to facilitate application of the paint. Solvents are usually organic liquids or water.

Since, in the broadest terms, paint consists of a particular pigment, dispersed in a particular binder, dissolved in a particular solvent, the number of generic types of paint is limited. The most common methods of classifying paints are either by their pigmentation or by their binder type.

Primers for steel are usually classified according to the main corrosion-inhibitive pigments used in their formulation, e.g. zinc phosphate, zinc chromate, red lead or metallic zinc. Each of these inhibitive pigments can be incorporated into a range of binder resins, e.g. zinc phosphate alkyd primers, zinc phosphate epoxy primers, zinc phosphate chlorinated rubber primers.

Intermediate coats and finishing coats are usually classified according to their binders, e.g. vinyl finishes, urethane finishes. Paints are applied to steel surfaces by many methods but in all cases they produce a “wet film”. The thickness of the wet film can be measured, before the solvent evaporates, using a comb gauge, Figure 5.



As the solvent evaporates, film formation occurs, leaving the binder and pigments on the surface as a “dry film”. The thickness of the “dry film” can be measured usually with a magnetic induction gauge. The relationship between the applied “wet film” thickness and the final “dry film” thickness (d.f.t.) is determined by the percentage volume of solids of the paint, i.e.

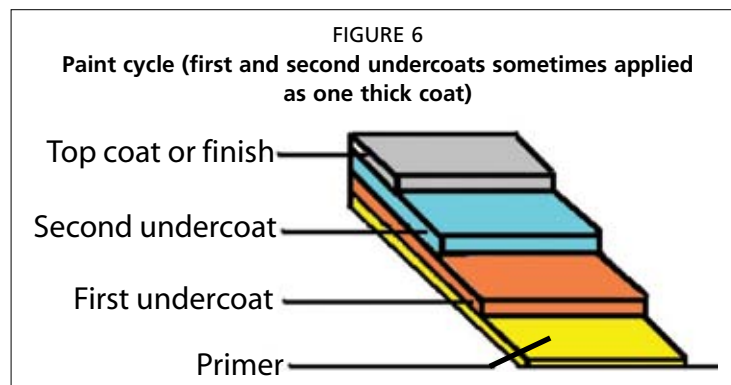
$$\text{d.f.t.} = \text{“wet film” thickness} \times \% \text{ vol. solids}$$

In general, the corrosion protection afforded by a paint film is directly proportional to its dry film thickness.

9.4.2 Paint systems

Paints are usually applied one coat on top of another, each coat having a specific function or purpose. The primer is applied directly on to the cleaned steel surface. Its purpose is to wet the surface and to provide good adhesion for subsequently applied coats. Primers for steel surfaces are also usually required to provide corrosion inhibition. The intermediate coats (or undercoats) are applied to build the total film thickness of the system. This may involve the application of several coats. The finishing coats provide the first-line defence against the environment and also determine the final appearance in terms of gloss, colour, etc., Figure 6. The various superimposed coats

within a certain system have, of course, to be compatible with one another. They may be all of the same generic type or may be different, e.g. chlor-rubber-based intermediate coats may be applied on to an epoxy primer. However, as a first precaution, all paints within a system should normally be obtained from the same manufacturer.



9.4.3 Main generic types of primers

Shop primers (also referred to as blast primers, temporary primers, weldable primers, temporary primers or holding primers) are used on steel, immediately after cleaning, to hold the reactive cleaned surface in a rust-free condition until the final painting cycle can be undertaken. The main requirements for a primer are:

- The primer should be capable of airless-spray application (see text on cleaning further on) to produce a very thin even coating. Dry-film thickness is usually limited to 15–30 microns. Below 15 microns the peaks of the blast profile are not protected and “rust-rashing” occurs on weathering. Above 30 microns the primer affects the quality of welds and produces excessive weld fume.
- The primer must dry very quickly. The interval between priming and handling is usually kept as is 1–10 minutes and hence the primer film must dry within this time.
- The primer coating should provide adequate protection. It should be noted that many manufacturers make misleading claims about the durability of their blastprimers and suggested exposure periods of 6–12 months are not uncommon. In practice, such claims are never met except in the least arduous conditions, e.g. indoor storage. In aggressive marine conditions, durability can be measured in weeks rather than months.
- The primed surface, after weathering, should require the minimum of preparation for subsequent painting and must be compatible with the intended painting system.

Many proprietary blast primers are available but they can be classified under the following main generic types:

- *Etch primers* are based on polyvinyl butyral resin reinforced with a phenolic resin to uprate water resistance. The curing agent contains phosphoric acid or alkyl phosphates and can be added as a separate component immediately before application. Alternatively, the primer can be supplied in a single-pack form. In general, two-pack etch primers provide better durability than the one-pack types which are usually preferred because of their handling convenience.
- *Epoxy primers* are two-pack materials utilizing epoxy resins and usually either polyamide or polyamine curing agents. They are pigmented with a variety of inhibitive and non-inhibitive pigments. Zinc phosphate epoxy primers are the most frequently encountered and give the best durability within the group.

- *Zinc epoxy primers* can be subdivided into zinc-rich and reduced-zinc types. Zinc-rich primers produce films which contain about 90 percent by weight of metallic zinc powder. These primers provide the highest order of protection of all primers. Reduced-zinc primers are formulated with metallic zinc content as low as 55 percent by weight on the dry film, the remainder of the pigmentation usually being made up with siliceous extenders. This reduces the cost of the primer, avoids possible difficulties with intercoat adhesion in marine environments, but slightly reduces the standard of protection that can be achieved. Zinc epoxy primers all produce zinc oxide fumes during welding and gas cutting which can cause a health hazard. When exposed in marine environments, zinc epoxy primers are prone to the formation of insoluble white zinc corrosion products which must be removed from the surface before subsequent overcoating.
- *Zinc silicate primers* can be based upon either ethyl silicate or inorganic silicates e.g. sodium or potassium. Only the ethyl silicate primers are suitable as primers. Ethyl zinc silicate primers produce a level of protection which is comparable with the zinc-rich epoxy types and they suffer from the same drawbacks, e.g. formation of zinc salts and production of zinc oxide fumes during welding. They are however more expensive and usually are less convenient to use.

9.4.4 Main generic types of paint

The main generic types of paint are:

- *Air-drying paints*, e.g. oil-based, alkyd, epoxy-ester, dry and form a film by an oxidative process which involves absorption of oxygen from the atmosphere. They are therefore limited to relatively thin films. Once the film has formed it has limited solvent resistance and usually poor chemical resistance.
- *One-pack chemical-resistant paints*, e.g. chlor-rubbers, vinyls, form a film by solvent evaporation and no oxidative process is involved. They can be applied as moderately thick films, although retention of solvent in the film can be a problem at the upper end of the range. The film formed remains relatively soft and has poor solvent resistance but good chemical resistance. Bituminous paints also dry by solvent evaporation. They are, essentially, solutions of either asphaltic bitumen or coal-tar pitch in organic solvents.
- *Two-pack chemical-resistant paints*, e.g. epoxy and urethane, are supplied as two separate components, usually referred to as the base and the curing agent. When the two components are mixed, immediately before use, a chemical reaction begins. These materials therefore have a limited “pot life” by which the mixed coating must be applied. The polymerization reaction continues after the paint has been applied and after the solvent has evaporated to produce a densely cross-linked film which can be very hard and has good solvent and chemical resistance. Liquid resins of low viscosity can be used in the formulation thereby avoiding the need for a solvent. Such coatings are referred to as “solvent-less” or “solvent-free” and can be applied as very thick films.

9.4.5 Methods of applying paint

The standard methods used for applying paint to steel are brush, roller, conventional air-spray and airless-spray.

- *Brush*. The simplest and also the slowest and therefore most expensive method. Nevertheless, it has certain advantages over the other methods, e.g. better wetting of the surface; can be used in restricted spaces; useful for small areas; less wastage; less contamination of surroundings; and can be used for application of certain toxic materials like lead-based primers which cannot be sprayed.
- *Roller*. Much quicker than brushing; useful for large flat areas; demands suitable fluidity of the paint.

- *Air-spray*. The paint is atomized at the gun-nozzle by jets of compressed air; application rates are quicker than for brushing or rolling; paint wastage by overspray is high.
- *Airless-spray*. The paint is atomized at the gun-nozzle by very high hydraulic pressures; application rates are higher than for air-spray and overspray wastage is greatly reduced.

9.4.6 Preparing a steel surface for coating

Structural steel is a hot-rolled product (that is, it is rolled into sections while it is still hot). Sections leave the last rolling pass at about 1 000 °C and as they cool the steel surface reacts with oxygen in the atmosphere to produce mill scale, a complex oxide which appears as a blue-grey tenacious scale completely covering the surface of the as-rolled steel section. Unfortunately, mill scale is unstable. On weathering, water penetrates fissures in the scale and rusting of the steel surface occurs. The mill scale loses adhesion and begins to shed.

Mill scale is therefore an unsatisfactory base and needs to be removed before protective coatings are applied. As mill scale sheds, further rusting occurs and this also needs to be removed before protective coatings are applied. Surface preparation of steel is therefore principally concerned with removal of mill scale and rust. Various methods of surface preparation are available:

- *Manual preparation*: The simplest form of surface preparation involving chipping, scraping and brushing with hand-held implements. This method is not very effective (although only about 30 percent removal of rust and scale can be achieved it is nevertheless often used, usually for economic reasons). The degree of cleaning achieved can be specified by reference to photographic standards included in ISO 8501 (International Organization for Standardization No. 8501).
- *Mechanical preparation*: Similar to manual preparation but utilizes power-driven tools, e.g. rotary wire brushing. A marginal improvement in efficiency can be achieved (up to 35 percent), and the same photographic standards can be used. Care must be taken to avoid confusing burnished scale with clean steel, both of which have a similar appearance. The above methods are used on site, usually after a weathering period to promote loosening of mill scale. A suitable primer must then be applied which is tolerant of poor surface preparation. Many modern primers are quite unsuitable for such surfaces and, indeed, the old tried and trusted red lead in oil primers cannot be bettered for manually cleaned surfaces.
- *Flame cleaning*: Not used extensively. An oxy-gas flame is applied to the surface. Differential thermal expansion and steam generated behind the mill scale serve to loosen the mill-scale layer, which can then be removed by mechanical scraping.
- *Acid pickling*: The steel is immersed in a bath of suitably inhibited acids which dissolve or remove mill scale and rust but do not appreciably attack the exposed steel surface. It can be 100 percent effective. Acid pickling is always used on structural steel intended for hot-dip galvanizing but is now rarely used as a pretreatment before painting.
- *Blast cleaning*: Abrasive particles are projected at high speed on to the steel surface. The abrasive can consist of either spherical particles, described as “shot”, or angular particles, described as “grit”. The abrasive is projected towards the surface either in a jet of compressed air or by a centrifugal impeller wheel. The particles impinge on the steel surface removing scale and rust, producing a rough, clean surface. The size and shape of the surface roughness produced is largely dependent upon the size and shape of the abrasive used; angular grits produce angular surface profiles, round shots produce a rounded profile. Grit-blast abrasives can be either metallic (e.g. chilled iron grit) or non-metallic (e.g. slag grit). The latter are used only once and are referred to as “expendable”.

They are used exclusively for site work. Metallic grits are expensive and are used only where they can be recycled. Grit blasting is always used for metal-sprayed coatings, where adhesion is at least partly dependent upon mechanical keying. It is also used for some paint coatings, particularly on site and for primers where adhesion may be a problem (e.g. zinc silicates). Shot-blast abrasives are always metallic, usually cast steel shot, and are used particularly on shot-blast plants, utilizing impeller wheels and abrasive recycling. They are the preferred abrasive for paints, particularly for thin film coatings (e.g. prefabrication primers). Blast-cleaned surfaces are normally specified in terms of surface cleanliness and surface roughness. A number of standards have been used in the past but these are now superseded by ISO 8501-1: 1988, which utilizes photographic replicas of four grades of surface cleanliness after blast cleaning: Sa1, Sa2, Sa2 1/2 and Sa3. Surface roughness of blast-cleaned surfaces is defined in ISO 8503-1: 1988 and Parts 2, 3 and 4 of this standard describe methods of measuring surface roughness.

- **Wet blasting:** A further variation on the blast-cleaning process. In this process, a small amount of water is entrained in the abrasive/compressed air stream. This is particularly useful in washing from the surface soluble iron salts that are formed in the rust by atmospheric pollutants (e.g. chlorides and sulphates) during weathering. These are often located deep in corrosion pits on the steel surface and cannot be removed by conventional dry blast cleaning methods. Wet blasting has proved to be particularly useful in marine environments.

9.4.7 Typical compatible paint cycles

Paint cycles should be designed for compatibility and Table 3 illustrates some typical cycles used in a marine environment.

To avoid mistakes with incompatible paint cycles, paints should always be purchased from the same manufacturer.

TABLE 3
Typical compatible paint cycles

Surface preparation	Paint cycle	Total thickness	Method of application
Manual or mechanical	Primer: Oil-based alkyd (red lead) Undercoat: Oil-based alkyd Finish: Oil-based alkyd	140–160 microns	Brush or roller
Blast cleaning	Primer: Zinc epoxy Undercoat: Chlor-rubber Finish: Chlor-rubber	120–140 microns	Brush, roller or spray
Blast cleaning	Primer: Epoxy polyamide Undercoat: Epoxy vinyl Finish: Vinyl	120–140 microns	Brush, roller or spray
Blast cleaning	Primer: Zinc epoxy Undercoat: Epoxy tar Finish: Epoxy vinyl	300–350 microns	Brush, roller or spray

9.4.8 Painting on galvanized surfaces

Whether thermally sprayed or hot dipped, the zinc coating can provide several years of protection by itself. Components may need to be painted or it may be necessary to apply a paint system to extend corrosion protection after the zinc is consumed. Quality painting after erection is both difficult and expensive, so it is always best to apply organic coatings beforehand, preferably in a shop setting. Surface preparation and painting of components in a shop can be accomplished under controlled conditions to provide optimum protection of the metal. Shop cleaning of zinc-coated surfaces is normally limited to detergent washing to remove loose contaminants and/or solvent cleaning to remove grease or oil. Sometimes, a thin film of grease or oil is applied at the factory to protect galvanizing from corrosion during exterior storage. Also, new galvanizing is sometimes treated with chromate corrosion inhibitors for corrosion protection during storage. Such treatment should specifically be excluded in specifications for galvanized steel components to be coated.

Galvanized steel components are best protected with one coat each of epoxypolyamide and aliphatic polyurethane coatings. If a delay of over four days occurs before the top coat is applied, the finish coat of polyurethane may not adhere because of the solvent resistance of the nearly fully cured epoxy coat. A thin film of the epoxy primer applied and allowed to cure to a tacky finish (e.g. four hours) will provide a suitable surface for the polyurethane finish coat. Epoxy and urethane coatings must have at least a six-hour pot life for practical coating. Oil-based paints (including oil/alkyds) are not recommended because of the inherent incompatibility of oil-based paints with the alkaline surface of galvanizing. Premature failure by peeling is predictable.

A two-coat latex system can also be used on galvanizing, but the protection and gloss and color retention may not be quite as good as with the epoxy/polyurethane system. The corrosivity of the exposure environment should be considered when choosing between the two systems.

9.4.9 Painting of sheet piles

Sheet-pile surfaces are subjected to abrasion from direct and indirect sources which may damage a normal coating. For long-term performance immersed in seawater, the coating system must be of high quality and is often specified in combination with a cathodic protection system (see further on). The recommended paint cycle for sheet piles is shown in Table 4.

TABLE 4
Painting of sheet piles

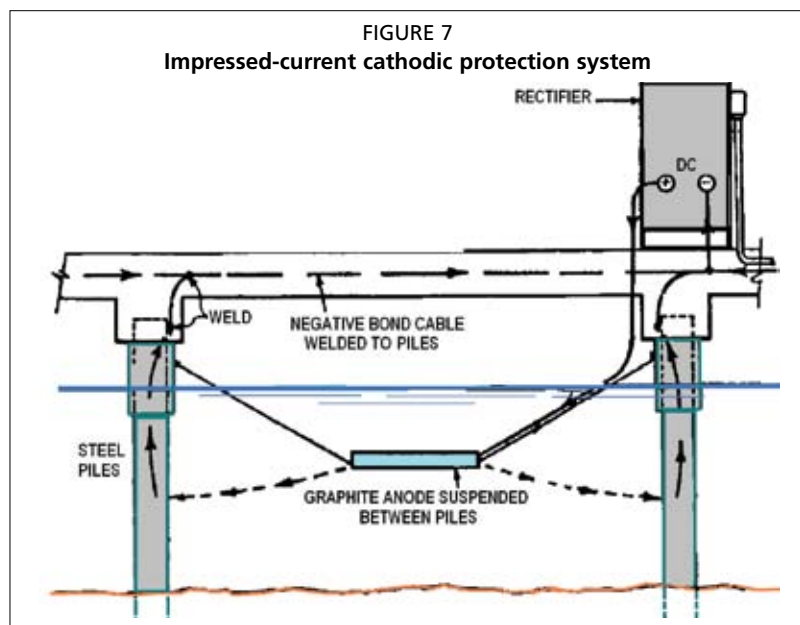
Surface preparation	Paint cycle	Total thickness	Method of application
Blast cleaning	Primer: Polyamide cured Epoxy primer Undercoat: Polyamide cured Coaltar epoxy Finish: Polyamide cured Coaltar epoxy	500 microns	Airless spray

9.5 CATHODIC PROTECTION

The corrosive effect on steel and other metals when submerged in seawater is known as galvanic corrosion and is analogous to the conditions prevalent in a battery, i.e. the presence of two dissimilar metals in an electrolyte. In the case of immersed steel (like a jetty's steel piles or a quay's sheet piles), the dissimilar metal consists of the non-

uniformities or non-ferrous impurities in the steel. These impurities establish a flow of current from the steel (positive pole or anode) through the electrolyte (seawater) to the impurity (negative pole or cathode).

Cathodic protection consists in reversing this current flow, i.e. to the steel and not from the steel, thus preventing the iron ions from flowing out of the steel and causing its corrosion (galvanic action).



Cathodic protection is accomplished by establishing a direct current (DC) voltage between the pile or sheet pile and an auxiliary anode suspended in the water in the vicinity of the structure, Figure 7. The density or strength of the current required depends on the rate of corrosion (specified in millimetres per year) and differs from place to place. Corrosion rates for a given type of steel generally depend on the salinity of the seawater, the ambient temperature and other environmental factors. If the steel has been coated, the efficiency of the coating, will also have a major effect on the rate of corrosion (the better the paint coating, the slower the corrosion rate). Various experiments worldwide indicate that typical current densities are of the order of 15 to 50 mA/m² (milliamperes per square metre of steel surface to be protected). This impressed current may be achieved in one of two ways:

- by using a galvanic anode or sacrificial anode, made of zinc, aluminium, magnesium or their alloys; and
- by forcing an external DC current through the auxiliary anode which may consist of a soluble metal, such as iron, or an insoluble material, such as graphite.

Galvanic anodes are generally supplied as ingots (weights from 2 to 100 kilograms) with cast-in suspension brackets which may be bolted or welded directly to the steel piles to be protected. Typical characteristics of galvanic anodes are listed in Table 5.

TABLE 5

Characteristics of sacrificial anodes

Metal	Zinc	Aluminium	Magnesium
Specific gravity	7.14	2.91	1.84
Potential in millivolts	-1 100.0	-1 150.0	-1 500.0
Current ampere/hour/kg	780	2 700	1 103
Current efficiency	95%	95%	50%
Kilogram of metal consumed to produce 1 ampere/year	11.23	3.24	7.94

On large structures, however, to gain better control of the current and regulate the magnitude thereof more accurately, an impressed external source of current is usually applied. Figure 7 illustrates a schematic diagram of an impressed-current cathodic protection installation, consisting of an alternating current (AC) supply, a rectifier (to convert the AC to DC) and the suspended graphite anode slung underneath the jetty in between the steel piles. Graphite anodes also become decomposed in time, primarily due to electrochemical oxidation, and must be replaced every 5 to 15 years, depending on the quantity, size and location of the anodes. Theoretically, when applying the recommended current density, the graphite anode life is of the order of 44 000 to 176 000 ampere hours per kilogram. Assuming the lower value of 44 000 ampere hours as a conservative value, a 30-kilogram graphite anode submerged in seawater would be completely consumed only after providing 7 amperes continuously for $[(44\ 000 \times 30) \text{ divided by } (7 \times 24 \times 365 \text{ days})]$ or 22 years. In practice, however, replacement must be made before the anode is greatly reduced in size in order to avoid an excessive current density as the exposed surface of the anode diminishes. The realistic useful life of a 30-kilogram graphite anode described above would be between 5 to 15 years.

Although the initial cost of the external impressed-current system is greater than that for galvanic anodes, the long-range economics over a ten-year period indicate that overall costs for impressed-current systems are considerably less than for galvanic anode systems.

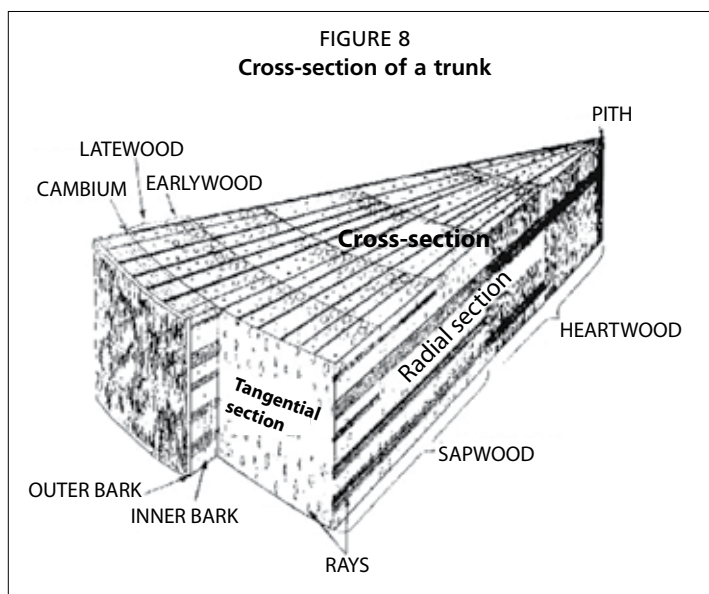
The step-down transformer and rectifier are usually mounted inside a weatherproof building not far from the structure to be protected.

9.6 TIMBER

9.6.1 Introduction

Timber is cut and machined from trees, themselves the product of nature and time. Humans have found timber to be a cheap and effective material and continue to use it in vast quantities.

However, criticisms levelled at timber as a material are a consequence of humankind's misuse of one of nature's most important products. Unlike so many other materials, especially those used in construction, timber cannot be manufactured to a particular specification; instead, the best use has to be made of the material already produced, though it is possible to select timbers with the most desirable range of properties.



A tree trunk consists of two distinct sections: the inner section or heartwood, and the outer section, or sapwood, Figure 8. The periphery of the trunk is formed of bark or, more correctly, an outer bark and an inner bark. The outer bark is rough in texture and dense enough to provide a protective “coat” covering the vital growth areas immediately inside it. The inner bark is soft, moist and spongy and transports the converted sap from the leaves to the growing parts of the tree. Between the inner bark and the actual growing timber is a thin layer of cells called the *cambium*.

It is here that growth takes place by the splitting of single cells into two cells, each of which grows and splits in a process which continues throughout the growing season, eventually forming a sheath of cells which in cross-section appears as a ring, referred to as an “annual ring”. These cells, which make up the wood tissue on the inner side of the cambium, are tubular in shape with diameters between about 0.02 mm and 0.50 mm, and vary in length from about 1 mm in hardwoods to 6 mm in softwoods.

The inner layer consists of cells with comparatively large cavities and thin walls. This cellular structure is due to a more rapid spring growth and, not illogically, is referred to as springwood or earlywood. Later in the year, cells grow more slowly and have thicker walls and smaller cavities, resulting in heavier, harder and stronger material called summerwood or latewood. The amount of summerwood may vary in different species of tree and as a result of different weather and soil conditions. This affects the overall density of the timber, which has a direct relationship with the strength of the timber. A group of cells known as the medullary rays run at right angles to the main cells from the outer layers inward. These carry food material by transporting the excess towards the centre of the tree, where it is stored in cells in the inner rings which cease to function as a live part of the tree. This older timber is known as heartwood and is usually dark in colour as well as being drier and harder than the living layer, known as sapwood.

Heartwood is composed of dead tissue, its cells being completely filled, and its function is the mechanical support of the tree. Sapwood, containing more moisture, is not as strong in the “green” state as heartwood but, after seasoning, when both heartwood and sapwood are reduced to the same moisture content, the difference in density and strength is very small.

Sapwood is inferior to heartwood in respect of durability, containing starches which may attract insects and fungi. Sapwood, however, is very permeable and more easily impregnated with preservative and, where the service conditions demand treatment, it may be beneficial to use sapwood as a deliberate choice.

The botanical name for those plants which grow outwardly, acquiring a new sheath of cellular tissue during each growing season, is exogens and this classification can be subdivided into:

- angiosperms, or dicotyledons, which have broad leaves shed in the autumn and which are normally classed as hardwoods; and
- gymnosperms, or conifers, which have needlelike leaves, broadly evergreen, and which are generally classed as softwoods.

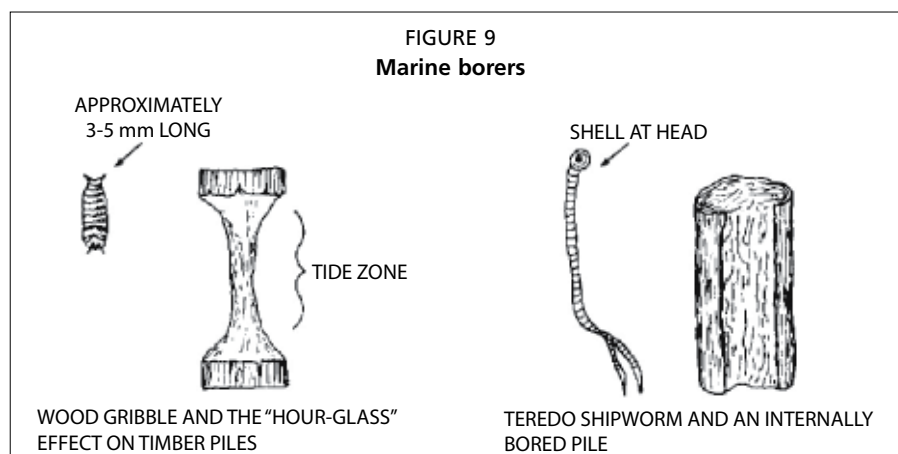
It should be noted that the terms hardwood and softwood in relation to species of tree do not necessarily indicate relative hardness or density; *balsa*, for example, although soft in texture, is a hardwood by classification whereas *yew*, softwood by classification, has a density six times that of *balsa*.

In the living tree, water is to be found not only in the cell cavity but also within the cell walls. Consequently, the moisture content of green wood (newly felled) is high, varying from about 60 percent to nearly 200 percent. Green or newly felled timber will yield moisture to the atmosphere with consequent changes in its dimensions and, with moisture contents above 20 percent, the timber is also subject to attack by fungi. For these reasons it is necessary to dry or season timber following felling of the tree.

9.6.2 Infestation

Although all timbers are susceptible to attack by at least one species of insect or fungus, in practice only a small portion of the timber in service actually becomes infested. The major types of attack are:

- Insect attack can take one of two forms. In certain insects the timber is consumed by the adult form and the best known example of this mode of attack are the termites. Few timbers are immune to attack by these voracious eaters. They are found principally in the tropics but certain species are also present in the Mediterranean region. The other mode of attack is by the grub or larval stage of certain beetles. The adult beetle lays its eggs in superficial cracks on the surface of the timber; the eggs hatch and produce grubs which tunnel their way into the timber, remaining there for periods up to three years.
- Fungal growth may be of two types: destructive or non-destructive. Some fungi, such as moulds, are present only on the surface and do not affect the strength of timber. Sapstain fungi live in the sugars present in the ray cells and impart a distinctive coloration to that region of the timber and may cause a considerable reduction in the strength of the timber. By far the most dangerous to timber are the fungi that cause decay by chemical decomposition; this is achieved by the digesting action of enzymes secreted in the fungi. The best known examples are *dry rot* or *Merulius lacrymans* and *wet rot* or *Coniophora cerebella*. Dry rot is the most destructive; during attack the wood usually darkens and in the advanced stages tends to break up into cubes and crumbles under pressure. A moisture content of 30 to 40 percent with an ambient temperature of 23 °C and lack of ventilation are required for growth. In temperatures above 26 °C, the fungus remains inactive. Wet rot may occur in timber which is excessively wet, whether located inside or outside a building. The fungus attacks all the chemical constituents of the cell wall and, unlike attack from dry rot, timber attacked by wet rot does not crumble under pressure but separates into a fibrous mass.
- Marine borers such as the shipworm (*Teredo* sp.) and the gribble (*Limnoria* sp.), Figure 9, are marine-boring animals that attack timber used in sea or brackish (salty) water. Marine borers are widely distributed, but they are particularly destructive in tropical waters. Most timbers do not have sufficient resistance to marine borers to be used untreated. Figure 9 also illustrates how the gribble and the shipworm destroy timber structures.



9.6.3 Durability

Durability is a term which has different meanings for many people: it is defined here in the broadest sense to embrace the resistance of timber to attack from weathering, salt water, corrosion of fastenings, fungi and insect attack.

In weathering, the action not only of light (especially ultraviolet radiation) but also of rain and wind render the timber silvery-grey in appearance: part of the process involves the degradation of the cellular fibres by ultraviolet radiation. However, the same cell walls that are attacked act as a filter for the intact cells below and the rate of erosion from the combined effects of ultraviolet radiation, light and rain is very slow indeed.

As a general rule, timber is highly resistant to a large number of chemicals. When in contact with steel in the presence of seawater, timber gives rise to a condition often known as “nail sickness”. Porous timbers absorb seawater, an electrolyte, and assume the role of an electrical conductor. Alkalis are produced at the cathodic surfaces and soluble metallic salts at the anodic areas. The metallic salts so formed degrade timber.

The principal factor conferring resistance to biological attack (insect, fungi and marine borers) is undoubtedly the presence of extractives in the heartwood. The far higher durability of the heartwood of certain species compared with the sapwood is attributable to the presence in the former of toxins (many of which are phenolic in origin), decreased moisture content, increased density and deposition of gums and resins. The decay resistance of most timbers varies a great deal and even pieces cut from the same tree will often show wide differences. For this reason, timbers have been classified into five broad grades based on the performance of their heartwood in contact with the ground. Table 6 illustrates the five grades.

Untreated timber in direct contact with sea or brackish water (jetty piles for example) should be heartwood of one of the species listed as **very durable**. Durable and moderately durable timbers should only be used if treated.

Table 7 presents a list of timbers suitable for marine construction. The heartwood is naturally resistant to marine borers and does not need treatment. The sapwood, however, is perishable unless treated.

TABLE 6
Grade of durability

Grade of durability	Useful life in contact with ground (Years)
Very durable	More than 25
Durable	15 to 25
Moderately durable	10 to 15
Non-durable	5 to 10
Perishable	Less than 5

TABLE 7
Typical timber species suitable for marine construction

Botanical name	Common name	Origin	Density (kg/m ³)	Resistance
<i>Pericopsis elata</i>	Afromosia	Ghana, Ivory Coast	710	Very durable
<i>Mezilaurus itauba</i>	Itauba	Brazil	820	Very durable
<i>Chlorophora excelsa</i>	Iroko	Sierra Leone, Ghana	660	Very durable
<i>Homalium species</i>	Aranga	Philippines	881	Very durable
<i>Ocotea rodiaei</i> Mez	Greenheart	Guyana, Suriname, Venezuela	1 040	Very durable
<i>Dialium species</i>	Keranj	Malaysia	1 120	Very durable
<i>Eucalyptus species</i>	Ironbark	Australia	1 120	Very durable

Note: These and other hardwood species suitable for marine construction are now strictly controlled to limit indiscriminate deforestation. In general, the design of a port should contain as little tropical timber as possible and that used should be sourced from plantations only. The species used should not be on the Convention on International Trade in Endangered Species of Wild fauna and Flora (CITES) list.

9.6.4 Timber preservatives

As stated above, not all timbers require treatment with a preservative to enable them to resist infestation and decay. Many timbers, like the ones mentioned in Table 7, owe their natural resistance to attack to the presence of toxic oils and resins. However, environmental considerations (most species come from virgin tropical rain forests) and cost mean that it is sometimes necessary to use timbers not so well endowed naturally and to subject them to some form of preservative treatment which will increase their durability. Timber preservatives must, by nature, be poisonous to the agents of decay: they must also satisfy conditions of permanency, economy, availability, penetrability and be non-corrosive and non-toxic to humans, animals and plants. Preservatives are generally classed into three groups, depending on the solvent used:

- tar-oil preservatives;
- water-soluble preservatives; and
- organic solvent preservatives.

9.6.4.1 Tar-oil preservatives

Tar-oil preservatives consist essentially of mixtures of distillate oils from coal tar (an aromatic hydrocarbon) and are known as coal tar creosotes or creosote and are the most widely used. Its efficacy as a preservative lies not in any natural toxicity, but rather in its supreme water repellence. It has a very distinctive odour, stains timber, and once treated timber cannot be painted unless primed with a metallic paint. The major drawback with this type of preservative is that it is a polycyclic aromatic hydrocarbon (PAH) which is a highly toxic compound. This product is gradually being phased out due to the pollution of the water environment.

9.6.4.2 Water-soluble preservatives

Water-soluble preservatives are generally odourless and non-staining. Because of the waterborne nature of this type of preservative it may be necessary to re-dry the timber to an acceptable moisture content. These preservatives function as toxins and commonly contain formulations of copper, chromium and arsenic salts. These chemicals are “fixed” in the timber and cannot leach out.

9.6.4.3 Organic solvent preservatives

These preservatives tend to be more expensive than the previous two, and are generally formulations of pentachlorophenol, tributyltin oxide or chlorinated naphthalenes. These preservatives also function as toxins and have good penetration characteristics. As with tar-oil creosotes, however, these preservatives are toxic to humans and should not be used.

Timber which has been treated with both water soluble and solvent type preservatives can be painted; it is also possible to glue together treated components. Preservatives may be applied by brush, by steeping or by pressure. Brushing is the least effective method but is better than none and, provided that the preservative is flooded over the surfaces to encourage absorption, reasonable penetration is possible in very permeable timbers. Steeping or dipping involves placing the timber sections inside a bath of preservative for a number of days. In this method of application, the timber section to be treated should be prepared in its final form, with all chamfers, holes and recesses cut. Some preheating of the preservative may be necessary to assist penetration. Pressure application is by far the most efficient and controllable method of preservation. Pressure application is the timber industry standard. In the process, the timber section is placed in a large enclosed pressure vessel and subjected to a vacuum for about an hour. While the vacuum is maintained the preservative is introduced into the vessel until it is filled. Pressure is then gradually increased until the required amount of preservative has been introduced into the timber. A further vacuum is applied for a brief period only long enough to

clean the surface of the timber from excess preservative. This method assumes that timber seasoning has taken place beforehand to ensure that during subsequent storage cracks do not expose untreated timber.

9.7 CONCRETE

9.7.1 Introduction

Concrete is a human-made composite, the major constituent of which is natural stone aggregate such as gravel, sand or crushed rock. The other principal constituent of concrete is the binding medium used to bind the aggregate particles together to form a hard composite material. The most commonly used binding medium is the product formed by a chemical reaction between cement and water. When this chemical reaction takes place (also known as hydration), heat is given off (also known as heat of hydration). In its hardened state concrete is a rock-like material with a high compressive strength but a low tensile strength. Compressive and tensile strengths in concrete are measured in N/mm^2 (Newtons per square millimetre) or MPa (Mega Pascals).

$$1 \text{ MPa} = 1 \text{ N/mm}^2$$

The tensile strength of normal concrete is low and this can be improved by incorporating steel bars to resist tension (reinforced concrete). The density of concrete is measured in Tonne/m^3 (Tonne per cubic metre) or kN/m^3 (kilonewtons per cubic metre).

$$1 \text{ Tonne/m}^3 = 10 \text{ kN/m}^3$$

It is not the intention here to teach concrete mix design but rather the site practice involved in producing good-quality concrete that is durable in time and compatible with the marine environment. Almost all the topics discussed are dealt with in greater detail in national or international standards for quality control, use of which requires access to a well-equipped concrete testing laboratory.

9.7.2 Cement

Portland cement is a finely ground powder developed in 1824 and derives its name from Portland limestone because of its close resemblance to this rock after hydration has taken place. The basic components used in the manufacture of Portland cement are calcium carbonate (found in limestone rock) and iron oxide, alumina and silica (found in clay). As a result of the chemical changes which take place inside a cement-making kiln, these constituents give rise to several compounds, only four of which are considered to be important:

- tricalcium silicate, also known by its chemical abbreviation as C_3S for short;
- dicalcium silicate or C_2S ;
- tetracalcium aluminoferrite or C_4AF ; and
- tricalcium aluminate or C_3A .

Over time, a variety of cements have been developed to ensure good durability of the concrete under different conditions and these cements each contain different amounts of the above constituent compounds. The main types of cement currently available in practice are:

- ordinary Portland cement;
- rapid hardening cement;
- low heat Portland cement;
- sulphate resisting cement; and
- portland blast furnace cement.

Marine works require a concrete which is durable in a marine environment and to achieve this only cement which performs well in this environment should be used. Both sulphate resisting cement and Portland blast furnace cement have these required characteristics.

During the process of hydration, the chemical reaction between the tricalcium aluminate and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) produces a compound called calcium sulphoaluminate. In hardened cement, calcium aluminate hydrate can react with a sulphate salt from outside the concrete in a similar manner: the product of addition is calcium sulphoaluminate, forming within the framework of the concrete's cement paste. Since the increase in volume of the solid phase is over 200 percent, gradual disintegration of the concrete results.

A second type of reaction is that of base-exchange between calcium hydroxide and the sulphates, resulting in the formation of gypsum with an increase in volume of the solid phase of 124 percent.

These reactions are known as sulphate attack. The salts particularly active are magnesium and sodium sulphate. Sulphate attack is greatly accelerated if accompanied by alternate wetting and drying, as in the case of marine structures. **The remedy lies in the use of cement with a low content of C_3A and such cement is known as sulphate resisting cement.** Portland blast furnace cement is also low in C_3A and suitable for marine concrete.

When large volumes of concrete are being poured, in excess of around 15 m^3 , the heat of hydration in ordinary Portland cement and rapid hardening cement will give rise to thermal cracking in the cast, depending on the shape of the cast, the ambient temperature and the temperature of the batched materials. Both sulphate resisting cement and Portland blast furnace cement have low heat characteristics and should be the preferred choice in the mix design.

9.7.3 Aggregate

Aggregate is much cheaper than cement and maximum economy is obtained by using as much aggregate as possible in a concrete mix. Its use also considerably improves both volume stability and durability of the resulting concrete. The properties of the aggregate known to have a significant effect on concrete behaviour are:

- shape and surface texture;
- grading;
- strength;
- deformation (toughness and hardness);
- porosity;
- specific gravity or the ratio of its unit weight to that of water; and
- impurities.

9.7.3.1 Shape and surface texture

The shape and surface texture of an aggregate can affect the properties of concrete in both its plastic (fresh) and hardened states. These external characteristics may be assessed by observation of the particles and classification of their particle shape and texture as shown in Boxes 1 and 2.

The best aggregate for concrete is one that is irregular and angular. Rounded aggregate provides a smaller mechanical bond with the hydrated paste, whereas the flaky and elongated aggregate tends to have little strength across the thinner sections, influencing the strength of the concrete.

The most suitable mechanical bond is obviously achieved with rough surfaces, followed by granular, smooth, crystalline and glassy. Honeycombed aggregate is generally very porous and is not suitable for good quality concrete.

BOX 1

Classification	Description of shape
Rounded	Fully water-worn such as beach shingle or pebbles
Irregular	Naturally irregular such as breccia and having rounded edges
Angular	Possessing well-defined edges such as crushed from rock
Flaky	Having a thickness considerably smaller than its length or width
Elongated	Usually angular but very long
Flaky and Elongated	A combination of the above two conditions

BOX 2

Surface texture	Characteristics
Glassy	Conchoidal fracture such as in broken basaltic rock
Smooth	Water-worn such as found on beach pebbles
Granular	Fracture showing more or less uniform rounded grains, as in sand
Rough	No visible crystalline constituents, such as crushed limestone
Crystalline	Visible crystalline structure such as in granite aggregate
Honeycombed	Visible pores and cavities such as in some types of coral stone

9.7.3.2 Grading

Grading of an aggregate defines the proportions of particles of different size in the aggregate. The size of the aggregate particles normally used in concrete varies from 0.15 mm to 37.5 mm. Generally, fine aggregate or sand has particles the majority of which are smaller than 5 mm. The rest are known commonly as the coarse aggregate. The grading of an aggregate can have considerable effect on the workability and stability of wet concrete and is a most important factor in designing a concrete mix. A mix with too little fine particles is defined as harsh and does not place easily because the main aggregate tends to segregate away from the cement paste. A mix with too many fine particles on the other hand requires more water, resulting in a concrete with inferior properties.

9.7.3.3 Strength

Strength of an aggregate limits the attainable strength of concrete only when its compressive strength is less than or of the same order as the required strength of the concrete. In other words, the strongest and not the most convenient aggregates should be used in the concrete mix. Typically, coral, which only attains strengths of the order of 20 N/mm² cannot be used to produce concrete with strength of 30 N/mm², which is considered to be the minimum strength suitable for a marine environment. Typical values of strength for good parent rock (from which the aggregates are extracted) are:

Granite	181 N/mm ²
Basalt	200 N/mm ²
Limestone	159 N/mm ²
Sandstone	131 N/mm ²
Quartzite	252 N/mm ²
Porphyry	230 N/mm ²

9.7.3.4 Deformation

Deformation characteristics of an aggregate are seldom considered in assessing its suitability for concrete work although they can easily be determined from compression tests on specimens from the parent rock. A commonly used standard is toughness or brittleness, i.e. its resistance to failure by impact. Another common standard is hardness, i.e. its resistance to wear or abrasion. Soft rock such as coral, for instance, abrades very quickly and a concrete surface made with coral aggregate ruts very easily. A good guide in the field for hardness is the “penknife scratch”; a steel penknife should not easily scratch the surface of a piece of aggregate.

9.7.3.5 Porosity

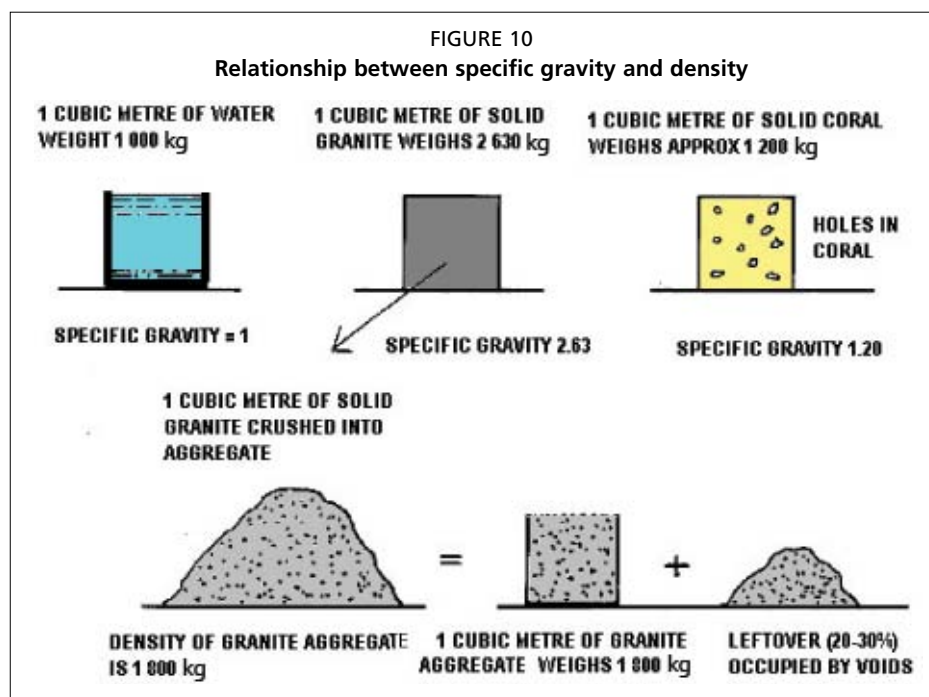
Porosity is an important factor which influences the amount of water required for a given mix and makes it very difficult to obtain good quality concrete. Porous aggregate tends to absorb the mixing water quickly, depriving the cement paste, and in the process rendering the wet concrete too dry to handle and place in the process. More water has to be added to make up for this “loss” thereby reducing the quality of the finished concrete.

For this reason, porous aggregate stockpiles should not be exposed to rain. Direct measurement of porosity is difficult and in practice a related property, water absorption, is measured.

9.7.3.6 Specific gravity

Specific gravity of a material is the ratio of its unit weight to that of water. Generally speaking, the higher the specific gravity of the parent rock from which the aggregate has been extracted (e.g. limestone, granite, basalt, etc.), the denser the concrete and hence the more durable.

Figure 10 illustrates the various terms used in defining the “weights” of the various components. The basic unit for specific gravity is water and everything else is referred to unity. For example, a cube measuring 1 metre cubed (1 m^3) of solid granite weighs 2 630 kilograms; granite is a very dense material. Its specific gravity is 2.63. The following provides the average specific gravity for parent rock.



Parent rock	Average specific gravity
Basalt	2.793
Granite	2.636
Hard limestone	2.60
Soft limestone	2.20
Porphyry	2.73

When a 1 cubic metre cube of solid granite is crushed to make aggregate, the bulk or the overall volume of the resulting aggregate occupies more than 1 cubic metre. The reason for this is that inside the aggregate there are now also voids and the volume occupied by these voids is the amount of leftover aggregate that will not fit inside the 1 cubic metre. The 1 cubic metre of granite aggregate typically weighs only 1 800 kilograms and the “weight” or more appropriately the bulk density of granite aggregate is specified as being 18.0 kN per cubic metre (1.8 t/m³). The density of other types of aggregate depends mainly on the specific gravity of the parent rock, the shape of the particles (some particles fit tightly together making the aggregate denser) and the relative size of the particles (if an aggregate has a lot of fine particles, i.e. dust, it weighs more). Dry cement powder typically weighs 18.0 kN/m³ or 1.80 Tonnes/m³.

9.7.3.7 Impurities

Natural aggregates may be sufficiently good in themselves and yet they may not be satisfactory for concrete making if they contain organic impurities which interfere with the chemical reactions of hydration. The organic matter found in aggregate consists usually of products of decay of vegetable matter and such materials are more likely to be present in sand than in coarse aggregate, which is easily washed. Clay may be present in aggregate in the form of surface coatings which interfere with the bond between aggregate and the cement paste. Another type of fine material present in some fine aggregates (i.e. in the sand) is silt and crusher dust. Both silt and fine dust (particle diameters in the range of 1 to 60 microns) may form coatings on the aggregate similar to those of clay. The presence of loose silt and dust in a mix necessitates the use of more water in the concrete, thereby decreasing the strength.

Sand from the seashore or from a river estuary also contains salt. This has to be washed away using freshwater. Due to their porosity, coral aggregates generally contain high levels of salt and should not be used, especially with reinforcing steel. A concrete surface containing coral also exhibits efflorescence and cannot be painted or rendered.

Other types of unsound materials, such as coal, mica and iron pyrites (iron sulphide), should also be removed or limited to trace levels. Some forms of aggregate are totally unsuitable for inclusion in concrete in that they react over a length of time with the hydrated cement paste causing the concrete to deteriorate.

9.7.4 Mixing water

The quality of the mixing water also plays a vital role in the strength of the concrete because impurities in the water may interfere with the hydration of the cement paste. In many specifications worldwide, the quality of water for mixing concrete is covered by a clause saying that water should be fit for drinking. Such water rarely contains dissolved solids in excess of 2 000 ppm or parts per million (i.e. 2 000 grams of dissolved salts per cubic metre of water), and as a rule less than 1 000 ppm. While the use of potable water is generally safe, water not fit for drinking may often be used to make concrete. As a rule, water with a pH of 6.0 to 8.0 which does not taste saline or brackish is suitable for use, but dark colour or bad smell does not necessarily mean that organic substances are present. A very good way of determining the suitability of dubious water is to compare the setting time of cement made with say, tap or distilled

water (the control test) and the dubious water. Brackish water contains chlorides and sulphates. When chlorides do not exceed 500 ppm and sulphates (SO_3) do not exceed 1 000 ppm, the water is harmless.

Seawater has a total salinity of around 35 000 ppm (i.e. 35 000 grams or 35 kilograms of dissolved salts per cubic metre of seawater) and 78 percent of these salts is sodium chloride (NaCl) and 15 percent magnesium sulphate (MgSO_4) and magnesium chloride (MgCl_2). When used for mixing concrete, seawater:

- may lower the long-term strength of concrete by about 15 percent;
- will increase the risk of corrosion of steel inside the concrete; and
- will cause persistent dampness and surface efflorescence.

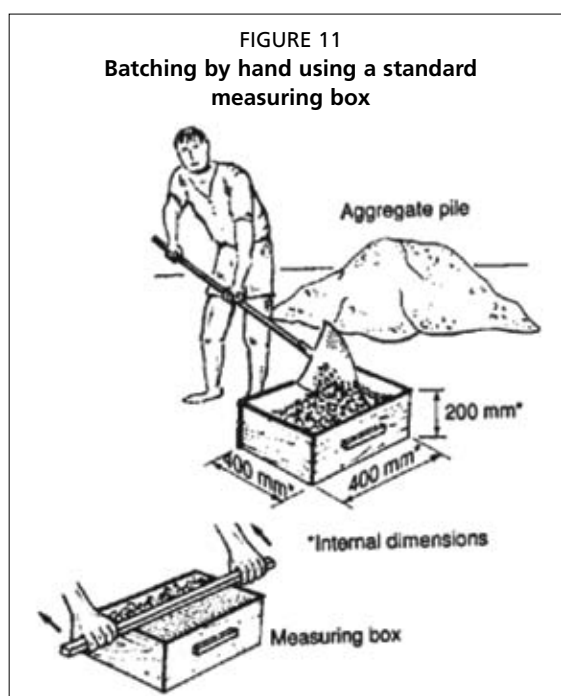
9.7.5 Batching

Concrete is made up from the various constituents mixed together according to a specific mix; the mix may either be a standard mix or a designed mix. Designed mixes are usually reserved for use on large projects and the science of designing a mix to suit local conditions is beyond the scope of this manual.

Concrete mixes are generally quoted by weight of the constituent materials but, knowing the densities of the constituents (remembering that cement always comes in 50-kilogram bags), mixes may also be converted to volumetric proportions; volumetric proportions are easier to follow in artisanal situations and will be dealt with in greater detail. A standard volumetric mix may be any one of those shown in Table 8.

TABLE 8
Batching volumes

Nominal proportions	Quantities of aggregate		Typical strength measured (per 50-kg bag of cement after 28 days in N/mm^2)
	Fine (Sand)	Coarse	
1 : 2 : 4	0.07 m^3	0.14 m^3	20.0 (general mass concrete)
1 : 1½ : 3	0.05	0.10	25.0 (not in much use)
1 : 1 : 2	0.035	0.07	30.0 (minimum marine concrete)



The above table gives the volumetric dosage of the constituent materials referred to a 50-kilogram bag of cement. The recommended minimum grade or strength for marine concrete is 30 N/mm^2 as this provides a good all-round mix with good durability. This mix is generally known as a “one one two” mix.

Batching is the term used for preparing the various dry constituents for mixing. To batch the aggregates by volume, a wooden measure box should be constructed with inside dimensions of 400 mm by 400 mm by 200 mm high as illustrated in Figure 11.

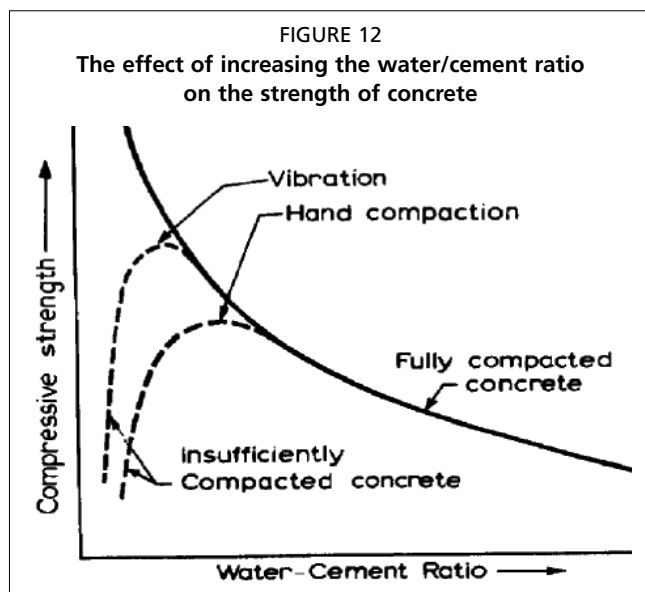
Each such level box contains 0.035 cubic metre of aggregate. Therefore, for each 50-kilogram bag of cement loaded into the concrete mixer, one box measure of sand (0.035 m^3) and two box measures of aggregate (0.070 m^3) are required. This hence completes the batching of the dry constituents.

The nominal mix table purposely leaves the water dosage out. In engineering practice, the strength of the concrete at a given age (28 days are generally prescribed as the minimum for testing) is assumed to depend primarily on two major factors in the field:

- the amount of water in the mix (known as the water-cement ratio or W/C ratio); and
- the degree of compaction.

Assuming that the concrete is fully compacted (by mechanical vibration, as described later on in the text), the strength is a function of the W/C ratio (i.e. the amount of water introduced into the mix divided by the weight of the cement in the mix), Figure 12.

This means that the less water is added to the mix (beyond the necessary minimum to turn the cement into a paste, albeit a stiff one), the stronger the concrete is. However, very stiff concrete is difficult to pour from a mixer and difficult to place inside a given mould and, generally speaking, more water has to be added beyond the minimum to make the mix workable.



In practice, if the aggregates have been chosen carefully, the W/C ratio can be set at around 0.35 to 0.40 as a starting point. A W/C ratio of 0.35 means that for every 50 kilograms of cement present in the mix, 17.50 litres ($0.35 \times 50 = 17.50$) of water should be added. This will undoubtedly result in a very stiff mix and further amounts of water will be needed to make the mix workable. Generally, water in the concrete consists of that added to the mix and that held by the aggregate at the time it enters the mixer (for example, aggregate which has been exposed to rain will automatically introduce more water into the mix, increasing the given W/C ratio). Conversely, when the aggregate is very dry (i.e. left exposed to the mid-day sun), a part of the water added to the mix will be taken away from the cement paste and absorbed by the hot aggregate during the first few minutes after mixing, decreasing the W/C ratio and resulting in a very stiff mix.

The workability of concrete has never been precisely defined. For practical purposes it generally implies the ease with which a concrete mix can be handled from the mixer to its finally compacted shape. The three main characteristics of the property are:

- consistency (a measure of the wetness or fluidity);

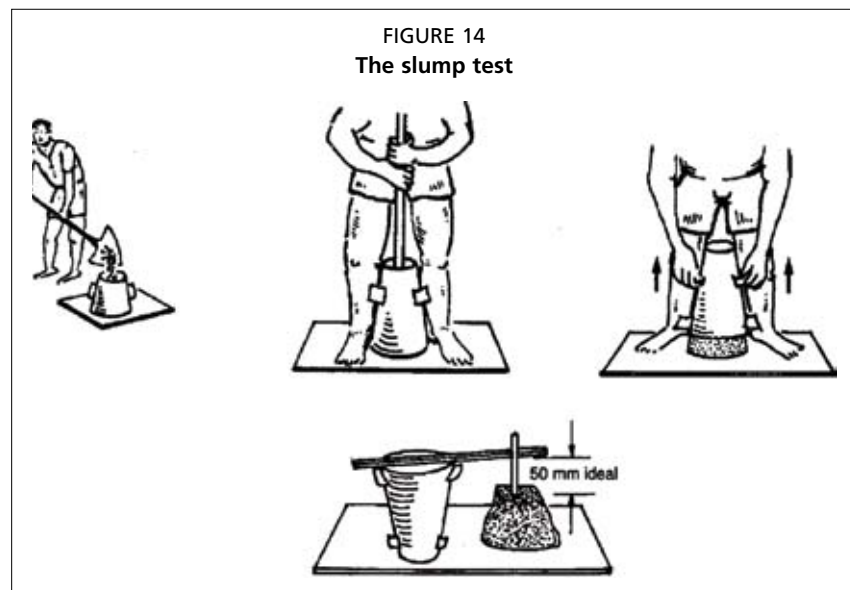
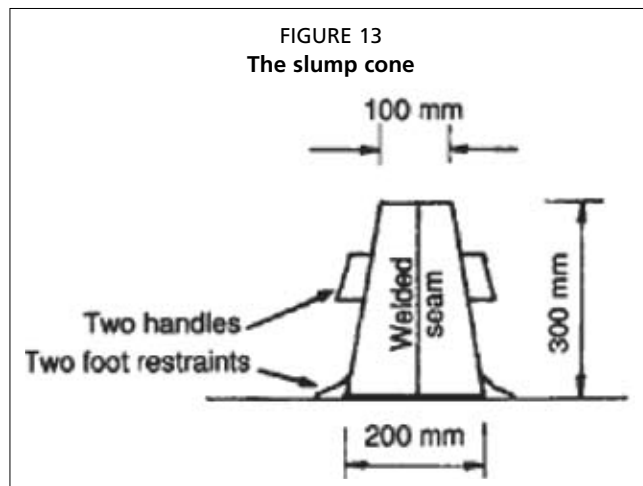
- mobility (the ease with which a mix can flow into and completely fill the formwork); and
- compactability (the ease with which a given mix can be fully compacted).

In this context, the required workability of a mix depends not only on the characteristics and volumetric proportions of the constituent materials but also on:

- the methods employed for conveyance and compaction;
- the size, shape and surface roughness of the formwork; and
- the quantity and spacing of any reinforcement.

A simple test devised to measure the consistency and workability of fresh concrete is the “slump test” and the apparatus involved is inexpensive, portable and robust. Figure 13 illustrates the dimensions of the steel cone required for the test. Figure 14 shows how a slump test is carried out.

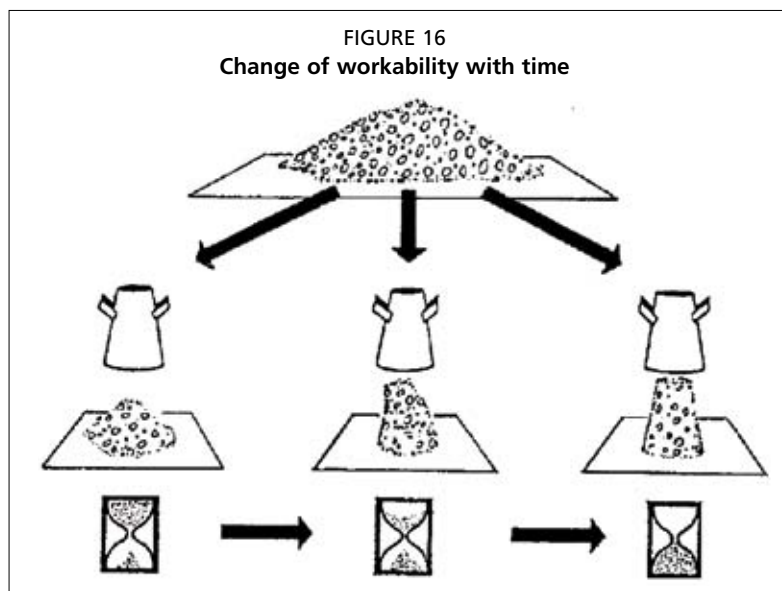
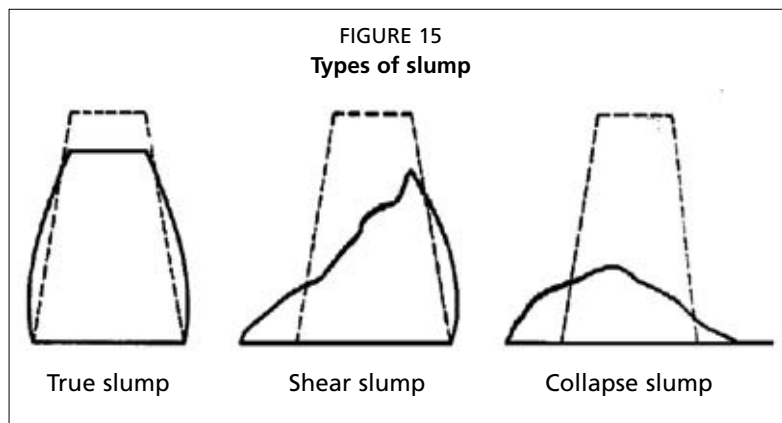
When just enough water has been added to the concrete mixer to make the concrete appear wet but stiff, the cone should be filled with three layers of concrete from the mixer, each compacted by hand using a 20 mm diameter steel poker. The top of the cone should then be towelled level and the cone lifted off. As soon as the steel cone is lifted off, the concrete will slump or settle down as shown in Figure 15. The ideal slump



for most practical work is 50 mm. Should the concrete not slump by 50 mm, a bit more water should be added to the mixer with a measuring can, half a litre at a time (and not directly through a water pipe). The test should then be repeated until the desired slump is achieved. This test is suitable for the quality control of consistency. It is not suitable for stiff mixes and very wet mixes.

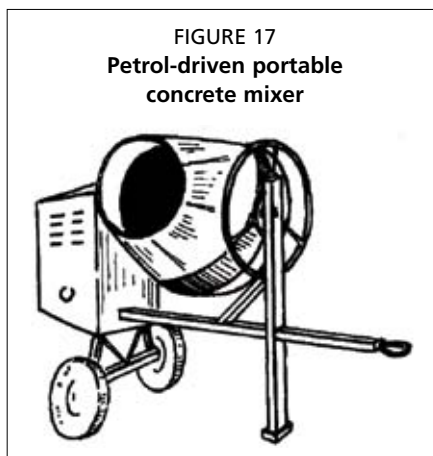
Figure 15 illustrates the three types of slump usually observed; true, shear and collapse slumps. A true slump is observed with cohesive and rich mixes for which the slump is generally sensitive to variations in workability (the ideal case). The shear slump tends to occur more often with leaner mixes and indicates a lack of cohesion generally associated with harsh mixes (low on fines). A collapse slump is an indication of a very wet mix and is generally taken to indicate poor workmanship or poor concrete.

The standard slump apparatus is only suitable for concretes in which the maximum aggregate size does not exceed 37.5 mm. It should be noted that the value of the slump changes with time after mixing owing to the normal hydration processes and evaporation of some of the free water and it is desirable, therefore, that tests are performed within a fixed period of time, Figure 16.



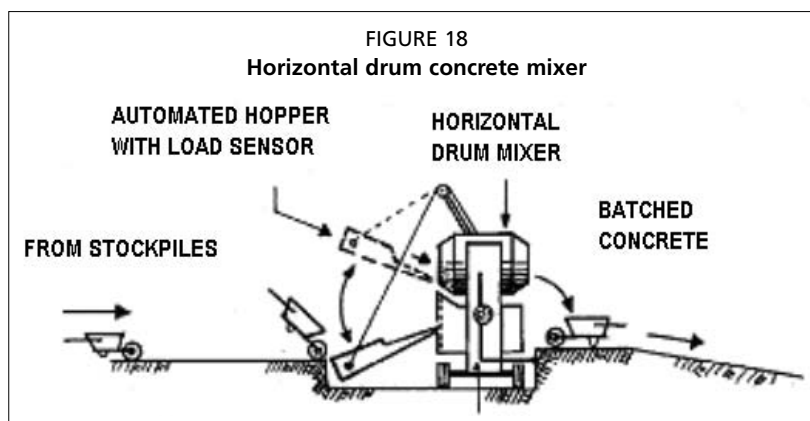
On a larger scale, concrete is batched by concrete mixers and concrete mixers come in many sizes and shapes but generally fall into three main categories:

- portable, tilting drum, mini-mixers, capacity not exceeding about 150 litres (0.15 m^3);
- transportable, fixed horizontal drum mixers, capacity not exceeding 1.0 m^3 ; and
- pan mixers, used mainly by ready-mixed operators, with much larger capacities.



Portable mixers, Figure 17, are available with a wide range of power options, such as petrol, diesel and electricity. They are small enough to be loaded on a light truck or towed behind a suitably equipped vehicle. The capacity of the tilting drum is usually enough to hold the batch for a 50-kilogram cement bag.

Allowing for loading and a minimum mixing time of about five minutes, a crew of five people can produce an average of about 1 m^3 of fresh concrete per hour (suitable for small pours, jute-bag filling, etc.). Petrol-powered versions tend to be lighter than diesel-powered ones. Electric-powered mixers are the lightest and easiest to maintain.



The fixed horizontal drum mixer is quite large and heavy and when towed to a site it is generally set up on a prepared concrete platform to ease loading and discharging of concrete, Figure 18. Modern horizontal drum mixers are quite sophisticated, generally incorporating a load cell on the tipping hopper (so that the mix can be batched by weight instead of by volume) and an automatic water dosimeter for dispensing the exact volume of mixing water directly into the drum. The drum capacity can range from 0.50 m^3 to 1.0 m^3 and needs a fairly large crew to operate. A fleet of wheelbarrows is generally needed to haul enough aggregate to keep it working at full capacity and enough wheelbarrows or a motorized skip or tipper to haul away the concrete to the formwork. The wheelbarrows loading the aggregate may be replaced by a small pay-loader and the wheelbarrows loading the batched concrete may be replaced by a tipper.

Pan mixers are generally used by ready-mix companies for discharging concrete into truck mixers. Pan mixers are the most efficient way to mix concrete and need mechanized feeding of all the dry constituents.

9.7.6 Reinforcement

As mentioned earlier, the tensile strength (resistance to pulling) of concrete is very low and reinforcing steel in the form of bars or mesh is used to increase this strength. Reinforcing bars are manufactured as deformed or ribbed bars to better grip the concrete as illustrated in Figure 19. Commonly available sizes are illustrated in Table 9 and the common types of steel mesh are illustrated in Figure 20.

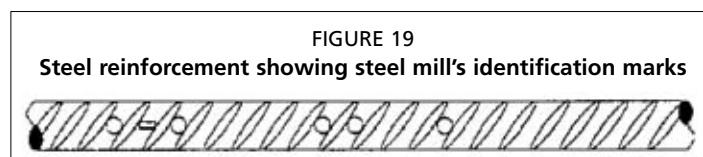


TABLE 9

Commonly available sizes of steel bars and steel mesh

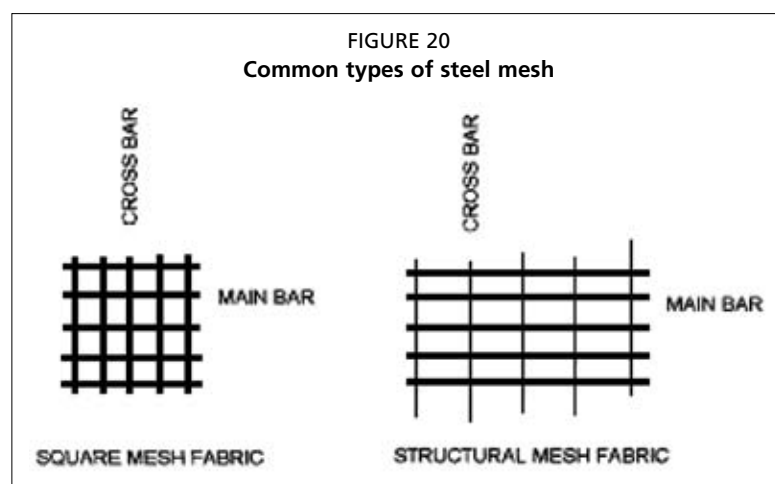
BAR DIAMETER mm	CROSS-SECTIONAL AREA mm ²
6	28.3
8	50.0
10	79.0
12	113.0
14	154.0
18	254.0
20	314.0
22	380.0
24	452.0

SQUARE STEEL MESH FABRIC

TYPE OF MESH	NOMINAL PITCH IN mm		BAR SIZE IN mm		STEEL AREA IN mm ²		WEIGHT Kg/m ²
	MAIN	CROSS	MAIN	CROSS	MAIN	CROSS	
SQUARE	200	200	10	10	393	393	6.16
SQUARE	200	200	8	8	252	252	3.95
SQUARE	200	200	7	7	193	193	3.02
SQUARE	200	200	6	6	142	142	2.22
SQUARE	200	200	5	5	98	98	1.54

STRUCTURAL STEEL MESH FABRIC

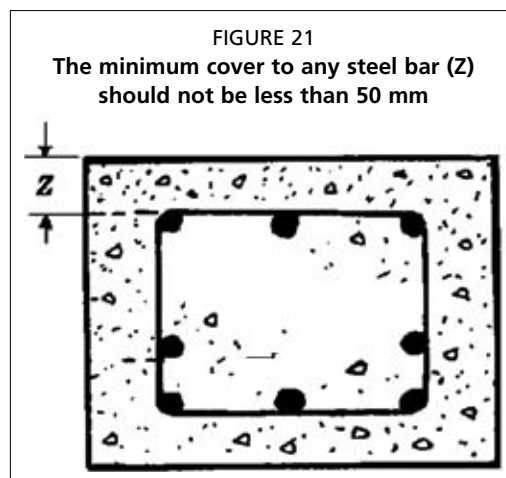
TYPE OF MESH	NOMINAL PITCH IN mm		BAR SIZE IN mm		STEEL AREA IN mm ²		WEIGHT Kg/m ²
	MAIN	CROSS	MAIN	CROSS	MAIN	CROSS	
STRUCTURAL	100	200	12	8	1131	252	10.90
STRUCTURAL	100	200	10	8	785	252	8.14
STRUCTURAL	100	200	8	8	503	252	5.93
STRUCTURAL	100	200	6	7	283	193	3.73
STRUCTURAL	100	200	5	7	196	193	3.05



When exposed to a marine environment, the steel bars inside the concrete may corrode if:

- The concrete is of poor quality (porous) and not very dense.
- The concrete cover to the steel bars is too small, allowing salt to reach the steel.
- The concrete (aggregates or mixing water) contains too much salt.

Assuming that the concrete has been manufactured to the right standard (i.e. good quality, dense and salt-free), the minimum cover to the steel should not be less than 50 mm as shown in Figure 21.



9.7.7 Placing, vibrating and curing

Placing, vibrating and curing complete the cycle of concrete construction. The formwork should be sturdy and properly anchored to prevent it from moving during the placing of concrete. It should be free of dust or organic matter (vegetation, cigarette butts, timber) and it should be properly oiled on the inside with an appropriate, water-based formwork release agent. **Diesel is not suitable for this purpose and should not be used.** The steel should be kept clean and free of oil-based compounds, such as diesel and oil. The reinforcement should be tied firmly to the sides of the formwork and workers should not be allowed to walk over it. Suitable planks should be provided across the formwork for this purpose. Concrete should not be dropped from a height exceeding 1.50 metres as this will lead to segregation of the aggregate and, if reinforcement is present, it may push the steel bars out of position. When concrete has to be placed underwater, a tremie pipe should be used, Figure 22 (left). The concrete should be made richer (cement content increased by about 25 percent from the standard nominal mix) and slightly wetter as no vibration of the concrete is allowed underwater. The flexible pipe should be raised along with the pour until the concrete breaks the surface of the water. Concrete should never be tipped into water, Figure 22 (right), as this will cause the cement to wash out. If a concrete pump is available, concrete may be pumped directly underwater.

The process of compacting the concrete consists essentially of the elimination of entrapped air bubbles. The use of vibration as a means of compaction makes it possible to use drier mixes than can be compacted by hand. Of the several types of vibrators,

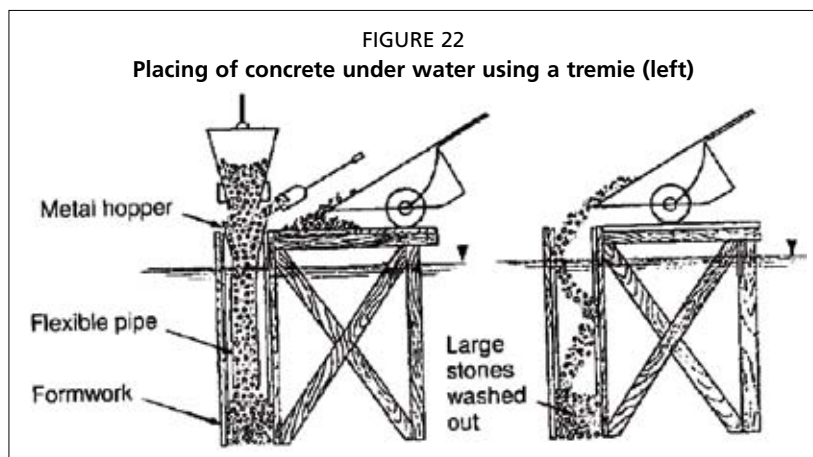
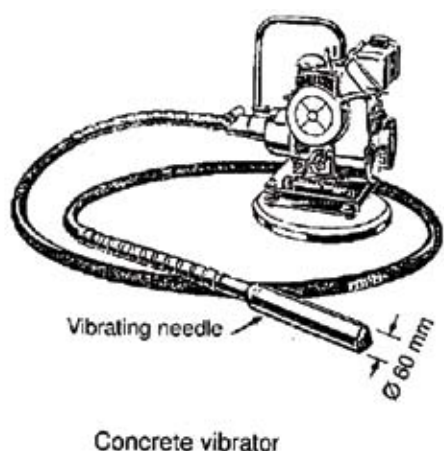


FIGURE 23
Petrol-driven poker vibrator with a
60-mm diameter poker



the poker vibrator, illustrated in Figure 23, is perhaps the most common one in use.

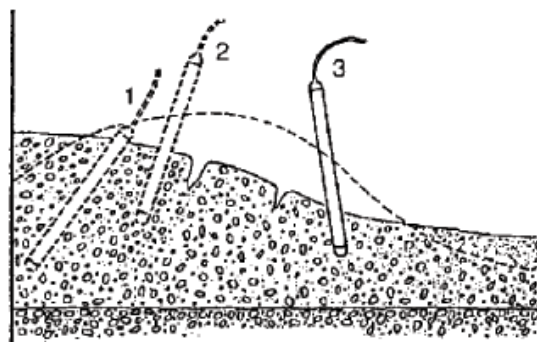
It consists essentially of a poker, housing an eccentric shaft driven through a flexible drive by a small petrol-driven engine. The frequency of vibration varies up to 12 000 cycles per minute, whereas 3 500 to 5 000 is considered as desirable minimum. The poker is easily moved from place to place, and should be applied every half a metre. The poker should be withdrawn from the concrete very gradually and in fresh layers of concrete not exceeding 300 mm in thickness. To achieve the best results it should be worked into the concrete at regular intervals in an orderly fashion, as illustrated in Figure 24. The actual completion of compaction can be judged

by the appearance of the surface of the concrete, which should neither be honeycombed nor contain an excess of mortar, which is generally due to overvibration. For heavily reinforced sections, a 50 mm to 60 mm diameter poker should be used. Mass concrete pours, such as quay wall blocks, should be vibrated with pokers at least 80 mm in diameter.

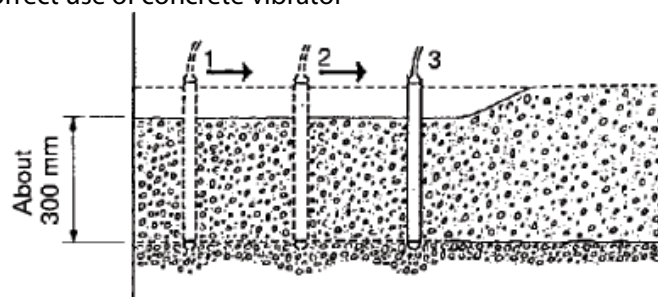
In order to obtain good concrete, the placing of an appropriate mix must be followed by curing during the early stages of hardening. Curing is the name given to procedures used for promoting the hydration of cement, and consists of a control of temperature

FIGURE 24
The correct way of using a poker vibrator to compact fresh concrete

Incorrect use of concrete vibrator



Correct use of concrete vibrator



and of the moisture movement from and into the concrete. Specifically, the object of curing is to keep concrete saturated with water until the original water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of the cement. The necessity for curing arises from the fact that the hydration of cement can take place only in water-filled capillaries. This is why a loss of water by evaporation from the capillaries must be prevented at all costs. Furthermore, water lost internally by self-desiccation (hydration of cement releases a lot of heat which in turn increases the rate of desiccation of the fresh concrete) has to be replaced by water from outside. Loss of water from the surface of freshly-poured concrete depends on:

- the ambient temperature (the higher the temperature, the greater the evaporation);
- the relative humidity (the drier the air, the faster the water evaporation);
- the wind speed (fast moving wind dries the surface very rapidly); and
- the speed at which the formwork is removed (early removal increases the exposed surface area).

Depending on the shape of the cast, curing may be achieved in a number of ways, such as:

- by flooding (suitable for large areas such as paving slabs, which can be flooded by surrounding them with an impermeable bund);
- by spraying or misting (requires a fine-mist sprinkler system and a good supply of freshwater);
- by covering the cast concrete, with damp hessian or plastic sheeting; and
- by impermeable curing membrane, a rubber latex emulsion sprayed over the cast. The membrane, provided it is not punctured or damaged, will effectively prevent evaporation of water from the concrete but will not allow ingress of water to replenish that lost by self-desiccation.

The period of curing cannot be prescribed by theory but it is usual to specify a minimum of seven days. The formwork should not be removed until at least 24 hours have elapsed since the casting operation and only if measures are taken immediately to establish a curing regime.

9.7.8 Admixtures

Nowadays, instead of using special cement, it is possible to change some of the properties of the cement in a mix by the use of a suitable additive. A vast range of proprietary products is available and these fall into three major groups:

- accelerators (they accelerate the setting of the concrete);
- retarders (they slow down the setting of the concrete); and
- water-reducers (they decrease the amount of mixing water, thereby increasing the strength of the concrete by virtue of lowering the W/C ratio).

There are other, less commonly used admixtures, such as air-entraining and water-proofing agents. An important feature of the majority of admixtures for concrete is that they are used primarily on the basis of experience or ad hoc tests: this is largely due to the marketing of admixtures as proprietary products.

9.7.8.1 Accelerators

The addition of calcium chloride to a concrete mix increases the rate of development of strength, and this accelerator is, therefore, sometimes used when the concrete needs to be “hardened” quickly, such as when concrete has to be placed underwater. Calcium chloride increases the rate of heat liberation during the first hours of mixing, but the normal process of hydration of cement is not changed. A calcium chloride content in

a mix of 1 percent of the cement by weight (i.e. 0.50 kilogram per 50-kilogram bag) is generally sufficient for most purposes. Using commercially available calcium chloride flakes, the admixture should be prepared in a concentrated aqueous solution and added to the concrete in the mixer. Calcium chloride must not be used in reinforced concrete as this will increase the risk of corrosion of the steel from the chloride ions. Chloride-free proprietary formulations also exist for use with reinforced concrete.

9.7.8.2 Retarders

A delay in the setting time of the cement paste can be achieved by the addition to the mix of a retarding admixture. These admixtures slow down also the hardening of the concrete. Retarders do not alter the composition of the products of hydration. Retarders are useful in concreting in hot weather, when the normal setting time is usually shortened by the high ambient temperatures. Retarding action is exhibited by sugar, carbohydrate derivatives, soluble zinc salts, soluble borates and others. Great care is necessary in using retarders as in incorrect quantities they can totally inhibit the setting and hardening of concrete. Sugar content in a mix of 0.05 percent of the cement by weight (i.e. 0.025 kilogram or 25 grams per 50-kilogram bag) is sufficient to delay setting by about four hours. In important concrete work, the performance of sugar as a retarder should be determined by trial experiments with the actual cement which is to be used in construction. Sugar may also be used to advantage in the event of a mixer breaking down; a 1 percent addition by weight of cement will “kill” the mix inside the drum, allowing repairs to be carried out without the risk of seizure.

9.7.8.3 Water-reducers

As their name implies, these admixtures allow concrete to be mixed with less water, thereby decreasing the W/C ratio. The reduction in quantity of the mixing water that can be achieved varies between 5 and 15 percent. A part of this is in many cases due to the entrained air introduced by the admixture. The actual decrease in the mixing water depends on the cement content and the type of aggregate used. Lignosulphonic acids and their salts are water-reducing admixtures only; hydroxylated carboxylic acids and their salts are water reducing and set retarders at the same time.

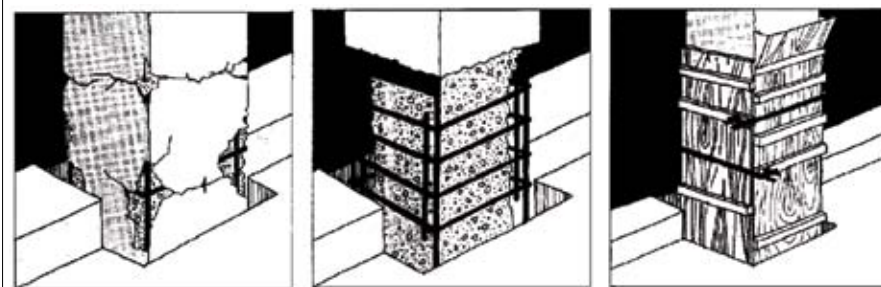
High-range water reducers are a modern type of water-reducing admixture and commonly known as a superplasticizer. Chemically, they are sulphonated naphthalene formaldehyde condensates, and at a given W/C ratio they typically increase the slump from 75 mm to 200 mm without compromising the cohesiveness of the mix. The plasticizing action of superplasticizers only lasts about 10 minutes: after about 30 to 90 minutes the workability returns to normal.

9.7.9 Polymer-modified cement mortars

Polymer-modified cement mortars are special proprietary formulations for the repair of spalled concrete. These cement mortars are generally supplied as a one-pack or a two-pack product. This type of mortar has increased mechanical strength, is very resistant to abrasion and chemical attack, and does not shrink during setting, making it ideal for repairing reinforced concrete. Its adhesive properties to old concrete are superior to those of a normal sand-cement mortar.

Spalled sections of a reinforced concrete member should be thoroughly cleaned of any residual cracked concrete, Figure 25 (middle), a tight-fitting formwork applied to the damaged sections and the cement mortar poured in from the top. Certain cement mortars are very stiff, in which case they need to be applied with a trowel.

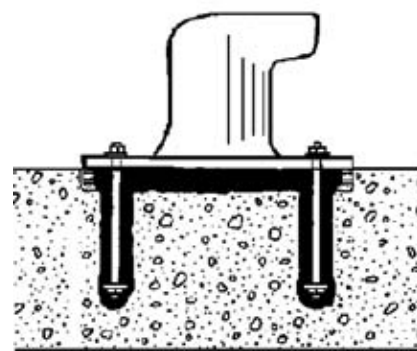
FIGURE 25
Repair of damaged or spalled reinforced concrete using
polymer-modified cement mortar



9.7.10 Non-shrink grouts

Non-shrink grouts are generally used for grouting in of anchor bolts and bearing plates, such as bollards, as illustrated in Figure 26. These grouts actually expand on setting and provide a very good mechanical bond with the base concrete. They are free-flowing (pourable), harden very rapidly, and can reach strengths of the order of 60 N/mm². They are all sold as proprietary products and generally come prebatched in 25-kilogram waterproof bags, needing only mixing water.

FIGURE 26
Grouting of bollards



9.7.11 Epoxy flooring compounds

An exposed concrete finish is not suitable as a floor inside “wet” fish markets and fish processing halls in general for the following reasons:

- Some fish oils attack concrete and lead to pitting in the surface texture of a concrete floor, Figure 27.
- Concrete is not waterproof and as blood soaks in it gives rise to bad odours.
- A concrete floor has to be laid in bays or sections to prevent it from cracking due to shrinkage; the resulting joints are difficult to clean and generally harbour bacteria.

FIGURE 27
Pitted concrete floor inside a wet fish market



Current food hygiene legislation in many countries stipulates that the floor finish in such cases should be:

- resistant to chemical attack, including the bleaching agents used to disinfect the premises;
- waterproof; and
- of seamless construction.

The only floor finish (the base is still concrete, in the form of a slab 200 mm to 250 mm thick) that satisfies the above requisites is that made from solvent-free epoxy resins. Typically, epoxy-resin flooring compounds are self-levelling and available in two-pack or three-pack form and come in grey, green, red and yellow pigment. Epoxy-resin flooring compounds are very strong and durable; after 14 days the compressive strength typically reaches values in the region of 80 N/mm² and their bond to the underlying concrete is superior to that of concrete over concrete. The components are usually mixed just prior to use (the pot life being in the region of 30 minutes depending on the ambient temperature) and applied by roller or trowel in a thickness not exceeding 3 mm to 4 mm. The finish may be rendered non-skid or non-slip by the application of a second roller just before the final setting takes place and has excellent resistance to abrasion. Ideally, epoxy-resin floor finishes should be applied to newly-laid concrete floor slabs. In the event that the epoxy floor needs to be retrofitted to a floor inside an existing market, and assuming that the concrete floor slab is still homogenous, the existing floor must first be “scabbed” (the upper 15 mm to 20 mm of the existing concrete removed by grit blasting to expose a fresh concrete surface) and a suitable solvent-free epoxy primer applied prior to the flooring compound. All epoxy flooring compounds are marketed as proprietary products and specifications vary from one manufacturer to the other.

9.7.12 Epoxy concrete coatings

Epoxy concrete coatings are specifically designed to prolong the life of reinforced concrete sections exposed to a harsh marine environment by rendering the surface waterproof. Most coatings are two-pack, water-based epoxy paints, which may be applied by brush, roller or airless spray. Both grey and colourless paints are available. These coatings may be applied to either dry or damp concrete surfaces in two to three separate coats. All coatings in this category are marketed as proprietary products.

9.7.13 Bituminous coatings

When the concrete surface to be waterproofed is not visible to the eye (such as the underside of a piled jetty, concrete piles, the inside of a concrete potable water tank, etc.) and not exposed to direct sunlight (i.e. ultraviolet radiation), bitumen provides the most cost-effective surface-sealing treatment. Prior to treatment, concrete surfaces must be thoroughly dry and free of dust particles. Bituminous coatings may be applied by brush, roller or airless spray. These coatings are suitable for waterproofing surfaces that come in contact with potable water, such as water reservoirs. Sunlight degrades bitumen.

9.7.14 Site practice and safety

Careful housekeeping on site ensures that all building materials remain suitable for construction purposes. In particular:

- Building materials should not be stored in areas subject to flooding.
- Some materials must not be exposed to direct sunlight.
- Cement should be purchased sealed in good quality bags; punctured bags should not be accepted.
- Cement should not be stored on site for more than six weeks.

- Cement should be stored indoors, 150 mm off the ground; if stored outside, it should be covered with plastic sheeting with plenty of space for air to circulate.
- Steel bars should not be stored in contact with the ground.
- Aggregates should be shaded from direct sunlight with netting or plastic sheets to keep them cool.
- If rain is forecast for the day, concreting should be postponed.
- Concreting should be avoided during hours of peak temperatures; early morning is ideal.

Although concrete mixing may be considered by some as a hazard-free activity, safety on site is in fact quite a serious matter. Cement, concrete, concreting and the various epoxy formulations in use nowadays do present a hazard to human health; for example:

- Airborne cement powder is toxic to human health.
- Skin bleeds when it comes into contact with cement and fresh concrete.
- Most epoxy formulations are toxic to human skin.

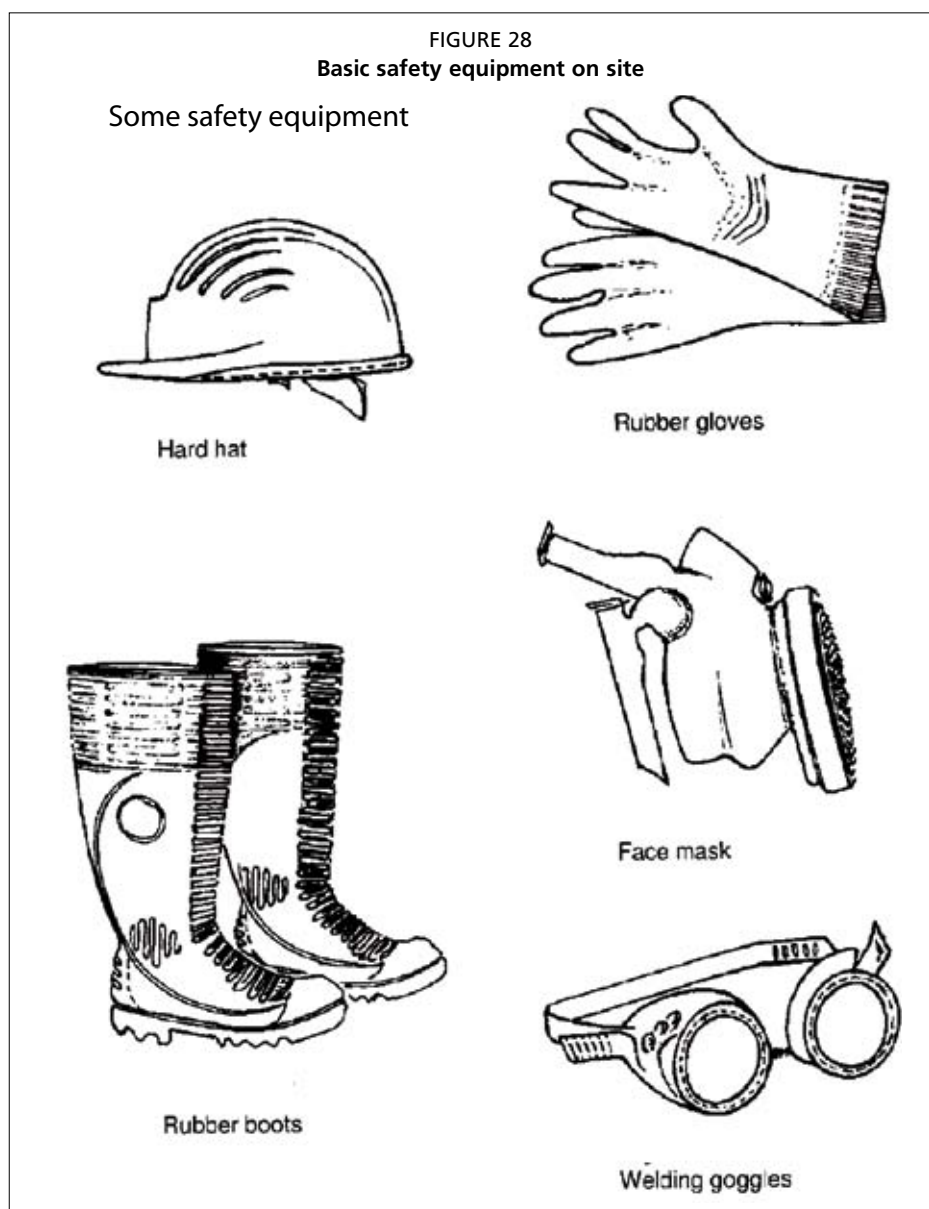


Figure 28 shows basic safety equipment to be used on site. In particular, persons handling cement (breaking bags and pouring out the contents into the mixer) should always wear goggles, a proper face mask, gloves and boots. People handling concrete should wear gloves and boots. Everybody on site should wear a safety helmet.

9.8 ROCK

9.8.1 Introduction

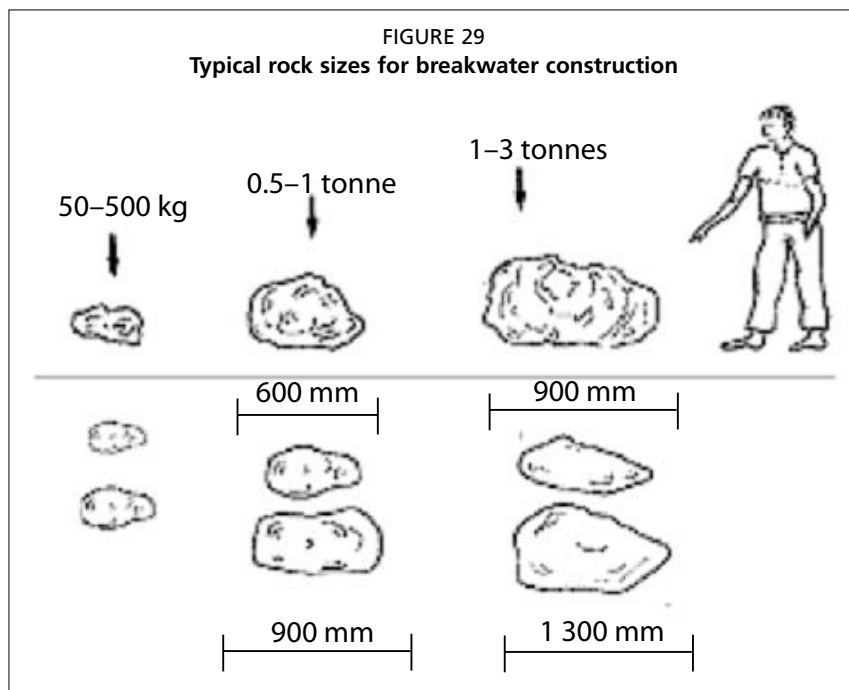
Stone for coastal structures should be sound, durable and hard. It should be free from laminations and weak cleavages, and should be of such character that it will not disintegrate from the action of air, seawater and undesirable weathering, or from handling and placing. In general, stone with a high specific gravity should be used to decrease the volume of material required in the structure and to increase the resistance to movement by the action of waves or currents. Characteristics that affect the durability of stone are texture, structure, mineral composition, hardness, toughness, and resistance to disintegration on exposure to wetting and drying and to freezing and thawing. Ordinarily, the most durable stone is one that is dense or fine textured, hard and tough, but exceptions to this general rule occur. The character of the stone for any project depends on what is available, and often the choice of material involves weighing the relative economy of using a local stone of lower quality against using a better quality stone from a distance.

Where the local stone is markedly inferior, the greater cost of transporting durable, high-quality stone from outside the immediate area may be justified and advisable.

9.8.2 Quarries

Rock is generally obtained from quarries but quarries do not normally supply rock in the sizes required for the construction of breakwaters, Figure 29.

This is generally due to the fact that blasting systems, drilling patterns and equipment are tailored to produce only small-size aggregates for concrete or road construction. Retooling a quarry to produce breakwater-type rock sizes is very expensive and should only be carried out if the potential yield of the quarry is deemed sufficient for the purpose; experienced geologists should be called in to carry out such investigations.

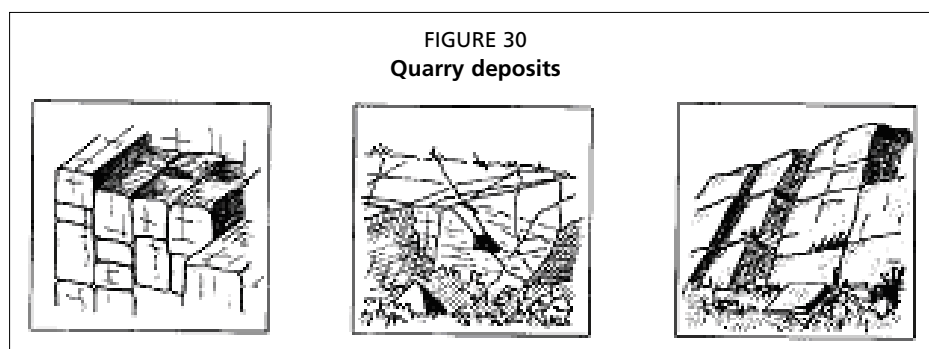


The potential yield in terms of breakwater-sized rock of a quarry depends almost entirely on the geological formation and the natural bedding of the deposits.

Figure 30 illustrates some commonly encountered geological formations or rock outcrops. The left figure illustrates regular block formation, heavily fractured, producing regular sizes of rock. The middle figure illustrates an irregular outcrop and the right figure shows heavily bedded layers that produce tabular rocks. Therefore, prior to constructing a rubble breakwater it is necessary to:

- Collect or obtain information on the geological formation of the quarry site, including faults, natural bedding of layers, etc., Figure 30;
- Obtain details of the vertical extension of the overburden (the rock strata may be underneath a top soil, which may be fertile and cannot be discarded); and
- Carry out laboratory tests to determine the geotechnical characteristics of the rock.

In addition, the quarry must be accessible without too much investment in access roads; and have adequate storage space for stockpiling and sorting of the rock into the required sizes.



9.8.3 Geological characteristics of rock

The strength of the parent rock essentially decides the degradation mechanisms of the individual armour rock. These mechanisms may be grouped into:

- *spalling*, commonly associated with salt attack, alteration of minerals within the rock and expansion or decay of clay minerals;
- *fracture*, linked to incipient planes of weakness in the rock deposit; and
- *abrasion*, caused by adjacent stones rubbing together under wave action or by much smaller particles of sand and rock thrown against the stone during wave action.

Typical deposits suitable for the production of breakwater rock are granite, basalt, limestone, sandstone, quartzite and porphyry. In the laboratory, the geotechnical characteristics of the rock are usually defined by the parameters, shown in Table 10, details of which are found in various national standards.

It is a generally accepted fact that all marine structures will degrade with time and that only adequate monitoring during the lifetime cycle will prevent serious damage from occurring to the structure.

The evaluation of a potential stone source should consider the extent that a quarry development might detract from natural beauty and otherwise cause environmental concern during and after operation. The quarry area should be graded and landscaped as practicable to restore a natural appearance and to control erosion upon closure.

TABLE 10
Geological characteristics of rock

Property	Suggested limit
Specific gravity	2.60 minimum
Water absorption	2.50 maximum
Particle shape	Angular
Surface texture	Crystalline
Impact value % ^[1]	25 maximum
Abrasion value % ^[2]	25 maximum
Magnesium sulphate	
Soundness test ^[3]	12 maximum

¹ Standard test for resistance to chipping from impact loads.

² Standard test for resistance to abrasion by other particles.

³ Standard chemical test for resistance to chemical alteration of the minerals.

9.9 PLASTICS, RUBBER AND BITUMINOUS COMPOUNDS

Nowadays, both plastics and rubber compounds play an ever-increasing role in marine works, typically replacing steel articles such as pipes, pipe fittings, gratings and covers.

9.9.1 Polyvinyl chloride

This material is available in two forms – plasticized or unplasticized. Both types are characterized by good weathering resistance, excellent electrical insulation properties, good surface properties and they are self-extinguishing. Plasticized PVC is flexible and finds applications in wire covering. Unplasticized PVC (uPVC) is a hard, tough material which is widely used for pipes and gutters.

PVC has a specific gravity of 1.38 to 1.45 and a surface hardness (Shore D) of 70 to 90, equivalent to that of aluminium.

9.9.2 Polypropylene

Polypropylene is an extremely versatile plastic and is available in many grades and also as a copolymer (ethylene/propylene). It has the lowest density of all thermoplastics (plastics that deform with an increase in temperature) in the order of 900 kg/m³ and this combined with strength, stiffness and excellent fatigue and chemical resistance make it attractive in many situations. Current uses of this plastic is in making fish boxes and fibre ropes.

9.9.3 Polycarbonates

The outstanding feature of these materials is their extreme toughness. They are transparent and have good temperature resistance but are attacked by alkaline solutions and hydrocarbon solvents. Typical applications include “vandal-proof” street lamp covers and lenses in marine lanterns.

9.9.4 Low-density polyethylene

Low-density polyethylene (LDPE) is one of the most widely used plastics. It is characterized by a density in the range 918 to 935 kg/m³ and is very tough and flexible. Major applications include pipes and cold water tanks.

9.9.5 High-density polyethylene

High-density polyethylene (HDPE) has a density in the range 935 to 965 kg/m³ and is more crystalline than LDPE. It has a surface hardness (Shore D) of 63. It is slightly more expensive than LDPE but it is much stronger and stiffer and applications include waste bins and pipes.

9.9.6 Polyurethane

This material is available in three forms: rigid foam, flexible foam and elastomer. They have high strength and good chemical and abrasion resistance. Foams find applications in insulation and elastomers in solid tyres.

9.9.7 Polyesters

The main application of this material is as a matrix for glass fibre reinforcement. The fibres (E-glass) are generally calcium aluminium borosilicate with a specific gravity of 2.05.

9.9.8 Rubber

Rubber is a unique engineering material possessing an ability to deform elastically by several hundred percent without failure. Raw rubber would in most cases be relatively unstable, so for engineering applications it is generally cross linked or vulcanized with a chemical such as sulphur. Rubber components are thus normally manufactured by means of a cure process in a metal mould. Most types of rubber used in engineering also incorporate at least one type of filler, such as carbon black or soot. Fillers generally reinforce rubber, improving its resistance to tear, abrasion.

The life and performance of a rubber component may be strongly influenced by its service environment (sunlight, weathering, ozone cracking), which can cause changes in stiffness and surface texture. Normally, effective protection against sunlight is given by the carbon black filler incorporated in the rubber; this acts by filtering out the ultraviolet radiation. If rubbers are not protected by the incorporation of appropriate antioxidants and antiozonants, then atmospheric ozone, sunlight and oxygen can damage rubber.

Nitrile rubber has the best resistance to petroleum products and is generally used for refuelling hoses. Neoprene rubber is used in the form of pads under precast concrete structural elements such as beams, lintels or roofing slabs to avoid concrete-to-concrete abrasion.

9.9.9 Bituminous compounds

All bituminous materials are for the most part used in mixtures with aggregates as binders. Binders all have certain valuable properties in common: they are water-resistant, have good adhesive properties and can withstand ordinary weathering. All binders, whether tars or bitumen, are exceedingly complex materials chemically. Different tars and bitumens have been characterized by separating them into fractions according to their solubility in a series of solvents of increasing dispersing power.

- *Tars* are obtained from the destructive distillation of coal or shale, where for engineering purposes all the lighter oils are distilled off leaving a hard, semi-solid residual material – pitch. Pitch is in itself too hard and viscous to use so lighter oils are fluxed back into the pitch to produce tar.
- *Bitumens* are obtained by the fractional distillation of petroleum (crude oil). In some cases this process occurs naturally, producing rock or lake asphalt, but the bulk of the world's bitumen is produced by refining crude oil. Chemically, bitumens are similar to tar and are also highly resistant to weathering agents.
- *Cutbacks* are mixtures of binders with light volatile oils, the resultant mixture having a much lower viscosity than the original binder, allowing various handling operations to be carried out at a much lower temperature than would otherwise be the case.
- *Emulsions* are mixtures of bituminous binders and water in a dispersant. The dispersant may consist of sodium stearate, soap or trimethyl-ammonium bromide.

- *Rubberized* binders consist of unvulcanized rubber powder, 0.50 to 5.0 percent, dispersed in bitumen. Rubberized bitumens are less susceptible to temperature changes and are more elastic.
- *Trinidad Lake Asphalt* is a natural asphalt. This asphalt has superior drying properties to those of refinery bitumens but is considerably more expensive.

The very term binder used to describe bituminous materials suggests an ability to act as adhesive and “bind” other materials together. As with all adhesives when tars or bitumens are used it is important that the materials to be bound together by these binders should be clean, dry and free from dust. If, for example, in coating stones for road mixes the binder is too thick or viscous, then it will not “wet” or coat the stone efficiently. If the stone is dusty, then the binder may not reach the stone surface. If there is water on the stone, then the binder will not adhere to the stone. Bituminous materials are used in engineering in a wide variety of consistencies or viscosity. For practical purposes, the viscosity may be measured empirically and expressed in terms of a simple unit, usually either seconds or degrees Celsius, when the liquid has been tested in a standard apparatus under specific standard conditions.

The standard test for ordinary bitumens is the penetration test. In this test a loaded needle is allowed to penetrate a sample of bitumen; the viscosity is then a measure of the depth of penetration at that temperature and under those loading conditions.

For normal test conditions in the penetration test, a 1 mm diameter needle is used, ground to a sharp point and loaded with 100 grams. The needle just touches the surface of the bitumen sample at the start and is allowed to fall under gravity for five seconds, the ambient test temperature being 25 °C. The penetration is measured in tenths of a millimetre.

If a bitumen is referred to as 70 pen, it is understood that a penetration of 70 tenths of a millimetre was obtained under the above conditions.

At ordinary temperatures most binders are much too stiff and hard to handle. In order that they may be sprayed, pumped and mixed, or compacted in a stone-binder mixture, their viscosity must be greatly reduced.

9.10 BIBLIOGRAPHY AND FURTHER READING

- Dinwoodie J.M.** 1981. *Timber: Its nature and behaviour*. New York, Van Nostrand Reinhold.
- Hornsby M.J.** 1995. *Hot-dip galvanizing: A guide to process selection and galvanizing practise*. London, Intermediate Technology Publications.
- Jackson N.** 1981. *Civil engineering materials*. UK, Macmillan Press Ltd.
- Moffat & Nichol Engineers.** 1983. *Construction Materials for Coastal Structures*. Virginia, USA, US Army Corps of Engineers Coastal Engineering Research Center.
- Neville A.M.** 1981. *Properties of concrete*. UK, Longman Scientific & Technical.

