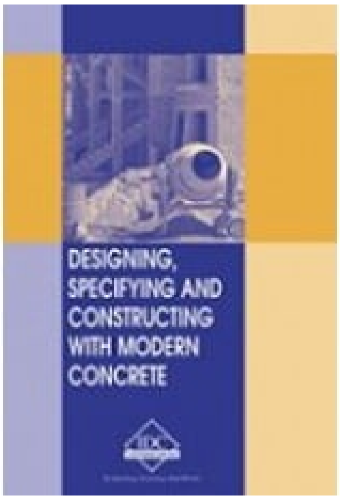
CT-E - Designing, Specifying and Constructing with Modern Concrete



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Short Description

This manual deals with the manufacture, design and maintenance of concrete, including details about ingredients and how quality and quantity affects the final product. Other areas covered are: concrete specifications standards and codes concepts such as ready-mix, precast and prestressed concrete and their applications suggestions for best practice for protection and maintenance of concrete.

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First Chapter

Understanding Concrete

1 Understanding Concrete

Concrete is everywhere! In pavements, building structures, foundations, motorways/roads, overpasses, parking structures, brick/block walls and bases for gates, fences poles and many more. Concrete is used more than any other man-made material on the planet. It has been said that instead of naming our era "The nuclear age" it should be named "The Concrete Age" as almost all of our modern lifestyle and constructions depend on this material.

Learning objectives

- Understand what is concrete and how it works
- Study the basic chemistry of concrete
- Analyze the strengths and weaknesses of concrete
- Study the extreme weather concreting
- Analyze of cracks are developed in concrete and how they can be avoided
- Learn the precautions to be taken while working with concrete

1. Introduction

Concrete has many properties that make it a popular construction material. The correct proportion of ingredients, placement, and curing are needed in order for these properties to be optimal.

As of 2005 over six billion tons of concrete are made each year. It powers a US$35 billion industry which employs over two million workers in the United States alone. Over 55,000 miles of freeways and highways in America are made of this material. China currently consumes 40% of world cement production.

Concrete is not found in nature the way we would find oil, gold or iron. Concrete is formed from combining water, a special cement and formations of rock:

PORTLAND CEMENT + H_2O + ROCK = HARDENED CONCRETE + ENERGY (HEAT)

A common mistake people make is to use the words cement and concrete interchangeably. It is important to remember that cement is only a component of concrete and concrete is the structural material. The cement used in concrete is not used as a building material because it would be too expensive and not as strong as concrete. Cement is a general name for a material that binds other materials together. Yes, one of the main uses of cement in concrete is just to act as glue.

Sometimes concrete is also confused with cement paste or mortar.

Cement Paste = Cement + water –

It is used for filling cracks or can be applied to prepare a clean and leveled surface.

Mortar = Cement + Sand + water (and possibly other additives)

It is used to build brickwork or blockwork. It can also be applied as a screed or a render, screed is a mortar applied to a floor, render is a mortar applied to a wall. Plastering is also one of the important uses of the mortar.

1. What is concrete?

As mentioned above, concrete is a composite building material made from the combination of aggregate and cement binder. About 70 to 75% of the volume of the concrete is occupied by aggregates, which gives strength to concrete. The voids between aggregates are filled by sand, similarly the voids between sand are filled by the finer material i.e. cement. Contrary to common belief, concrete does not solidify from drying after mixing and placement. Instead, the cement hydrates, gluing the other components together and eventually creating a stone-like material, which is called concrete. Figure 1.1 shows the ingredients of concrete.

Figure 1.1

Ingredients of concrete

1. Concrete as a structural material

These days there are two commonly used structural materials:

- concrete
- steel

Steel is manufactured under carefully controlled circumstances; in highly sophisticated plants. Every property and each and every type of steel is determined in laboratory and specified in the manufacturer's certificate. On the other hand, the situation for concrete is totally different. Even though the quality of cement is guaranteed as it is manufactured in the factory, there are quite a few other factors which influence the quality of concrete. Cement is to concrete what flour is to a cake, the quality of cake depends on other ingredients and cook also.

Maintaining quality and quantity of other concrete ingredients like aggregates, sand, even water is important. The mixing, transporting, compacting processes make significant impact on the final product. The labor needs to properly trained to prepare good quality on site concrete.

Advantages of concrete over other construction materials-

A good quality concrete has many advantages that add to its popularity. Few of them are enlisted below-

- It is economical when ingredients are readily available.
- Concrete has long life
- Relatively low maintenance requirements increase its economic benefits.
- Concrete is not as likely to rot, corrode, or decay as other building materials.
- High fire resistance
- Concrete has the ability to be molded or cast into almost any desired shape. Building of the molds and casting can occur on the work-site which reduces costs.
- Concrete is a non-combustible material which makes it fire-safe and able withstand high temperatures. It is resistant to wind, water, rodents, and insects. Hence, concrete is often used for storm shelters.

Concrete does have some limitations despite its numerous advantages. Concrete has a relatively low tensile strength, compared to other building materials, low ductility, low strength-to-weight ratio, and is susceptible to cracking. it remains the material of choice for many applications regardless of these limitations.

1. History of concrete

Ancient Romans were probably the first ones to use concrete. Cement has been around for almost last 12 million years. It was the natural cement that was used first as the binding material. The word ‘hydraulic cement’ has a Latin origin, that is a material which hardens under water. The major milestones in the development of concrete are listed in Table 1.1 below.

Table 1.1

History of Concrete

Time	**Development**

12,000,000 BC	Reactions between limestone and oil shale during spontaneous combustion occurred in Israel to form a natural deposit of cement compounds. The deposits were characterized by Israeli geologists in the 1960's and 70's.
3000 BC Egyptians	Used mud mixed with straw to bind dried bricks. They also used mortars of gypsum and lime in the pyramids.
Chinese	Used cementitious materials to hold bamboo together in their boats and in the Great Wall.
300 BC Babylonians & As Syrians	Used bitumen to bind stones and bricks.
300 BC - 476 AD Romans	Used pozzolana cement from Pozzuoli, Italy near Mt. Vesuvius to build the Appian Way, Roman baths, the Coliseum and Pantheon in Rome, and the Pont du Gard aqueduct in south France. They used lime as a cementitious material. *These structures still exist today!*
1200 - 1500 The Middle Ages	The quality of cementing materials deteriorated. The use of burning lime and pazzolana (admixture) was lost, but reintroduced in the 1300's.
1678	Joseph Moxon wrote about a hidden fire in heated lime that appears upon the addition of water.
1779	Bry Higgins was issued a patent for hydraulic cement (stucco) for exterior plastering use.
1796	James Parker from England patented a natural hydraulic cement by calcining nodules of impure limestone containing clay, called Parker's Cement or Roman Cement.
1802	In France, a similar Roman Cement process was used.
1810	Edgar Dobbs received a patent for hydraulic mortars, stucco, and plaster, although they were of poor quality due to lack of kiln precautions.
1818	Maurice St. Leger was issued patents for hydraulic cement. Natural Cement was produced in the USA. Natural cement is limestone that naturally has the appropriate amounts of clay to make the same type of concrete as John Smeaton discovered.
1824	Joseph Aspdin of England invented Portland cement by burning finely ground chalk with finely divided clay in a lime kiln until carbon dioxide was driven off. The sintered product was then ground and he called it portland cement named after the high quality building

	stones quarried at Portland, England.
1867	Joseph Monier of France reinforced William Wand's (USA) flower pots with wire ushering in the idea of iron reinforcing bars (re-bar).
1889	The first concrete reinforced bridge is built.
1891	George Bartholomew placed the first concrete street in the USA in Bellefontaine. *It still exists today!*
1903	The first concrete high rise was built in Cincinnati, OH.
1908	Thomas Edison built cheap, cozy concrete houses in Union, NJ. *They still exist today!*
1936	The first major concrete dams, Hoover Dam and Grand Coulee Dam, were built. *They still exist today!*
1967	First concrete domed sport structure, the Assembly Hall, was constructed at The University of Illinois, at Urbana-Champaign.
1970's	Fiber reinforcement in concrete was introduced.
1980's	Superplasticizers were introduced as admixtures.
1985	Silica fume was introduced as a pozzolanic additive.
	The "highest strength" concrete was used in building the Union Plaza constructed in Seattle, Washington.
1992	The tallest reinforced concrete building in the world was constructed at 311 S. Wacker Dr., Chicago, Illinois.

1. Ingredients of concrete

Water

Water is the key ingredient of concrete. When it is mixed with cement, it forms a paste that binds the aggregate together. Both quality and quantity of water which is added in concrete play important role in deciding the properties of concrete.

The quality of water is important because impurities in it may interfere with setting of cement and many affect the strength of concrete. Usually the potable water, i.e the water which considered as safe for drinking purpose is considered as good for mixing in concrete. As a rule, the water which has pH between 6.0 to 8.0, which does not test saline or brackish can be considered as safe for concrete. Experiments were made on using the sea water for concrete. Sea water usually contains about 3.5% total salinity. Such water leads to slightly higher early strength but lower long term strength. Loss of the long term strength is usually not more than 15%.

The water causes the hardening of concrete through a process called hydration. Hydration is a chemical reaction in which, the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products. The water needs to be pure, typically drinkable, in order to prevent side reactions from occurring which may weaken the concrete or otherwise interfere with the hydration process.

Not only quality but quantity of water, which is added in the concrete also plays important role. The role of water is important because the water to cement ratio is the most critical factor in the production of "perfect" concrete. Too much water reduces concrete strength, while too little will make the concrete unworkable. Concrete needs to be workable that it may be consolidated and shaped into different forms (i.e. walls, domes, etc.). Because concrete must be both strong and workable, a careful balance of the cement to water ratio is required when making concrete.

Aggregates

Approximately 75% of the volume of concrete is occupied by aggregates, so quality of aggregates plays an important role in determining properties of concrete. Aggregates are chemically inert, solid bodies held together by the cement. Aggregates come in various shapes, sizes, and materials ranging from fine particles of sand to large, coarse rocks. Natural aggregates are formed by process of weathering and abrasion or by artificially crushing large parent mass.

Because cement is the most expensive ingredient in making concrete, it is desirable to minimize the amount of cement used. 70 to 80% of the volume of concrete is aggregate in order to keep the cost of the concrete low. The selection of an aggregate is determined, in part, by the desired characteristics of the concrete. For example, the density of concrete is determined by the density of the aggregate. Soft, porous aggregates can result in weak concrete with low wear resistance, while using hard aggregates can make strong concrete with a high resistance to abrasion. Aggregates are of two basic types:

- Corse: crushed rock, gravel or screenings.
- Fine: fine and coarse sands and crusher fines

Aggregates should be clean, hard, and strong. The aggregate is usually washed to remove any dust, silt, clay, organic matter, or other impurities that would interfere with the bonding reaction with the cement paste. It is then separated into various sizes by passing the material through a series of screens with different size openings. The final properties of the concrete will depend on the cement characteristics, the type and amount of aggregate, the water-cement ratio, and the completeness of the reaction subject to time, humidity, and temperature.

Examples of classes of concrete aggregate are shown in Table 1.2

Table 1.2

Types of Aggregates

Class	**Uses**	**Examples**
ultra-lightweight	Lightweight concrete which can be sawed or nailed, also for its insulating properties	Vermiculite ceramic spheres
lightweight	used primarily for making lightweight concrete for structures, also used for its insulating properties.	expanded clay shale or slate crushed brick
normal weight	used for normal concrete projects	crushed limestone sanc river gravel crushed recycled concrete
heavyweight	used for making high density concrete for shielding against nuclear radiation	steel or iron shot steel c iron pellets

The choice of aggregate is determined by the proposed use of the concrete. Normally sand, gravel, and crushed stone are used as aggregates to make concrete. The aggregate should be well-graded to improve packing efficiency and minimize the amount of cement paste needed. Also, this makes the concrete more workable. Some of the important properties of aggregates are discussed below.

Moisture Content

Aggregate can contain water, both internal, based on porosity, and external, surface moisture. This gives aggregate the ability to absorb water. This will effectively reduce the amount of water available for hydration; or conversely, if the aggregate is very wet, add excess water to a cement mix. There are four moisture states:

- **Oven-dry (OD)**; all moisture removed.
- **Air-dry (AD)**; surface moisture removed, internal pores partially full
- **Saturated-surface-dry (SSD)**; surface moisture removed, all internal pores full.
- **Wet**; pores full with surface film.

Of these four states, SSD, saturated-surface-dry, is considered the best reference state. It is an equilibrium state, where the aggregate will not absorb or give water to the cement paste, simulates actual field conditions more closely, and used to determine bulk specific gravity. However, this moisture state is not easy to obtain.

Absorption and Surface Moisture

To determine the amount of water an aggregate will add or subtract from a cement paste, the following three quantities are used:

- **Absorption capacity (*AC*)**- maximum amount of water the aggregate will absorb. The range for most normal-weight aggregates is 1 - 2%.

AC = (W_{SSD} – W_{OD})/ W_{OD} * 100%

- **Effective Absorption (*EA*)**- amount of water required to bring an aggregate from the AD state to the SSD state.

EA = (W_{SSD} – W_{AD})/ W_{AD} * 100%

The weight of water absorbed by the aggregate ***Wabs*** is calculated from the weigh of the aggregate ***Wagg*** in a concrete mix using effective absorption (***EA***).

W_{abs} = (EA) W_{agg}

- Surface Moisture (*SM*) - amount of water in excess of SSD

SM = (W_{wet}- W_{SSD})/ W_{SSD}) * 100%

It is used to calculate the additional water $\boldsymbol{W_{add}}$ of the concrete mix

W_{add} = (SM) W_{agg}

The moisture content (***MC***) of aggregate is given by:

MC= (W_{STOCK} – W_{SSD}/ W_{SSD}) * 100%

If the moisture content (***MC***) is positive, there is surface moisture. If the ***MC*** is negative, it has the potential for absorption. Therefore, the total moisture associated with an aggregate is:

$W_{MC} = (MC)\ W_{AGG}$

Stockpiled fine aggregate is often in a wet state with a surface moisture of 0 to 5%. More water can be held in the interspace between particles than in coarse aggregates. This also leads to thicker films of water which in turn push the aggregate apart and increase the apparent volume. This is called bulking.

Specific Gravity

A dimensionless ratio of density of the material in question to the density of water.

SG = [density of solid] / [density of water]

Absolute specific gravity (ASG) considers the weight and volume of the solid part of the aggregate. Whereas, bulk specific gravity (BSG) is a measure of the weight/volume of solids and pores of a material.

ASG > BSG*SSD* > BSG*OD*

However, since the porosity of most rocks used in concrete is 1 to 2%, the values of all specific gravities are approximately the same; in the range of 2.5 to 2.8.

Unit Weight

Unit weight (UW) or bulk density is the weight of a given volume of material. Basically, unit weight is measured by filling a container of known volume with a material and weighing it. The degree of moisture and compaction will affect the unit weight measurement. Therefore, a standard has been set for oven-dry moisture content and a rodding method for compaction. The maximum unit weight of a blend of two aggregates is about 40% fine aggregate by weight. Therefore, this is the most economical concrete aggregate since it will require the least amount of cement.

Durability of Aggregates

Aggregates makeup the largest part of concrete mixes and are responsible for the durability of the mix. Durability is a measure of how well concrete will handle freezing and thawing, wetting and drying, and physical wear. Chemical reactions also can contribute to problems with durability.

Table 1.3 enlists some important properties of aggregates.

Table 1.3

Properties of Aggregates

Property	Description
Soundness	Rocks that undergo volume changes due to wetting and drying are rare. However, aggregate is susceptible to volume change during freezing and thawing cycles. Freezing can cause internal stresses to build up as water inside the aggregate freezes and expands. A critical size can be calculated below which freeze-thaw stress is not a problem; however, for most rock it is greater than normal sizes.
Wear Resistance	A good aggregate will be hard, dense, strong, and free of porous material. The abrasion resistance of aggregate can be tested by the Los Angeles abrasion test; however, this test does not match well with concrete wear in the field.
Alkali-Aggregate Reaction	An expansive reaction between some reactive forms of silica with the aggregate and alkalis in the cement paste. The result is overall cracking in the structure, manifesting

	itself in map or pattern cracking at the surface. This reaction can be controlled most easily by using low-alkali cements. However, due to changes in manufacturing, low-alkali cements may not be feasible. A better approach is to avoid aggregate with the potential or proven record of reactivity. A low *w/c* ratio is very impermeable and will slow down the reaction but not stop it. No adverse reactions will occur without external water.
Other Alkali-Silica Reactions	Sand-gravels found in river systems of Kansas and Nebraska are highly reactive and cause map cracking. Replacement of 30% of the aggregate with crushed limestone is effective in reducing the damage. Basically, it results in the separation of flat clay minerals causing very slow expansion.
Alkali-Carbonate Reactions	An expansive reaction involving clayey carbonate rock. Reaction can be controlled by using low-alkali cements or blending aggregate with other less reactive material. ASTM has set standards for deleterious substances in aggregates, which depend on application. This can be divided into two categories:
Impurities	**Solid materials -** particles passing a 200-mesh sieve. These fine particles may increase water requirements and interfere with surface bonding between cement and coarse aggregates.
	Soluble substances - organic matter may interfere chemically with alkaline cement pastes affecting setting time. Aggregates obtained from the sea should be thoroughly cleaned to avoid problems from salt contamination.
Unsound particles	Soft particles such as clay lumps, wood, and coal will cause pitting and scaling at the surface. Organic compounds can be released which interfere with setting and hardening. Weak material of low density which have low wear resistance should also be avoided.

Special Aggregates

Aggregates are classified by their specific gravities into three categories

- **Lightweight**- A general characteristic of lightweight aggregate is high internal porosity. Most of these materials are synthetic, however, some natural materials can be treated to provide low specific gravity. Clays, shale, or slates will bloat at high temperatures resulting in an expansion in volume. Lightweight aggregates have high absorption capacity associated with their high porosity. However, some materials have a coating resulting from the fusion process and water cannot penetrate. This coating can be damaged during handling resulting in an abrupt increase in absorption.

- **Normal-weight**–

- **Heavy-weight**- A material with a high specific gravity. These types of materials are mostly used for radiation shielding and application where a high mass-to-volume ratio is required.

In addition there are aggregates required with some specific properties.

- **Abrasion and Skid-Resistant Aggregates**- Hard, dense aggregates used in heavy-industry applications where high resistance to abrasion is required. The strength of the cement paste and the cement-aggregate bond are more important than the aggregate hardness.

- **Marginal Aggregates**- Use of this type of aggregate will require more care and thought in design, and generally more cost. In considering marginal aggregates, there are four areas of interest:

    - concrete properties,
    - weaknesses of aggregate,
    - beneficiation, and
    - use of protective measures

Cement

Portland cement is the most commonly used cement for manufacturing concrete. Portland cement accounts for about 95% of the cement produced in North America. It was patented in England by Joseph Aspdin in 1824 and named after a quarried stone it resembled from the Isle of Portland.

When water is mixed with Portland cement, the product sets in a few hours and hardens over a period of weeks. The initial setting is caused by a reaction between the water, gypsum, and tricalcium aluminate (C_3A), concrete hardens at this stage and it takes a certain shape too. It becomes very difficult to change the shape after the initial setting is complete. The later hardening and the development of cohesive strength is due to the reaction of water and tricalcium silicate (C_3S), forming an amorphous hydrated product called calcium-silicate-hydrate(CSH gel). In each case the hydration products surround and cement together the individual grains. The hydration of dicalcium silicate (C_2S) proceeds slowly increasing later-age strength. All three reactions mentioned above release heat. Cement is discussed in detail in section …

- Cement should be stored off the ground in a well-aired, clean, dry place.
- Wrapping the cement bags in plastic sheets gives extra protection,
- Bulk cement will normally be stored in silos.

Admixtures

In the modern days it has become a common practice to add some chemicals to the concrete to change its properties. Admixtures are organic or non-organic materials in form of solids or fluids that are added to the concrete to give it certain characteristics. In normal use the admixtures make up less than 5% of the cement weight and are added to the concrete at the time of batching/mixing. Some of the commonly used admixtures are listed below.

- Accelerators: Speed up the hydration (strengthening) of the concrete.
- Retarders: Slow the hydration of concrete.
- Air-entrainers: Add and distributes tiny air bubbles to the concrete, which reduces damage due to freeze-thaw cycles.
- Plasticizers: Can be used to increase the workability of concrete, allowing it be placed more easily with less compactive effort. Superplasticisers allow a properly designed concrete to flow around congested reinforcing bars. Alternatively, they can be used to reduce the water content of a concrete (termed water reducers) yet maintain the original workability. This improves its strength and durability characteristics
- Pigments: Change the colour of concrete for aesthetics.

1. Types of Cement

There are various types of cement available all over the world, the basis of classification also changes from place to place and as per the requirements. In order to produce some consistent standards all over the world two institutes are working. The two major standards are:

- American ASTM C150
- European EN-197.

ASTMC 150 is basically a manual for all materials and their properties and proper uses. EN 197 cement Types CEM I, to V do not correspond to the cement types in ASTM C 150, nor can ASTM cements be substituted for EN specified cement, without the designer’s approval.

ASTM C150

There are five types of Portland cements with variations of the first three according to American Society of Testing Materials, ASTM C150. In addition, pozzolanic ash or other pozzolans are often added to cement to improve its properties and lower its cost.

Type I (Common Cement) – Any cement is assumed to be this type of cement unless another type is specified. It is commonly used for general construction especially when making precast and precast- prestressed concrete that is not to be in contact with soils or ground water. The typical compound compositions of this type are:

55% (C_3S), 19% (C_2S), 10% (C_3A), 7% (C_4AF), 2.8% MgO, 2.9% (SO_3), 1.0% Ignition loss, and 1.0% free CaO.

A limitation on the composition is that the (C_3A) shall not exceed 15%. This type is the most basic and common type of Portland cement. It is available all over the world.

Type II (Moderate Sulfate Resistance Cement) - As the name indicates this is a Portland cement with moderate sulfate resistance and with or without moderate heat of hydration. This type of cement costs about the same as Type I. Its typical compound composition is:

51% (C_3S), 24% (C_2S), 6% (C_3A), 11% (C_4AF), 2.9% MgO, 2.5% (SO_3), 0.8% Ignition loss, and 1.0% free CaO.

A limitation on the composition is that the (C_3A) shall not exceed 8% which reduces its vulnerability to sulfates. This type is for general construction that is exposed to moderate sulfate attack. This is meant for use when concrete is in contact with soils and ground water especially where there is the high sulfur content of the soil e.g in western USA.

Another limitation is the percentage of (C_3S) + (C_3A) shall not exceed 58%. The two limitations are meant to minimize cracking caused by temperature gradients.

Cement is increasingly sold as a blend of Type I/II on the world market these days.

Type III (High Early Strength Cement) - It is usually used for emergency construction and repairs and construction of machine bases and gate installations. It can also be used in concrete that comes in contact with soil and ground water. It can specifically used for constructions where early development in strength is necessary. Its typical compound composition is:

57% (C_3S), 19% (C_2S), 10% (C_3A), 7% (C_4AF), 3.0% MgO, 3.1% (SO_3), 0.9% Ignition loss, and 1.3% free CaO.

This cement is produced grinding clinker, bonded cement chunks, with a high percentage of (C_3A) and (C_3S) into a finer texture. The gypsum level is also increased a small amount. This gives the concrete using this type of cement a three day compressive strength equal to the seven day compressive strength of types I and II. Its seven day compressive strength is almost equal to types I and II 28 day compressive strengths. The only downside is that the six month strength of type III is the same or slightly less than that of types I and II. Therefore the long-term strength is sacrificed a little. The highly early strength is gained by increasing the tricalcium silicate, (C_3S), in the mix. This increased amount of tricalcium silicate brings the danger of free lime in the cement and high volume changes after setting.

Type IV (Low Hydration heat cement) – This type of Portland cement is generally known for its low heat of hydration. This cement is used for very large concrete structures, such as dams, which have a low surface to volume ratio. This type of cement is generally not in stock and has to be special ordered in large quantities. Type IV cement is not really used any in industry, but manufactured for the special circumstances only. Its typical compound composition is:

28% (C_3S), 49% (C_2S), 4% (C_3A), 12% (C_4AF), 1.8% MgO, 1.9% (SO_3), 0.9% Ignition loss, and 0.8% free CaO.

The percentages of (C_2S) and (C_4AF) are relatively high and (C_3S) and (C_3A) are relatively low. This causes the heat given off by the hydration reaction to develop at a slower rate. However, as a consequence the strength of the concrete develops slowly. After one or two years the strength is higher than the other types after full curing.

A limitation on this type is that the maximum percentage of (C_3A) is seven, and the maximum percentage of (C_3S) is thirty-five. Another negative about this type of cement is its higher cost. Recently mix designs using pozzolans and water-reducing admixtures have been developed to decrease the cement content which has allowed for Type II Portland cement to be substituted in for Type IV in the production of dams. This helps lower the cost of the dam.

Type V (Sulfate Resisting Cement) – Just as the name indicates this type of cement is known for its sulfate resistance. This type is used in concrete that has a tendency to be exposed to alkali soil and ground water sulfates. It is generally not meant for use around seawater, but it can be done as long as the (C_3A) composition is above two percent. It usually requires an advance order and is generally available to the western United States and Canada. Its typical compound composition is:

38% (C_3S), 43% (C_2S), 4% (C_3A), 9% (C_4AF), 1.9% MgO, 1.8% (SO_3), 0.9% Ignition loss, and 0.8% free CaO.

This cement has a very low (C_3A) composition which accounts for its high sulfate resistance. The maximum content of (C_3A) allowed is 5% for type V Portland cement. This type of cement is essential in the construction of canal linings, culverts, and siphons because of their contact with ground waters containing sulfates. This is required because sulfates cause serious deterioration and swelling to the other types of Portland cement. The serious deterioration will eventually cause the concrete to fail. Type V Portland cement is a very uncommon type used in everyday construction but is routinely used in harsh marine environments.

Similarly, European Union has also developed a base for classification of cement. It is discussed briefly in Table 1.4.

EN 197

Table 1.4

Classification of Cement

Type	**Name**	**Properties**
I	Portland cement	Comprising Portland cement and u additional constituents
II	Portland-composite cement	Portland cement and up to 35% of constituents
III	Blastfurnace cement	Portland cement and higher percer blastfurnace slag
IV	Pozzolanic cement	Comprising Portland cement and h percentages of pozzolana
V	Composite cement	Comprising Portland cement and h percentages of blastfurnace slag a fly ash

1. Cement manufacturing Process

The raw materials used in cement production are widely available in great quantities. The common row materials used are:

- Common sources of calcium in cement - Limestone, marl, and chalk
- Common sources of silicon - clay, sand, and shale, certain waste products, such as fly ash,
- Iron, aluminum recycled metals can also be used.
- About 5% of cement by weight is gypsum, a common calcium- and sulfur-based mineral.

Portland cement consists of five major compounds and a few minor compounds. The composition of a typical portland cement is listed by weight percentage in Table 1.5.

Table 1.5

Composition of Portland cement

Cement Compound	**Weight Percentage**	**Chemical Formula**
Tricalcium silicate	50 %	Ca_3SiO_5 or $3CaO \cdot SiO_2$
Dicalcium silicate	25 %	Ca_2SiO_4 or $2CaO \cdot SiO_2$
Tricalcium aluminate	10 %	$Ca_3Al_2O_6$ or $3CaO \cdot Al_2O_3$
Tetracalcium aluminoferrite	10 %	$Ca_4Al_2Fe_{10}$ or $4CaO \cdot Al_2O_3 \cdot F$
Gypsum	5 %	$CaSO_4 \cdot 2H_2O$

It takes 3,200 to 3,500 pounds of raw materials to produce one ton (2,000 lbs.) of finished cement, according to the Environmental Research Group at the University of British Colombia (UBC). Major steps in cement manufacturing are:

1. Preparation of the raw mixture
2. Production of the clinker

3. Preparation of the cement

The chemistry of cement is very complex, so cement chemist notation was invented to simplify the formula of common molecules found in cement.

The raw materials for Portland cement production are a mixture (as fine dust in the 'Dry process' or in the form of a slurry in the 'Wet process') are listed above. The raw materials are usually quarried from local rock, which in some places is already practically the desired composition and in other places requires the addition of clay and limestone, as well as iron ore, bauxite or recycled materials.

The raw mixture is heated in a kiln, a gigantic slowly rotating and sloped cylinder, with temperatures increasing over the length of the cylinder up to 1480°C approximately. The temperature is regulated so that the product contains sintered but not fused lumps. Too low a temperature causes insufficient sintering, but too high a temperature results in a molten mass or glass. In the lower-temperature part of the kiln, calcium carbonate (limestone) turns into calcium oxide (lime) and carbon dioxide. In the high-temperature part, calcium oxides and silicates react to form dicalcium and tricalcium silicates (C_2S C_3S). Small amounts of tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) are also formed. The resulting material is clinker, and can be stored for a number of years before use. Prolonged exposure to water decreases the reactivity of cement produced from weathered clinker.

Figure 1.2

Cement manufacturing Clinker

The energy required to produce clinker is around 1700 J/g. However, because of heat loss during production, actual values can be much higher. The high energy requirements and the release of significant amounts of carbon dioxide makes cement production a concern for global warming.

In order to achieve the desired setting qualities in the finished product, about 2% gypsum is added to the clinker and the mixture is finely pulverized. The powder is now ready for use, and will react with the addition of water.

The flow chart given below shows the step by step process of cement manufacturing.

Figure 1.3

Cement manufacturing process

1. Chemistry of cement

Cement is the key ingredient in concrete products. Cement is the binding agent that holds sand and other aggregates together in a hard, stone-like mass.

Cement production requires a source of calcium (usually limestone) and a source of silicon (such as clay or sand). Small amounts of bauxite and iron ore are added to provide specific properties. These raw materials are finely ground and mixed, then fed into a rotary cement kiln. The kiln is a long, sloping cylinder with zones that get progressively hotter up to about 2700°F (1400-1500°C). The kiln rotates slowly to mix the contents moving through it. In the kiln, the raw materials undergo complex chemical and physical changes which make them able to react together through hydration. The most common type of cement kiln today is a dry process kiln, in which the ingredients are mixed dry. In older days wet process was more popular in kilns. The important chemical reactions that take place in the kiln are:

- The first important reaction to occur is the calcining of limestone (calcium carbonate) into lime (calcium oxide) and carbon dioxide, which occurs in the lower-temperature portions of the kiln--up to about 1650°F (900°C).
- The second reaction is the bonding of calcium oxide and silicates to form

dicalcium and tricalcium silicates. Small amounts of tricalcium aluminate and tetracalcium aluminoferrite are also formed.

The relative proportions of these four principal compounds determine the key properties of the resultant portland cement. These reactions occur at very high temperatures with the ingredients in molten form. As the new compounds cool, they solidify into solid pellet form called clinker. The clinker is then ground to a fine powder, a small amount of gypsum is added, and the finished cement is bagged.

1. Hydration of Portland Cement

Concrete is prepared by mixing cement, water, and aggregate together to make a workable paste. It is molded or placed as desired, consolidated, and then left to harden. Concrete does not need to dry out in order to harden as commonly thought. All portland cements are hydraulic cements that set and harden through a chemical reaction with water. During this reaction, called hydration, a node forms on the surface of each cement particle. . The process of hardening or setting is actually a chemical reaction called hydration. When water is added to the cement, it forms a slurry or gel that coats the surfaces of the aggregate and fills the voids to form the solid concrete.

The concrete (or specifically, the cement in it) needs moisture to hydrate and cure (harden). When concrete dries, it actually stops getting stronger. Concrete with too little water may be dry but is not fully reacted. The properties of such a concrete would be less than that of a wet concrete. The reaction of water with the cement in concrete is extremely important to its properties and reactions may continue for many years.

When water is added to cement, each of the compounds undergoes hydration and contributes to the final concrete product. Only the calcium silicates contribute to strength. Tricalcium silicate is responsible for most of the early strength (first 7 days). Dicalcium silicate, which reacts more slowly, contributes only to the strength at later times. Tricalcium silicate will be discussed in the greatest detail.

The equation for the hydration of tricalcium silicate is given by

Tricalcium silicate + Water--->Calcium silicate hydrate+Calcium hydroxide + heat

$2\ Ca_3SiO_5 + 7\ H_2O \text{ ---> } 3\ CaO^{\cdot}2SiO_2{}^{\cdot}4H_2O + 3\ Ca(OH)_2 + 173.6kJ$

When water is added, tricalcium silicate rapidly reacts to release calcium ions, hydroxide ions, and a large amount of heat. The pH quickly rises to over 12 because of the release of alkaline hydroxide (OH^-) ions. This initial hydrolysis slows down quickly after it starts resulting in a decrease in heat evolved.

The reaction slowly continues producing calcium and hydroxide ions until the system becomes saturated. Once this occurs, the calcium hydroxide starts to crystallize. Simultaneously, calcium silicate hydrate begins to form. Ions precipitate out of solution accelerating the reaction of tricalcium silicate to calcium and hydroxide ions. (Le Chatlier's principle). The evolution of heat is then dramatically increased.

Heat is evolved with cement hydration. This is due to the breaking and making of chemical bonds during hydration. The heat generated is shown below as a function of time.

Figure 1.4

Heat of Hydration

The temperature at which hydration occurs greatly affects the rate of heat development. Curing begins after the exposed surfaces of the concrete have hardened sufficiently to resist marring. Curing ensures the continued hydration of the cement and the strength gain of the concrete. Concrete surfaces are cured by sprinkling with water fog, or by using moisture-retaining fabrics such as burlap or cotton mats. Other curing methods prevent evaporation of the water by sealing the surface with plastic or special sprays.

1. Concrete Proportioning

The key to achieving a strong, durable concrete rests in the careful proportioning and mixing of the ingredients.

A concrete mixture that does not have enough paste to fill all the voids between the aggregates will be difficult to place and will produce rough, honeycombed surfaces and porous concrete.

A mixture with an excess of cement paste will be easy to place and will produce a smooth surface; however, the resulting concrete is likely to shrink and would be uneconomical.

A properly designed concrete mixture will possess the desired workability for the fresh concrete and the required durability and strength for the hardened concrete. Typically, a mix is about 10 to 15 percent cement, 60 to 75 percent aggregate and 15 to 20 percent water. Entrained air in many concrete mixes may also take up another 5 to 8 percent. Table 1.6 shows the proportions of ingredients in concrete.

Table 1.6

Proportion of ingredients in concrete

Ingredient	**Proportion**
Cement	10-15%
Sand & Aggregates	60-75%

Water	15-20%
Air	5-7%
Admixtures	

From the time of adding water to the cement the chemical reaction begins and there is only a limited amount of time available to place and compact the concrete, this is usually 90 minutes maximum.

1. Stages in Concrete formation

The various stages from mixing the ingredients up to formation of concrete are commonly known as ‘concrete states’.

- The very first state of concrete formation is Plastic State. It is also called as fresh concrete. When the concrete is first mixed it appears like 'bread dough'. It is soft and can be moulded into any desired shapes. Concrete is plastic during placing and compaction. The most important properties of plastic concrete are workability and cohesiveness. A person can sink into plastic concrete if he steps on it.

Figure 1.5

Plastic state of concrete

- The plastic state is usually followed by Setting State. This state comes when the concrete then begins to stiffen. The stiffening of concrete, when it is no longer soft, and has gained minor strength is called setting. Setting takes place after compaction and during finishing. Concrete that is sloppy or wet may be easy to place but will be more difficult to finish. A person leaves footprints in setting concrete if he tries to walk on it.

Figure 1.6

Setting state of concrete

- The last and final state is called as Hardening State. After concrete has set it begins to gain strength and harden. The properties of hardened concrete are strength and durability. Hardened concrete will have no footprints on it if walked on.

Figure 1.7

Hardening State of concrete

Approximate time periods for the different stages of hydration of modern cement:

- Initial set (after 45 min): The concrete is ready to be troweled.
- Final set (after about 10 hrs): The concrete is hard enough for the forms to be removed.
- Full hydration (after about 7 days): The concrete is said to be cured. After, there is no need to insure the presence of water in the concrete.
- Full strength (after about 28 days): Evaporation is essentially complete, and the concrete can accept full loading.

Figure 1.8 shows a graph between time and compressive strength of concrete.

Figure 1.8

Development of strength with age

Curing

After concrete is placed, satisfactory moisture content and temperature (between 18°C and 30°C) must be maintained, a process called curing. Adequate curing is vital to quality concrete.

Curing has a strong influence on the properties of hardened concrete such as durability, strength, watertightness, abrasion resistance, volume stability, and resistance to freezing and thawing and deicer salts. Exposed slab surfaces are especially sensitive to curing. Surface strength development can be reduced significantly when curing is defective.

Curing the concrete aids the chemical reaction called hydration. Most freshly mixed concrete contains considerably more water than is required for complete hydration of the cement; however, any appreciable loss of water by evaporation or otherwise will delay or prevent hydration. If temperatures are favorable, hydration is relatively rapid the first few days after concrete is placed; retaining water during this period is important. Good curing means evaporation should be prevented or reduced. Curing is discussed in detail section 3.--.

1. Characteristics of concrete

During hydration and hardening, concrete develops certain physical and chemical properties. The important characteristics are strength, workability, durability etc. All these properties affected in great extent by the proportioning, mixing, transporting, curing and other surrounding conditions. Some of these important characteristics are discussed below.

Strength in concrete

Concrete is a very strong material when it is placed in compression. It is, however, extremely weak in tension. Engineering design of concrete is based on concrete's compressive strength. Compressive strength refers to what concrete is capable of resisting from loads when they are pushing on the concrete (compression). Compressive strengths for concrete are usually in the range of 3,000 to 5,000 psi (pounds per square inch). To correct for the lack of tension strength in concrete, high tensile strength steel is placed in the tension side of concrete. The steel used for reinforcement usually consists of steel bars. When this combination occurs it is called reinforced concrete. The reinforcement, which is usually steel, takes up the slack for the weakness of the concrete in tension.

There are many ways to test the strength of a batch of concrete. The tests used can be categorized as destructive and nondestructive tests.

The compressive strength of concrete is usually at least ten times its tensile strength, and five to six times its flexural strength. The principal factors governing compressive strength are given below:

- Water-cement ratio is by far the most important factor.
- The age of the cured concrete is also important. Concrete gradually builds strength after mixing due to the chemical interaction between the cement and the water. It is normally tested for its 28 day strength, but the strength of the concrete may continue to increase for a year after mixing.
- Character of the cement, curing conditions, moisture, and temperature. The greater the period of moist storage (100% humidity) and the higher the temperature, the greater the strength at any given age.
- Air entrainment, the introduction of very small air voids into the concrete mix, serves to greatly increase the final product's resistance to cracking from freezing-thawing cycles. Most outdoor structures today employ this technique.

Once the concrete has been placed for a particular structure, there is a nondestructive test that can be performed to estimate the strength of the concrete without disturbing it. This method is discussed in detail in chapter 4.

Concrete's strength may also be affected by the addition of admixtures. Admixtures are substances other than the key ingredients or reinforcements which are added during the mixing process. Some admixtures add fluidity to concrete while requiring less water to be used. An example of an admixture which affects strength is superplasticizer. This makes concrete more workable or fluid without adding excess water. Note that not all admixtures increase concrete strength. Strength of concrete is affected by the water content or the water cement ratio in great extent. Figure 1.9 shows a graph which explains the relationship between water cement ratio and concrete strength. The admixtures which affect the strength of concrete are discussed in detail in chapter 6.

Figure 1.9

Compressive Strength of Concrete

Durability of concrete

Durability is a very important concern in using concrete for any structure. Concrete provides good performance through the service life of the structure when concrete is mixed properly and care is taken in curing it. Good concrete can have an infinite life span under the right conditions.

Concrete durability can defined as its resistance to weathering action, chemical attack, abrasion and other degradation processes. Durability becomes even more important factor when concrete is intended to be used for roads/pavements or pipes construction.

Water, although important for concrete hydration and hardening, can also play a role in decreased durability once the structure is built. This is because water can transport harmful chemicals to the interior of the concrete leading to various forms of deterioration.

Come of the degradation mechanisms in concrete structures include the following:

- Physical effects, weathering - Freeze-thaw damage
- Chemical effects -Alkali-aggregate reactions
- Chemical effects - Sulfate attack.
- Chemical effects - Microbiological induced attack
- Chemical effects - Corrosion of reinforcing steel embedded in concrete
- Physical effects - Abrasion
- Physical effects - Mechanical loads

Such deterioration ultimately adds costs due to maintenance and repair of the concrete structure.

Workability

A good concrete is one which has workability in the fresh state and develops adequate strength. Workability is the ability of a fresh concrete mix to fill the form/mould properly with the desired work and without reducing the concrete's quality. The ease of placing, consolidating, and finishing freshly mixed concrete and the degree to which it resists segregation is called workability. Concrete should be workable but the ingredients should not separate during transport and handling.

Workability depends on water content, additives, aggregate (shape and size distribution) and age (level of hydration). Raising the water content or adding plasticizer can increase the workability. Too much water will lead to bleeding (loss of water) and/or segregation (concrete starts to get heterogeneous) and the resulting concrete will have reduced quality.

Workability is normally measured by the "slump test", a simplistic measure of the plasticity of a fresh batch of concrete. The workability tests are discussed in detail in chapter 4.

The principal factors which affect the workability of concrete are:

- Method and duration of transport
- Concrete and ambient air temperatures;
- Consistency - The degree of consistency will depend on the nature of work and type of compaction i.e. by hand or vibrator. The degree of consistency can be determined by slump test.
- Water/Cement ratio- It is the ratio of water in a mix (excluding water already absorbed by the aggregate) to the weight of cement therein. The correct quantity of water required for a mix depends on the mix proportions, type and grading of aggregate, method of compaction and the weather conditions.
- Aggregate Grading - Other things being equal, the workability of concrete is greater with larger size aggregates. A smooth and rounded aggregate will produce a more workable concrete than a sharp angular one. A flaky aggregate produces the hardest or most unworkable concrete.
- Cement quantity -The higher the cement content, the greater the workability, and less the effect of grading. As such, a greater latitude in grading can be permitted with high cement content (called rich mix), than with a mix with less cement content (a lean mix).
- Admixtures

Permeability

Concrete durability depends largely on the ease with which fluids (water, carbon dioxide, oxygen) in the form of liquid or gas can migrate through the hardened concrete mass. Concrete is a porous material. Therefore, moisture movement can occur by flow, diffusion, or sorption. We are concerned with all three, but generally the overall potential for moisture and ion ingress in concrete by these three modes is referred to as its permeability. Experts have widely agreed for decades that the use of pozzolana, or supplementary cementing materials, can reduce concrete permeability by 7 to 10 times. Permeability in concrete should be controlled in order to prevent the corrosion of the reinforced steel bars.

Porosity

Concrete porosity is usually expressed in terms of percentage by volume of concrete. It is the interconnectivity of pores, rather that total porosity that determines a concrete's permeability. A concrete with a high proportion of disconnected pores may be less permeable that a concrete with a much smaller proportion of connected, or continuous pores. With greater particularity, it is the overall nature of the matrix pore structure that ultimately affects its permeability, and diffusivity. The size, distribution, interconnectivity, shape, are all determining factors in the overall permeability of a concrete matrix.

Water-proof or water-tight portland cement concrete is not a real possibility. Instead, goal in design should be the formulation of durable concrete mixes is to slow and minimize the potential for, and rate of, moisture ingress and movement.

The paste-aggregate interfacial zone is known to be different from the cement paste mass in general. It is usually more porous, and is more prone to microcracking than the rest of the paste matrix. The interfacial zone can occupy 30 - 50% of the total volume of cement paste in concrete. In comparison to the bulk hydrated cement paste, the paste-aggregate interfacial zone is weaker, more soluble, and can be a least resistant path for migrating moisture and other harmful substances.

It should be noted that although aggregates are porous, their pores are normally discontinuous in a concrete matrix, being completely enveloped by cement past