Chapter 8. Hardened Concrete

8.1 Introduction.

Fully cured, hardened concrete must be strong enough to withstand the structural and service loads which will be applied to it and must be durable enough to withstand the environmental exposure for which it is designed. If concrete is made with high-quality materials and is properly proportioned, mixed, handled, placed and finished, it will be the strongest and durable building material.

Concrete is a highly complex heterogeneous material whose response to stress depends not only on the response of the individual components but also upon the interaction between those components.

8.2 Properties of Hardened Concrete

The properties which determine the quality of the hardened concrete broadly fall into the following three groups:

- **Strength.**
- **Dimensional stability.**
- **Durability.**

8.3 Strength

Strength of concrete is its resistance to rupture. It may be measured in a number of ways, such as, strength in compression, in tension, in shear or in flexure. All these indicate strength with reference to a particular method of testing. When concrete fails under a compressive load the failure is essentially a mixture of crushing and shear failure. There are several factors affecting the strength of concrete as follows:

1- **Concrete constituents and mix proportions:**
   - a- **Cement** (type, amount, cement fineness, etc.)
   - b- **Aggregates** (type, MSA, FM, surface area, unit weight, aggregate grading, inertness, aggregate/cement ratio, fine aggregates/coarse aggregates, etc.)
   - c- **Mixing water** (type, amount, water/cement ratio, etc.)
   - d- **Admixtures** (type, dosage, chemical effectiveness, etc.)

2- **Concrete production: (batching, mixing, transporting, casting, compaction).**

3- **Concrete curing: (curing method, temperature, degree of humidity, curing period).**

4- **Concrete age and testing conditions:** (shape and size of specimen, loading rate, loading direction, saturation of specimen, specimen contact surface with the machine, etc.).

8.3.1 Compressive Strength

The compressive strength of concrete is one of the most important and useful properties of concrete. In most structural applications concrete is employed primarily to resist compressive stresses. Therefore, the concrete making properties of various ingredients of mix are usually measured in terms of the compressive strength.

Compressive strength is also used as a qualitative measure for other properties of hardened concrete. No exact quantitative relationship between compressive strength and flexural strength, tensile strength, modulus of elasticity, wear resistance, fire resistance, or permeability have been established. However, approximate or statistical relationships, in some cases, have been established and these give much useful information to engineers.

The compressive strength of concrete is generally determined by testing cubes or cylinders made in laboratory or field or cores drilled from hardened concrete at site or from the non-destructive testing of the specimen or actual structures.

Stress-Strain Relationship of Concrete

Stress strain curve of concrete is a graphical representation of concrete behavior under load. It is produced by plotting concrete compress strain at various interval of concrete compressive loading (stress). Concrete is mostly used in compression that is why its compressive stress strain curve is of major interest.

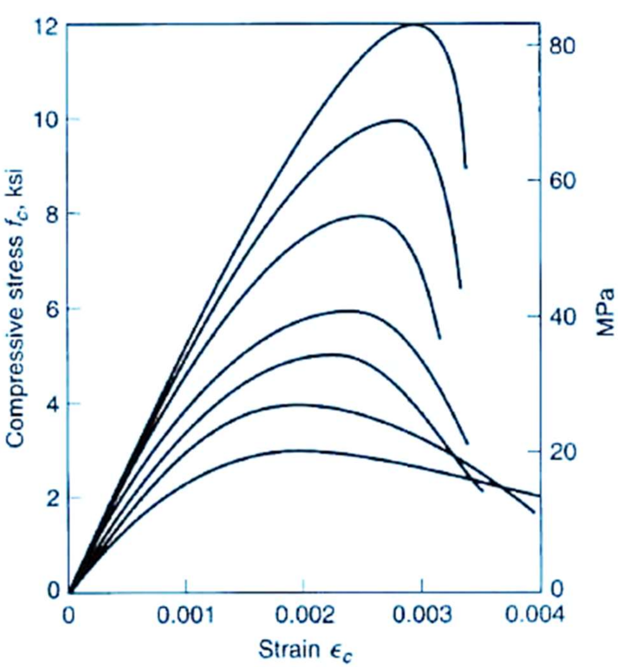


Figure 1

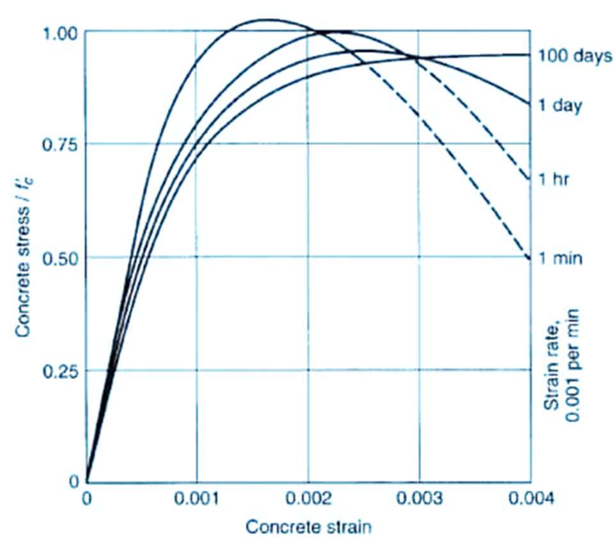


Figure 2

Figure 1 shows strain stress curve for normal weigh concrete. There is a set of curves which represents the strength of the concrete. So, higher curves show higher concrete strength. Figure 2 shows how the shape of concrete stress strain curve changes based on the speed of loading.

1- Straight or Elastic Portion

Initially, all stress strain curves in Figure 1 are fairly straight; stress and strain are proportional. With this stage, the material should be able to retain its original shape if the load is removed. The elastic range of concrete stress strain curve continues up to 0.45fc' (maximum concrete compressive strength).

The slope of elastic part of stress strain curve is concrete modulus of elasticity. The modulus of elasticity of concrete increases as its strength is increased. Design Codes provide equations for computing concrete modulus of elasticity.

2. Peak Point or Maximum Compress Stress Point

When a load is further increased, the elastic range is exceeded and concrete begin to show plastic behavior (Nonlinear). After elastic range, the curve starts to horizontal; reaching maximum compress stress (maximum compressive strength).

For normal weight concrete, the maximum stress is realized at compressive strain ranges from 0.002 to 0.003. For normal weight concrete, the ACI Code specified that, a strain of 0.003 is maximum strain that concrete can reach and this value used for design of concrete structural element. However, the European Code assumes concrete can reach a strain of 0.0035, and hence this value is used for the design of concrete structural element.

3. Descending Portion

After reaching maximum stress, all the curves show descending trend. The characteristics of the stress strain curve in descending part is based on the method of testing.

8.3.2 Tensile Strength

Plain concrete (without steel reinforcement) is quite weak in tensile strength which may vary from 0.05 to 0.125 % of the ultimate compressive strength. It is primarily for this reason that steel bars (reinforcement) are introduced into the concrete to get very strong concrete in compression as well as in tension.

8.3.3 Shear Strength

Shear strength of concrete is taken approximately equal to 20 % its compressive strength

8.3.4 Bond Strength

The strength of bond between steel reinforcement and concrete is called as bond strength of concrete. Bond strength develops primarily due to friction and adhesion between steel reinforcement and concrete.

In general, bond strength is approximately proportional to the compressive strength of concrete up to about 20 MPa (3000 psi). For higher compressive strengths of concrete, the increase in bond strength becomes progressively smaller and eventually negligible.

8.3.5 Impact Strength

Impact strength of concrete is of importance in driving concrete piles, in foundations for machines exerting impulsive loading, and also when accidental impact is possible, e.g. when handling precast concrete members.

Some researchers have found that impact is related to the compressive strength, and it has been suggested that the impact strength varies from 0.50 to 0.75 of the compressive cube strengths.

8.3.6 Fatigue Strength

The strength of concrete against cyclic or repeated loading is called as its fatigue strength. The fatigue strength of concrete is much less than that from static strength due to sustained loading. A fatigue limit of (50-60) % of compressive strength in static, is observed, when stress is applied in 2,000,000 cycle, for a maximum stress starting from zero.

8.4 Types of Concrete Testing

During construction, an estimate of the in-place strength of concrete may be desired for determining the safe time to strip forms or to proceed with further work. The adequacy of mix proportions may need to be verified. Compressive strength data is necessary for quality control.

The measured results are dependent upon adhering strictly to standardized uniform procedures. Most testing errors produce lower strength results.

Testing concrete is classified into two types based on whether destructive stresses are applied or not.

- **Destructive Testing**
- **Non-Destructive Testing (NDT)**

8.4.1 Destructive Testing

Destructive testing of concrete samples involves applying direct stresses (compression, tensile, flexural, etc.) on representative concrete samples, after which these samples became destroyed.

Variables that Influence Measured Concrete Compressive Strength

- Sampling
- Casting
- Initial Curing
- Transporting
- Laboratory Curing
- Capping
- Testing (moisture condition and temperature, loading rate, specimen misalignment, seating behavior, machine calibration, post-failure inspection)
- Reporting

8.4.2 Non-Destructive Testing of Concrete

The standard method of evaluating the quality of concrete in buildings or structures is to test specimens cast simultaneously for compressive, flexural and tensile strengths. The main disadvantages are that results are not obtained immediately. Concrete in specimens may differ from that in the actual structure as a result of different curing and compaction conditions. Further, strength properties of a concrete specimen depend on its size and shape.

Therefore, several non - destructive methods (NDT) of assessment have been developed. These depend on the fact that certain physical properties of concrete can be related to strength and can be measured by non-destructive methods. Such properties include hardness, resistance to penetration by projectiles, rebound capacity and ability to transmit ultrasonic pulses and X- and Y-rays.

These non-destructive methods may be categorized as:

1- **penetration tests**
2- **rebound tests**
3- **pull-out techniques**
4- **dynamic tests**
5- **radioactive tests,**

These methods are briefly described below including their advantages and disadvantages.

Penetration Tests

The Windsor probe is generally considered to be the best means of testing penetration. Equipment consists of a powder-actuated gun or driver, hardened alloy probes, loaded cartridges, a depth gauge for measuring penetration of probes and other related equipment.

Limitations and Advantages. The probe test produces quite variable results and should not be expected to give accurate values of concrete strength. It has, however, the potential for providing a quick means of checking quality and maturity of in situ concrete. It also provides a means of assessing strength development with curing.

Rebound Tests

The rebound hammer is a surface hardness tester for which an empirical correlation has been established between strength and rebound number. The only known instrument to make use of the rebound principle for concrete testing is the Schmidt hammer.

Limitations and Advantages. The Schmidt hammer provides an inexpensive, simple and quick method of obtaining an indication of concrete strength, but accuracy of ±15 to ±20 per cent is possible only for specimens cast cured and tested under conditions for which calibration curves have been established. The results are affected by factors such as smoothness of surface, size and shape of specimen, moisture condition of the concrete, type of cement and coarse aggregate, and extent of carbonation of surface.

Pull-Out Tests

A pull-out test measures, with a special ram, the force required to pull from the concrete a specially shaped steel rod whose enlarged end has been cast into the concrete to a depth of 3 in. (7.6 cm). The concrete is simultaneously in tension and in shear, but the force required to pull the concrete out can be related to its compressive strength. The pull-out technique can thus measure quantitatively the in-situ strength of concrete when proper correlations have been made.

Limitations and Advantages. Although pullout tests do not measure the interior strength of mass concrete, they do give information on the maturity and development of strength of a representative part of it. Such tests have the advantage of measuring quantitatively the strength of concrete in place. Their main disadvantage is that they have to be planned in advance and pull-out assemblies set into the formwork before the concrete is placed.

Dynamic Tests

At present the ultrasonic pulse velocity method is the only one of this type that shows potential for testing concrete strength in situ. It measures the time of travel of an ultrasonic pulse passing through the concrete. It consists of a pulse generator and a pulse receiver.. The time taken for the pulse to pass through the concrete is measured by electronic measuring circuits.

Applications and Limitations. The pulse velocity method is an ideal tool for establishing whether concrete is uniform. It can be used on both existing structures and those under construction. Usually, if large differences in pulse velocity are found within a structure for no apparent reason, there is strong reason to presume that defective or deteriorated concrete is present.

High pulse velocity readings are generally indicative of good quality concrete. A general relation between concrete quality and pulse velocity is given in Table below.

Table I. Quality of Concrete and Pulse Velocity

General Conditions	Pulse Velocity ft/sec
Excellent	Above 15,000
Good	12,000-15,000
Questionable	10,000-12,000
Poor	7,000-10,000
Very Poor	below 7,000

In summary, ultrasonic pulse velocity tests have a great potential for concrete control, particularly for establishing uniformity and detecting cracks or defects. Its use for predicting strength is much more limited, owing to the large number of variables affecting the relation between strength and pulse velocity.

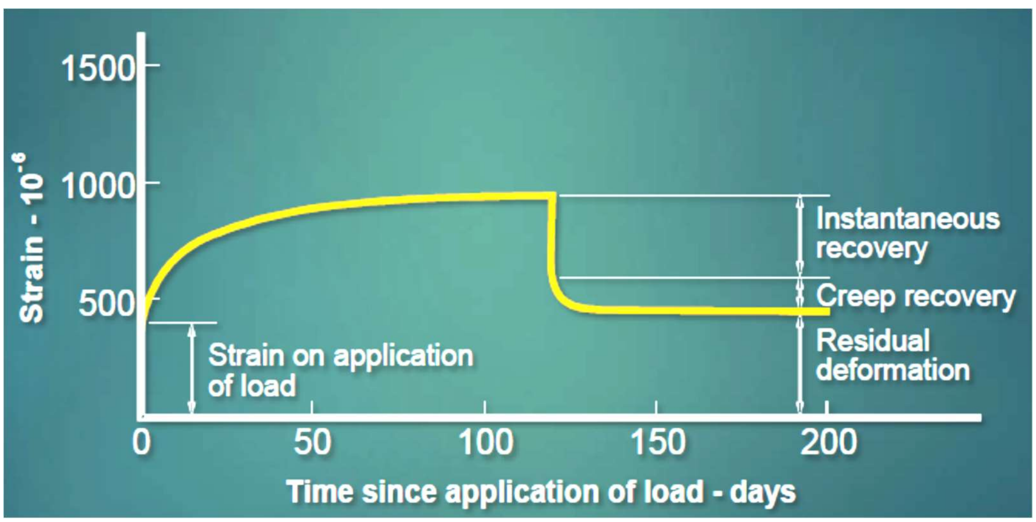
8.5 Dimensional Stability (Creep and Shrinkage).

Dimensional stability of a construction material refers to its dimensional change over a long period of time. If the change is so small that it will not cause any structural problems, the material is dimensionally stable. For concrete, drying shrinkage and creep are two phenomena that compromise its dimensional stability

8.5.1 Creep of Concrete

Creep is time dependent deformations of concrete under permanent loads (self-weight). When concrete is subjected to compressive loading it deforms instantaneously. This immediate deformation is called instantaneous strain.

Now, if the load is maintained for a considerable period of time, concrete undergoes additional deformations even without any increase in the load. This time-dependent strain is termed as creep.



- The ability of concrete to creep imparts a degree of ductility to concrete that enables it to tolerate the normal range of structural deformations encountered in practice. Creep provides a structure with the ability to redistribute excessive stresses.
- However, creep also may have detrimental effects such as increased deflection resulting in cracking, loss of pre-stress, and buckling of slender columns.
- In reinforced concrete beams, creep increases the deflection with time and may be a critical consideration in design. In eccentrically loaded columns, creep increases the deflection and can load to buckling.

- Due to the delayed effects of creep, the long-term deflection of a beam can be 2-3 times larger than the initial deflection.
- It is therefore important that the designer takes the necessary steps to allow for creep in the design of concrete structures.

8.5.2 Shrinkage of Concrete

Shrinkage of concrete is caused by the following causes:

- Settlement of solids and the loss of free water from the plastic concrete (**plastic shrinkage**),
- Chemical combination of cement with water (**autogenous shrinkage**) and
- Drying concrete (**drying shrinkage**).

1- Plastic Shrinkage

Shrinkage, which takes place before concrete has set, is known as plastic shrinkage. It occurs as a result of the loss of free water and the settlement of solids in the mix.

Plastic shrinkage is most common in slab construction and is characterized by the appearance of surface cracks which can extend quite deeply into the concrete.

Preventive measures: reduce water loss by any curing methods (cover concrete with wet polythene sheets or by spraying a membrane-curing compound).

2- Autogenous Shrinkage

As hydration continues in an environment where the water content is constant, such as inside a large mass of concrete, this decrease in volume of the cement paste results in shrinkage of the concrete. This is known as **autogenous shrinkage**; it is self-produced by the hydration of cement.

3- Drying Shrinkage

When a hardened concrete, cured in water, is allowed to dry it first loses water from its voids and capillary pores and only starts to shrink during further drying when water is drawn, out of its cement gel. This is known as **drying shrinkage**.

After an initial high rate of drying shrinkage concrete continues to shrink for a long period of time, but at a continuously decreasing rate.

Cracking Mechanism:

If the tensile stress induced by restrained shrinkage exceeds the tensile strength of concrete, cracking will take place in the restrained structural element. If shrinkage cracks are not properly controlled, they permit the passage of water, expose steel reinforcements to the atmosphere, reduce shear strength of the member and are bad for appearance of the structure.

Shrinkage cracking is often controlled with the incorporation of sufficient reinforcing steel, or the provision of joints to allow movement.

Factors Affecting Drying Shrinkage

- Type, content and proportion of the constituent materials of concrete (cement, water, aggregates, etc.),
- Size and shape of the concrete structure,
- Amount and distribution of reinforcement,
- Relative humidity of the environment.

Drying shrinkage is directly proportional to the water-cement ratio and inversely proportional to the aggregate-cement ratio (Figure below).

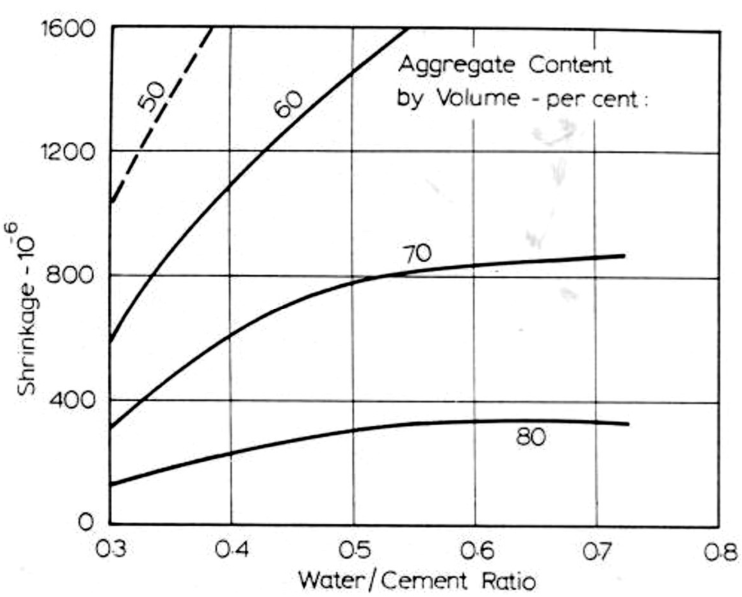


Figure. Influence of water/cement ratio and aggregate content on shrinkage

Because of the interaction of the effects of aggregate-cement and water-cement ratios, it is possible to have a rich mix with a low water-cement ratio giving higher shrinkage than a leaner mix with a higher water-cement ratio.

8.6 Durability of Concrete






8.6.1 Definitions

- Durability is the ability of concrete to withstand the conditions for which it is designed without deterioration for a long period of years.
- Durability of concrete may be defined as the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.
- Durability is defined as the capability of concrete to resist weathering action, chemical attack and abrasion while maintaining its desired engineering properties.

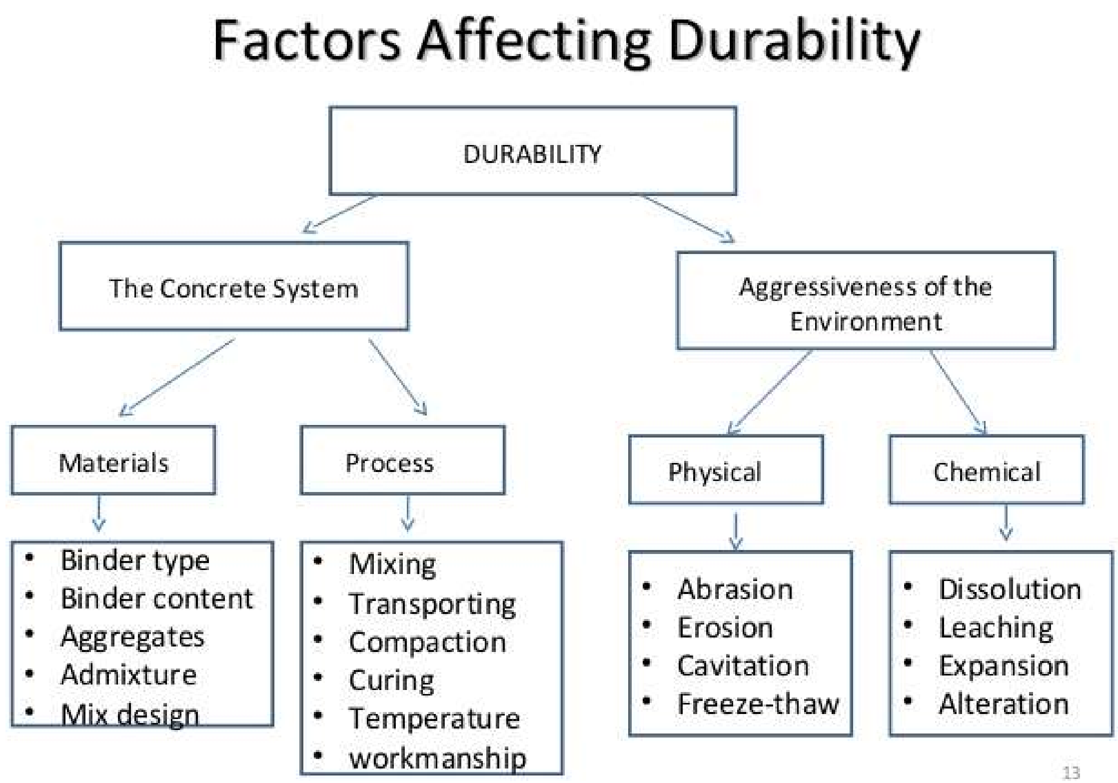
Different concretes require different degrees of durability depending on the exposure environment and properties desired. For example, concrete exposed to tidal seawater will have different requirements than indoor concrete.

Concrete will remain durable if:

- The cement paste structure is dense and of low permeability.
- It is made with graded aggregate that are strong and inert.
- The ingredients in the mix contain minimum impurities such as alkalis, Chlorides, sulphates and silt.

8.6.2 Factors affecting durability of concrete

Durability of Concrete is influenced by the factors shown in the following figure



Other factors are:

1- Concrete Cover

Thickness of concrete cover must follow the limits set in codes.

2- Permeability

It is considered the most important factor for durability. It can be noticed that higher permeability is usually caused by higher porosity. Therefore, a proper curing, sufficient cement, proper compaction and suitable concrete cover could provide a low permeability concrete.

Permeability of water into concrete expand its volume and lead to formation of cracks and finally disintegration of concrete occurs. To prevent permeability, lowest possible water cement ratio must be recommended. Use of pozzolanic materials also helps to reduce permeability by filling capillary cavities.

3- Carbonation

When moist concrete is exposed to atmosphere, carbon dioxide present in atmosphere reacts with concrete and reduces pH of concrete. When pH of concrete reaches below 10, reinforcement present in the concrete starts corroding. Corrosion of reinforcement causes cracks in concrete and deterioration takes place.

8.7 Types of Durability

There are many types but the major ones are:

1. **Chemical durability of concrete.**
2. **Physical durability of concrete.**

8.7.1 Chemical Durability

When dealing with durability, chemical attack which results in volume change, cracking and consequent deterioration of concrete become a major cause of concern. Types of the chemical attacks are as follows:

- Sulphate attack
- Alkali aggregate reaction
- Chloride ion attack - Corrosion
- Carbonation
- Acid Attack
- Effect on concrete in Seawater

1. Sulphate attack

- Sulphate attack denotes an increase in the volume of cement paste in concrete or mortar due to chemical action between the products of hydration of cement and solution containing sulphate, and also sodium, magnesium and Chlorides.

- In hardened concrete, calcium aluminate hydrate (CAH) can react with sulphate salt from outside, product of reaction is calcium sulphoaluminate, which can cause an increase in volume up to 227%

- Rate of sulphate attack increases with a saturated sulphate solution.

- A saturate solution of magnesium sulphate can cause serious damage to concrete with high w/c ratio.

Methods of controlling sulphate attack

- Use SRC (sulphate resisting cement)
- Quality concrete - low w/c ratio, well designed and compacted dense concrete
- Use of air-entrainment
- Use of puzzolana
- Use of high alumina cement

2. Alkali - Aggregate Reaction

Alkali-aggregate reaction (AAR) is basically a chemical reaction between the hydroxyl ions in the pore water within concrete and certain types of rock minerals. Since reactive silica in the aggregate is involved in this chemical reaction it is often called alkali-silica reaction (ASR). It is recognized as one of the major causes of cracking of concrete.

Its occurrence is due to :

1. High alkali content in cement (more than 0.6%)
2. Reactive silica in aggregate
3. Availability of moisture

Remedial Measures:

1. Use non-reactive aggregates from alternate sources
2. Use low-alkali cement
3. Reduce cement content in concrete.

3. Chlorides in Concrete.

- Chlorides in concrete increases risk of corrosion of steel (Electrochemical reaction)
- Higher Chloride content or exposure to warm moist conditions increase the risk of corrosion.
- To minimize the chances of corrosion, the levels of chlorides in concrete should be limited
- Total amount of chloride content (as Cl) in concrete at the time of placing is provided by common specifications and standards.

Methods of Controlling Chlorides

1. Chlorides in cement to be less than 0.1 % max (or 0.05% max for prestressed works)
2. Chlorides in water to be less than 2000 mg/ltr for PCC and below 500 mg/ltr for RCC

3. Chlorides in aggregates are generally not encountered but, it’s a good practice to wash sand containing salt more than 3%
4. Chloride traces are also found in chemical admixtures. Chloride free admixtures should be generally preferred.

4. Carbonation of Concrete

Carbonation of concrete is a process by which carbon dioxide from the air penetrates into concrete and reacts with calcium hydroxide to form calcium carbonates.

In actual practice, CO2 present in atmosphere permeates into concrete and carbonates the concrete and reduces the alkalinity of concrete.

When all the $Ca(OH)_2$ has become carbonated, the pH value will reduce up to about 8.3. In such a low pH value, the protective layer gets destroyed and the steel is exposed to corrosion.

Rate of Carbonation depends upon relative humidity, grade of concrete, permeability of concrete, depth of cover and time

Protective coating is required to be given for long span bridge girders, flyovers, Industrial structures and chimneys. Such as plastic paints (Impermeable). Deep cover plays an important role in protecting the steel from carbonation.

8.7.2 Physical Durability

Physical durability is against the following actions:

1. Freezing and thawing action.
2. Percolation / Permeability of water.
3. Temperature stresses i.e. high heat of hydration.