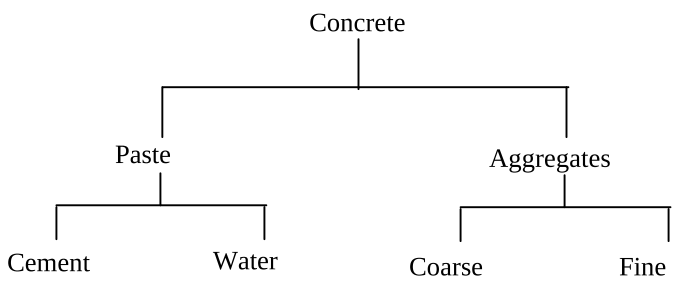
CONCRETE

Concrete is one of the most common engineered construction materials and is used in a wide variety of applications, such as buildings, bridges, dams, piles, storage tanks, pipes, foundations, and pavements. Concrete is a particulate composite of stone and sand bonded together by inorganic cement gel. After curing, concrete hardens into a rock-like solid mass.



- Cement paste is 25 to 40% of the total concrete volume
- Aggregates are 60 to 75% by volume
- Aggregates are dense and strong, so the weak phase is the hardened cement paste

Portland Cement

Hydraulic cement is a powdery material that reacts with water and produces a strong, water insoluble solid rocklike mass. Portland cement was first patented by Joseph Aspdin in 1824 as Portland cement, because of the resemblance of hardened cement with the Portland stone found near Dorset, England.

The raw materials for manufacturing the cement are silicates and aluminates of lime obtained limestone and clay. The mixture of limestone and clay is ground, blended, and fused in a kiln at about 1500°C. The end product of this process, called clinker, is cooled and ground to obtain cement.

Table: Major Constituents of Portland Cement

Compound	Chemical Formula	Notation
Dicalcium Silicate	$2CaO.SiO_2$	C_2S
Tricalcium Silicate	$3CaO.SiO_2$	C_3S
Tricalcium Aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium Aluminoferrite	$4CaO.Al_2O_3.\ Fe_2O_3$	C_4AF

Hydration of Cement

When cement is mixed with sufficient water, the resulting paste looses its fluidity after 2 - 4 hours. This is called *initial set*. The final set is marked by the disappearance of the plasticity. At this stage, the paste becomes brittle with a little strength. The gain of strength, that is the hardening process, begins after the setting, and continues for an extended period of time (in months).

The setting and hardening of the cement paste are the result of a series of chemical reactions between water and the constituents of the cement, referred to as the hydration of Portland cement.

- The aluminate (C_3A) is most reactive compound and hydrates at much faster rate than silicates. The setting is due largely to the hydration of aluminates in first 4 hours..
- The hardening of cement takes place due to hydration of calcium silicates.
- Tricalcium silicate (C_3S) hardens rapidly, and is responsible for early strength development.
- Dicalcium silicate (C_2S) hardens slowly and contributes to the strength increase beyond one week.
- Calcium silicates (C_3S, C_2S), which constitute 75% of the cement, react with water to form calcium silicate hydrate (Tobomorite gel), which is a key product responsible for the strength of the cement.
  $2C_3S + 6H = C_3S_2H_3 + 3CH + \text{Heat}$ ($H = H_2O$, water)
  $2C_2S + 4H = C_3S_2H_3 + CH + \text{Heat}$

The tobomorite gel ($C_3S_2H_3$) is the main binding material which occupies 70% of the hardened cement.

- Hydration is *exothermic* process, i.e., heat is generated during the hydration.
- The rate of hydration depends on the relative proportions of silicates and aluminates, fineness of cement, and ambient temperature and humidity.

Characteristics of Cement Compounds

Property	C_3S	C_2S	C_3A	C_4AF
Cementing value	Good	Good	Poor	Poor
Rate of reaction	Medium	Slow	Fast	Slow
Heat generated	Medium	Small	Large	Small

Types of Portland Cements

CSA Standard A5 specifies five types of Portland cements, similar to ASTM Standard.

Type	Description
Type 10, Normal	General purpose cement, used in a wide range of applications
Type 20, Moderate	It has moderate sulphate resistance and moderate heat of hydration. Use (1) in drainage structures exposed to soil and groundwater with high sulphate content, (2) in massive structures, e.g., piers, retaining walls due to less heat of hydration than type 10.
Type 30, High-early strength	It provides high early strength in about a week time. Use (1) when structure needs to be put into service quickly, (2) In cold weather with limited controlled curing time.
Type 40, Low heat	The rate and amount of heat (of hydration) generated are minimum. It is used in massive concrete structures, e.g., gravity dams, where temperature rise needs to be minimized.
Type 50, Sulphate resistant	It is used when concrete is exposed to severe sulphate action by soil or water. It gains strength much slowly than Type 10. It has low tricalcium aluminate content. For use in seawater and sewage disposal sites.

Typical Composition of Cements

Cement Type	C_3S	C_2S	C_3A	C_4AF
10	50	24	11	8
20	42	33	5	13
30	60	13	9	8
40	26	50	5	12
50	40	40	3.5	9

Relative Strength of Different Cement Types
(obtained by testing 50mm mortar cubes)

Cement Type	Minimum Required Compressive strength (% of Type 10 at 28 days)			
	1 day	3 days	7 days	28 days
10	–	47	68	100
20	–	38	60	100
30	47	83	–	–
40	–	32	–	94
50	–	40	60	100

Other Types of Cement

High Alumina Cement

This primarily contains calcium aluminates. The alumina-lime ratio is typically between 0.85 and 1.3. Main characteristics are: high early strength (usually setting and hardening to full strength at 48 hours, compared to 28 days for Portland cement), high heat of hydration, and durability against the chemical attack. Rapid development of heat makes it suitable for construction in freezing weather. Its use in hot weather, however, is limited due to increased porosity, hence reduction in strength.

Waterproofed Cement

It is Portland cement interground with a water-repellent material, such as calcium stearate, to reduce the permeability of concrete.

Hydrophobic Cement

It is Portland cement interground with a small amount of hydrophobic (water-repellent) material, such as oleic acid, with the purpose of prolonging the storage time of cement. Hydrophobic cement is suitable for transport in bulk.

Antibacterial Cement

It is Portland cement interground with an antibacterial agent. It is used in food-processing plants to minimize deterioration caused by fermentation

White Cement

It is used for decorative purposes. It is produced by reducing iron and manganese compounds from the Portland cement.

Aggregates

Despite the high strength of hardened cement paste, Portland cement alone is not suitable for use as a construction material due to (1) dimensional instability due to creep and shrinkage, and (2) high cost of production. These disadvantages are overcome, in part, by adding the aggregates (crushed rocks, sand) to the cement paste, thus producing concrete. Aggregates are inert filler material. The objective is to bind as much aggregate as possible using the minimum amount of cement paste.

Properties of Fresh Concrete

Civil engineers are responsible for the production, transport, placing, compacting, and curing of fresh concrete. Without adequate attention to all of these, desired strength and durability of the structural element will not be achieved. The main properties of interest are:

1. *Fluidity (or Consistency).* Concrete must be capable of flowing into the formwork and around the reinforcing steel.
2. *Compactability.* It should be possible to remove most of the voids from the concrete by a suitable compacting system, e.g., vibrators.
3. *Stability or cohesiveness.* Concrete should remain as a homogeneous mass. For example, fine aggregates should no segregate from the coarse aggregates.

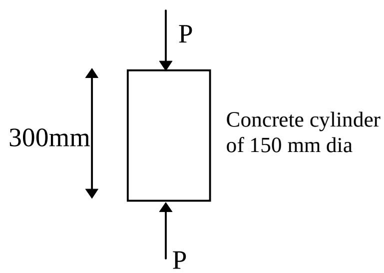
Curing of Fresh Concrete. Curing is the process of maintaining enough moisture in concrete to facilitate the hydration process during its early stages. Unless the concrete is cured properly, it will not achieve the desired strength. The rate of strength development in a properly cured concrete is much higher than in concrete that is left to dry out. the concrete must be maintained at humidity over 80% if hydration has proceed at an appreciable rate.

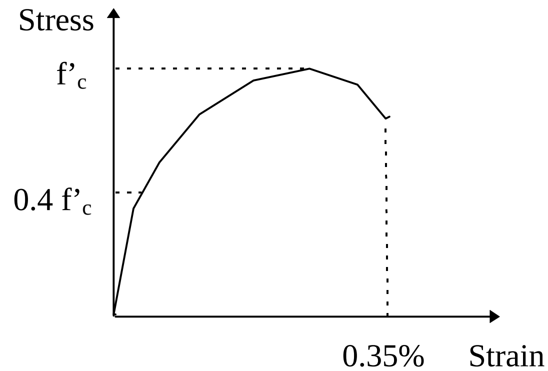
In the Figure below, compressive strength of concrete with time is plotted for different curing period. The vertical axis of the plot represents % of the strength of 28-day moist cured concrete. For example, strength of concrete dried in air (without any curing) will be about 52% of that cured for 28 days.

Material Properties of Concrete

The main properties of hardened concrete can be grouped as follows: (1) Strength - compressive, tension, (2) Stiffness - modulus of elasticity, (3) Creep and shrinkage, and (4) Durability.

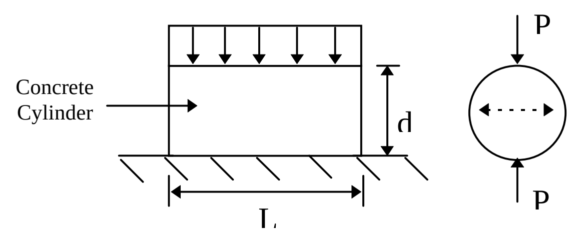
Compressive Strength of Concrete





- Compressive strength (*f*'c) is the most important property of concrete from the structural design viewpoint.
- *f*'c is estimated by testing standard cylinders (as shown above) after 28-day curing
- Stress-strain relation is normally linear up to 0.4 f'c stress value.
- Beyond 0.4 f'c stress, concrete behaviour becomes nonlinear. The nonlinear relation is due to micro-cracking at the interfaces between the aggregate and paste.
- Concrete fails (crushing failure) at about 0.35% compressive strain.
- Increase in concrete strength, that is kept moist, continues for more than a year. However, for engineering design purposes the strength at 28 days is used.
- Typically, f'c for normal density concrete ranges from 20 to 40 MPa. Concrete columns and other highly loaded compressive elements routinely are specified with strengths of 60 MPa and 100 MPa can be provided on a commercial basis in Toronto.

Tensile Strength of Concrete

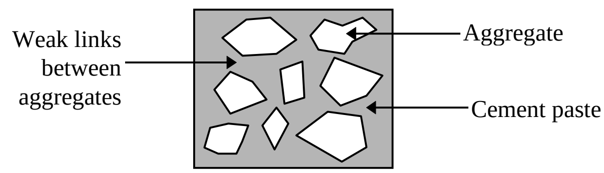


Concrete is weak in tension. The tensile strength is about 10% of the compressive strength. The reason is that the cement paste, which binds aggregates, has little tensile strength due to voids, and porosity. The tensile strength can also be correlated with f'c. As the compressive strength increases, the tensile strength is a smaller fraction of the compressive, until at 100 MPa, the tensile capacity is typically only about 5% of f'c. The split cylinder test is commonly used to estimate the tensile strength. From this test, tensile strength = $2P/\pi dL$, where P is the load at which the cylinder splits, and d and L are the cylinder diameter and length, respectively.

Modulus of Elasticity

Concrete modulus of elasticity (E_c)is defined as the slope of a line (secant) connection the origin and the point corresponding to 0.4 f'c. According to CSA Standard A23.3, E_c of a normal density concrete can be calculated as $E_c = 4500\sqrt{f'_c}$. E_c increases with the age, quality of aggregates, and the overall strength of concrete.

Factors Affecting the Concrete Strength



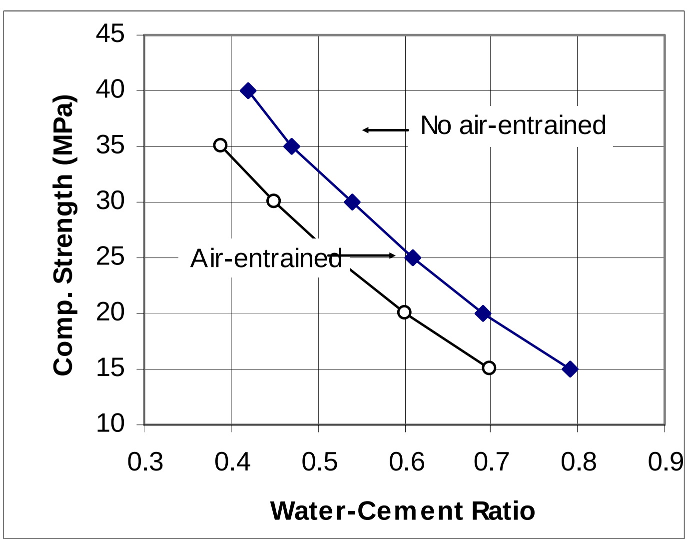
In hardened concrete in essence, aggregates are bonded by the cement paste. As aggregates are typically chosen to be very strong (strength>50 MPa), the cement paste is the weak element. Therefore, the concrete strength primarily depends on the strength of the cement paste, which is a product of hydration. In some cases only weak aggregate is available, and this will govern the strength that can be achieved.

There are a number of factors that affect the hydration process and hence the concrete strength. They are: (1) amount of cement, (2) amount of water, (3) curing temperature, (4) humidity, (5) age, (6) voids, (7) air entrainment, and (3) aggregate strength. The most important variables are the amount of cement (typically given as kg/m^3), and the water-to-cement ratio (typically reported as w/c, the mass ratio of water to cement).

Water/Cement Ratio

For a fixed cement content, concrete strength decreases rapidly with an increase in the amount of mixing water. The reason is that water unused in hydration process leaves a network of interconnected pores that serves as weak links and result in the early loss of strength (and are very damaging for durability). Water/cement ratio required for complete hydration is approximately 0.30, but this level of water is well below practical minimums of 0.35 to 0.40. Note that concrete with insufficient water becomes too dry to handle and compact efficiently.

In the past, concrete has commonly been specified with a w/c of 0.60 or more, and was often placed on site with added water to increase flowability. As the awareness of the importance of w/c to the durability of concrete has grown and the availability of plasticizers (see later) has increased, lower w/c are more commonly specified where durability is important (e.g., sidewalks, bridges, parking garages).



Effect of the water-cement ratio on concrete strength

Effect of Curing and Age

The degree of hydration of Portland cement increases with age and curing duration, leading to the beneficial effect of age on the strength. Strength is typically rated at 28 days (since over 90% of total strength is usually achieved at this age) but special high-strength concrete, concrete with fly ash, or cold-weather casting may require one to wait until 90 or 180 days to reach most of the strength.

Curing Temperature
The rate of hydration tends to increase with the curing temperature. At early age, gain in strength increases with the curing temperature. However, curing at lower temperatures results in higher long term strength than that obtained from high-temperature curing. An optimum temperature for curing is about 13°C.

Air-Entrainment
Concrete strength decreases with increase in the air content (see the Figure above). Air entrainment is a process by which a large number of small bubbles (20 to 2000 microns diameter) are dispersed throughout the concrete. The benefit is that the entrained air disrupts the continuity of capillary pores in the concrete and provides gaps for water that may be escaping a freezing front, to move into. This results in improved resistance to freeze-thaw cycles. The overall durability of air-entrained concrete is higher than that without air- entrainment.

Voids
Concrete strength decreases with increase in the void content. A large number of voids are a result of excessive water (the evaporation of which after curing leaves pores), excessively large aggregates, inadequate amount of cement (which acts as a lubricant and a space filler around large aggregate), and poor compaction of concrete (which can leave large voids, easily visible to the unaided eye.

Admixtures

Admixtures are chemicals that are added to the concrete (before or during the concrete mixing) to modify the properties of fresh or hardened concrete.

Accelerators: are added to accelerate the setting and early strength development of concrete, particularly in cold weather applications. Example- Calcium chloride. However, the addition of calcium chloride aggravates corrosion of reinforcing steel. It also increases heat of hydration, creep, and shrinkage.

Retarders: are added to delay the setting and hardening of concrete, especially in hot weather applications, and in construction of massive structures.

Air Entraining Admixtures: are used to increase the air content in concrete to improve its resistance to the damage caused by freeze and thaw cycles. Example- salts of wood resins, and detergents.

Moist concrete contains free water in capillary voids, which expands on freezing and produces disruptive internal stresses. Successive freeze-thaw cycles, say over a winter, may result in progressive deterioration. Entrained air voids provide a reservoir for the water to expand upon freezing. Optimum entrained air volume is about 4 to 7%.

The other two secondary effects are: (1) There is a general increase in workability of concrete, as the air bubbles reduce the internal friction in concrete mix. (2) Air entrained concrete has smaller compressive strength than that without entrained air. The reason for this is the increased porosity of concrete

Water Reducing Admixtures (Plasticizers): are added to increase the fluidity or workability of concrete which results in (1) reduction in the quantity of mixing water required, (2) improvement in concrete strength due to lower water-cement ratio. The quantity of mixing water is approximately reduced by 5 to 10%.

Superplasticizers are added to achieve a drastic increase in the concrete workability at low water-cement ratio. This allows low w/c ratio concrete to be easily poured and properly compacted, thereby resulting in high strength concrete.