Factors Affecting Strength of Concrete

1. Water/cement ratio:

Practically, it is assumed that the strength of concrete at a certain age, and cured at a specific temperature, primarily depends on two factors: the water/cement ratio and the degree of compaction.

At this stage, the focus will be on fully compacted concrete, which practically means that hardened concrete contains approximately 1% of its volume as air voids. When concrete is fully compacted, its strength is considered inversely proportional to the water-to-cement ratio, as outlined in Duff Abrams' Law published in 1919, which states that the strength is given by:

$$S = \frac{K_1}{\mathrm{K}_2^{\mathrm{W/C}}}$$

Where:

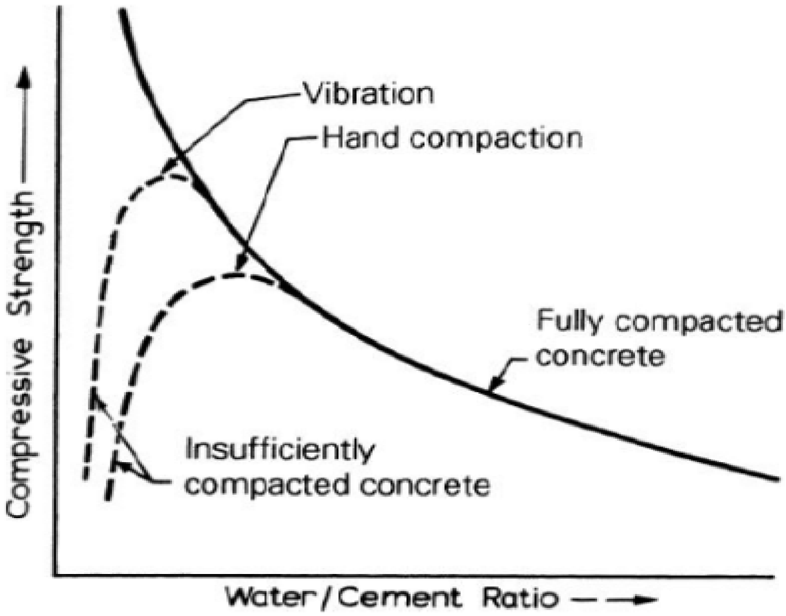
W/C: water/cement ratio of the mix.

K_1 and K_2: empirical constants.

The general form of the strength versus water/cement ratio curve is shown in Fig. 7.1.

It must be noted here that the water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. Therefore, both the water/cement ratio and the degree of compaction affect on the size of voids in concrete.

Figure 7.1 illustrates that the predominant relationship between compressive strength and water/cement ratio is limited and can be applied within a certain range of water/cement ratios. At the lower end of the scale, when the water-to-cement ratio is low and complete compaction is difficult to achieve, the relationship takes on a different shape and does not follow the curve's slope. The actual location of the point where the curve's slope changes depends on the available compaction methods. It also appears that mixtures with very low water/cement ratios, where the cement content is very high (470-530 Kg/m^3), exhibit a decrease in strength, especially when using aggregate with large-sized particles. Therefore, for such mixtures in later ages, the low water/cement ratio does not lead to high strength. This behavior may be due to stresses resulting from restraining shrinkage by aggregate particles, which can cause cracking of the cement paste or loss of bond between cement and aggregates.



Fig, 7.1: The relation between strength and water/cement ratio of concrete.

2. Effective water in the mix:

Effective water is the water that occupies the voids outside the aggregate particles during the concrete volume stabilization stage, i.e. approximately at the time of setting.

In general, water in concrete consists of the water added to the mix, in addition to the water retained by the aggregate when it is placed in the mixer. Part of this water is absorbed within the porous structure of the aggregate, while the other part remains as free water on the surface of the aggregate. Therefore, it does not differ directly from the water added to the mixer. On the other hand, when the aggregate is not saturated and some of its pores are filled with air, a portion of the water added to the mix will be absorbed by the aggregate during the first half hour or so after mixing. Under these conditions, it becomes difficult to distinguish between free water and absorbed water.

On the construction site, as a rule, the aggregate can be either wet or dry depending on the weather conditions. The excess water needed to saturate the aggregate and dry its surface will be included with the effective water in the mix when the aggregate is wet. On the other hand, when the aggregate is dry, it is essential to consider the water absorbed by the aggregate to saturate it and dry its surface, and add it to the quantity of water in the mix. The design of concrete mixtures in various specifications is based on the assumption that the aggregate is saturated and has a dry surface. Therefore, it is essential to pay attention when using the results of laboratory tests to determine the mix proportions used at the construction site.

3. Gel/space ratio:

The strength at any water-cement ratio depends on several factors: the degree of cement hydration and its chemical and physical properties, the temperature at which hydration occurs, the air content in the concrete, and the occurrence of cracking due to shrinkage. Therefore, it is more accurate to correlate strength with the concentration of solid products resulting from the cement hydration process in the available voids.

Powers has determined the relation between the strength development and the gel/space ratio. This ratio is defined as the ratio of the volume of the hydrated cement paste to the sum of the volumes of the hydrated cement and of the capillary pores. The actual relationship between the compressive strength of mortar and the gel/space ratio is illustrated in Figure7-2, showing that the strength approximately varies with the gel/space ratio.

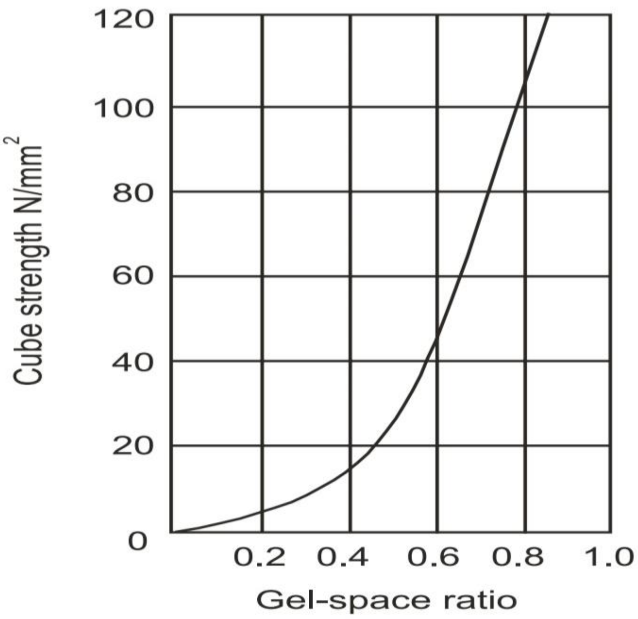


Fig. 7.2: Relation between the compressive strength of mortar and gel/space ratio.

4. Influence of properties of coarse aggregate:

The effect of aggregate type on the compressive strength of concrete is secondary because these types of aggregates are stronger than the surrounding cement paste. Moreover, the difference in maximum aggregate size, when well-graded, has contrasting effects on the compressive strength of concrete. With a constant cement content and consistency, larger maximum size aggregate requires less water compared to smaller maximum size aggregate. On the other hand, with constant cement content and consistency, larger maximum size aggregate provides lower strength, likely due to the occurrence of cracks in the cement paste surrounding the larger pieces.

Through laboratory tests, it has been found that the magnitude of stress at which cracks form depends significantly on the properties of coarse aggregate: Smooth, fine-textured gravel leads to crack formation at lower stresses compared to using coarse, angular gravel or crushed stone. This is likely due to the mechanical interlocking influenced by the surface properties of the coarse aggregate.

The effect of coarse aggregate on concrete strength varies in magnitude and depends on the water/cement ratio in the mix. When the ratio is less than 0.4, using crushed aggregate may lead to an increase in strength by approximately 38% compared to using gravel. However, as the water/cement ratio increases, the effect of the coarse aggregate decreases, assuming that the strength of the cement paste becomes the critical factor for failure.

5. Influence of aggregate/cement ratio:

There is no doubt that the aggregate-to-cement ratio is a secondary factor in determining the strength of concrete, but it does affect the strength of all mixtures with medium and high strengths.

It has been found that with a constant water/cement ratio, concrete mixes with lower cement content and mixes containing a larger quantity of aggregate tend to have higher strength. This behavior is likely related to the absorption of water by the aggregate, as a larger quantity of aggregate absorbs a greater amount of mixing water, thereby reducing the effective water/cement ratio. Additionally, other factors may also play a role, for example, the total water content per cubic meter of concrete will decrease in the mix with lower cement content compared to the richer mix. As a result, the voids in the mix with lower cement content will constitute a smaller portion of the total volume of concrete, and these voids have an inverse effect on strength.

6. Quality of mixing water:

The quality of the water used in mixing and its impurity content may conflict with cement hydration, affecting the concrete's strength inversely, and it may also lead to the corrosion of reinforcement steel. For these reasons, it is essential to consider the suitability of the water used in mixing or curing concrete.

Most specifications define the quality of water used in mixing and indicate that drinkable water can be used. As a rule, water that is not salty is suitable for use, but dark color or foul odor does not necessarily mean the presence of harmful substances in the water. In cases where the water contains large amounts of suspended solids such as silt or clay, it is preferable to let the water settle in tanks and allow these solids to settle.

On the other hand, laboratory tests have shown that seawater accelerates the setting time of cement, and water containing large amounts of chlorides leads to the appearance of moisture on the surface of concrete, in addition to the occurrence of efflorescence. In the case of reinforced concrete, the use of seawater increases the risk of corrosion of the reinforcement steel. Generally, the use of seawater in mixing is not recommended unless absolutely necessary. In the case of prestressed concrete, seawater should never be used due to the small wire section and the risk of corrosion. In cases where natural and slightly acidic waters are used in the mix, they are usually harmless. However, water containing organic acids or highly alkaline water must be tested for suitability before use through laboratory tests. As for water used for concrete curing, there is a general note that any water considered acceptable for mixing can also be used for curing concrete.

7. Effect of age on strength:

Different types of cement require different time periods to develop the same amount of gel formation. Knowing the rate at which concrete gains strength through laboratory tests is important to verify the suitability of the mix for use before the specified period (28 days), as this helps to shorten the time factor and has economic implications. However, even if curing conditions are accurately controlled, it can be difficult to estimate the strength of concrete at 28 days from that measured at 7 days, and the main reason for this is the fundamental difference in the rate of hardening of commercial cement.

Additionally, mixtures with a low water/cement ratio achieve strength more rapidly than mixtures with a high water/cement ratio. The reason for this is that in the first case, cement particles are closer to each other, resulting in the formation of a continuous gel network more quickly. Therefore, determining the strength at 28 days from the strength at 7 days is not a simple matter, even if only one type of cement is used.

When no specific information about the materials used is available, the strength at 28 days may be assumed to be about 1.5 times that at 7 days. Laboratory tests on concrete made from Portland cement have generally indicated that the ratio of strength at 28 days to that at 7 days falls between 1.3 and 1.7. However, in hot weather, early strength development is higher, and the ratio of strength at 28 days to that at 7 days tends to be lower than in cold weather.

In Germany, the relationship between the strength at 28 days and the strength at 7 days is often considered to fall between:

S_{28} (MPa) = 1.4 S_7 + 1.0

S_{28} (MPa) = 1.7 S_7 + 5.9

8. Influence of temperature on strength:

An increase in temperature during the curing process accelerates the chemical reactions for hydration and positively affects the early strength of concrete without negatively impacting the later strength. However, when the temperature is high during the placement and curing of concrete, despite significantly enhancing early strength, it may have a detrimental effect on the strength at 7 days and beyond. This is because rapid initial hydration leads to the formation of hydration products with weak physical structures, which are likely to be more porous. As a result, a large proportion of these pores will remain unfilled. Following the principle of the gel/space ratio, it can be concluded that the strength will be weaker compared to slowly hydrated cement paste containing fewer pores as a result.

Another explanation for this is that an increase in the rate of initial hydration at high temperatures leads to a slowdown in later hydration. As a result, the distribution of hydration products within the cement paste becomes irregular, adversely affecting the strength because the gel/space ratio in the interstitial spaces will be lower than if hydration occurred continuously at a normal rate. Consequently, localized weak zones form within the cement paste, leading to a decrease in overall strength.