# Concrete Strength

Chapters 7

# Introduction

- **Strength of concrete** is commonly considered to be its **most valuable property**, although in many practical cases other characteristics, such as durability, impermeability and volume stability, may in fact be more important.

- Concrete can be considered as
  - **A brittle material**
  - **Anisotropic** (materials whose properties are directionally dependent).
  - **Weak in tension and relatively strong in compression**. Accordingly **compressive strength** is the most important characteristic

# Introduction

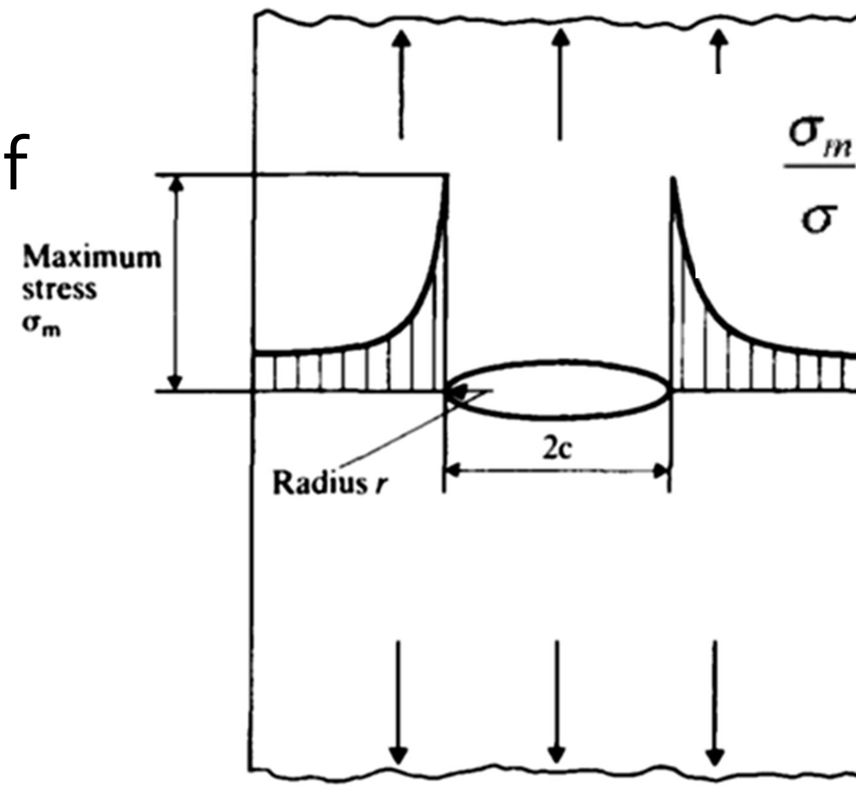
- **Theoretically the sources of concrete weakness are:**

  - **Porosity** of the cement paste.
  - The **presence of the aggregate** (itself may contain flaws in addition to being the cause of microcracking at the interface with the cement paste).

# Tensile Strength Considerations

- It was noticed that the actual tensile strength of paste is very much lower than the theoretical strength (calculated on the basis of molecular cohesion of the atomic structure). The measured stress is 1000 times less than the theoretical. WHY?

- The difference is attributed to existence of flaws, microcracks, or other defects that have the effect of concentrating the stress as shown in fig.



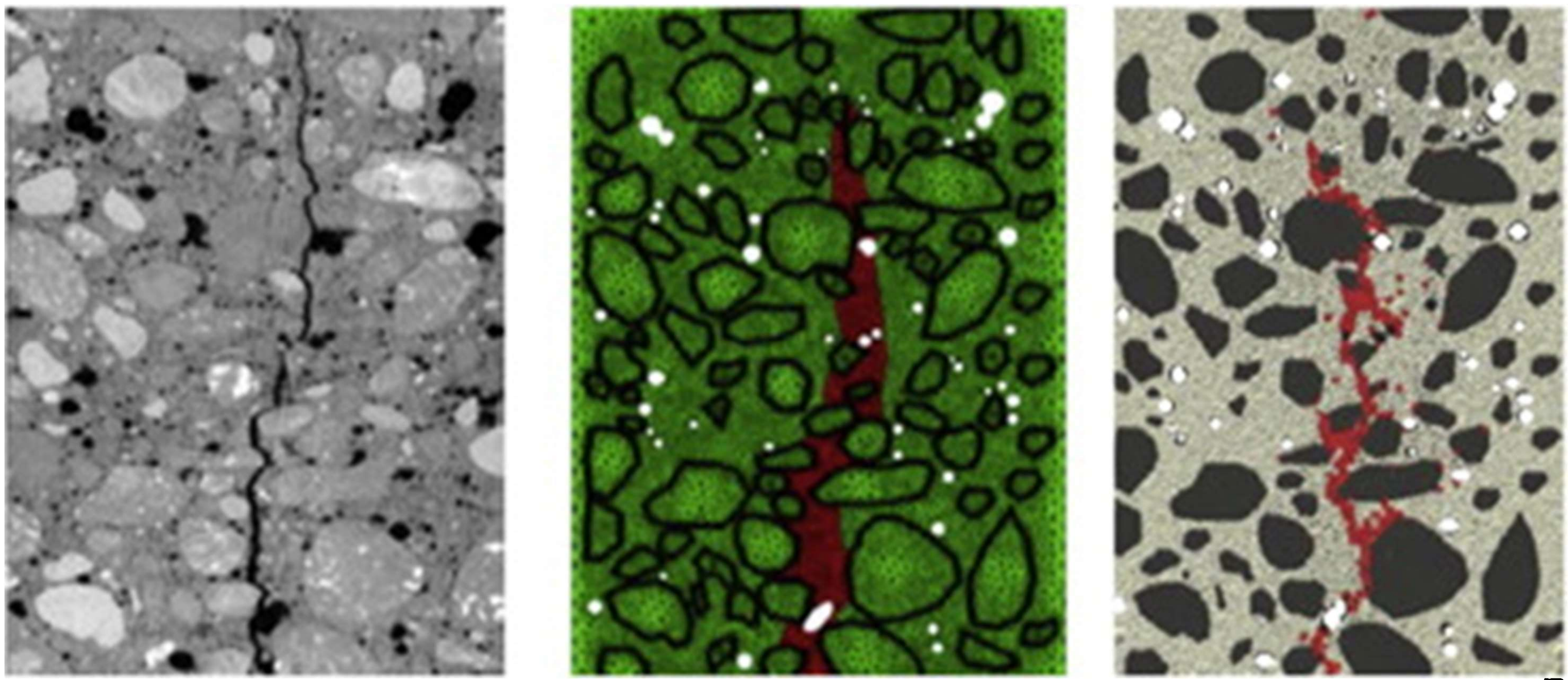

$$\frac{\sigma_m}{\sigma} = 2\left(\frac{c}{r}\right)^{\frac{1}{2}}.$$

# Tensile Strength Considerations

- According to the brittle fracture theory, failure is initiated by the largest crack which is oriented in the direction normal to the applied load, and thus the problem is one of statistical probability of the occurrence of such a crack.
- This means that size and, possibly, shape of the specimen are factors in strength because, for example, there is a higher probability that a larger specimen contains a greater number of critical cracks which can initiate failure.

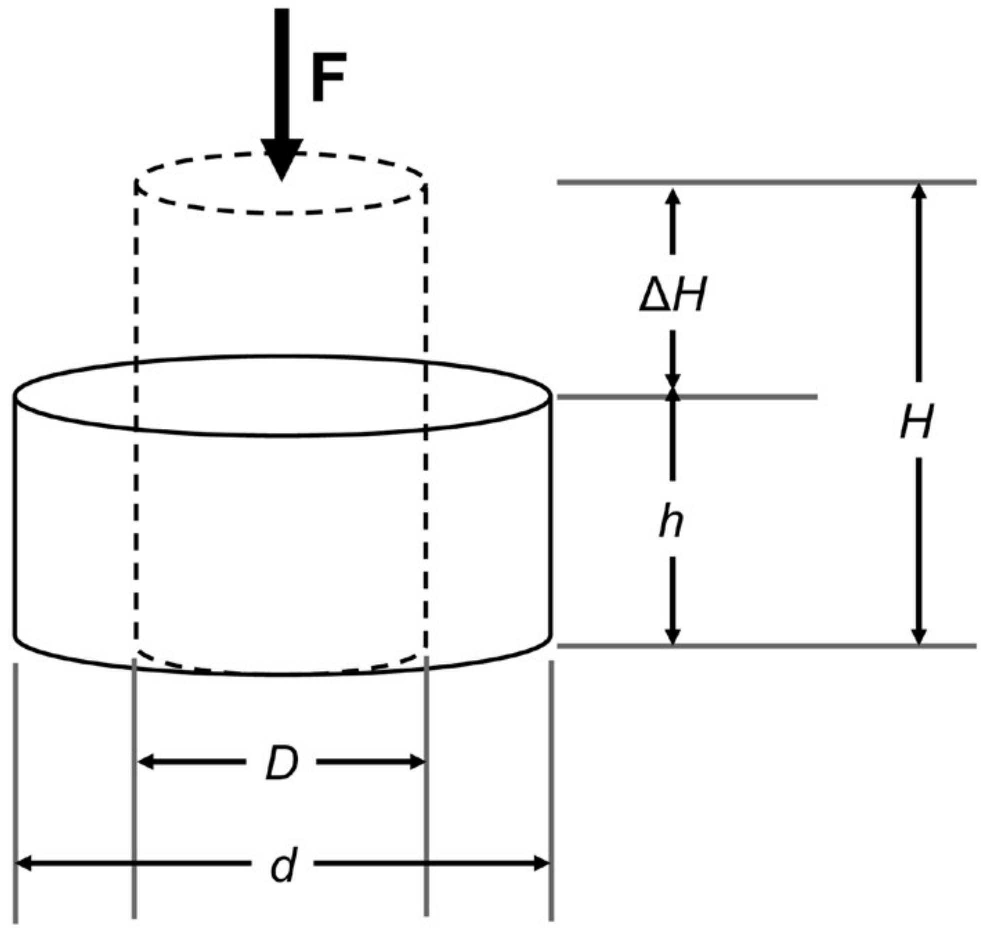
# Tensile Strength Considerations

- In test samples, the actual failure paths usually follow the interfaces of the largest aggregate particles, cut through the cement paste, and occasionally also through the aggregate particles themselves as shown below.



# Behavior Under Compressive Stress

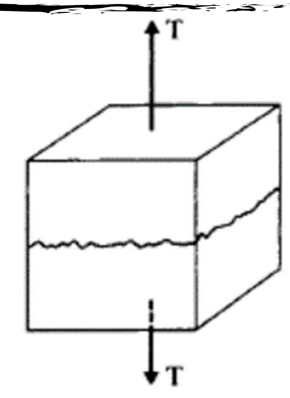
Even when concrete is subjected to compressive stress, it fails due to tension stress.



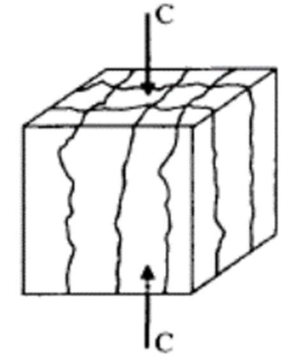
# Behavior Under Compressive Stress

The figure shoes the observed fracture patterns under different states of stress.

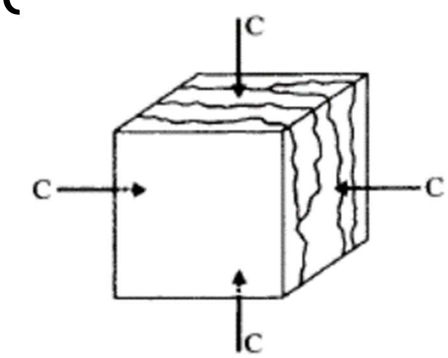
- Under uniaxial tension, fracture occurs in a plane normal to the direction of the load (figure a).
- Under uniaxial compression, the cracks are approximately parallel to the applied load. column-type fragments (Fig. b).
- Under biaxial compression, failure takes place in one plane parallel to the applied load and results in the formation of slab-type fragments (Fig. c).
- Under triaxial compression, failure takes place by crushing.



(a)



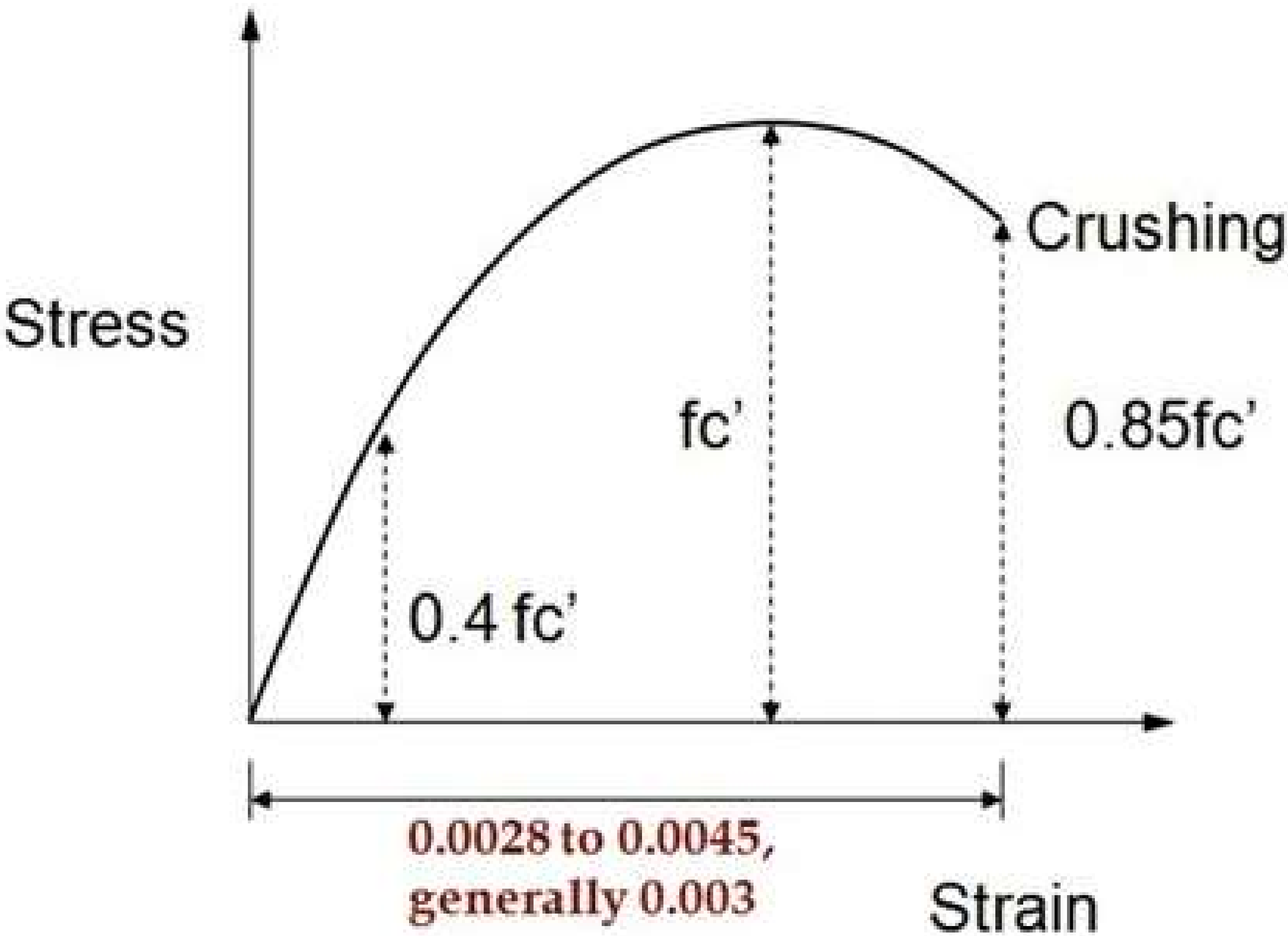
(b)



(c)

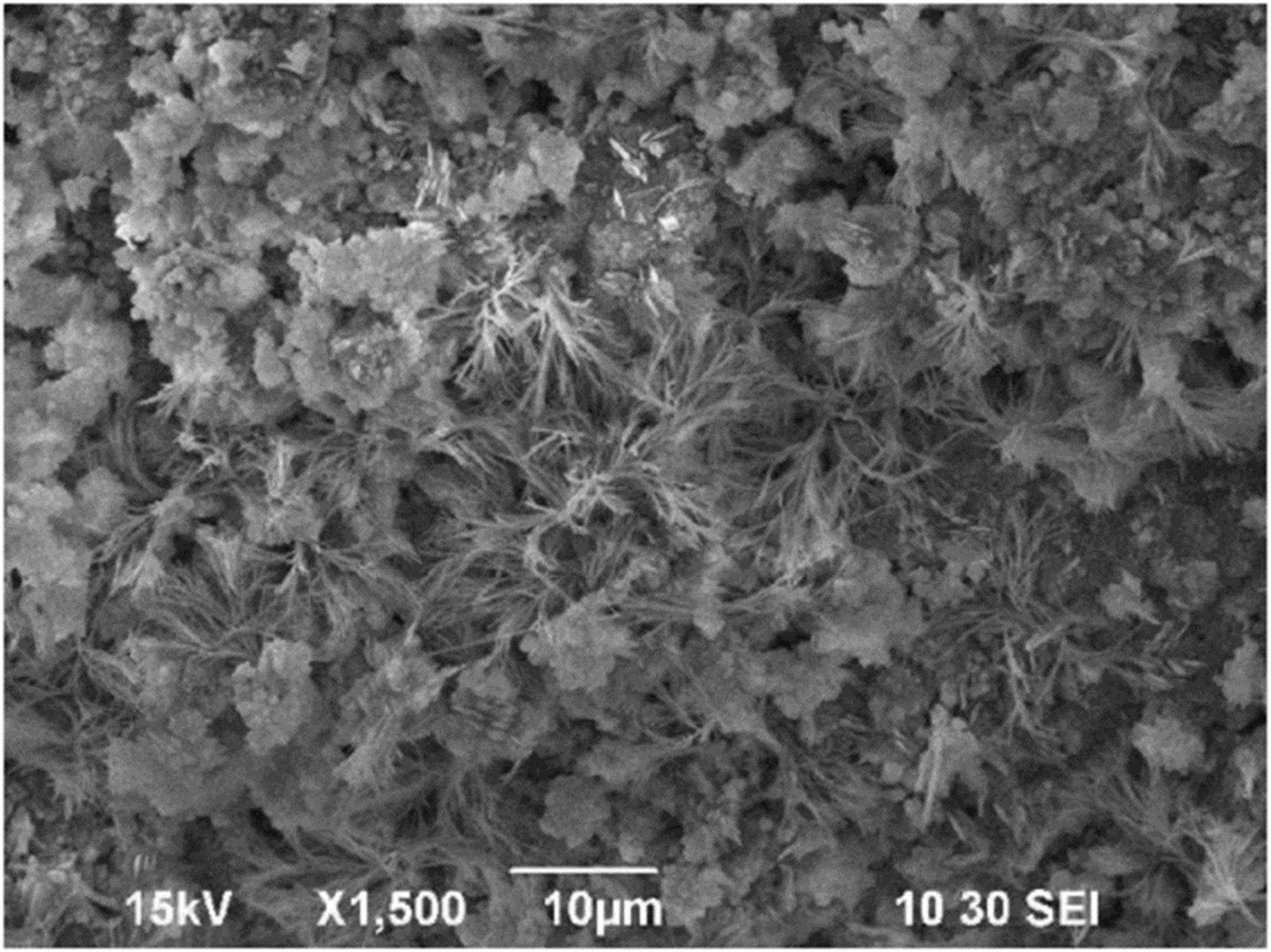
# Behavior Under Compressive Stress

Stress strain curve of concrete under compression load




- The first portion of curve, to about 40% of the ultimate strength $f_c'$, can be considered linear.
- The lower the strength of concrete the greater will be the failure strain

# Cement Paste Porosity




**Micrographs of cement hydration products (about .1X.1 mm)**

# Cement Paste Porosity

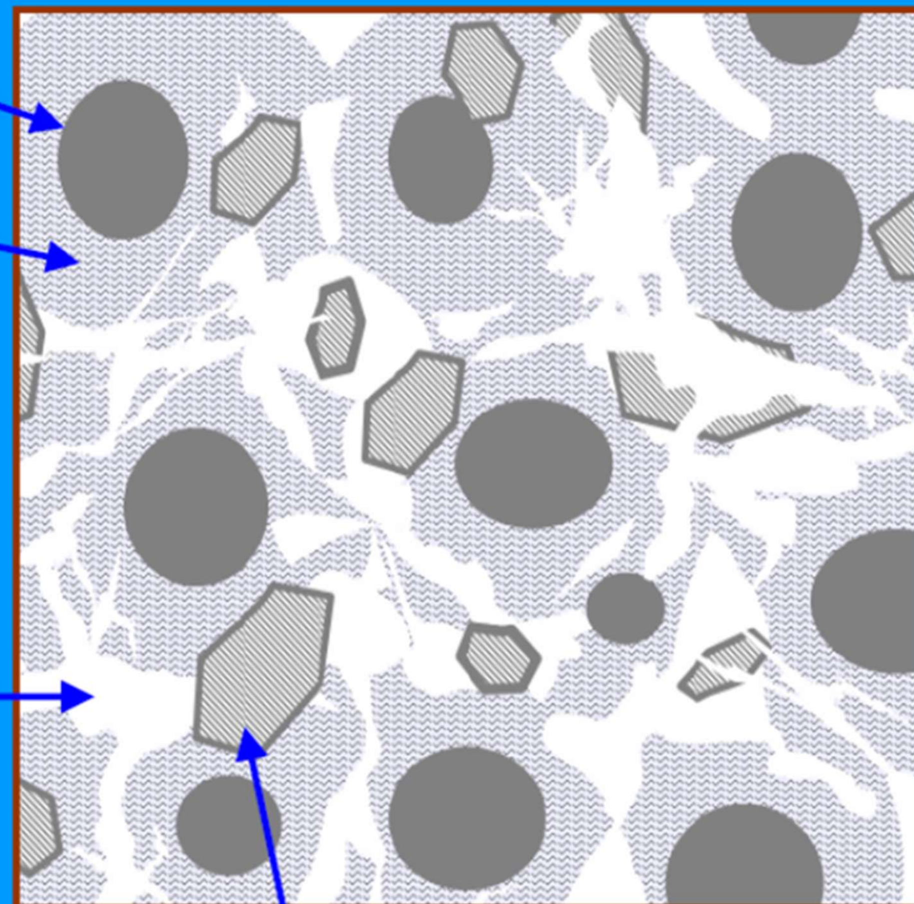
1. Unhydrated cement

2. C-S-H gel containing gel pores (interlayer water)

**Gel (or interlayer) pores** have size of 0.5-2.5 nm and occupy about 28 vol. % of C-S-H gel

3. Capillary pores (capillary water)

**Capillary pores** can have sizes from 10 to 1000 nm (1 μm) and even up to 5 μm. Volume and size depends on water/cement ratio and degree of hydration



4. Hexagonal crystals of calcium hydroxide (portlandite)

**Simplified scheme of Hydrated paste microstructure**

# Cement Paste Porosity

- **Air Pores**. In addition to gel and capillarity pores air pores can also exist due to the air that can be trapped in the cement paste during mixing or due to poor compaction.

# Cement Paste Porosity

**Capillary Porosity, $P_c$**

Is the volume of the capillary pores as a fraction of the total volume of the hydrated cement paste given by:

$$P_C = \frac{\frac{W}{C} + \frac{a}{C} - 0.36h}{0.317 + \frac{W}{C} + \frac{a}{C}}$$

**Total porosity of the cement paste, $P_t$**

Is the ratio of the sum of the volumes of gel pores and of capillary pores to the total volume of cement paste

$$P_t = \frac{\frac{W}{C} + \frac{a}{C} - 0.17h}{0.317 + \frac{W}{C} + \frac{a}{C}}$$

Where

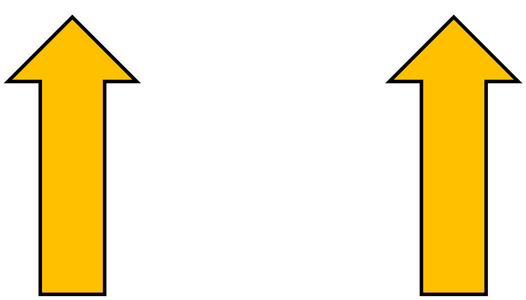
a = volume of air in the fresh cement paste.

h = Degree of hydration

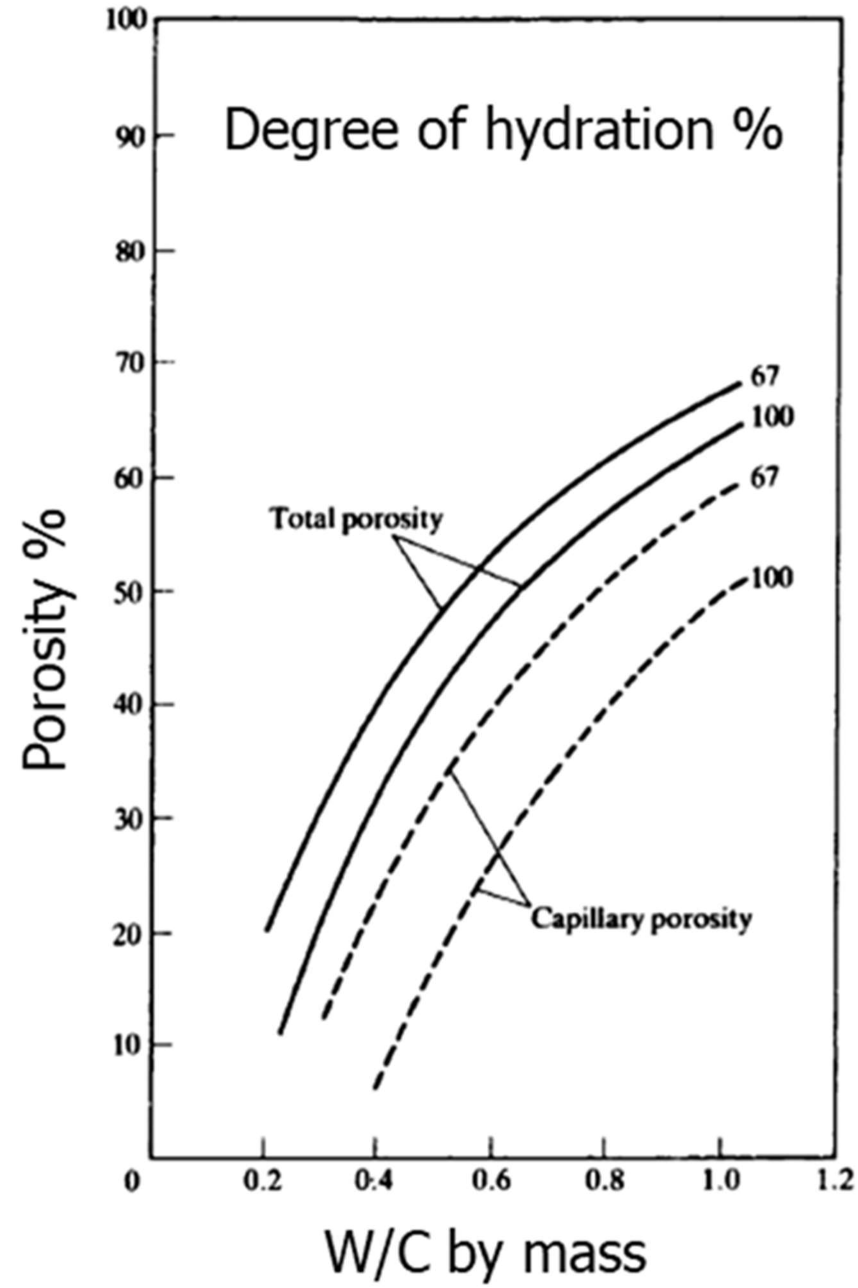
W/C = water cement ratio.

# Cement Paste Porosity

Previous Equations demonstrate that porosity depends upon the water/cement ratio and on the degree of hydration (h). In fact, the term W/C in the numerator of the equations is the main influencing factor on porosity,



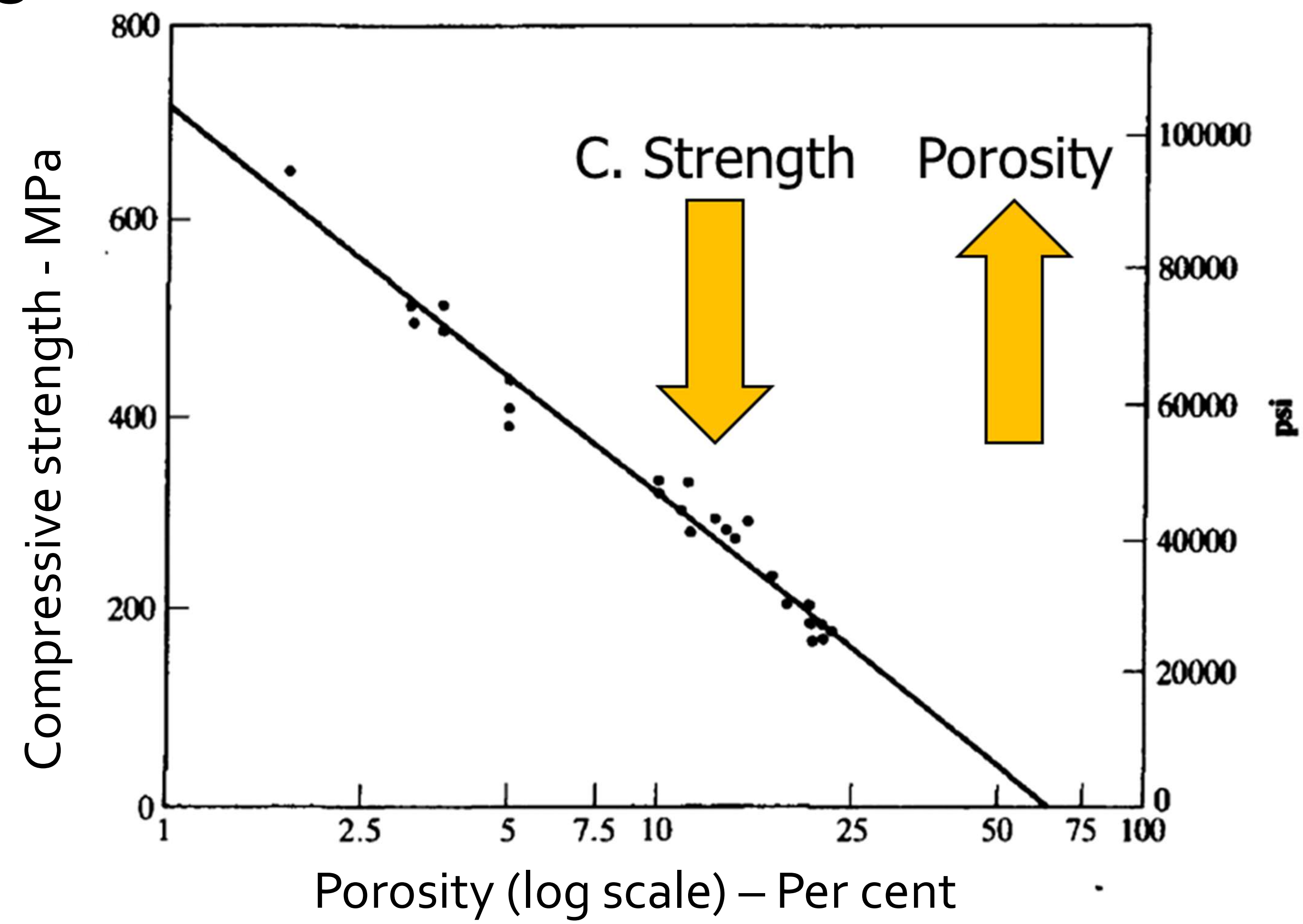
**W/C** **Porosity**



# Cement Paste Porosity

**<u>Relation between compressive strength and porosity</u>**

There is a corresponding relation between porosity and strength. The Figure shows the relation between porosity and strength for cement pastes.



# Factors in Strength of Concrete

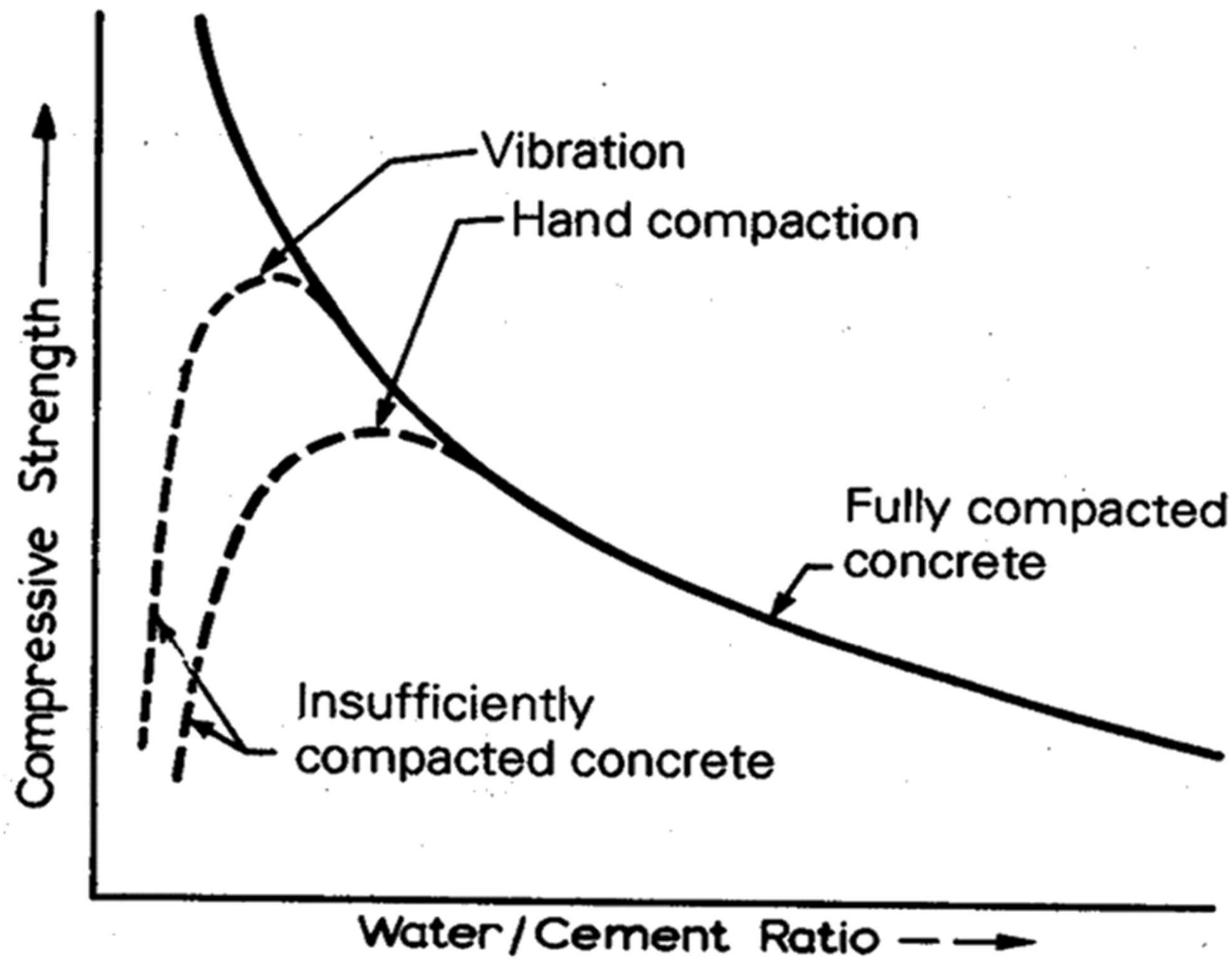
- Although porosity is a primary factor influencing strength, it is a property difficult to measure in engineering practice, or even to calculate since the degree of hydration is not easily determined.
- For this reason, the main influencing factors on strength are taken in practice as: water/cement ratio, degree of compaction, age, and temperature. In addition to quality and quantity of aggregates.

# Factors in Strength of Concrete

| **Theoretical** | **Practical** |
| --- | --- |
| **Porosity** (relative volume of pores or voids in the cement paste)<br>▪ Constituent materials<br>• **W/C ratio**<br>• Aggregate/cement ratio<br>• Quality of the aggregate<br>• Transition zone<br>▪ Age and Temperature | ▪ Preparation and handling method<br>▪ Degree of compaction<br>▪ Curing |

# Effect of W/C ratio

**Abrams law**: Assuming full compaction, and at a given age and normal temperature, strength of concrete can be taken to be inversely proportional to the water/cement ratio.

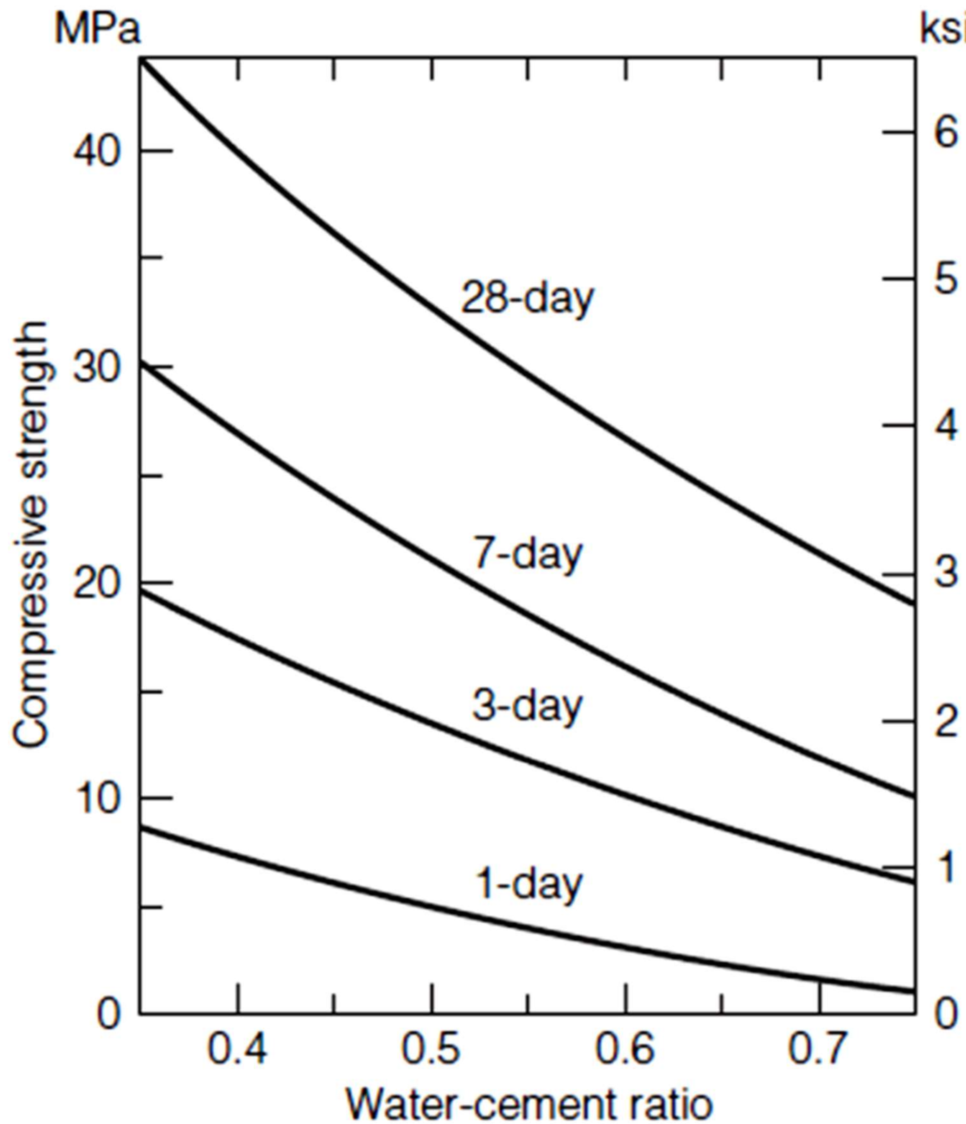


# Comments on Abrams law

- A low water–cement ratio also increases resistance to weathering, provides a good bond between successive concrete layers, provides a good bond between concrete and steel reinforcement, and limits volume change due to wetting and drying.
- It should be noticed that **Curing** is crucial to maintains satisfactory moisture content and temperature in the hardened concrete for a definite period of time to allow for hydration and thus full strength.
- W/C in Abrams law is the effective water/cement ratio, which is calculated on the basis of the mix water less the water absorbed by the aggregate.

# Effect of concrete age on strength

As a general rule, the ratio of 28-day to 7-day strength of concrete lies between 1.3 and 1.7, but it is usually less than 1.5.




Typical age-strength relationships of concrete

# Effect of aggregates on concrete strength

- **Aggregate/Cement Ratio**

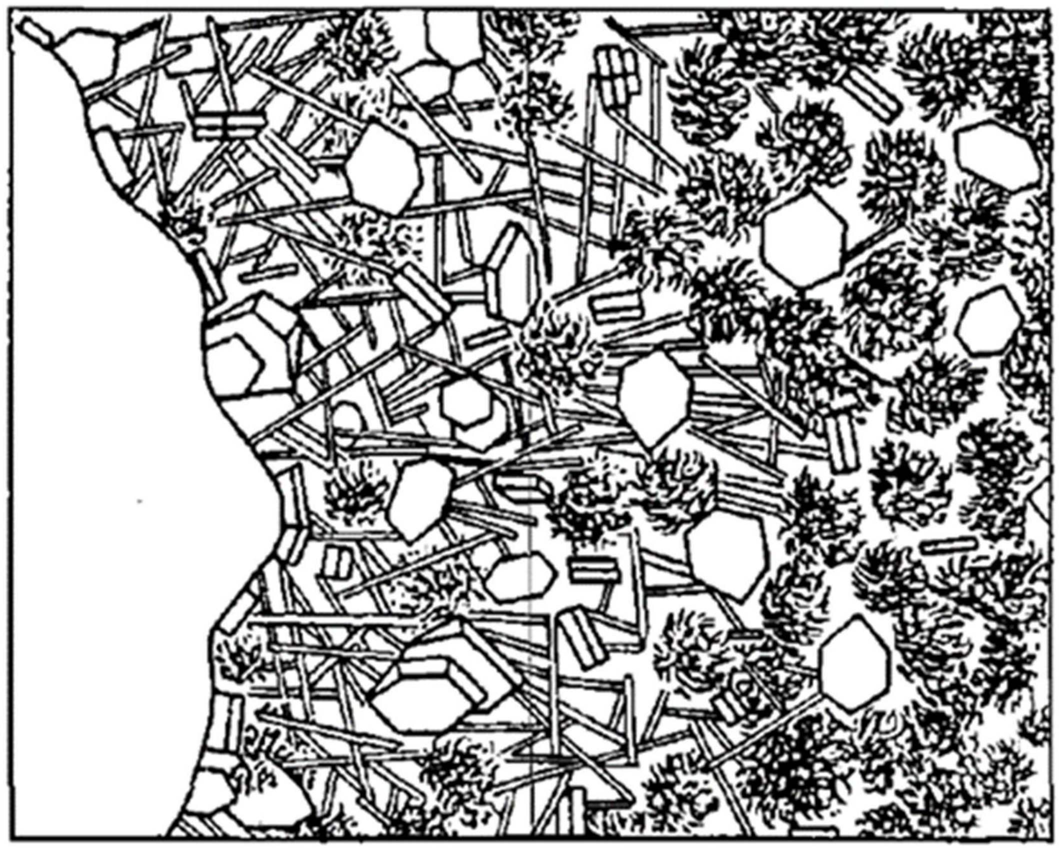
- It has been found that, for a constant water/cement ratio, mixes with high aggregate/cement ratios leads to a higher strength.

- This can be explained as if the paste represents a smaller proportion of the volume of concrete, then the total porosity of the concrete is lower, and hence its strength is higher

- **Aggregate Properties**: The influence of the aggregate properties on strength is of secondary importance. For example: smooth gravel leads to cracking at lower stresses than rough and angular crushed aggregate.

# Effect of The Interfacial Transition Zone (ITZ)

- ITZ is the interface between the aggregate and hydrated cement paste. ITZ is typically 20-40 Micron thick and has:




- Higher porosity, and is therefore weaker, than the hydrated paste further away from the aggregate.
- Large oriented crystals of calcium hydroxide; and greater concentration of ettringite.

# Effect of The Interfacial Transition Zone (ITZ)

- The strength of the interfacial transition zone has a small, but measurable, effect on the compressive strength of concrete and a major effect on the tensile and fracture properties of concrete.

- Major changes in the strength of the interfacial transition zone can affect compressive strength on the order of 10 to 15% and may affect the tensile strength on the order of 40%.