Republic of Iraq
The Ministry Of Higher Education and Scientific research
University of Anbar -Engineering College
Civil Engineering Department

Advanced Concrete Durability
Master Course

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Sustainability:

- Definition of Sustainability
- Sustainability in Civil Engineering
- Sustainability in Construction Engineering

What is the difference between Sustainability and Durability?
Does Sustainability related to concrete Engineering?

❖ **Sustainability of concrete structures**

✓ Materials
✓ Design
✓ Performance (thermal, mechanical, ….)
✓ Durability

Durability of concrete:

- Durability of concrete: is the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.
- The concrete structures are designed to perform their intended function. The most important one is maintain the required strength and switch-ability during the designed age.
- The vast majority structures/ infrastructure projects ,in Iraq, are concrete
- Recently, high performance concrete (HPC) was developed.
- High strength concrete and ultra-high strength concrete.

Causes of inadequate durability:

1. External factors.
2. Internal factors.

Both of them (external and internal) could be caused by physical, chemical or mechanical actions.

Physical causes:

1. High temperature.
2. Differences in thermal expansion of aggregate.
3. Hardened cement paste.
4. Freezing and thawing of concrete and the associated action of de-icing salts.

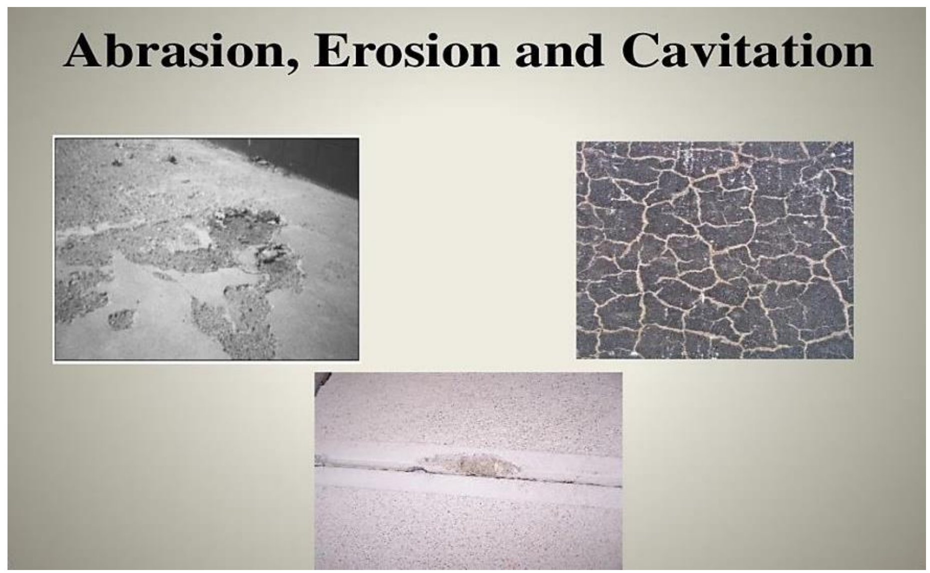
Chemical Causes:

1. Alkali-silica and alkali-Carbone reactions.
2. External chemical attack that occurs mainly due to the action of aggressive ions, such as chlorides, sulfate, carbon dioxide and many natural or industrial liquids and gases.

* The damage in this kind of cause could be directly or indirectly.
* Chemical and physical processes of deterioration could be act in a synergistic manner.

Mechanical Causes:

1. Impact
2. Abrasion
3. Erosion
4. Cavitation



Transport of Fluids in Concrete:

- The relevant fluids to concrete durability are water (pure or contaminated with aggressive ions), carbon dioxide and oxygen.
- The transport of all aforementioned types are mainly governed by the hydrated cement paste structure in addition to pores distribution i.e. permeability (different than porosity, would be explained later). Permeability is referring to the ability of the fluids to flow through a porous medium.
- The movement of fluids through a concrete body occurs not only by flow through the porous system but also by diffusion and sorption (penetrability of concrete). However, permeability is the common used term.

Pores Size and Types:

1. Gel pore (**28%** of the total gel volume) **0.5-4 ηm** (diameter).
2. Capillary pore **10 ηm - 10µm**.

Gel and capillary pores are known active pore spaces as they affected by hydration of cement and moisture content.

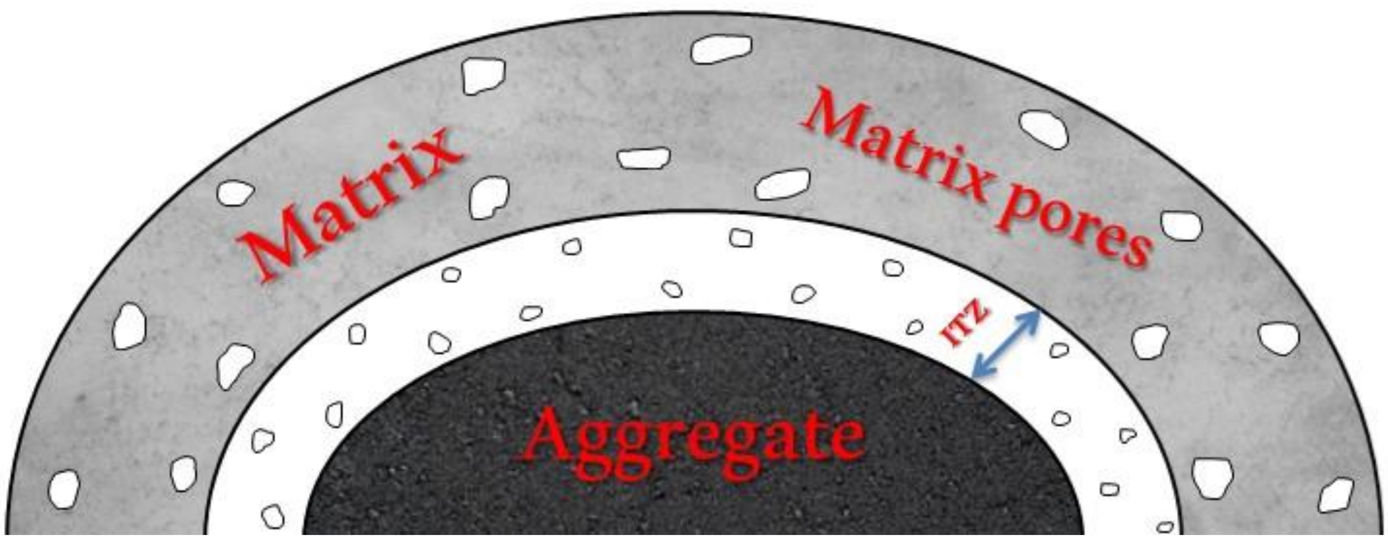
* Water molecule is **2.75°A = 0.275 ηm**

The non-active pores are

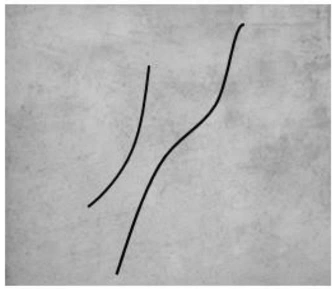
3. Entrained air voids which caused by air entraining agents **1-500 µm**.
4. Entrapped air voids **1000-10,000 µm.**

Influence of the pore system:

- The hardened cement paste is directly connected to the permeability
- Permeability is affected by the nature of the pore system within the bulk of the HCP and also in the Interfacial Transition Zone ITZ between the cement paste and the aggregate. What is the width of ITZ?
- ITZ has different microstructure than the bulk in addition to having micro-cracks. Therefore, it was found that ITZ is significantly influenced the concrete permeability.



- Neville claimed that there is no significant difference in the cement paste and concrete permeability due to the active and non-active pores concept.
- The presence of the aggregate makes the fluid path is longer and more tortuous.



Concrete Paste

Concrete

70-80 %
Aggregate

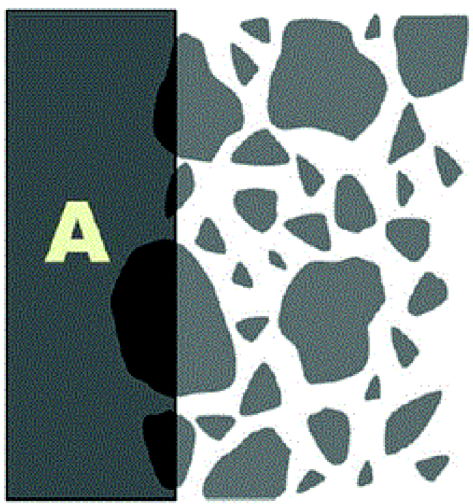
* It is said that pores to be affective should have at least **120-150 ηm** diameter and also they should be continuous i.e. this pore system would increase permeability but otherwise would increase porosity rather than permeability.

* Although aggregate contain pores, they do not contribute in increasing permeability as they are usually discontinuous and also they are enveloped by the cement paste. The same applied to discrete air voids, such as entrapped/entrained air bubbles in addition to the voids that caused by in completed compaction and/or by trapped bleed water. These voids together may occupy (except the entrained air as they aimed) up to **10%** that caused a low quality concrete i.e. more than that is not permissible to be used as a structural concrete. **Why?**

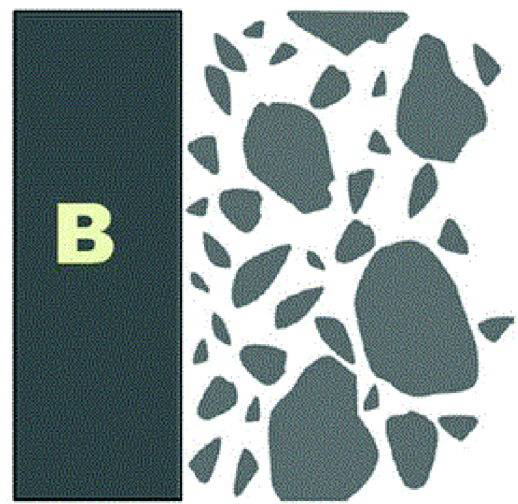
Interfacial Transition Zone (ITZ):

Concrete is regarded as a three phase material; aggregate, HCP and the ITZ. The cement paste in the ITZ is essentially different than the bulk paste and it is considerably weaker than the rest of the paste. This could be attributed to:

1. Wall effect phenomenon that caused by the large different sizes between cement grains (**1-100 µm**) and aggregate particles e.g. **10-20mm**. this means that each aggregate particle works as a “mini wall” facing the packing of the cement grain, resulting in the “wall” effect as illustrated in the Figure below (A).

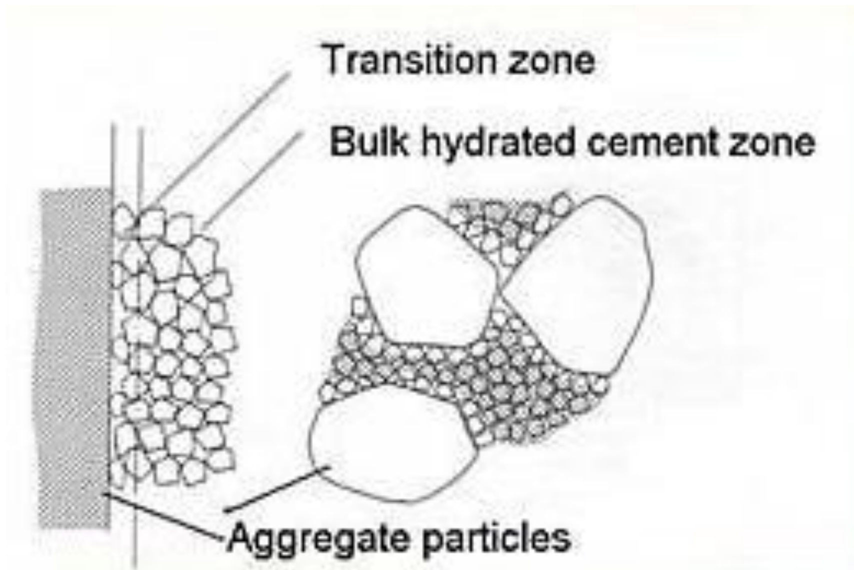


Without aggregate Wall



With aggregate Wall

- This would not effectively allow the proper packing of the cement grains leading to accumulation of smaller grains in the zone close the aggregate and therefore higher porosity.
- However, there is another explanation of wall effect that is as cement grains are almost having same size, they cannot be uniformly packed i.e. there would be voids among them (B) and as below.



Cited from somewhere else

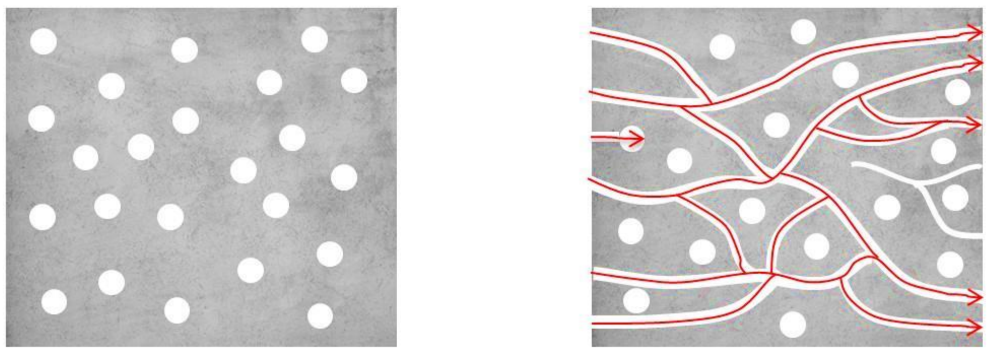
2. The localized water on the aggregate surface which occurs when the aggregate id fully-saturated leading to local increases in w/c causing a weak cement paste. This is also caused by bleeding /micro bleeding. In this case the water can accumulate beneath the aggregate particles leading to a local weakness at the interface and more prone to micro-cracking under loading.

In conventional concrete, it was found that the width of ITZ is between **30 to 50 µm** (Scrivener claimed that the most effective distance is the first **15-20 µm**). As mentioned earlier, the cement paste in ITZ has a simple microstructure in comparison with the rest of the paste, where it consists of a very thin layer of calcium silicate hydrate (C-S-H) that surrounds the aggregate particle surface in addition to some crystals of calcium hydroxide and fine needles of calcium sulfoaluminate (Ettringite). (Go back to Concrete Technology lectures).

It was found that ITZ is of importance in determining concrete strength and durability, where when concrete is loaded micro/cracking starts normally at the ITZ (**Why ?**) and begins to widen and propagate in concrete body until the failure occurs.

Permeability and Porosity:

As previously mentioned that there are different kinds of pores some of them contribute to permeability and some of them do not do so, it is important to understand that there is a difference between permeability and porosity. Porosity is a measure of proportion of the total volume of concrete occupied by pores, and is usually expressed in percent. In the case of high porosity and intersection pores, the permeability would increase by contributing in the fluids transport through concrete. Unlike the discontinuous pores or that ineffective with respect to transport, the concrete permeability would not be effective even though its porosity is high (See Figure below).



Porosity **Permeability**

Porosity can be measured using mercury intrusion and an indication of porosity can be obtained from the measurement of absorption of concrete

https://www.youtube.com/watch?v=8mfBomrw0rs (porosity and permeability)

Transportation mechanism:

- Fluids could more through a concrete body by three different mechanisms that are flow, diffusion and sorption.
- Permeability refers to the flow under a pressure (differential).
- Diffusion is the process in which a fluid moves under a differential in concentration, the relevant property of concrete is diffusivity. Gases can diffuse through water-filled space or through air-filled, but in the case of water-filled the process is slower by **10^4 - 10^5** times than that for air-filled.
- Sorption is the result of capillary movement in the concrete pores which are open to the ambient medium. Capillary sorption can take place only in partially dry concrete; there is no sorption of water in completely dry concrete or in saturated concrete.

Coefficient of permeability:

Flow in capillary pores in saturated concrete follows Darcy's law for laminar flow (What is the other kind of flow?) through a porous medium.

$$\frac{dq}{dt}\frac{1}{A} = \frac{K'\rho g}{\eta}\frac{\Delta h}{L}$$

Where:

$\frac{dq}{dt}$= rate of flow of water in m^3/s. A= cross-section area of the sample in m^2.

Δh= drop in hydraulic head through the sample, measured in m.

L=thickness of the sample in m.
η= dynamic viscosity of the fluid in $N.s/m^2$.
p= density of the fluid in kg/m^3.
g= acceleration due to gravity.

The coefficient K´ (m^2) represented the intrinsic permeability of the material, independently on the fluid involved (check).
As the fluid involved is generally water:

$$\boldsymbol{K = \frac{k' p g}{\eta}}$$

The coefficient k´ is then expressed in m/s and is referred to as the coefficient of permeability of concrete (at room temperature) as the water viscosity changes with temperature, the previous equation can be written as:

$$\boldsymbol{\frac{dq}{dt}\frac{1}{A} = K\,\frac{\Delta h}{L}}$$

When a steady state of flow $\frac{\mathrm{dq}}{\mathrm{dt}}$ reaches, K is directly determine.

Depth of water penetration under pressure:

- There is standard test for measuring the permeability. However, there are many tests that used to assess permeability. One of these tests is measuring the depth of water penetration under pressure and this test is conducted based on BS EN 12390-8:2009 using a commercial machine called water impermeable tester.
- The depth of water penetration could be used to calculated the coefficient of permeability as suggested by "Valenta" using the following equation:

$$K = \frac{e^2 V}{2ht}$$

Where:

e= depth of water penetration in concrete (m)

h= hydraulic head (m)

t= time under pressure

V= the fraction of the volume of concrete occupied by pores.

Diffusion:

- It takes place due to the transport of gas or vapor through concrete as a result of a concentration gradient, not of a pressure differential.
- Carbon dioxide leads to carbonation of hydrated cement paste while Oxygen leads to a possible corrosion of steel reinforcements.

- Diffusivity coefficient of a gas is inversely proportion to the square root of its molar mass. Theoretically, oxygen diffuses **1.17** times, faster than carbon dioxide, so this relation makes it possible to calculate the diffusion coefficient of one gas from experimental data on another gas.
- The diffusion equation applicable to water vapor and air can be expressed by Fick's law as:

$$J = -D\frac{dC}{dL}$$

Where:

$\frac{dC}{dL}$= concentration gradient in kg/m^4 or moles/m^4.

D= diffusion coefficient in m^2/s.

J= mass transport rate in kg/m^2.s or (moles/m^2.s).

L= sample thickness (m).

- Diffusion take place through the pores (3D), However, J and D refer to the cross-section of the concrete sample (2D), thus D is in reality represents the effective diffusion coefficient.
- The diffusion coefficient of a gas can be experimentally determined under a steady-state system, with two sides of a concrete specimen being exposed, each to a different pure gas.
- The mass of gases on the side opposite to that where they originally present is then determined. The pressure on each side of the specimen should be the same because the driving face in diffusion is the difference in molar concentration and not a pressure differential.

Suggestions for Further Reading

1. Diffusion through air and water
2. Absorption
3. Surface absorption test
4. Sorptivity

Air and vapor permeability:

- Water vapor and some gases (O and CO_2) can penetrate into concrete which have action relevant to the durability aspects.
- It should be distinguished between the case when there is a pressure differential (permeability), and when the pressure and temperature are the same on two sides of concrete specimen or member (diffusion).
- Diffusivity is linearly related to the intrinsic permeability of concrete, therefor, diffusivity can be calculated from permeability test, which is easier to perform.
- Because gases are compressible, the pressure, p_0 at which the volume flow rate q (m^3/s)is measured, has to be taken into account in addition to the inlet pressure, P and outlet pressure Pa, all pressures are absolute values in N/m^2.
- The intrinsic permeability coefficient, K expressed in $m^2$is:

$$K = \frac{2qp_{\circ}L\eta}{A(P^2 - Pa^2)}$$

Where:
A=cross-section area of the specimen (m^2)
L=specimen thickness (m)
η= dynamic viscosity in $N.s/m^2$.
* For example Oxygen has **$\eta=20.2*10^{-6}$** at 20 Cº.

- In theory, K should be the same for a given concrete regardless of whether a gas or a liquid is used in the test. However, gases yield a higher value of K because of the phenomenon of the gas slippage i.e. gas has a finite velocity at the flow boundary.
- The difference between gas permeability and liquid permeability is large at lower value of K and the ratio of gas to liquid permeability is ranging between 6 and up to 100.
- Air permeability is more affected by the curing type especially in low and moderate strength of concrete as it can be seen in the the Figure below.