Portland Cement Concrete

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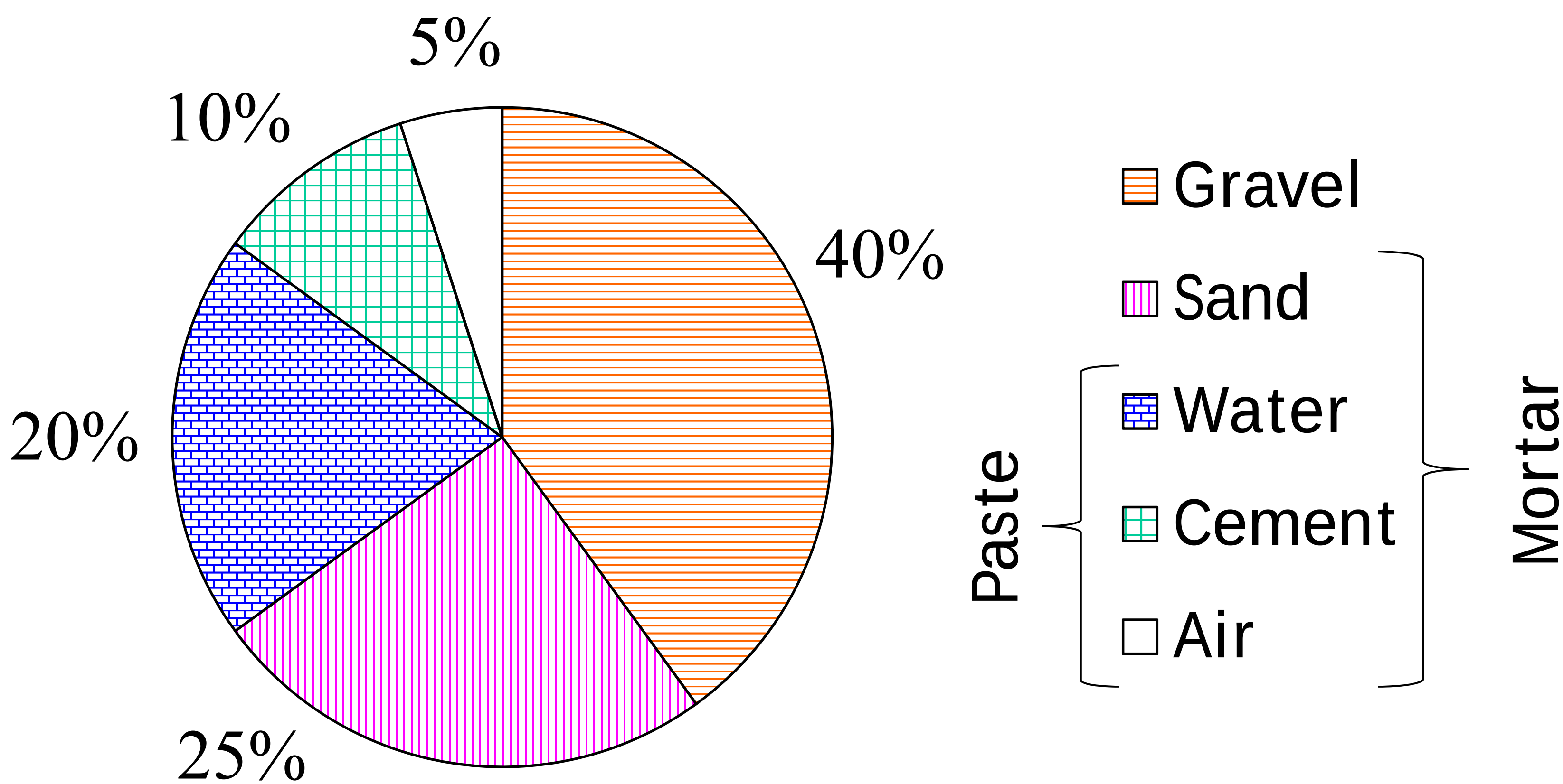
Portland cement concrete consists of a mixture of portland cement, coarse and fine aggregates, and water. It may be amended with admixtures, fibers, or certain supplementary cementitious materials.

The voids between the coarse aggregate particles are filled with ***mortar***, which consists of ***cement paste*** and fine aggregate (sand).

A typical concrete mix is 40% gravel, 25% sand, and 35% cement paste by volume.

Concrete Ingredients



Important Properties

workability

harshness

compressive strength

tensile / flexural strength

stiffness

durability

permeability

shrinkage / creep

Workability

Workability is the ease with which the concrete ingredients can be mixed, transported, placed, consolidated (to remove trapped air), and finished with minimum loss of ***homogeneity***.

For a concrete to be workable, it has to be fluid enough to properly fill the formwork and allow for the expulsion of trapped air, but also "sticky" enough that the ingredients stay mixed together.

Workability

refers to the stickiness of the concrete and how easily it can be placed and finished without inhomogeneity

workability = consistency + cohesion

refers to the fluidity of the concrete and how easily it can be transported, placed, and consolidated without inhomogeneity

Inhomogeneity

segregation (*n.*) the tendency for gravel particles to sink within the concrete mixture.

bleeding (*n.*) the tendency for the mixing water to rise within the concrete mixture.

Segregation

Segregation of concrete is the separation of the cement paste and aggregates from each other during handling, placement, and/or consolidation.

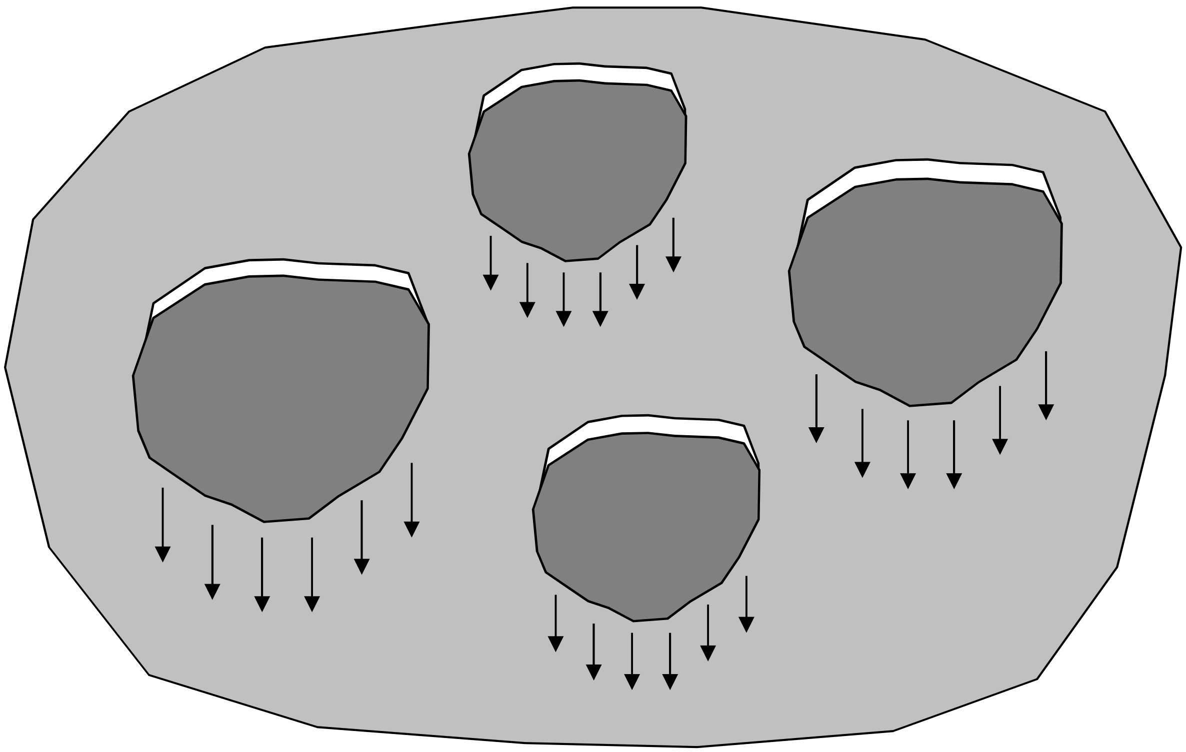
In most cases, the coarse aggregate sinks and the mortar rises; in other cases the cement paste itself separates from the aggregate. In extreme cases, the separation is almost complete, but in many cases, the aggregate sinks just a little, leaving an air void above the aggregate particle.

Segregation

https://www.quora.com/What-is-segregation-of-concrete

Segregation

(coarse aggregate sinks)



Causes of Segregation

improper placement

too much mixing water

over-vibration

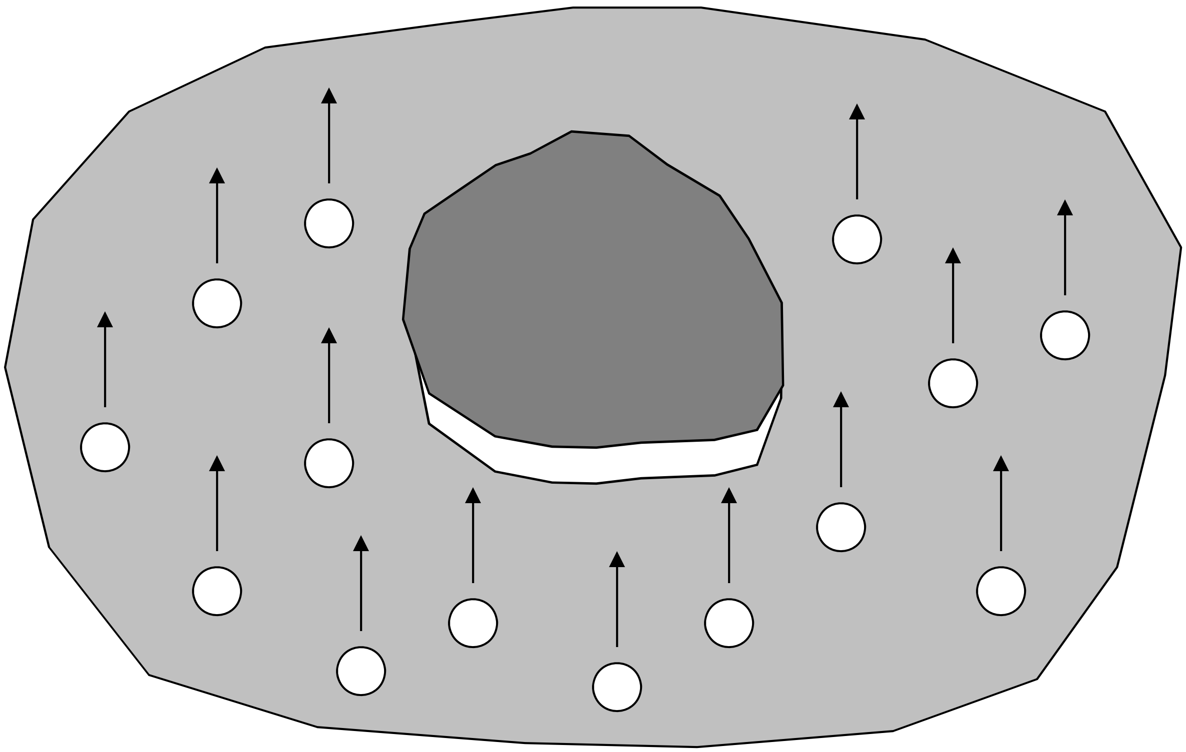
Bleeding

Bleeding refers to the process where free water rises as heavier components such as cement and aggregate settle. Some bleeding is normal but excessive bleeding can be problematic.

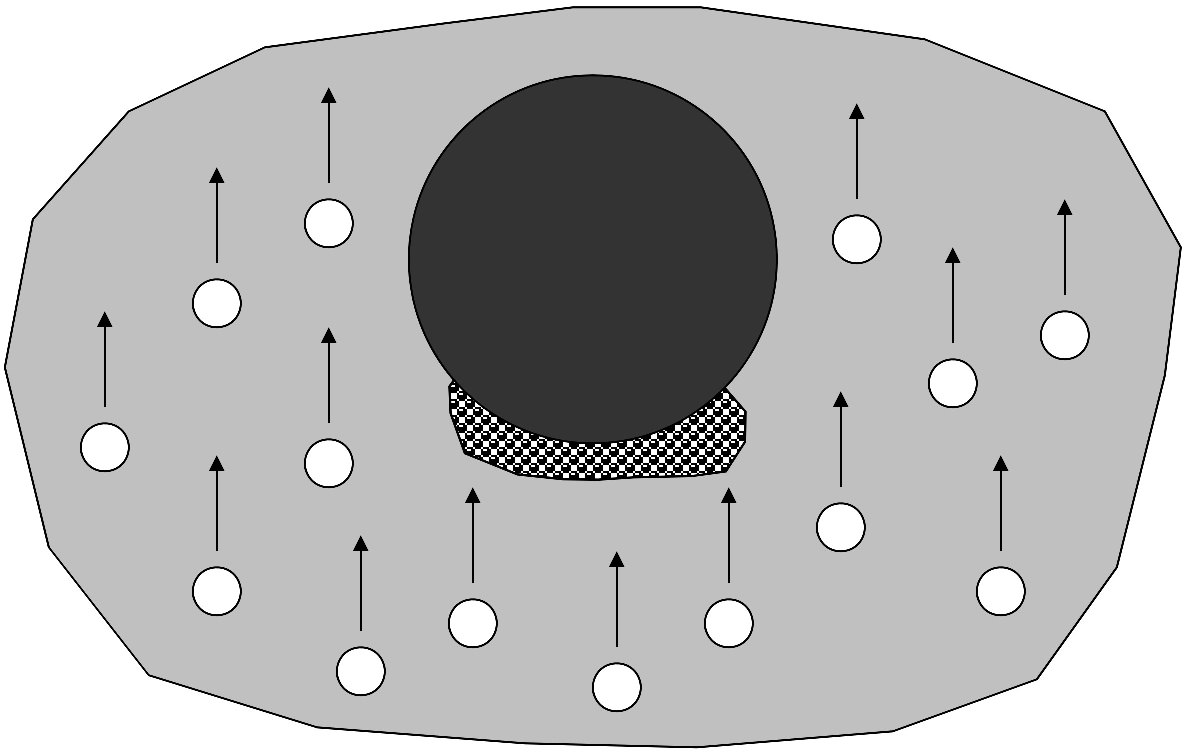
Not all bleed water will reach the surface. Some bleed water may rise and remain trapped under aggregates and reinforcing, weakening the bond between the cement paste and those elements.

Bleeding

(water droplets rise)



Bleeding
(rebar corrosion)



Causes of Bleeding

too little cement

too much water

over-vibration

over-working

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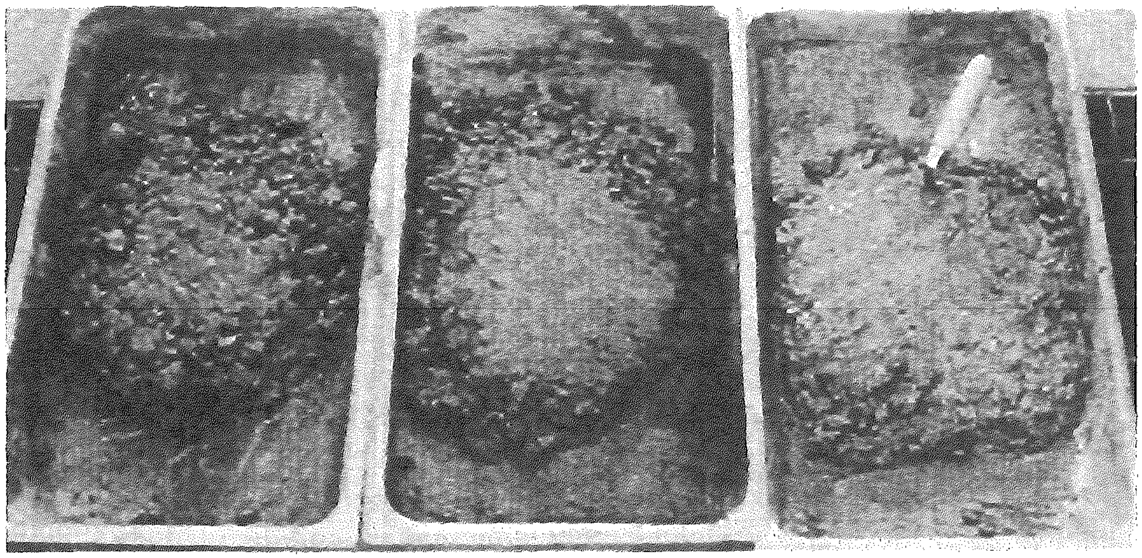
Harshness

A ***harsh*** mix is a concrete mixture that lacks the required workability because there is too much gravel (coarse aggregate) relative to the amount of mortar. There's not enough mortar to keep the gravel particles from bumping into each other.

If a concrete mix has, instead, too little gravel, it is ***oversanded***. The mix will be very workable but more expensive than it needs to be because the gravel is an inexpensive space filler!

Harshness



(a) (b) (c)

Figure 7–15 Harshness of concrete: (a) *harsh mix*—not enough cement-sand mortar to fill the spaces between the coarse aggregate particles; (b) *good mix*—with a light troweling, all the spaces between the coarse particles are filled (note the good supply of coarse particles at the edge of the pile); (c) *oversanded mix*—finishes well but with an excess of mortar, making it an uneconomical and possibly porous mix.

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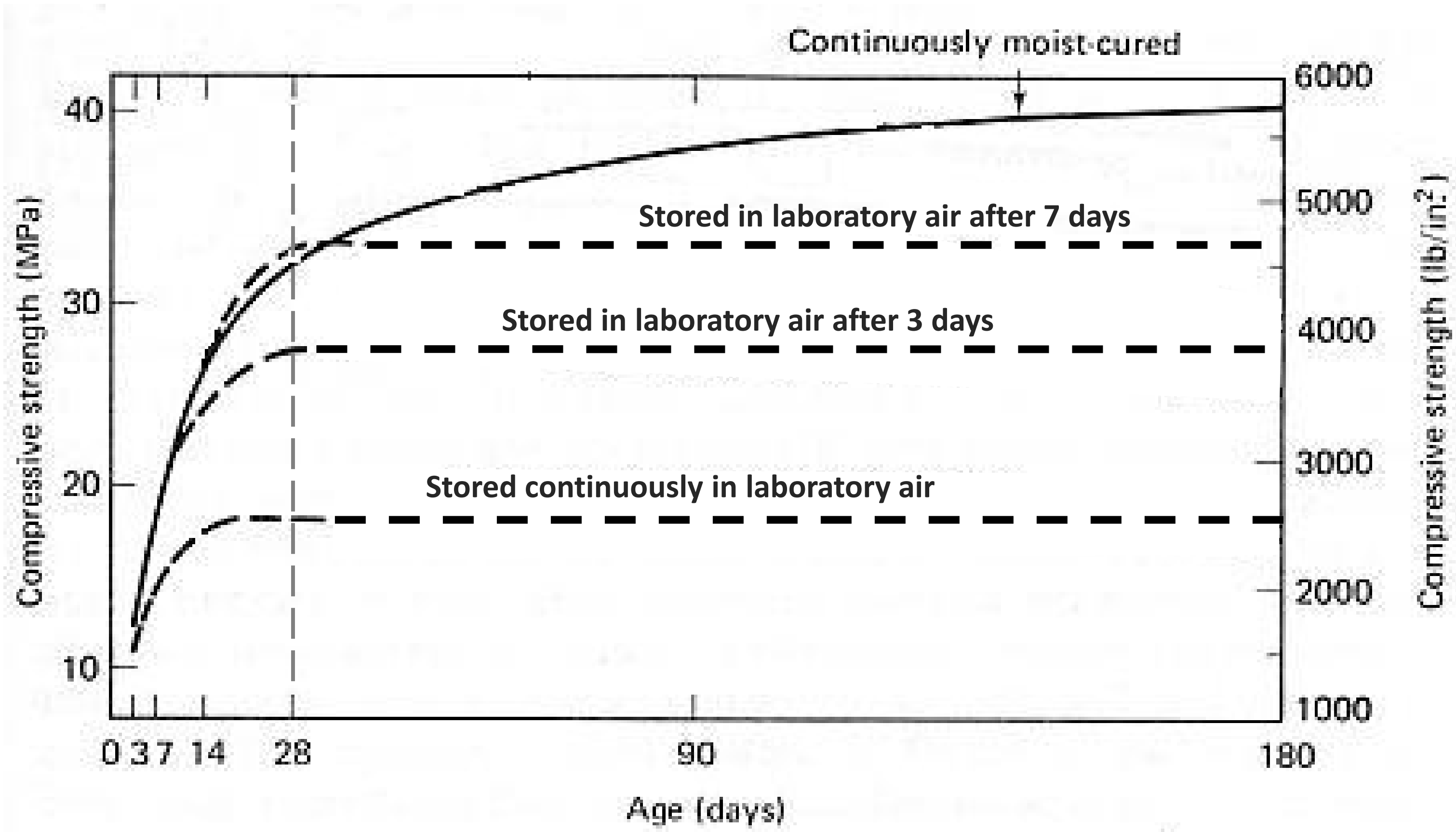
Compressive Strength

Structural concrete is usually designed so as to have some minimum compressive strength. This is usually defined as the maximum resistance of a cylindrical concrete specimen to axial load and is expressed as force per unit cross sectional area.

Traditionally, compressive strength is specified at a concrete age of 28 days due to a long-held (and overly simplistic) assumption that the concrete has gained 99% of its ultimate strength by that time.

Effects of Water Loss

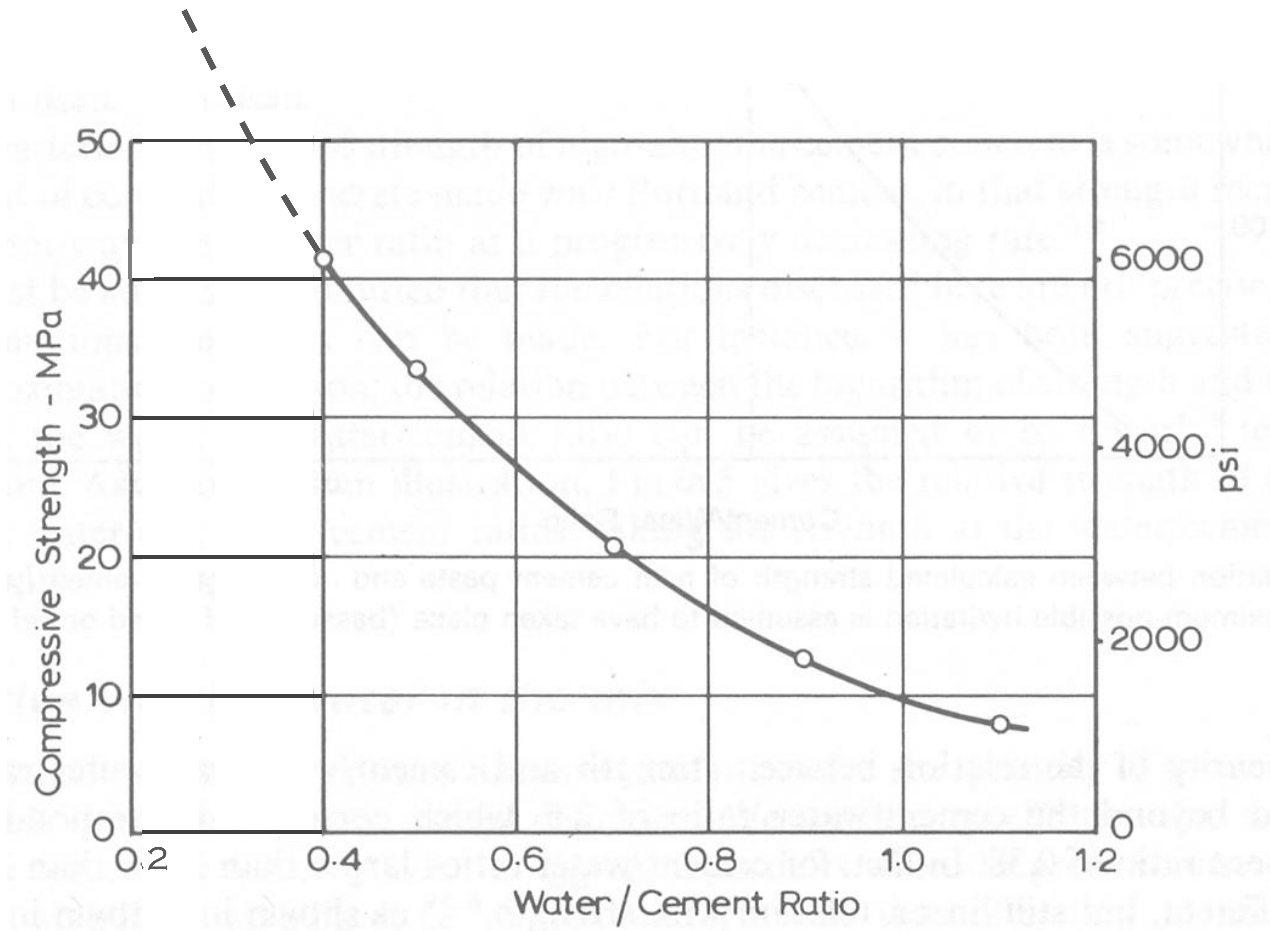


Concrete Strength

Concrete strength comes from three sources:

1. Aggregate Strength
   - Depends on the type of aggregate
   - Usually not a factor in normal-strength concrete
2. Cement/Aggregate Bond Strength
   - Depends on how "clean" the aggregate is
3. Cement Paste Strength
   - Depends primarily on the water/cement ratio
   - Greatly affected by curing conditions

Water-Cement Ratio



Water-Cement Ratio

(historical definition)

$$w/c = \frac{\text{gallons of water}}{\text{sacks of cement}} \quad (\text{gallons/sack})$$

$$1 \text{ sack of cement} = 1\,\text{ft}^3 \text{ bulk} = 94\text{ lb}$$

$$1 \text{ gallon of water} = 8.34\text{ lb}$$

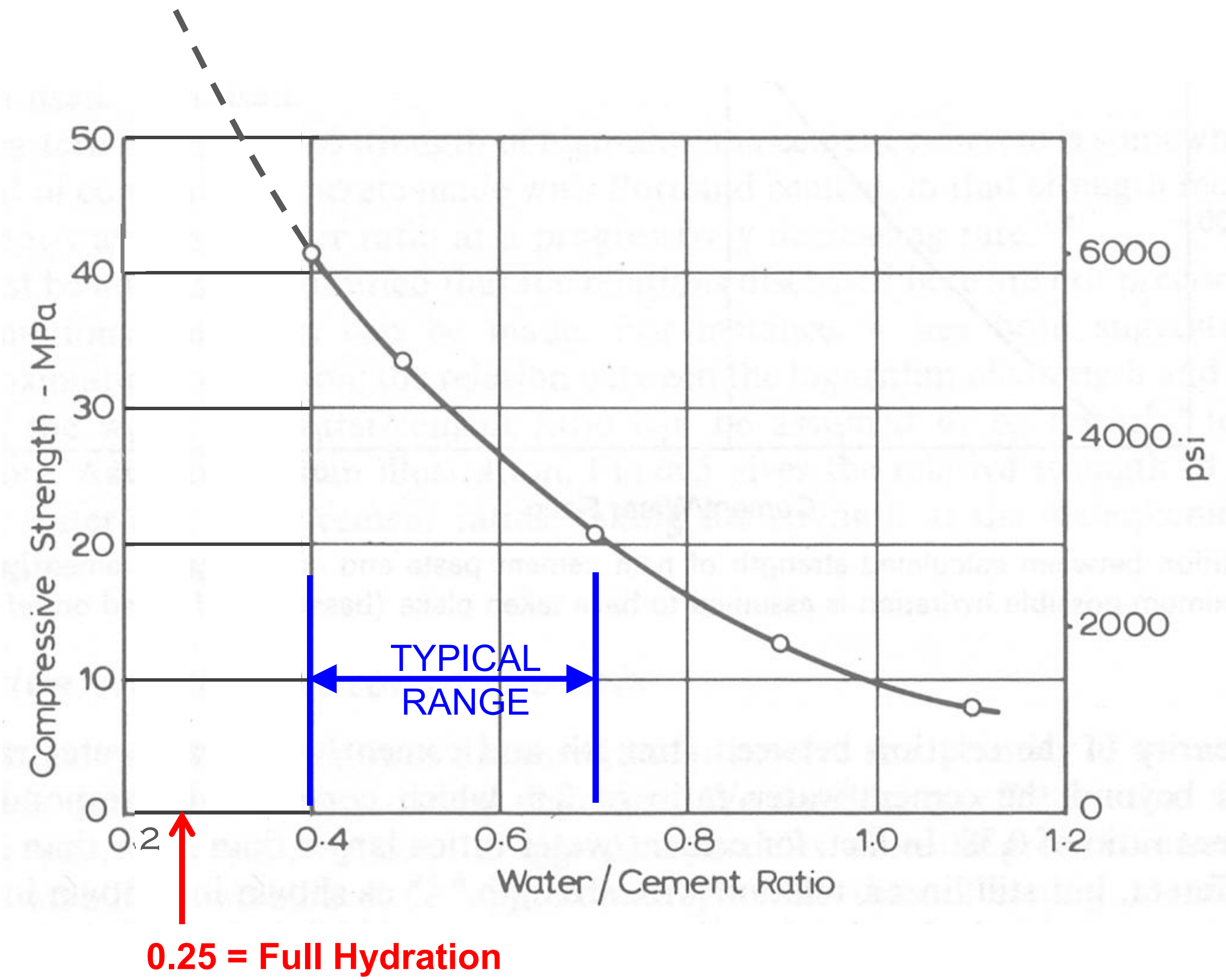
Water-Cement Ratio

(newer definition)

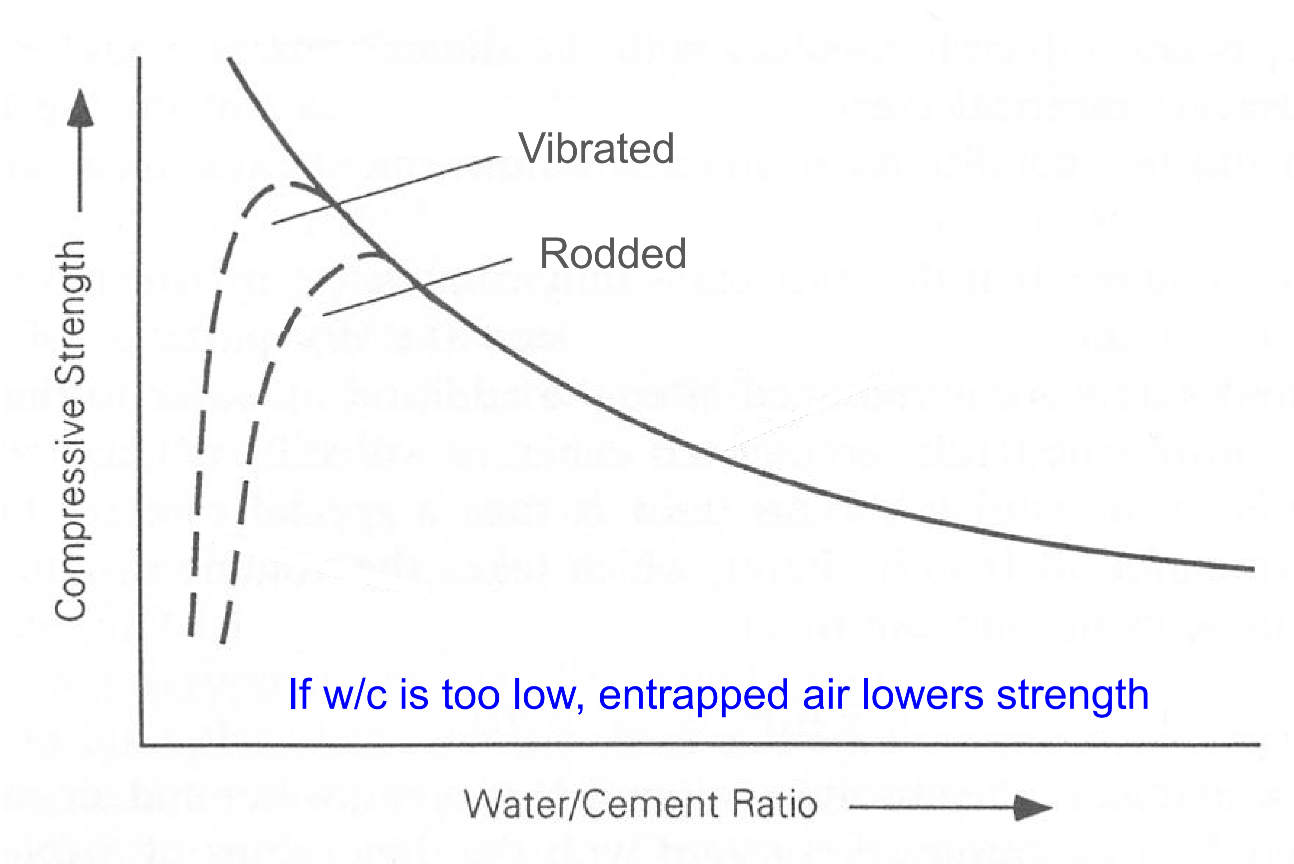
$$\text{w/c} = \frac{\text{mass of water}}{\text{mass of cement}} \quad (\text{dimensionless})$$

It takes about 25 lb of water to hydrate 100 lb of cement; everything else is strictly to make the concrete workable. If the concrete is too stiff, you can't expel the entrapped air and the strength of the concrete suffers as a result.

Water-Cement Ratio



Water-Cement Ratio



Water-Cementitious Materials Ratio

(modern definition)

$$\text{w/cm} = \frac{\text{mass of water}}{\text{mass of cement} + \text{mass of SCMs}}$$

supplementary cementitious materials

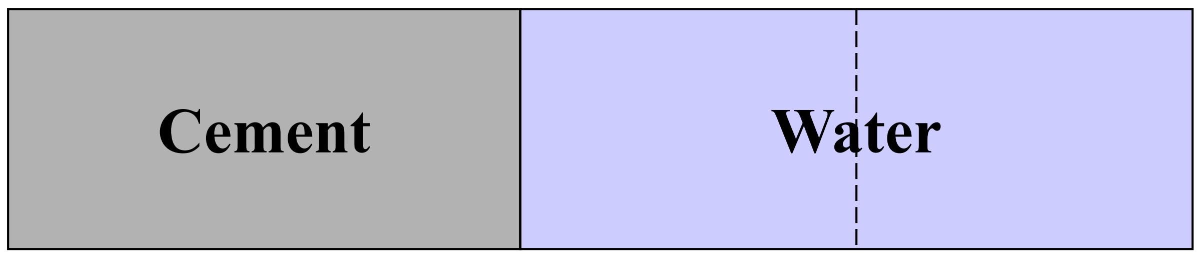
SCMs include things like fly ash, silica fume and ground granulated blast furnace slag (GGBFS) that enhance the strength of the cement

Water-Cement Ratio

The reason strength varies with water-cement ratio is not because of the water, per se, but because of what happens to any mixing water left over after the cement has completely hydrated.

Typically only half of the water in the mix is used to hydrate the cement; the rest is for workability. That excess water produces microscopic pores in the hardened cement paste that lower its strength.

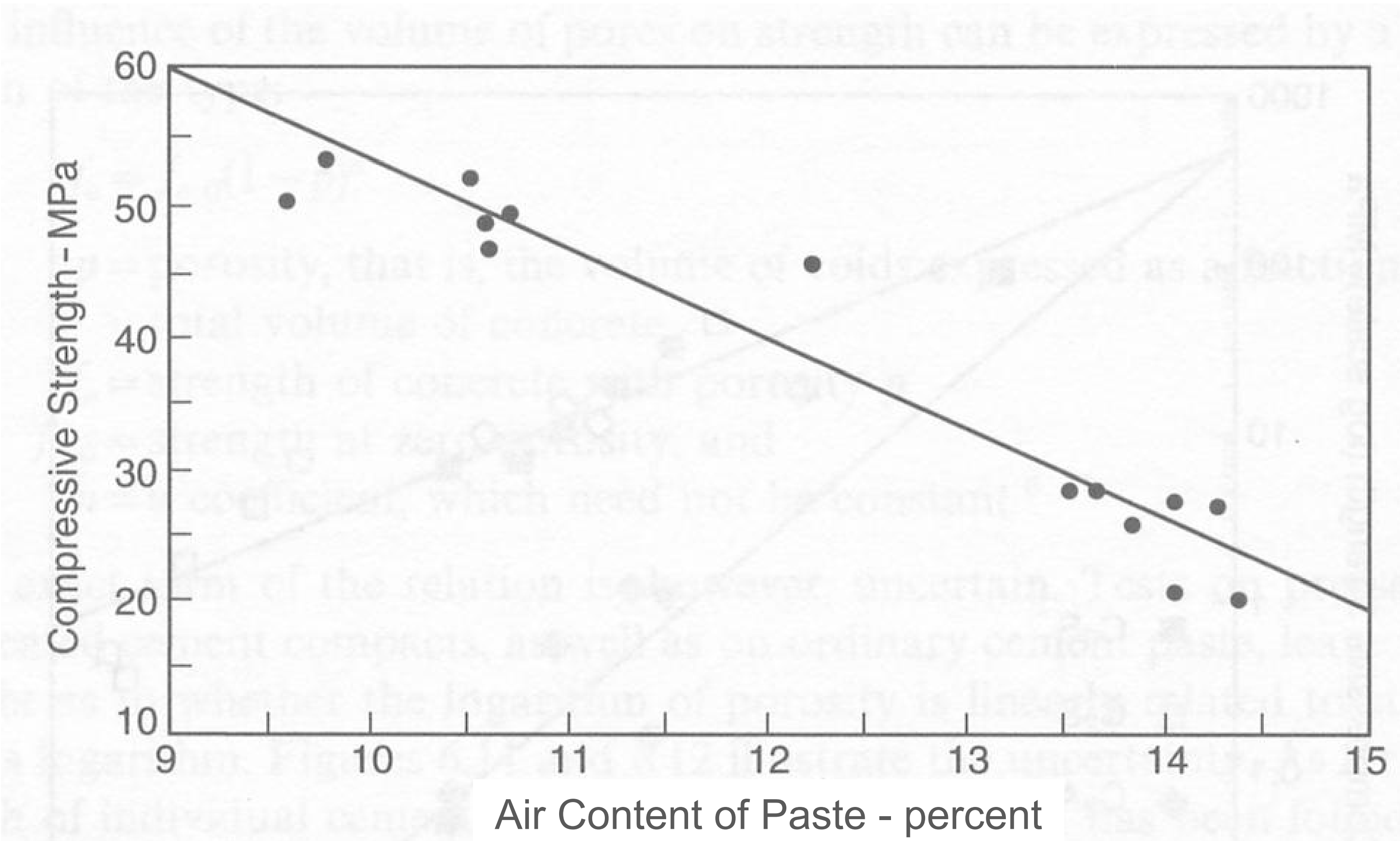
Water-Cement Ratio



0% Hydration

100% Hydration

Cement Paste Strength



Important Properties

workability

harshness

compressive strength

tensile / flexural strength

stiffness

durability

permeability

shrinkage / creep

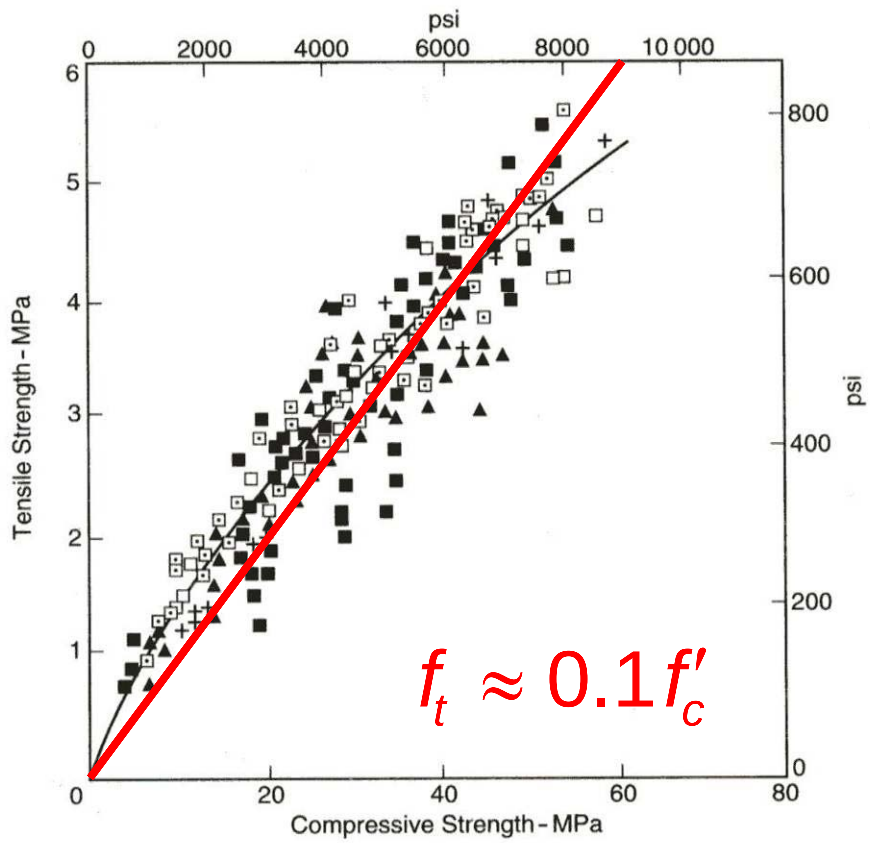
Tensile Strength

Concrete has a relatively high compressive strength but significantly lower tensile strength. A general rule-of-thumb is that the tensile strength is 1/10th of the compressive strength.

In reality, the relationship is nonlinear; the tensile strength of concrete with a high compressive strength is proportionately less than for concrete with a low compressive strength.

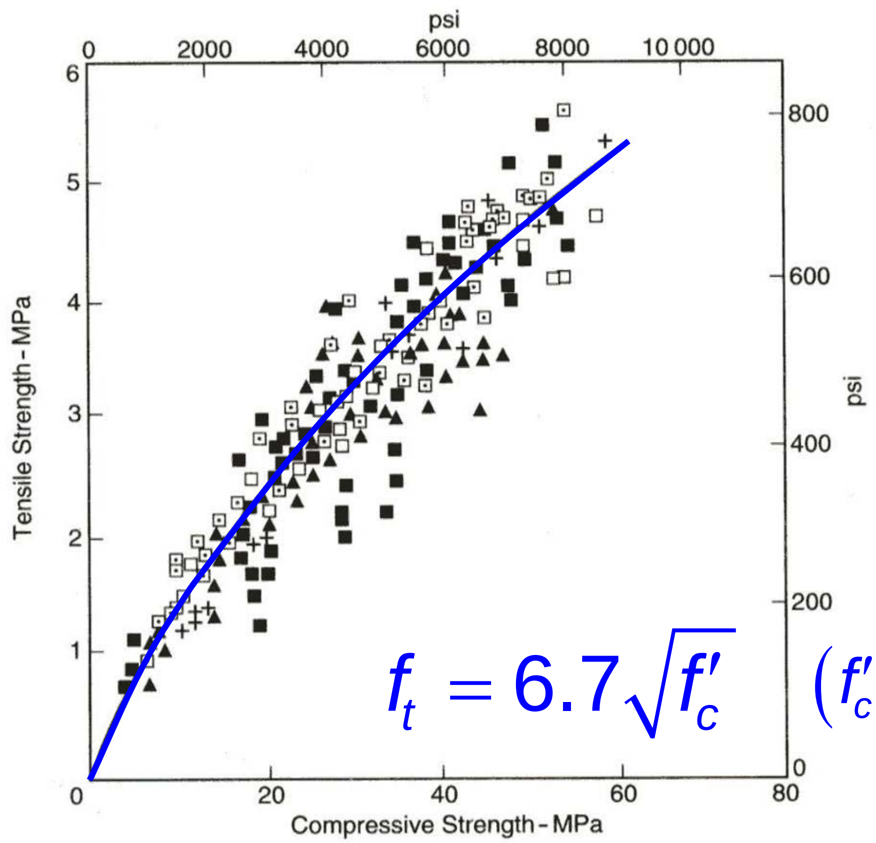
Tensile Strength

(general rule-of-thumb)



Tensile Strength

(ACI approximation)



$$f_t = 6.7\sqrt{f'_c} \quad \left(f'_c \text{ in } psi\right)$$

Flexural Strength

Because the tensile strength of concrete is so low, most structural concrete is reinforced with steel rebar. The concrete carries the compressive loads while the rebar carries the tensile and shear loads.

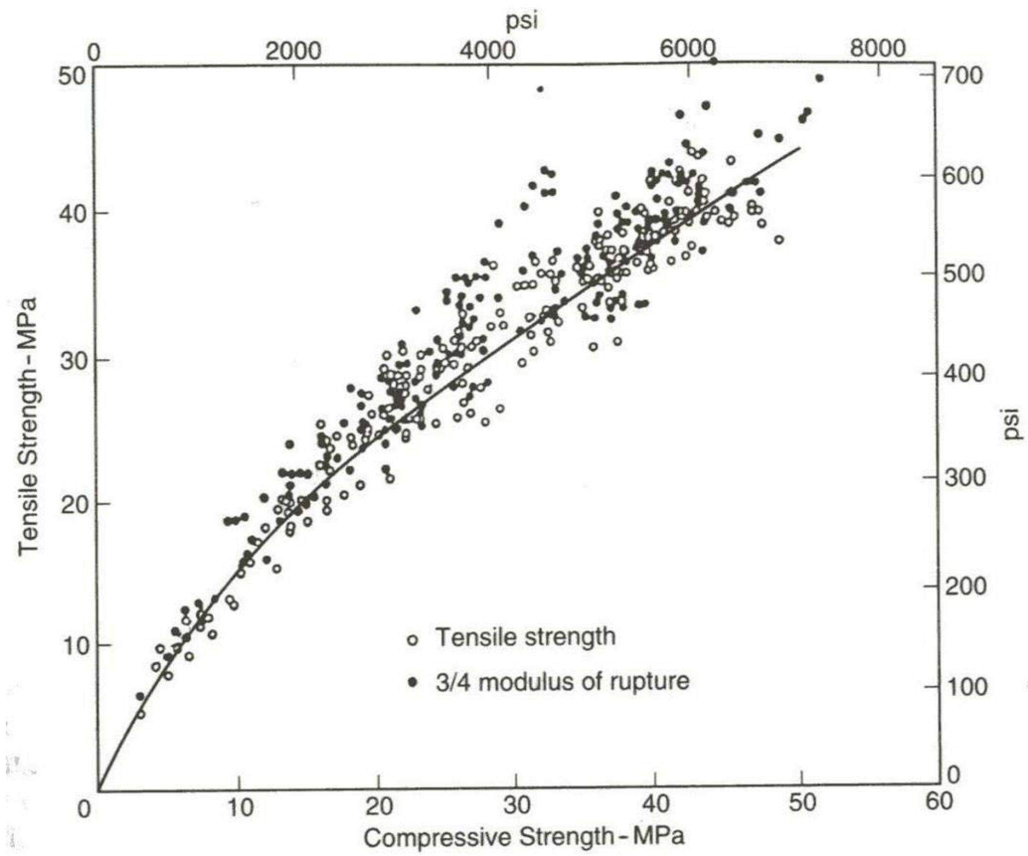
This is not true of concrete slabs and pavements. They are unreinforced and the concrete itself must be able to withstand the flexure of the slab under heavy wheel loads.

Flexural Strength

The flexural strength of concrete is determined using beam bending tests. The tensile stress in the bottom chord of the beam at failure is estimated using the beam bending formula. This estimated failure stress is called the ***modulus of rupture***.

The modulus of rupture is typically 25-30% higher than the actual tensile strength of the concrete due to the way it is calculated.

Flexural Strength



Flexural Strength

(ACI approximation)

$$MOR = 8.4\sqrt{f_c'} \quad (f_c' \text{ in psi})$$

$$f_t = 6.7\sqrt{f_c'} \quad (f_c' \text{ in psi})$$

$$MOR \approx 1.25\, f_t \quad \text{or} \quad f_t \approx 0.8\ MOR$$

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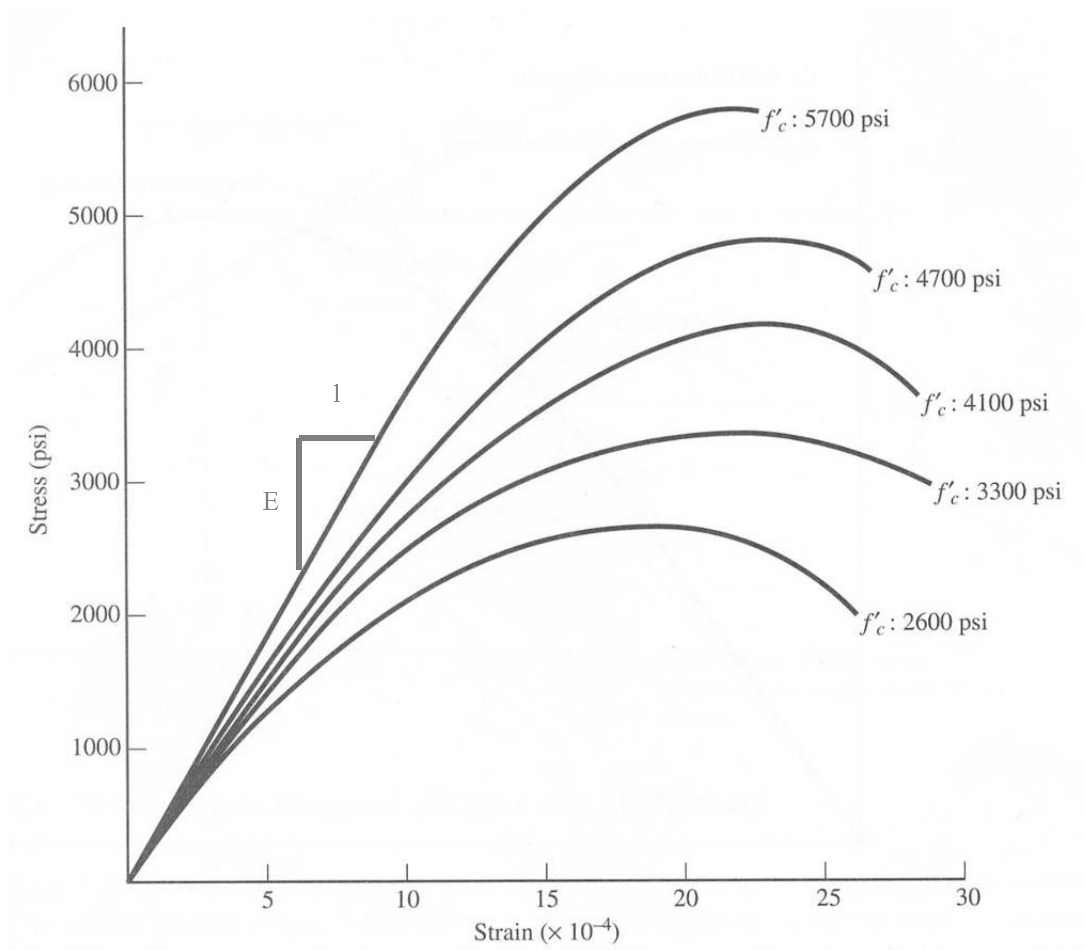
Concrete Stiffness

The stiffness of concrete is quantified by the elastic modulus of a cylindrical concrete specimen under axial load. Most concrete is linear-elastic at lower stresses but becomes nonlinear as it approaches failure.

Concrete with high compressive strength tends to be stiffer than concrete with low strength.

Stiffness and Strength



Stiffness and Strength

Source: ACI Manual of Concrete Practice

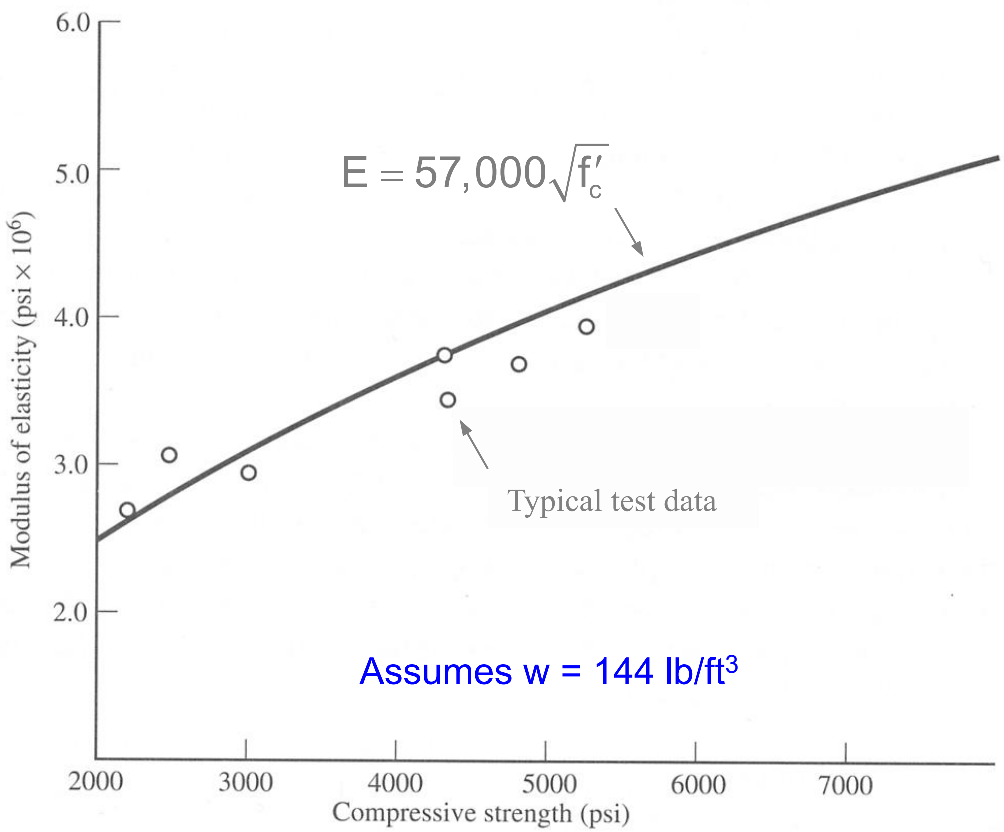
$$E = 33w^{1.5}\sqrt{f_c'}$$

$E =$ elastic modulus in $\mathrm{lb/in^2}$

$w =$ unit weight in $\mathrm{lb/ft^3}$

$f_c' =$ compressive strength in $\mathrm{lb/in^2}$

Stiffness and Strength



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Concrete Durability

Durability is the ability to last a long time without significant deterioration.

The durability of concrete may be defined as the ability to resist ***weathering*** and ***chemical attack*** while maintaining its engineering properties.

The most common forms of chemical attack are ***alkali-silica reactivity*** and ***sulfate attack***.

Concrete Durability

Alkali-Silica Reaction is an expansive reaction between certain forms of silica in aggregate and naturally occurring potassium and sodium alkalis in the cement paste. It can be controlled through proper aggregate selection and through the use of supplementary cementitious materials (such as fly ash). Lithium-based admixtures have also been shown to prevent deleterious expansion due to alkali-silica reaction.

Concrete Durability

Sulfate attack is an expansive reaction between sodium and magnesium sulfates in soil or water and naturally occurring compounds (primarily calcium aluminate hydrate) in the cement paste.

Sulfate attack can be reduced by using a cement that is formulated to be sulfate resistant.

Concrete Durability

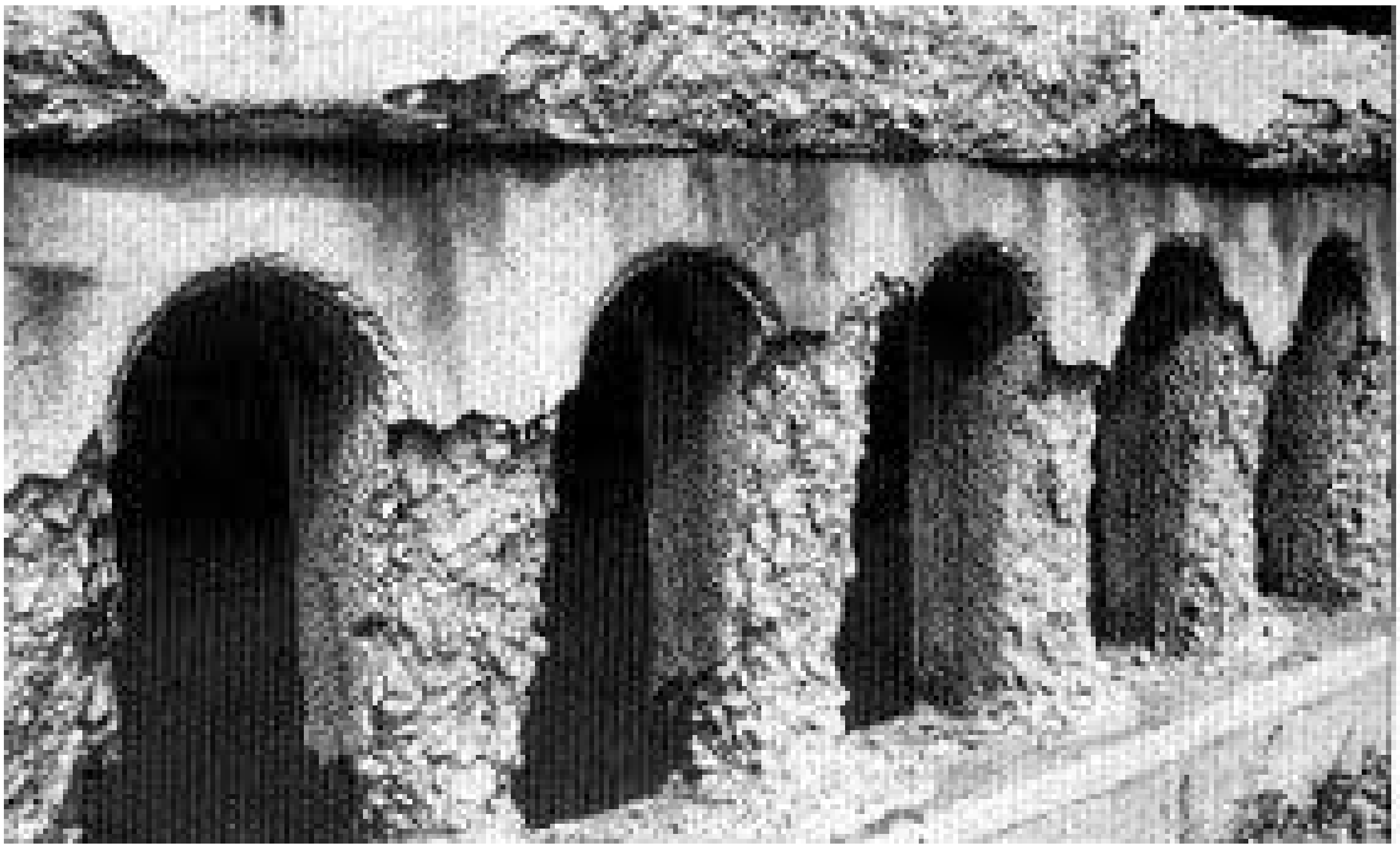
The most destructive ***weathering*** factor is ***freezing and thawing*** that occurs while the concrete is wet. Water in the pores of the cement paste or the aggregate will expand when it freezes and cause the concrete to crack.

Concrete can be made resistant to freeze/thaw by incorporating microscopic air bubble in the mix to accommodate the expansion of the freezing water.

Freeze-Thaw Durability

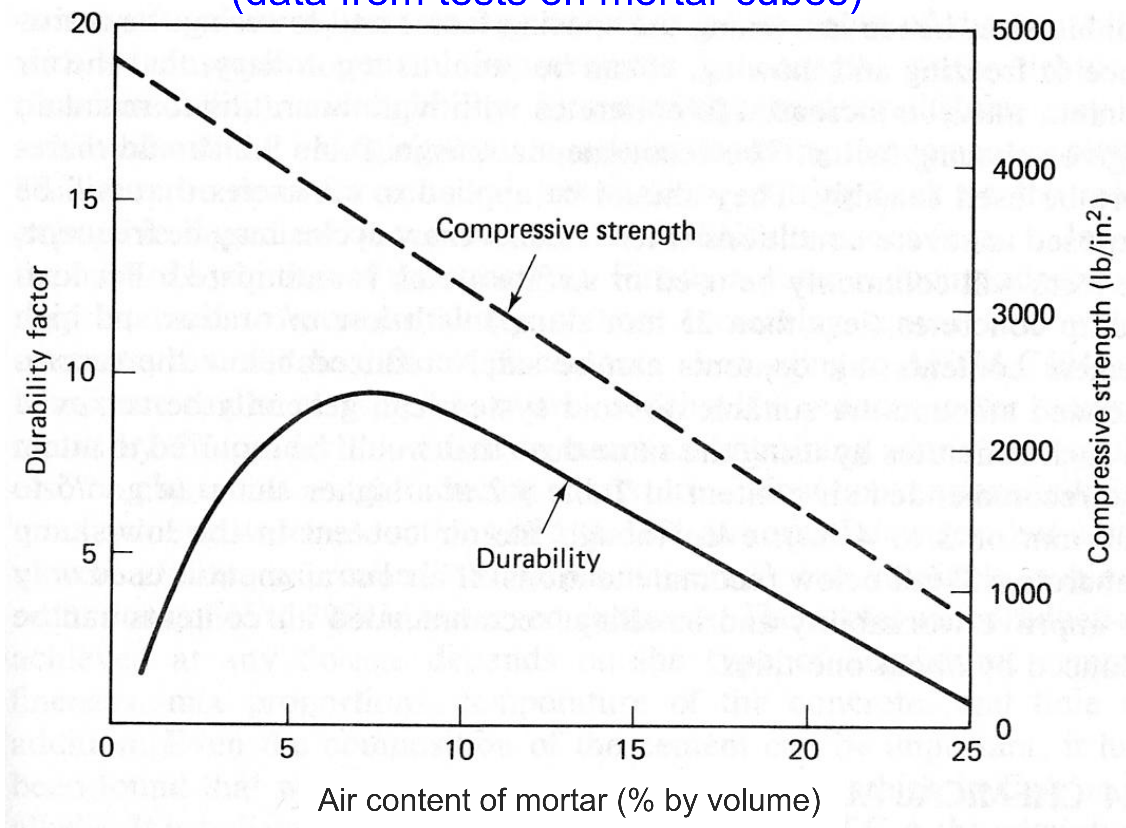



Freeze-Thaw Durability



Strength and Durability

(data from tests on mortar cubes)



Air Entrainment Goals

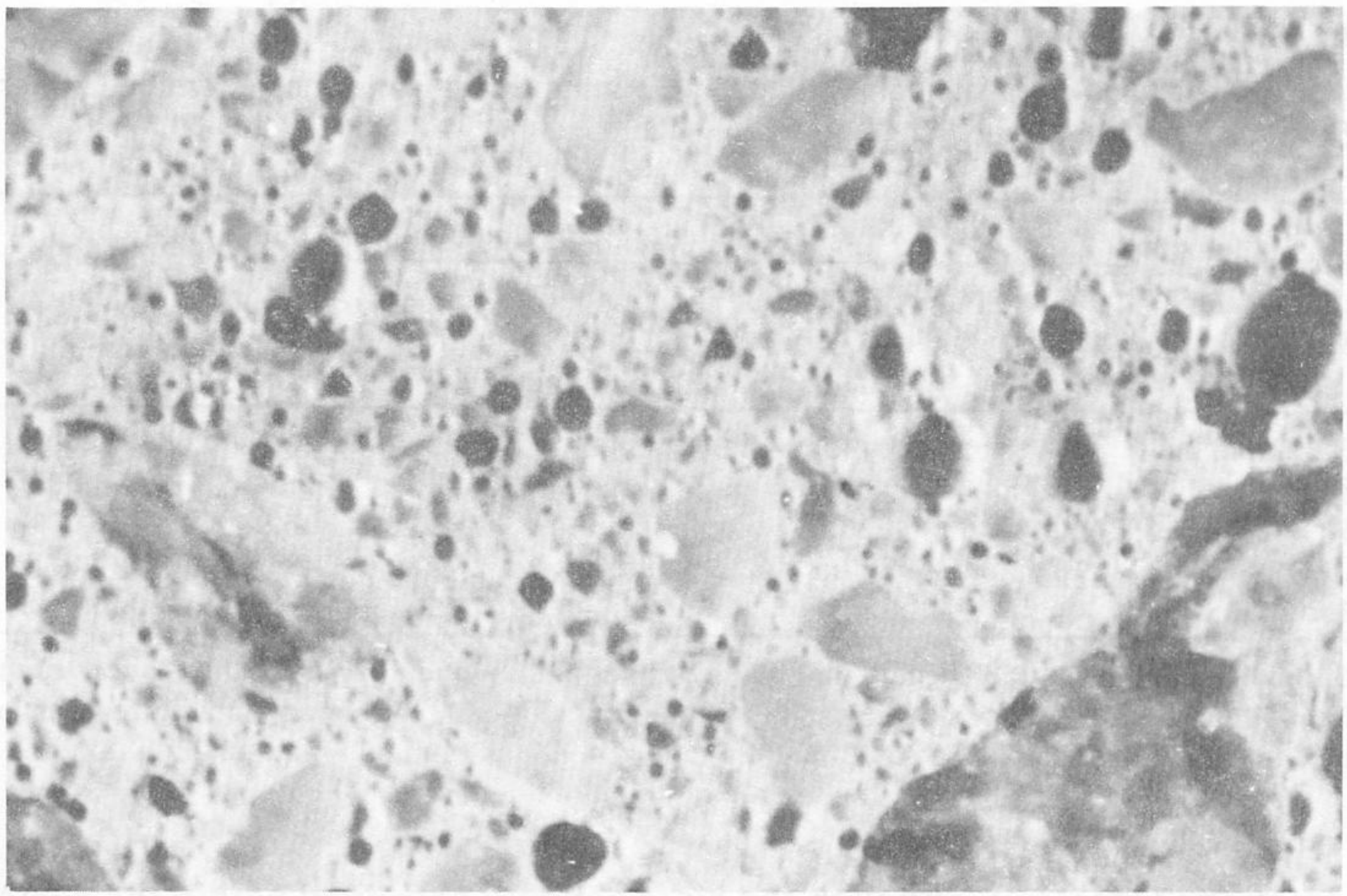
tiny air bubbles, uniform in size

uniform dispersion in cement paste

air content = 9% of mortar volume

one billion bubbles per cubic yard

Air Entrainment



Properties Affected by Air Content

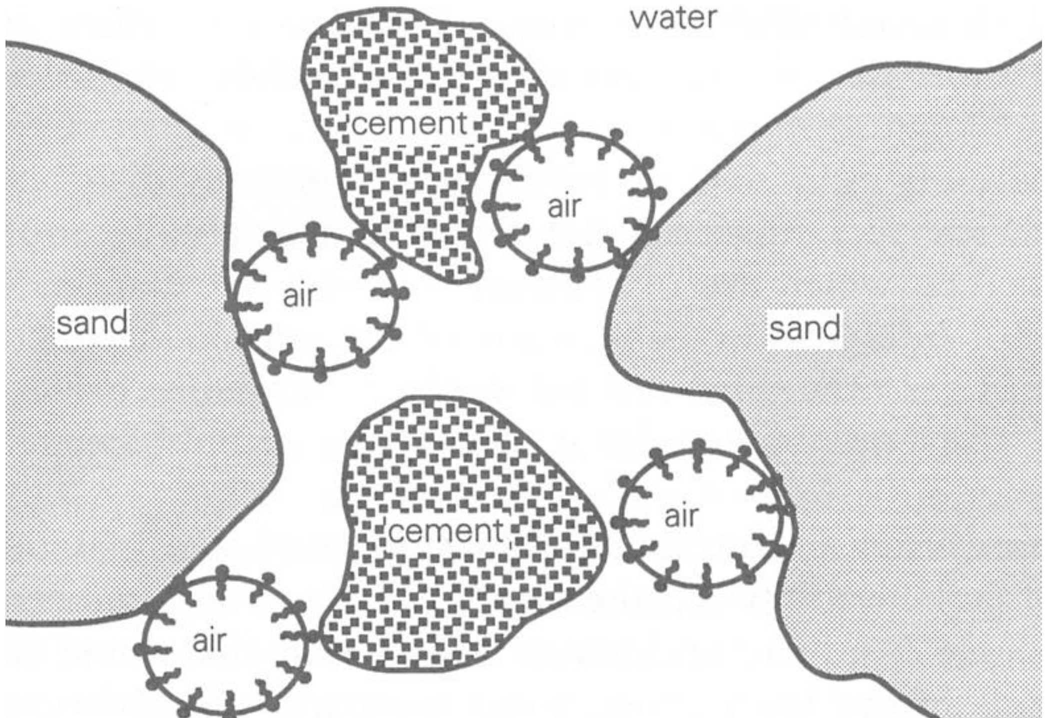
durability

consistency

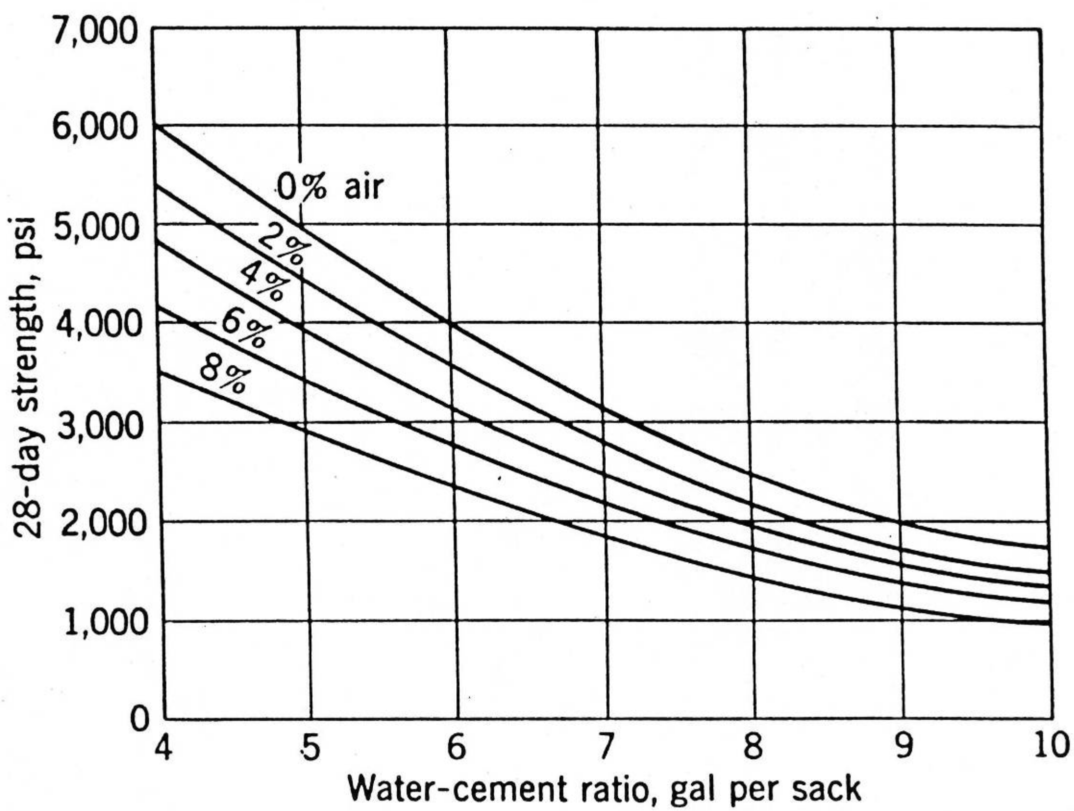
strength

bleeding

Air Entrainment Effect on Consistency



Air Entrainment Effect on Strength



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shrinkage / creep

Concrete Permeability

Permeability is a measure of the amount of water, air, and other fluids that can enter the concrete matrix. Permeability can be a primary reason for concrete deterioration due to reinforcing steel corrosion and other deterioration mechanisms.

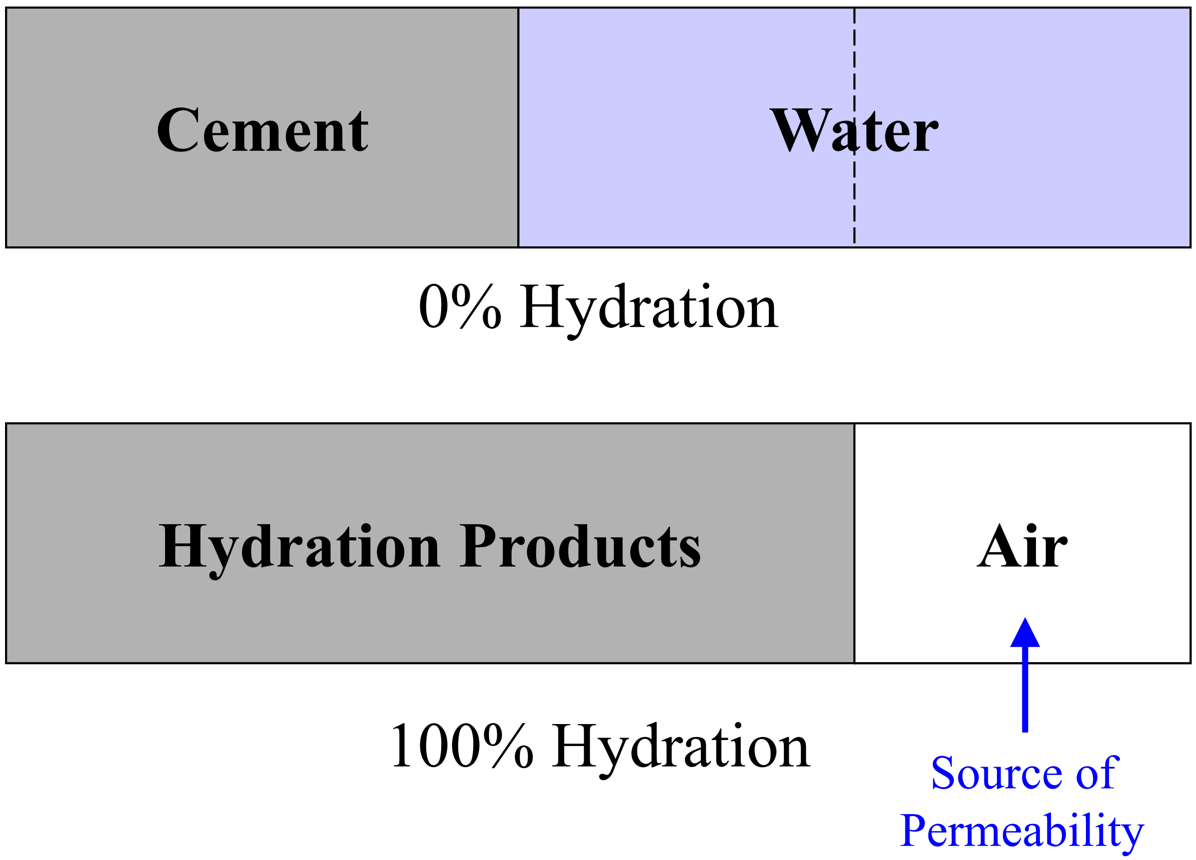
There are three major factors that influence the permeability of concrete: the water-cement ratio, proper consolidation, and proper curing.

Concrete Permeability

Water-cement ratio influences permeability to a great extent. The higher the w/c ratio the greater the concrete permeability.

Any free water remaining in the concrete after hydration is completed will eventually evaporate, leaving behind interconnected pores that allow fluids to enter and leave the concrete.

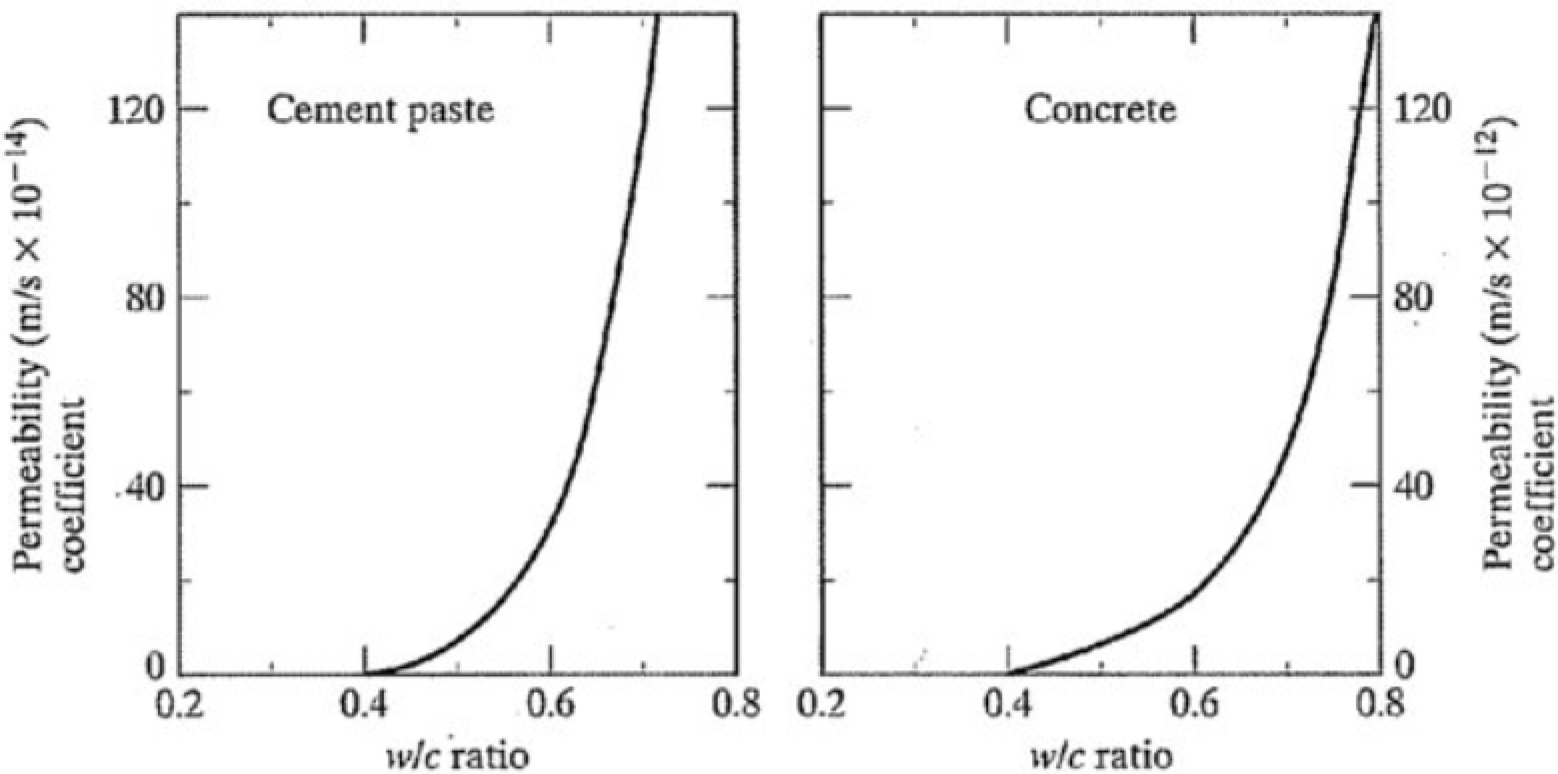
Water-Cement Ratio



Concrete Permeability

Concrete made with w/c ratios less than 0.4 are practically impermeable, but the permeability goes up exponentially as the w/c ratio increases.

Permeability



Source: Mindess and Young, *Concrete*, Prentice-Hall, 1981

Concrete Permeability

When concrete is adequately compacted, air voids and trapped bleed water are minimized. This reduces permeability by reducing the volume of interconnected pores in the cement paste.

Proper curing of concrete substantially influences its permeability because it allows proper cement hydration. As a result, more pores in the concrete will be filled with hydration products than free water.

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Concrete Shrinkage

Concrete can develop shrinkage cracks when it undergoes restrained volume changes, meaning it wants to shrink but can't. The tendency to shrink can be the result of drying, autogenous shrinkage (curing) or thermal effects. The restraint can be provided by friction with the ground, embedded reinforcing, or adjacent structural members.

Shrinkage

- Sources of Volume Change
  - Temperature Changes
  - Drying/Curing Shrinkage
  - Creep Strains

Temperature Changes

Like most materials, concrete shrinks and expands due to changes in temperature. The ***coefficient of thermal expansion*** expresses how much uniaxial strain develops due to each 1-degree change in the temperature.

In concrete, the coefficient of thermal expansion depends primarily on the type of aggregate used.

Coefficient of Thermal Expansion

Aggregate Type	Coefficient (10^{-6} in/in/^oF)
Quartz	6.6
Sandstone	6.5
Gravel	6.0
Granite	5.3
Basalt	4.8
Limestone	3.8

Typical 5.5

Example

How much strain would develop in a concrete slab made with natural river gravel due to a 60°F drop in temperature?

$$\varepsilon = \left(6.0\times10^{-6}\ \text{in/in/°F}\right)\left(60\text{°F}\right) = 3.6\times10^{-4}\ \text{in/in}$$

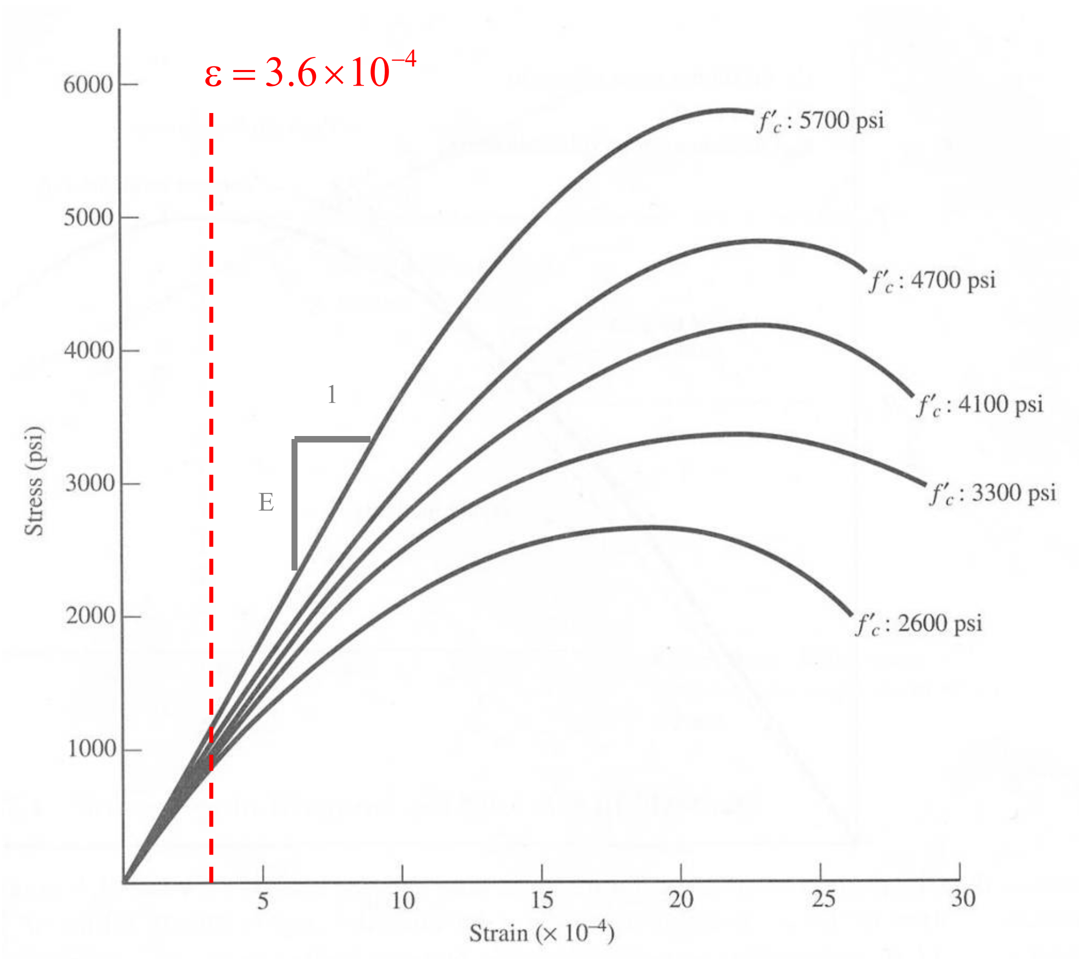
Example

How much tensile stress will develop in the slab in the previous example if it is completely restrained? Assume $E = 3\times10^6$ psi.

$$\sigma = E\varepsilon = \left(3\times10^6 \text{ psi}\right)\left(3.6\times10^{-4} \text{ in/in}\right) = 1080 \text{ psi}$$

typical

Example



$\varepsilon = 3.6 \times 10^{-4}$
6000
5000
4000
3000
2000
1000
Stress (psi)
1
E
f'c: 5700 psi
f'c: 4700 psi
f'c: 4100 psi
f'c: 3300 psi
f'c: 2600 psi
5
10
15
20
25
30
Strain (× 10⁻⁴)

Curing Shrinkage

As concrete matures it continues to shrink due to the ongoing chemical reaction taking place in the material. This is called autogenous (self-generated) shrinkage. At the same time, the evaporation of free water also causes the concrete to shrink as it cures (drying shrinkage), as does the eventual loss of the heat of hydration (thermal contraction).

Drying/Curing Shrinkage

Tensile Strength (psi)	Shrinkage Coefficient (in/in)
300 or less	0.0008
400	0.0006
500	0.00045
600	0.0003
700 or more	0.0002

Typical 0.0006

Example

How much will a typical 14-ft pavement slab shrink during curing if it is unrestrained?

$$\Delta = \left(6.0\times10^{-4}\ \text{in/in}\right)\left(14\ \text{ft}\right)\left(12\ \text{in/ft}\right) = 0.10\ \text{in}$$

Example

How much tensile stress will develop in the slab in the previous example if it is completely restrained?

$$\sigma = E\varepsilon = \underset{\text{typical}}{\left(4\times10^{6}\ \text{psi}\right)}\left(6.0\times10^{-4}\ \text{in/in}\right) = 2400\ \text{psi}$$

Concrete Creep

Concrete under any sustained load will deform over time even if the load doesn't change. This is called ***creep***. The magnitude of the creep strain can be 1-3 times as much as the instantaneous elastic strain that occurs when the concrete is first loaded.

Creep does not necessarily cause concrete to fail, but it may deform to an intolerable extent if not accounted for in the design.

Concrete Creep

The cement paste is the origin of the creep strains since aggregate itself creeps very little. The higher the paste volume in the mix, the higher the creep and the poorer the paste quality (i.e., the higher the w/c ratio), the higher the creep.

The aggregate can help to restrain the cement paste and limit creep, so the more aggregate in a mix, the less the creep.