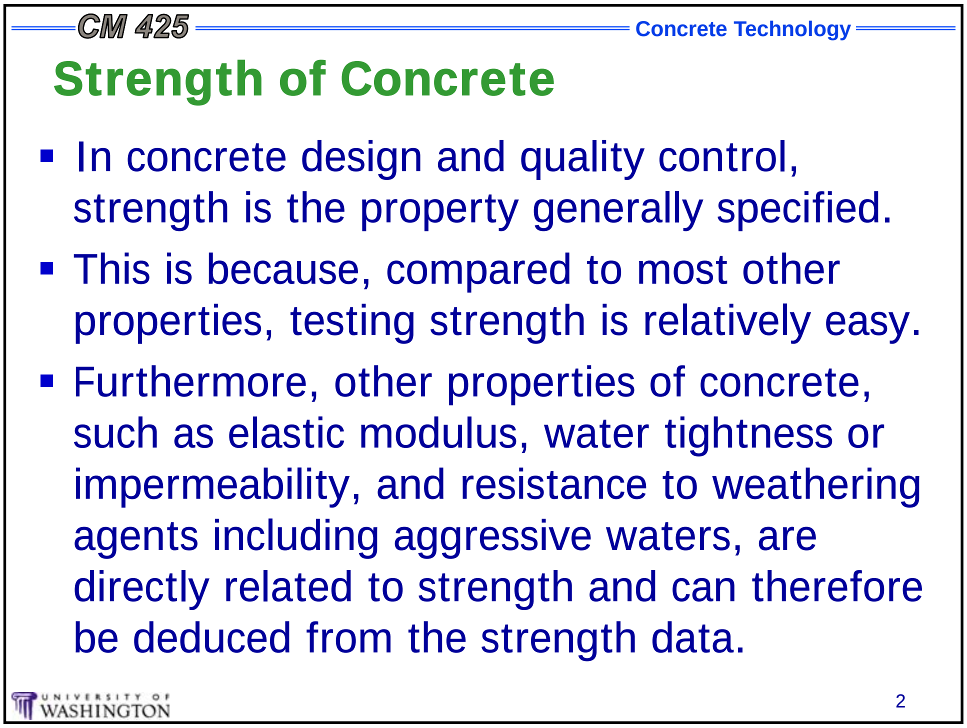
CM 425

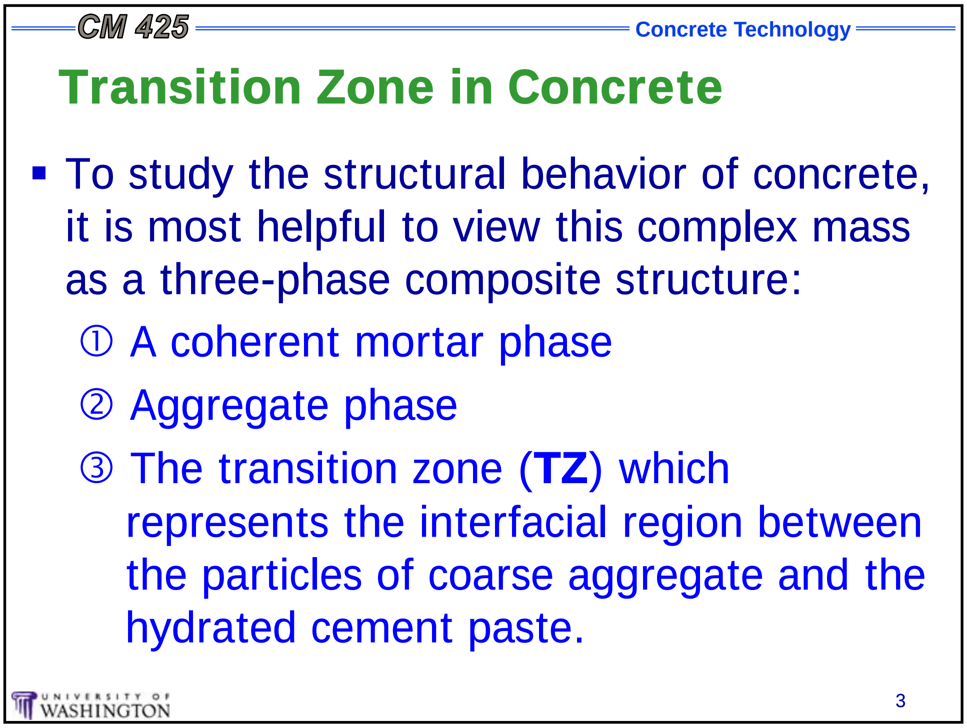
Concrete Technology

Strength of Concrete



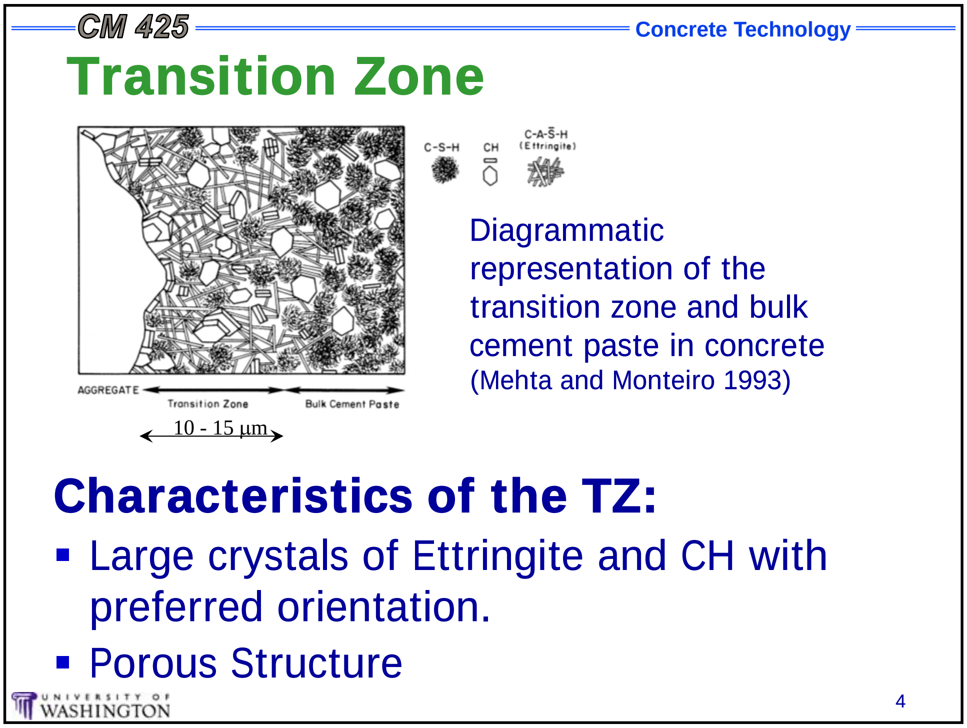
Strength of Concrete

- In concrete design and quality control, strength is the property generally specified.
- This is because, compared to most other properties, testing strength is relatively easy.
- Furthermore, other properties of concrete, such as elastic modulus, water tightness or impermeability, and resistance to weathering agents including aggressive waters, are directly related to strength and can therefore be deduced from the strength data.



Transition Zone in Concrete

- To study the structural behavior of concrete, it is most helpful to view this complex mass as a three-phase composite structure:
  - ① A coherent mortar phase
  - ② Aggregate phase
  - ③ The transition zone (**TZ**) which represents the interfacial region between the particles of coarse aggregate and the hydrated cement paste.

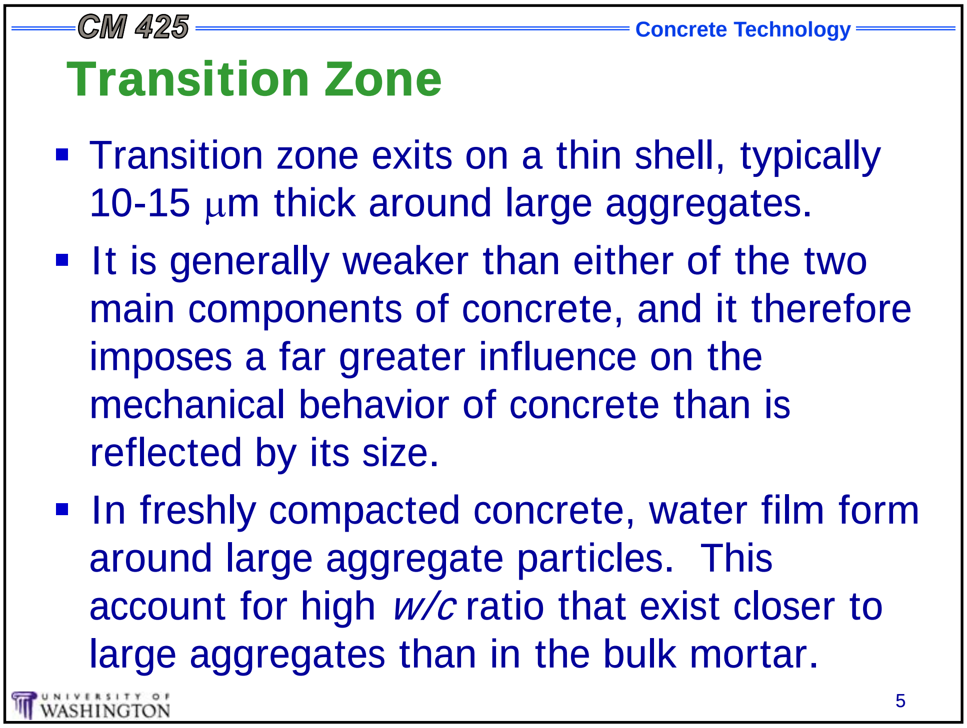


Transition Zone

Diagrammatic representation of the transition zone and bulk cement paste in concrete (Mehta and Monteiro 1993)

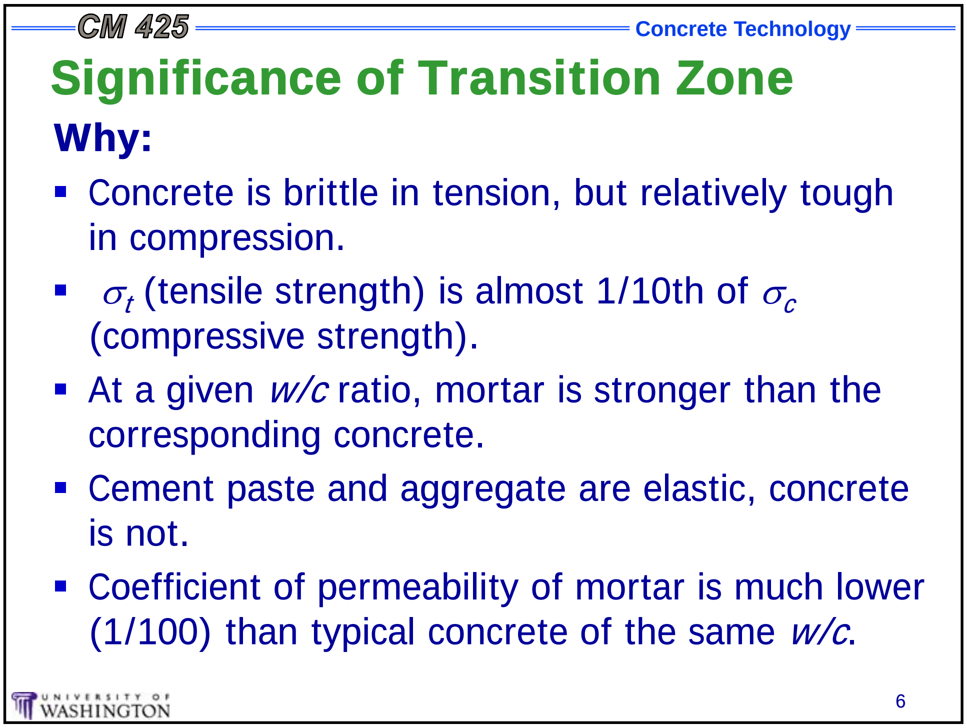
Characteristics of the TZ:

- Large crystals of Ettringite and CH with preferred orientation.
- Porous Structure



Transition Zone

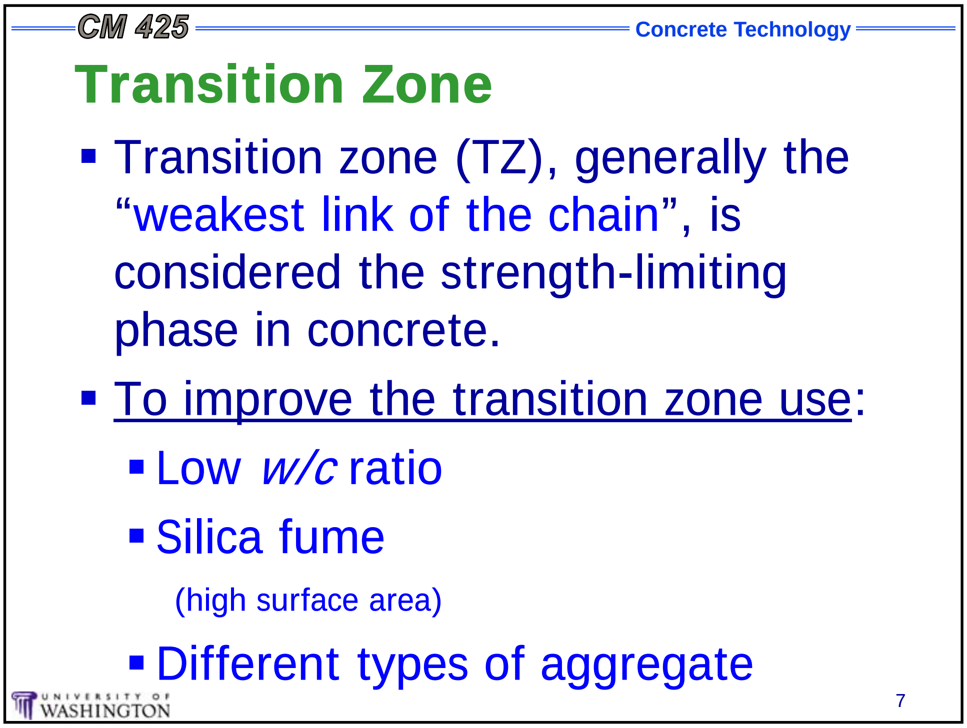
- Transition zone exits on a thin shell, typically 10-15 μm thick around large aggregates.
- It is generally weaker than either of the two main components of concrete, and it therefore imposes a far greater influence on the mechanical behavior of concrete than is reflected by its size.
- In freshly compacted concrete, water film form around large aggregate particles. This account for high *w/c* ratio that exist closer to large aggregates than in the bulk mortar.



Significance of Transition Zone

Why:

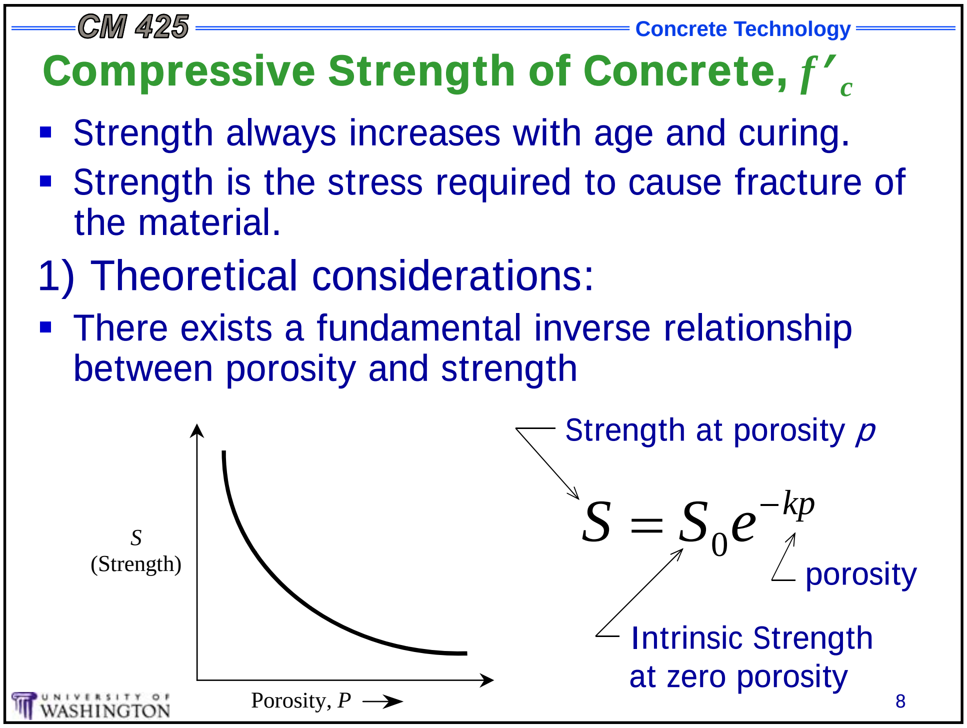
- Concrete is brittle in tension, but relatively tough in compression.
- σ_t (tensile strength) is almost 1/10th of σ_c (compressive strength).
- At a given *w/c* ratio, mortar is stronger than the corresponding concrete.
- Cement paste and aggregate are elastic, concrete is not.
- Coefficient of permeability of mortar is much lower (1/100) than typical concrete of the same *w/c*.



Transition Zone

- Transition zone (TZ), generally the "weakest link of the chain", is considered the strength-limiting phase in concrete.
- To improve the transition zone use:
  - Low *w/c* ratio
  - Silica fume

    (high surface area)
  - Different types of aggregate



Compressive Strength of Concrete, f'_c

- Strength always increases with age and curing.
- Strength is the stress required to cause fracture of the material.

1) Theoretical considerations:

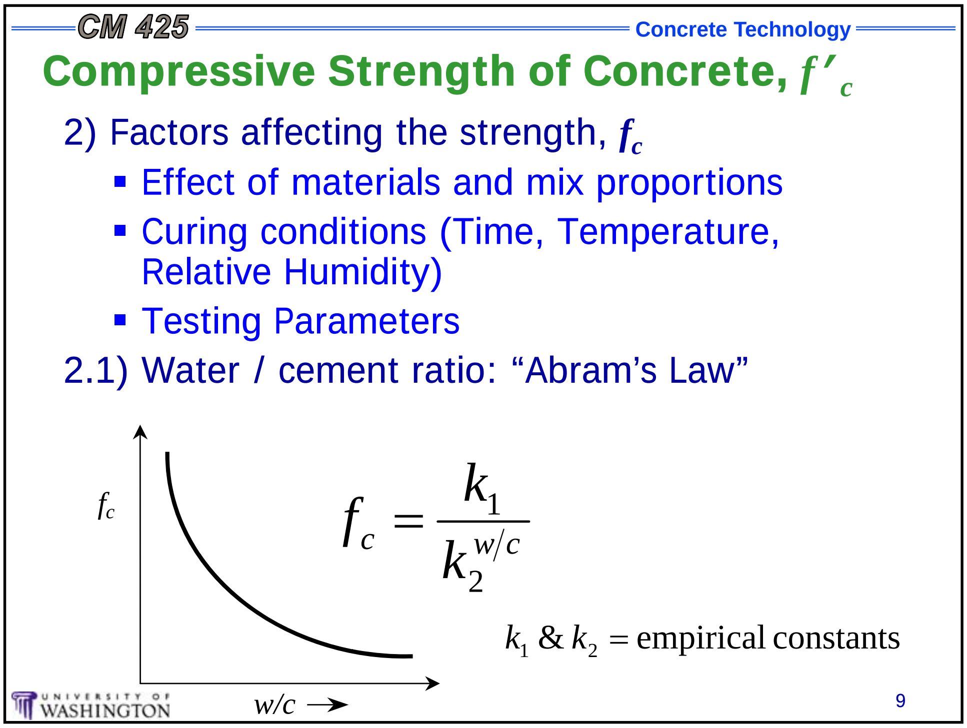
- There exists a fundamental inverse relationship between porosity and strength

Strength at porosity *p*

$$S = S_0 e^{-kp}$$

porosity

Intrinsic Strength at zero porosity



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Compressive Strength of Concrete, f'_c

2) Factors affecting the strength, f_c

- Effect of materials and mix proportions
- Curing conditions (Time, Temperature, Relative Humidity)
- Testing Parameters

2.1) Water / cement ratio: “Abram’s Law”

$$f_c = \frac{k_1}{k_2^{w/c}}$$

k_1 & k_2 = empirical constants

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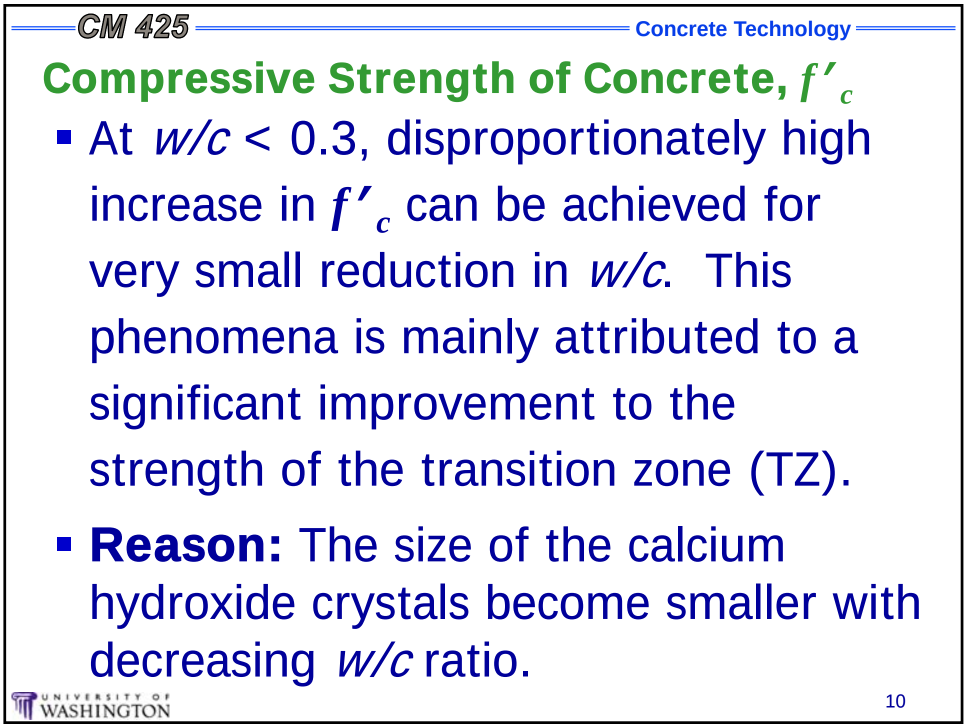

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Compressive Strength of Concrete, f'_c

- At *w/c* < 0.3, disproportionately high increase in f'_c can be achieved for very small reduction in *w/c*. This phenomena is mainly attributed to a significant improvement to the strength of the transition zone (TZ).
- **Reason:** The size of the calcium hydroxide crystals become smaller with decreasing *w/c* ratio.

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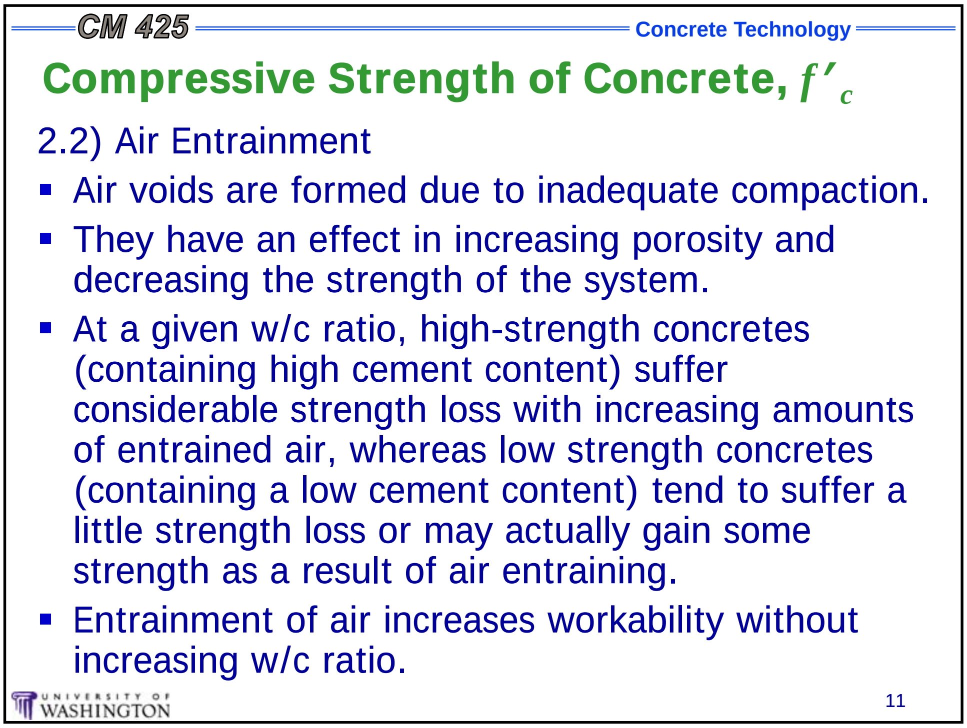
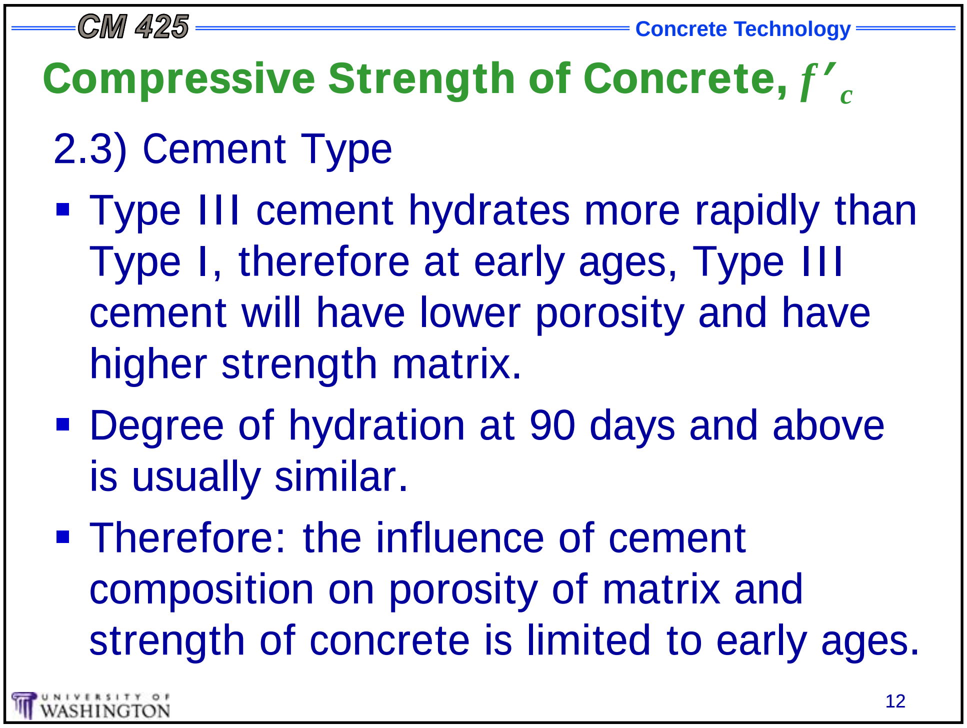


Compressive Strength of Concrete, f'_c

2.2) Air Entrainment

- Air voids are formed due to inadequate compaction.
- They have an effect in increasing porosity and decreasing the strength of the system.
- At a given w/c ratio, high-strength concretes (containing high cement content) suffer considerable strength loss with increasing amounts of entrained air, whereas low strength concretes (containing a low cement content) tend to suffer a little strength loss or may actually gain some strength as a result of air entraining.
- Entrainment of air increases workability without increasing w/c ratio.



Compressive Strength of Concrete, f'_c

2.3) Cement Type

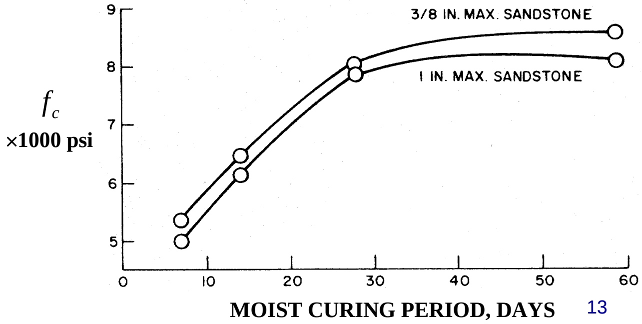
- Type III cement hydrates more rapidly than Type I, therefore at early ages, Type III cement will have lower porosity and have higher strength matrix.
- Degree of hydration at 90 days and above is usually similar.
- Therefore: the influence of cement composition on porosity of matrix and strength of concrete is limited to early ages.

Compressive Strength of Concrete, f'_c

2.4) Maximum Size Aggregate (MSA)

- Economy mandates that you should use maximum size of aggregate possible.
- Concrete mixtures containing larger aggregate particles require less mixing water.
- Larger aggregates tend to form weaker transition zone (TZ), containing more microcracks.

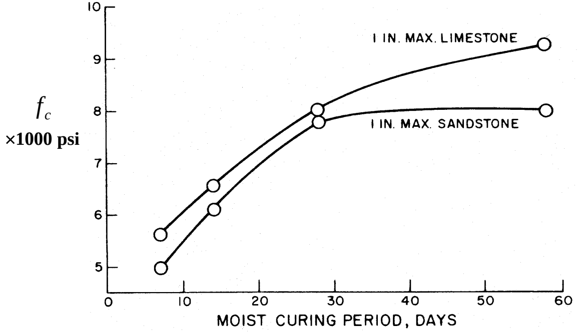
Influence of the aggregate size on compressive strength of concrete.



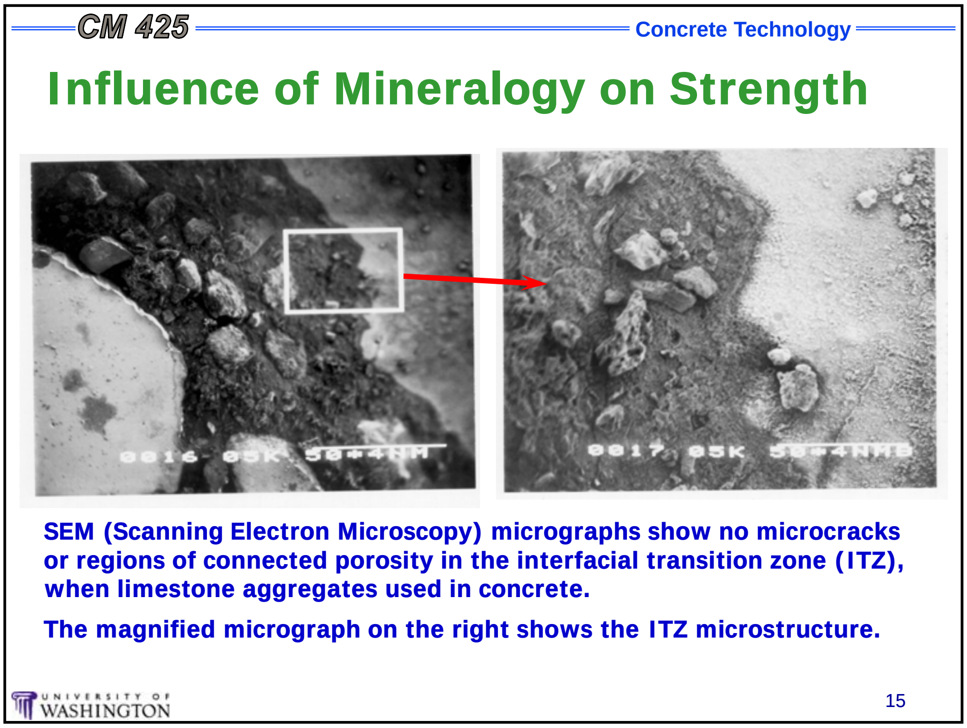
Compressive Strength of Concrete, f'_c

2.4a) Influence of Mineralogy

- Differences in the mineralogical composition of aggregates affect concrete strength.



The reason for limestone to produce higher strength is because $CaCO_3.Ca(OH)_2.xH_2O$ is formed at interface in TZ. This chemical strengthens the Transition zone.



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Influence of Mineralogy on Strength

SEM (Scanning Electron Microscopy) micrographs show no microcracks or regions of connected porosity in the interfacial transition zone (ITZ), when limestone aggregates used in concrete.

The magnified micrograph on the right shows the ITZ microstructure.

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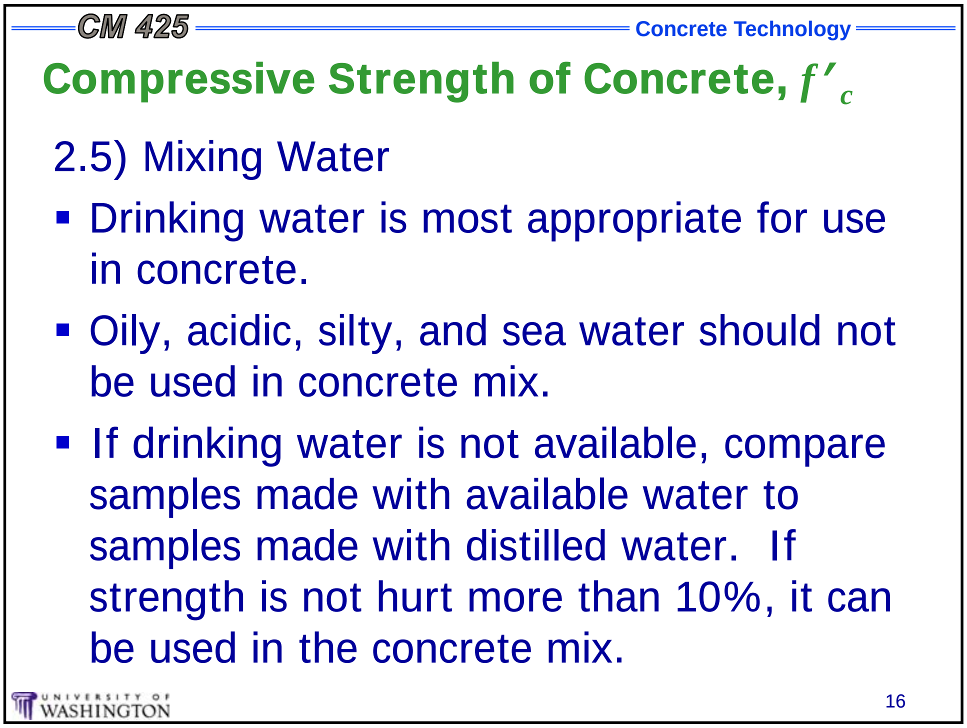

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Compressive Strength of Concrete, f'_c

2.5) Mixing Water

- Drinking water is most appropriate for use in concrete.
- Oily, acidic, silty, and sea water should not be used in concrete mix.
- If drinking water is not available, compare samples made with available water to samples made with distilled water. If strength is not hurt more than 10%, it can be used in the concrete mix.

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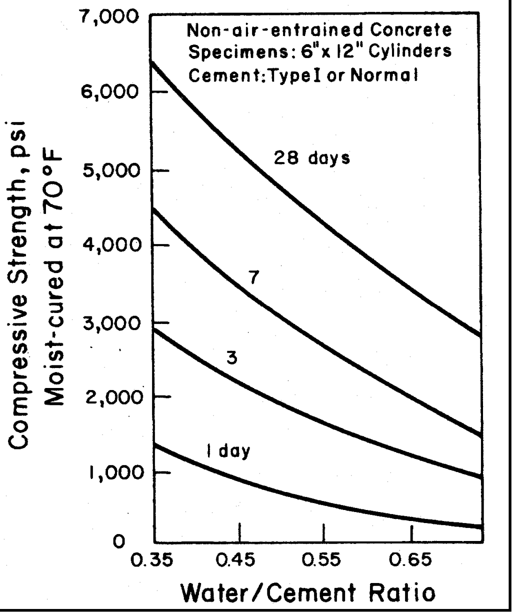
Curing of Concrete

- Procedures developed to promote cement hydration, consisting of control of time, temperature, and humidity conditions immediately after the placement of a concrete mixture into formwork.
- Curing Temperature is much more important than casting temperature.



Curing of Concrete

- **TIME:**
  - At a given *w/c* ratio, the longer the moist curing period, the higher the strength.
  - ACI Committee 209 recommends the following relationship for moisture-cured concrete made with normal portland cement (ASTM Type I):

$$f_{cm}(t) = f_{c28}\left(\frac{t}{4+0.85t}\right)$$

or for concrete specimens cured at 20°C, the CEB-FIB models code (1990) suggests:

$$f_{cm}(t) = \exp\left[s\left(1-\left(\frac{28}{t/t_1}\right)^{1/2}\right)\right] f_{cm}$$

where $f_{cm}(t) =$ mean compressive strength at age t days

f_{cm} & $f_{c28} =$ mean 28-day compressive strength

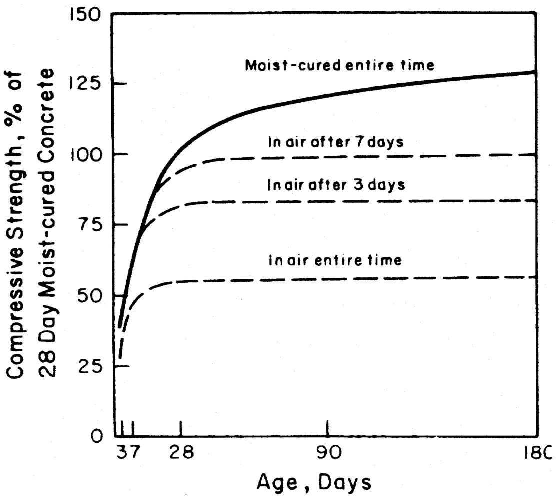
$S =$ Coefficient depending on cement type; $S = 0.25$ NSC

$t_1 = 1$ day

Curing of Concrete

HUMIDITY:

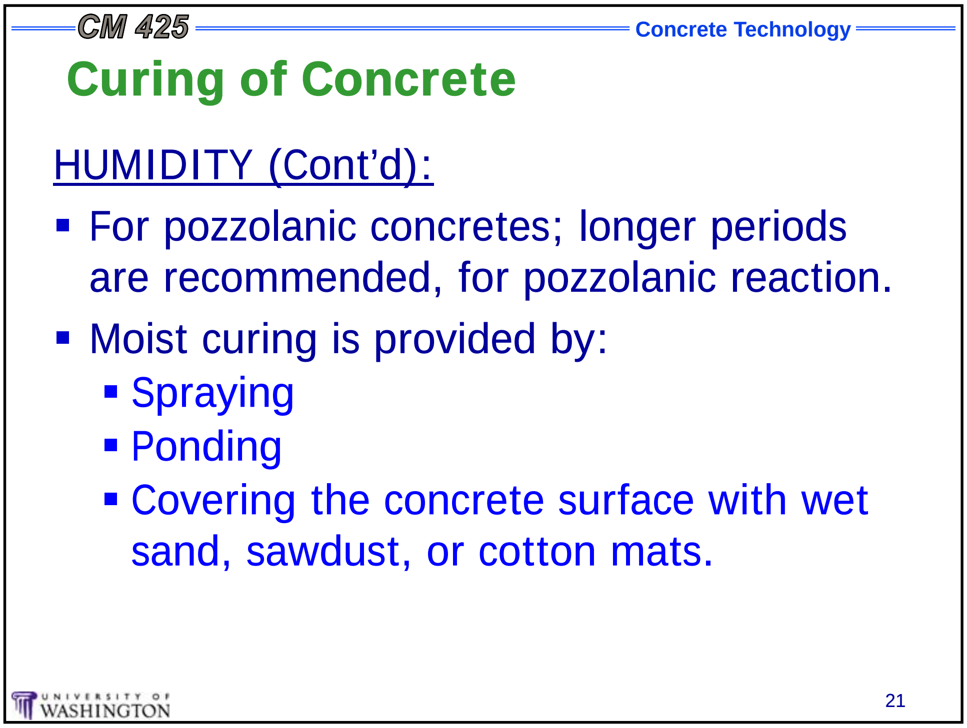
- Opposite figure shows that after 180 days at a given *w/c* ratio, the strength of the continuously moist-cured concrete was three times greater than the strength of the continuously air-cured concrete.



Curing of Concrete

HUMIDITY (Cont'd):

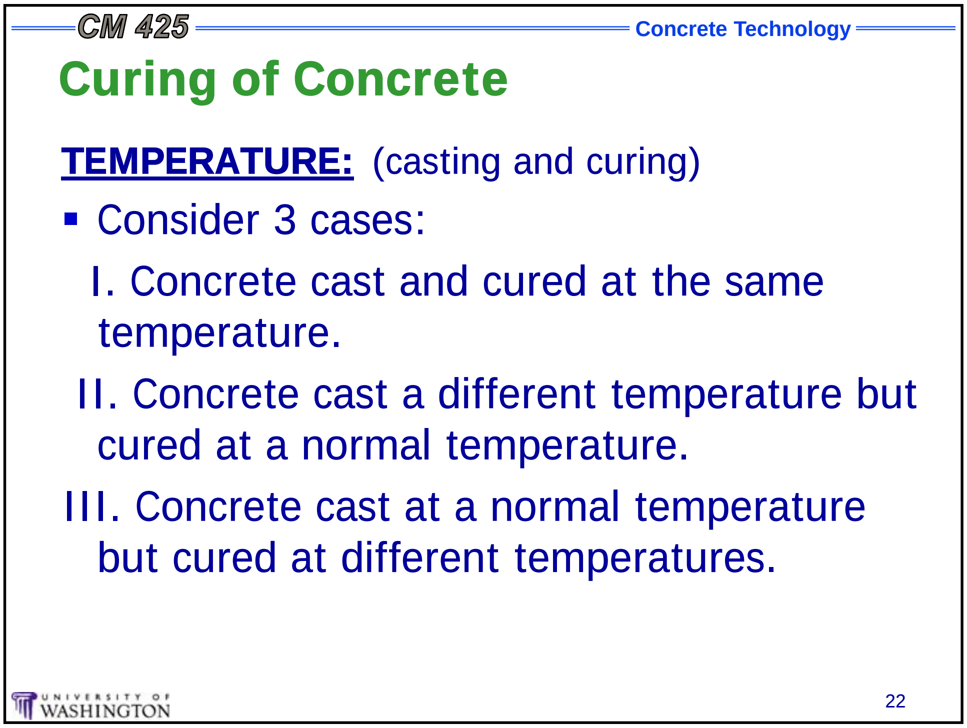
- Concrete increases in strength with age if drying is prevented.
- When the concrete is permitted to dry, the chemical reactions slow down or stop.
- Concrete should be kept moist as long as possible.
- A minimum period of 7-day moist curing is generally recommended for concrete containing normal portland cement.



Curing of Concrete

HUMIDITY (Cont'd):

- For pozzolanic concretes; longer periods are recommended, for pozzolanic reaction.
- Moist curing is provided by:
  - Spraying
  - Ponding
  - Covering the concrete surface with wet sand, sawdust, or cotton mats.



Curing of Concrete

TEMPERATURE: (casting and curing)

- Consider 3 cases:

I. Concrete cast and cured at the same temperature.

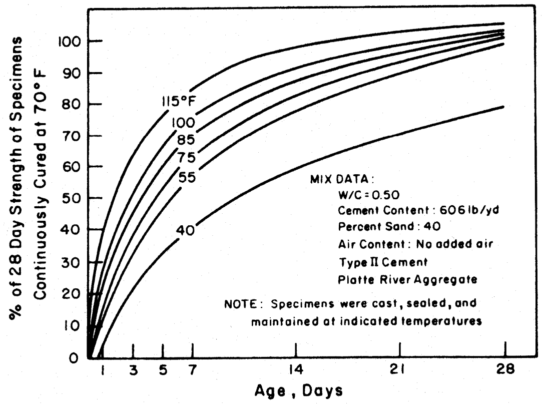
II. Concrete cast a different temperature but cured at a normal temperature.

III. Concrete cast at a normal temperature but cured at different temperatures.

Curing of Concrete

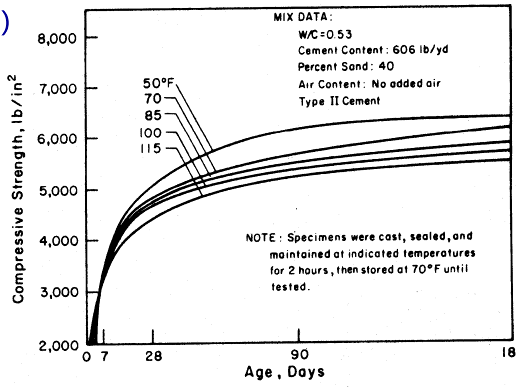
Case I: (Cast and cured at the same temperature)

- Up to 28-days, the higher the temperature, the more rapid the cement hydration and the strength gain resulting from it.



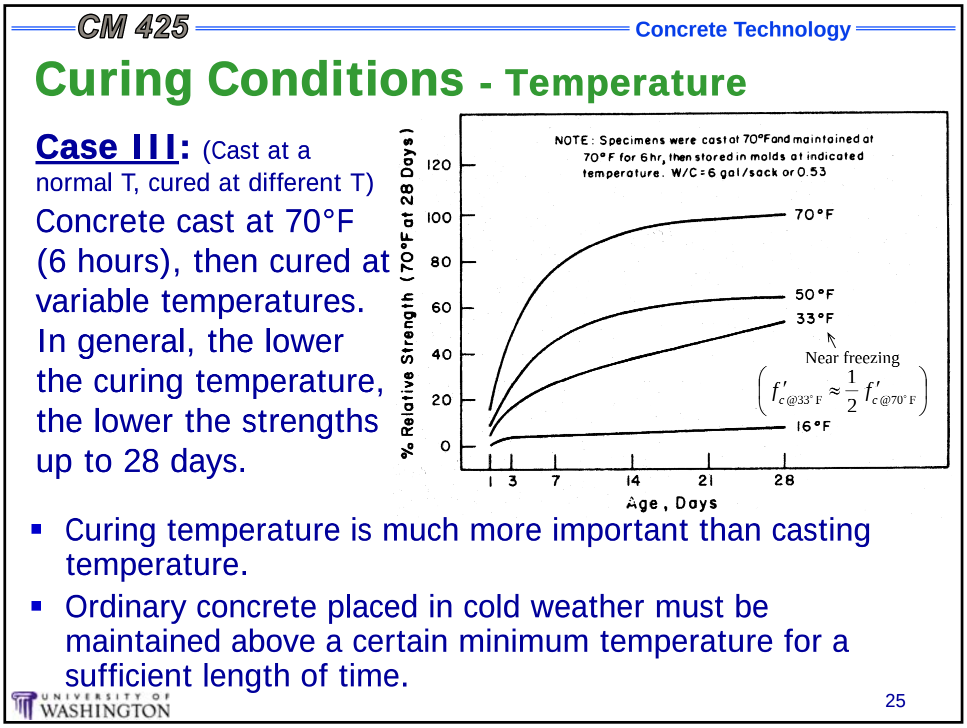
Curing of Concrete - Temperature

Case II: (Cast a different T, cured at a normal temperature) 2-hours at temperatures as shown in the figure, then cured at 70°F. Data show that ultimate strength (180 days) of the concretes cast at 50°F were higher than those cast at 100°F.



Reason:

Microscopic studies show that with low temperature curing, a relatively more uniform microstructure of the hydrated cement paste and pore size distribution accounts for the higher strength.



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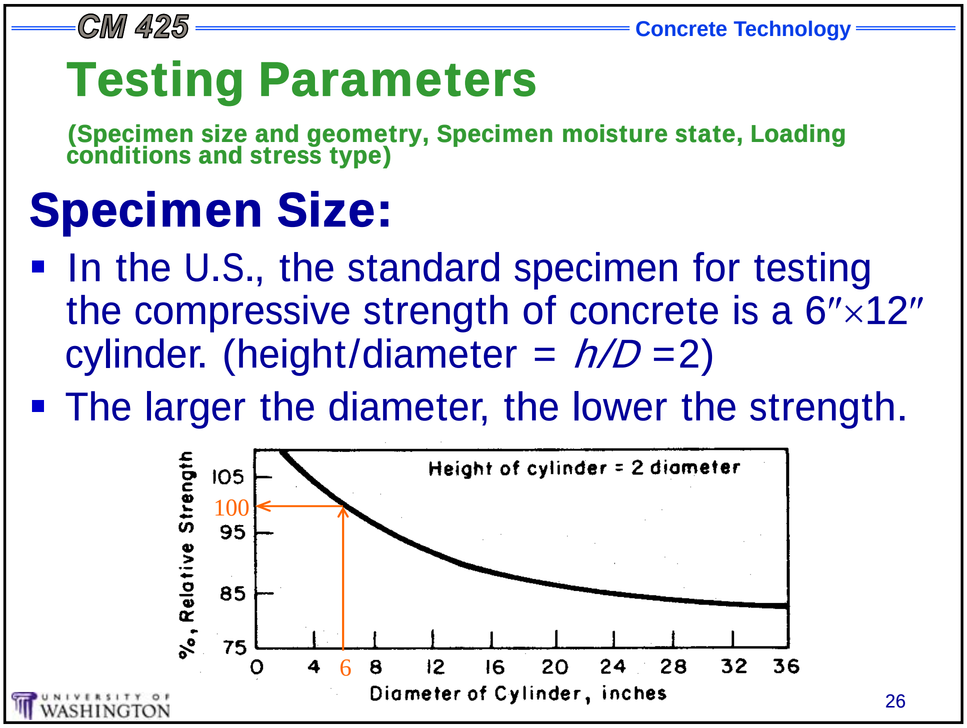
Curing Conditions - Temperature

Case III: (Cast at a normal T, cured at different T)

Concrete cast at 70°F (6 hours), then cured at variable temperatures. In general, the lower the curing temperature, the lower the strengths up to 28 days.

$\left(f'_{c@33^\circ F} \approx \frac{1}{2} f'_{c@70^\circ F}\right)$

- Curing temperature is much more important than casting temperature.
- Ordinary concrete placed in cold weather must be maintained above a certain minimum temperature for a sufficient length of time.



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Testing Parameters

(Specimen size and geometry, Specimen moisture state, Loading conditions and stress type)

Specimen Size:

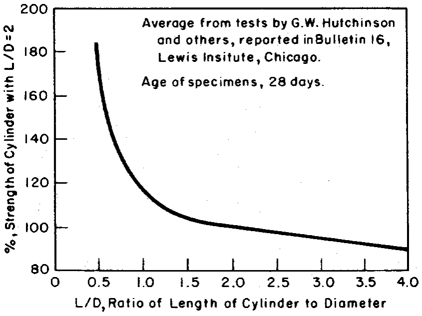
- In the U.S., the standard specimen for testing the compressive strength of concrete is a 6″×12″ cylinder. (height/diameter = *h/D* =2)
- The larger the diameter, the lower the strength.

Testing Parameters

(Specimen size and geometry, Specimen moisture state, Loading conditions and stress type)

Reason:

- Variation in strength with varying specimen size are due to the increasing degree of statistical homogeneity in large specimens



Testing Parameters

Moisture State:

- Standard: Specimen must be in moist condition at the time of testing.
- Air-dried specimens show 20 to 25% higher strength than corresponding saturated specimen.

Reason: Due to existence of disjoining pressure within the cement paste.

Loading Condition:

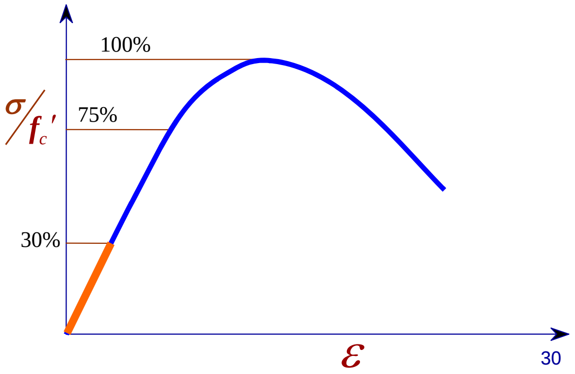
- The compressive strength of concrete is measured by a uniaxial compression test. i.e., load is progressively increased to fail the specimen within 2 to 3 minutes.

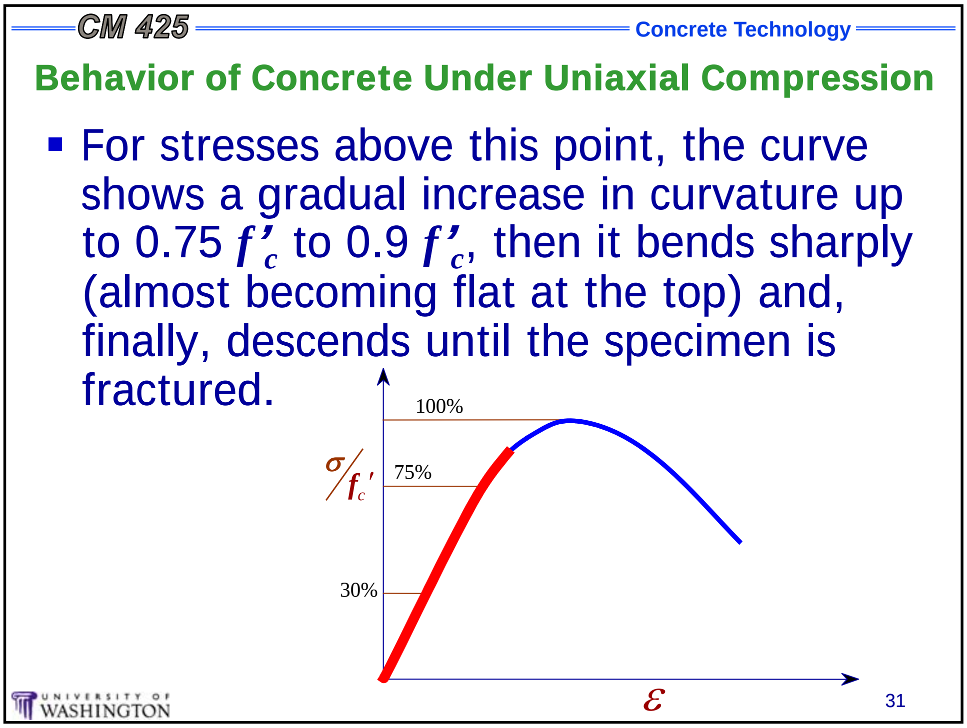
Rate of Loading

- The more rapid the rate of loading, the higher the observed strength value.
- ASTM C 469 says that in a uniaxial compression test, the load should be progressively increased to fail the specimen within 2 to 3 minutes.
- The usual rate of loading is 35±5 psi/second.

Behavior of Concrete Under Uniaxial Compression

- Stress-strain curve shows a linear-elastic behavior up to 30% of the ultimate strength, f'_c, because under short-term loading the TZ microcracks remain undisturbed.





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Behavior of Concrete Under Uniaxial Compression

- For stresses above this point, the curve shows a gradual increase in curvature up to 0.75 f'_c to 0.9 f'_c, then it bends sharply (almost becoming flat at the top) and, finally, descends until the specimen is fractured.

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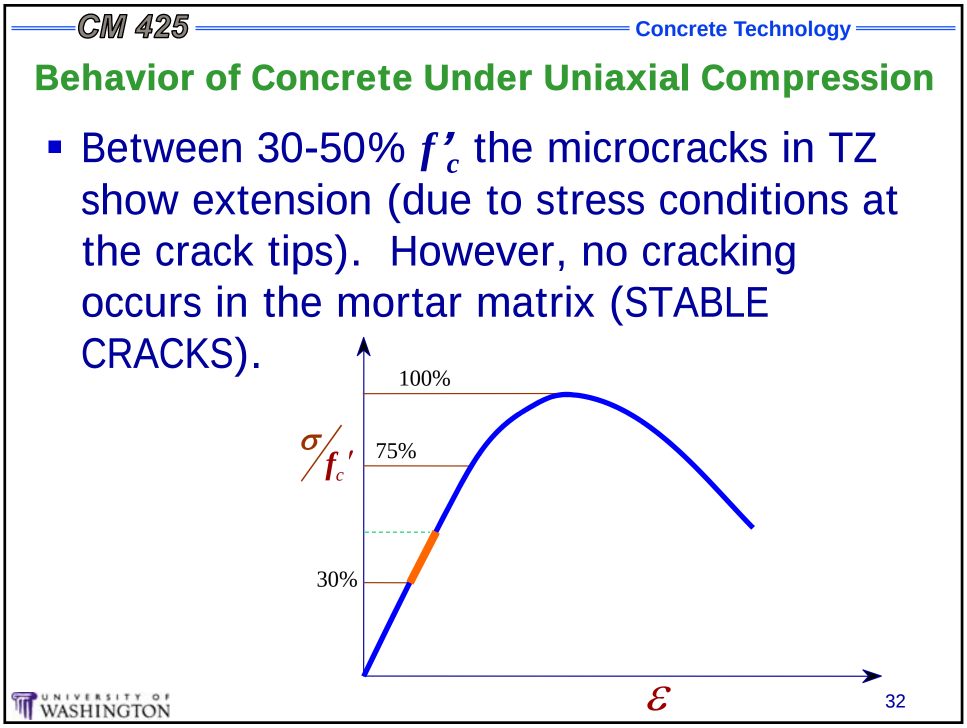

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Behavior of Concrete Under Uniaxial Compression

- Between 30-50% f'_c the microcracks in TZ show extension (due to stress conditions at the crack tips). However, no cracking occurs in the mortar matrix (STABLE CRACKS).

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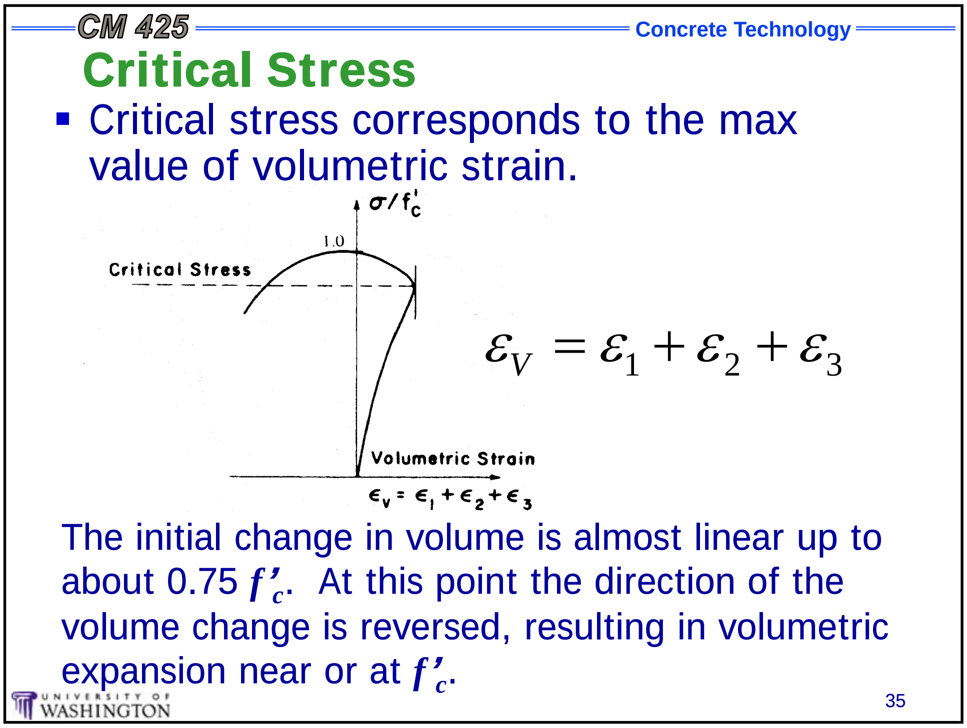
Behavior of Concrete Under Uniaxial Compression

- For a stress between 50 to 75% of f'_c, increasingly the crack system tends to be unstable as the TZ cracks begin to grow again.
- When available internal energy exceeds the required crack-release energy, the rate of crack propagation will increase and the system becomes UNSTABLE.

Behavior of Concrete Under Uniaxial Compression

- This happens at a compression stress above 0.75 f'_c, when the complete fracture of the specimen can occur by bridging the mortar and TZ cracks.
- The stress level of about 75% of f'_c, which represents the onset of unstable crack propagation, is called **critical stress**.

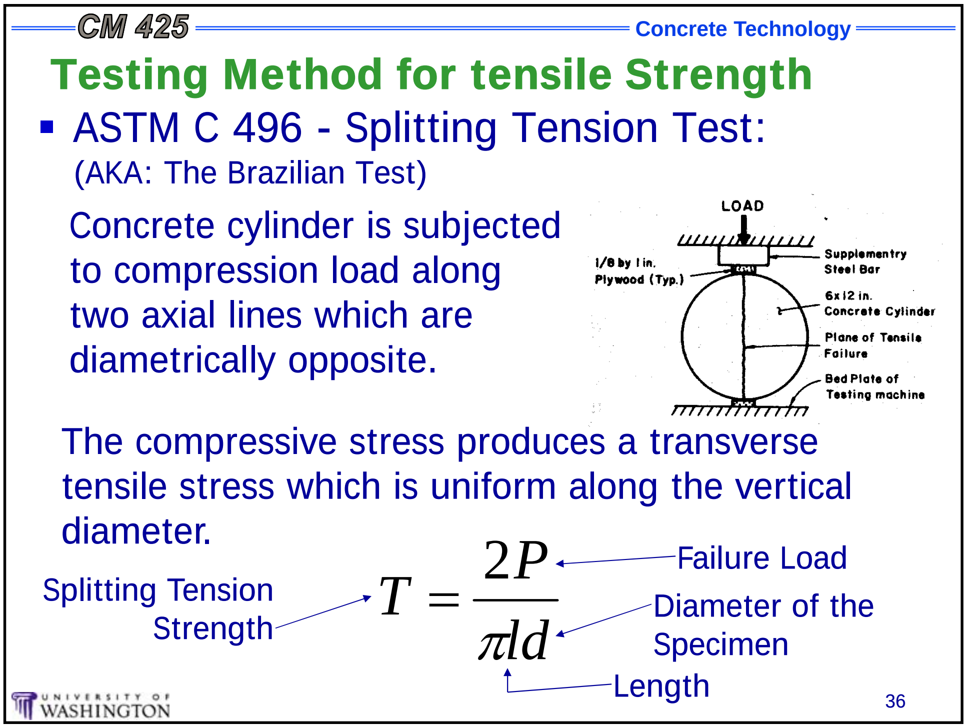


Critical Stress

- Critical stress corresponds to the max value of volumetric strain.

$$\varepsilon_V = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

The initial change in volume is almost linear up to about 0.75 f'_c. At this point the direction of the volume change is reversed, resulting in volumetric expansion near or at f'_c.



Testing Method for tensile Strength

- ASTM C 496 - Splitting Tension Test:
  (AKA: The Brazilian Test)

Concrete cylinder is subjected to compression load along two axial lines which are diametrically opposite.

The compressive stress produces a transverse tensile stress which is uniform along the vertical diameter.

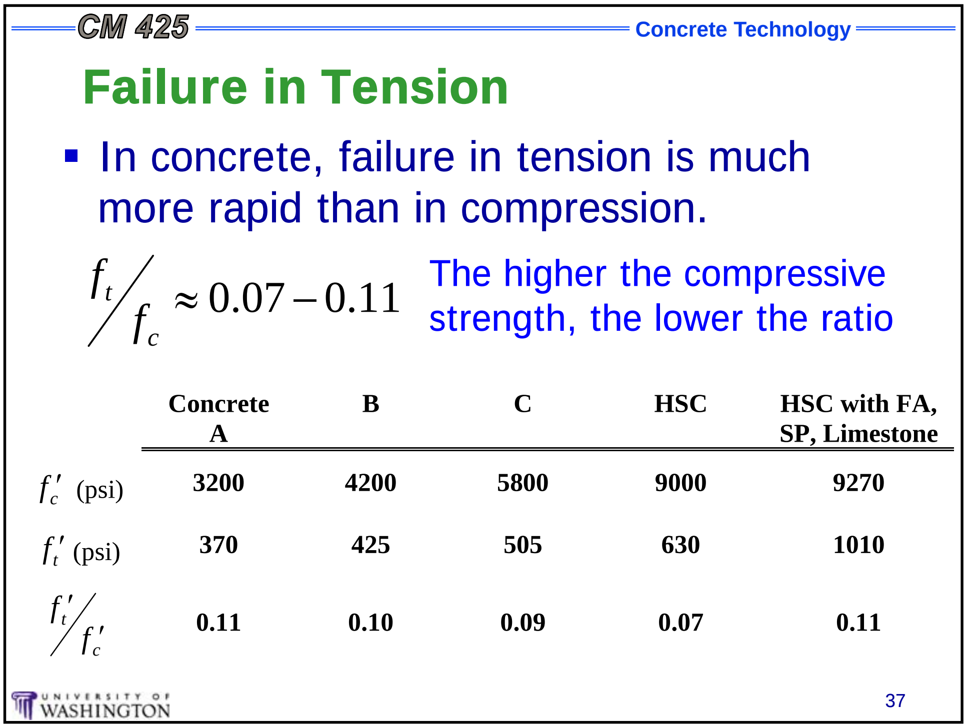
$$T = \frac{2P}{\pi l d}$$

Splitting Tension Strength

Failure Load

Diameter of the Specimen

Length



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Failure in Tension

- In concrete, failure in tension is much more rapid than in compression.

$$f_t / f_c \approx 0.07 - 0.11$$

The higher the compressive strength, the lower the ratio

	Concrete A	**B**	**C**	**HSC**	**HSC with FA, SP, Limestone**
f'_c (psi)	**3200**	**4200**	**5800**	**9000**	**9270**
f'_t (psi)	**370**	**425**	**505**	**630**	**1010**
f'_t / f'_c	**0.11**	**0.10**	**0.09**	**0.07**	**0.11**

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