Dimensional Stability

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Overview of Topics

EARLY AGE CONCRETE

Plastic shrinkage – shrinkage strain associated with early moisture loss

Thermal shrinkage – shrinkage strain associated with cooling

LATER AGE CONCRETE

Drying shrinkage -shrinkage strain associated with moisture loss in the hardened material

Deformations occur under loading

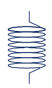
- Elastic
- Viscoelastic

When does concrete crack?

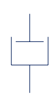
To understand this, we must consider the way concrete deforms under loading:

- Concrete exhibits both elastic and viscous (time-dependent deformation) behavior
- Concrete is a viscoelastic material
- Viscoleastic behavior can be described using rheological models with 2 components:

linear elastic spring



linear viscous dashpot



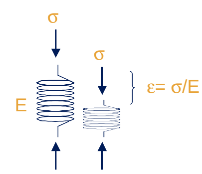
Pure Linear Elastic Behavior

- Visualized by a spring
- Deformation quantified by Hooke's Law

  Stress(t) = E x strain(t)

  where E is the spring constant
- Deformation is instantaneous;

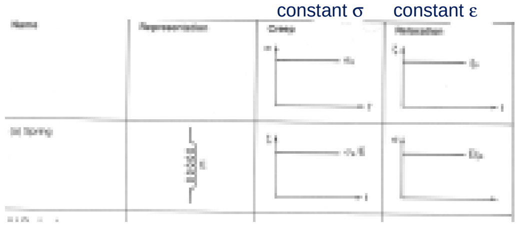
  no continued deformation with time



Pure Linear Elastic Behavior

for constant σ

for constant ε



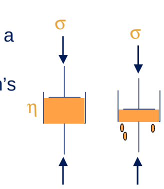
Pure Viscous Behavior

- Visualized by a dashpot
- Piston displaces a viscous fluid in a cylinder with a perforated bottom
- Deformation quantified by Newton's Law of viscosity

  $\dot{\varepsilon}(t) = \sigma(t)/\eta$

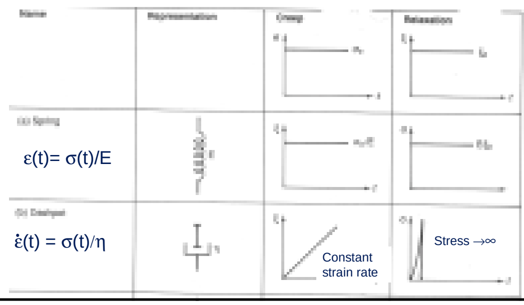
  where $\dot{\varepsilon}$ is the strain rate $d\varepsilon/dt$

  η is the viscosity coefficient



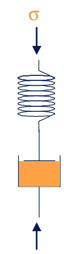
Linear elastic vs. Viscous Behavior

for constant σ | for constant ε



Combinations of these two elements can be used to describe more complex behavior.

For example, the Maxwell model:



<u>Equilibrium equation:</u>

$\sigma_E(t) = \sigma_\eta(t) = \sigma(t)$

<u>Compatibility equation:</u>

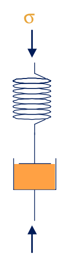
$\varepsilon(t) = \varepsilon_E(t) + \varepsilon_\eta(t)$

<u>Constitutive relationships:</u>

$\sigma_E(t) = E\varepsilon_E(t)$ spring

$\sigma_\eta(t) = \eta\dot{\varepsilon}_\eta(t)$ dashpot

Maxwell Model



- Differentiating $\varepsilon(t) = \varepsilon_E(t) + \varepsilon_\eta(t)$, we get

$\dot{\varepsilon}(t) = \dot{\varepsilon}_E(t) + \dot{\varepsilon}_\eta(t)$

- Differentiating $\sigma_E(t) = E\varepsilon_E(t)$, we get

$\dot{\sigma}_E(t) = E\dot{\varepsilon}_E(t)$

- Assuming $\sigma_E(t) = \sigma_\eta(t) = \sigma(t)$ and remembering that $\sigma_\eta(t) = \eta\dot{\varepsilon}_\eta(t)$ substituting into we get

$\dot{\varepsilon}(t) = \dot{\sigma}(t)/E + \sigma(t)/\eta$

- Integrating, we get, for an initial applied stress, σ_o

$\varepsilon(t) = \sigma_o/E + (\sigma_o/\eta)t$

Which predicts that for a constant applied stress σ_o (i.e., creep), there will be an instantaneous strain and then strain will increase without bounds

Maxwell Model

$\varepsilon(t) = \sigma_o/E + (\sigma_o/\eta)t$

- If after loading, the system is unloaded, there will be an instantaneous recovery (σ_o/E) in the spring, while a permanent strain $[(\sigma_o/\eta)t]$ remains in the dashpot.

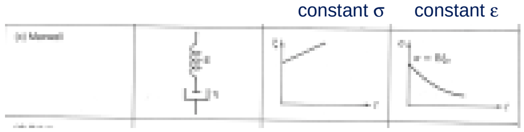
For relaxation, where the *strain* ε_o is constant, integration of $\dot{\varepsilon}(t) = \dot{\sigma}(t)/E + \sigma(t)/\eta$ gives

$\sigma(t) = E\varepsilon_o e^{-Et/\eta}$

The ratio η/E is defined as the relaxation time; a small relaxation time indicates that the relaxation process will be fast

Maxwell Model

for constant σ | for constant ε



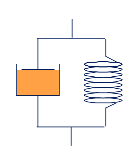
Kelvin Model

<u>Equilibrium equation:</u>

$\sigma(t) = \sigma_E(t) + \sigma_\eta(t)$

<u>Compatibility equation:</u>

$\varepsilon(t) = \varepsilon_E(t) = \varepsilon_\eta(t)$



<u>Constitutive relationships:</u>

$\sigma_E(t) = E\varepsilon_E(t)$ spring

$\sigma_\eta(t) = \eta\dot{\varepsilon}_\eta(t)$ dashpot

Resulting in: $\sigma(t) = E\varepsilon_E(t) + \eta\dot{\varepsilon}_\eta(t)$

Kelvin Model: Creep

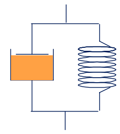
$\sigma(t) = E\varepsilon_E(t) + \eta\varepsilon_\eta(t)$

- For creep under stress σ_o, integrating at t=0, yields

$\varepsilon(t) = (\sigma_o/E)(1 - e^{-Et/\eta})$

Showing that the strain $\varepsilon(t)$ increases at a decreasing rate, with an asymptote of σ_o/E

The ratio η/E is defined as the retardation time; a small value indicates creep will proceed quickly.

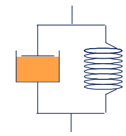


- In creep, the strain is initially carried by the dashpot and is over time transferred to the spring
- The limit on total deformation is set by the spring

Kelvin Model: Creep and Stress Relaxation

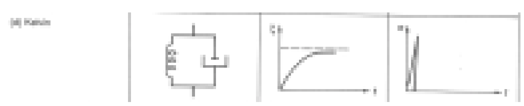
$\sigma(t) = E\varepsilon_E(t) + \eta\varepsilon_\eta(t)$

- Upon unloading, in creep, there is no permanent deformation predicted
- Kelvin models cannot be used for stress relaxation, because an infinite stress would be required to produce an instantaneous strain condition.

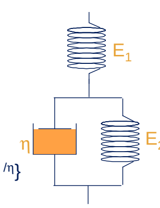


Kelvin Model

for constant σ | for constant ε



Standard Solid Model



For creep:

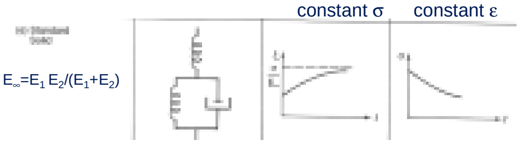
$1/E_c(t) = \varepsilon(t)/\sigma_o = [(E_1+E_2)/E_1 E_2] - (1/E_2)e^{-E_2 t/\eta}$

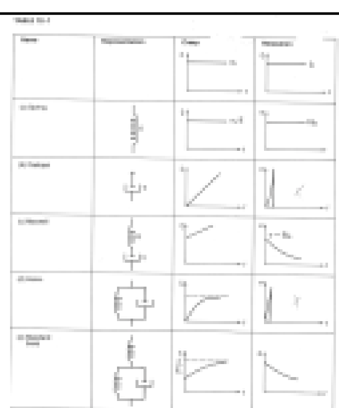
For relaxation:

$E_r(t) = [E_1 E_2/(E_1+E_2)] + \{E_1 - [E_1 E_2/(E_1+E_2)]e^{-(E_1+E_2)t/\eta}\}$

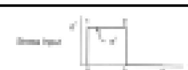
for constant σ | for constant ε

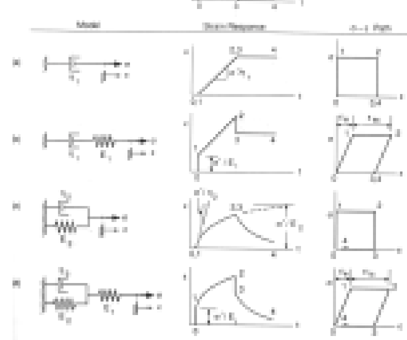
$E_\infty = E_1 E_2/(E_1+E_2)$





Creep

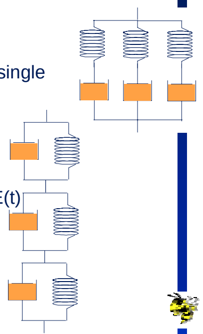




More Sophisticated Rheological Models

- Combine Maxwell elements in parallel
  - A series combination would reduce to a single Maxwell element
- Combine Kelvin elements in series
  - A parallel combination would reduce to a single Kelvin element
- Allow E and η to be time-dependent [i.e, E(t) and η(t)] to allow for aging in concrete
- For variable loading, use principle of superposition to make the effects additive
  - applicable for basic creep only

See Mehta and Monteiro for more details…



When does concrete crack?

To understand this, we must consider the way concrete deforms under loading:

- Concrete exhibits both elastic and viscous (time-dependent deformation) behavior
- Concrete is a viscoelastic material
- Under constant load, deformation increases with time (creep)
- Under constant strain - such as when a concrete member is under restraint - stress decreases with time (stress relaxation)
- Therefore, STRESS RELAXATION REDUCES ACTUAL STRESSES IN CONCRETE!

Extensibility

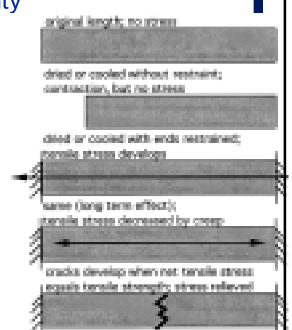
Original State

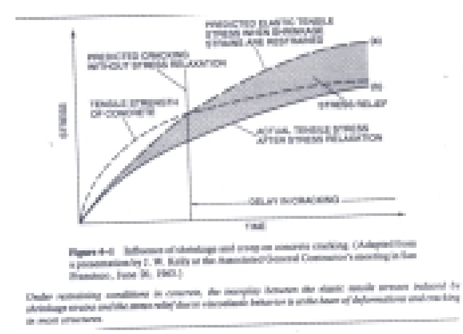
Unrestrained Shrinkage

Restrained Shrinkage

Stress Relaxation

When $\sigma_t \geq f_t$, cracking occurs

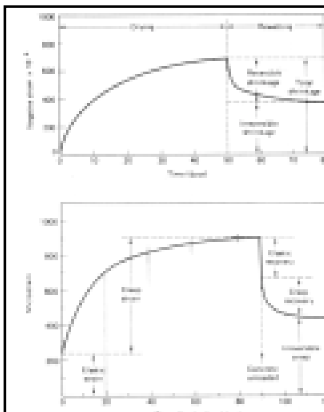


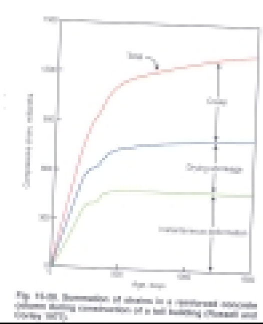


Drying Shrinkage and Creep

- Drying Shrinkage - strain *in hardened concrete* caused by loss of water; occurs in the paste; is restrained by the aggregate
  - Chemical Shrinkage - shrinkage due to change in solid volume during hydration
  - Autogenous Shrinkage - shrinkage due to "self-dessication" during hydration
  - Carbonation Shrinkage - shrinkage due to reaction with CO_2
- Creep - time-dependent strain *in hardened concrete* results from applied stress; occurs in the paste; is restrained by the aggregate

Drying Shrinkage and Creep





Parameters Affecting Drying Shrinkage and Creep

TABLE 16.1 Parameters Affecting Drying Shrinkage and Creep of Concrete

Paste parameters
- Porosity } w/c ratio and degree of hydration
- Age of paste }
- Curing temperature
- Cement composition
- Moisture content
- Admixtures

Concrete parameters
- Aggregate stiffness
- Aggregate content (cement content)
- Volume: surface ratio
- Thickness

Environmental parameters
- Applied stress } affect only creep
- Duration of load }
- Relative humidity
- Rate of drying
- Time of drying

Drying Shrinkage

- Inadequate allowance for drying shrinkage can lead to cracking and warping or curling
- Must provide adequately spaced joints in slabs and pavements
- Joints define where the crack will form, rather than allowing for random crack formation
- Can then seal joints to prevent moisture ingress

Drying Shrinkage

Domain 1 - loss of water from large capillary pore (macropores, > 50nm)

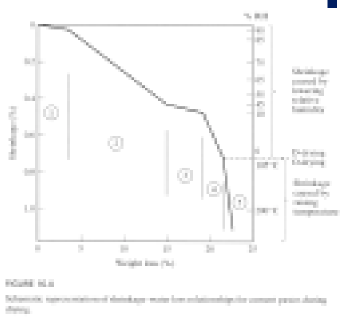
Domain 2 - loss of water from small capillary pores and interlayer space in C-S-H (I.e, meso- and micropores)

Domain 3 - loss of adsorbed water

Domain 4 - continued loss of adsorbed water and loss of interlayer water

Domain 5 - loss of water to due decomposition of C-S-H

DUE TO FIRE



Mechanisms

Three phenomena are believed to contribute to drying shrinkage, resulting in a volumetric contraction:

(1) Capillary stress, P_{cap}

(2) Disjoining pressure, P_{dis}

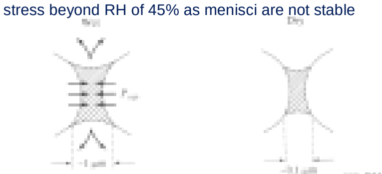
(3) Changes in the surface free energy, P_{sfe}

Each are related to:

- Porosity and pore structure in the HCP
- Van der Waals bonding in the C-S-H
- High surface area of the C-S-H
- Microporosity of the C-S-H

Capillary Stress

- Active in Domains 1 and 2, between RH 95% and 45%
- Water held in small capillary pores is partially under the influence of surface interactions exerted by the pore walls
- At suitably low RH, water can be lost
- In this case, water is under hydrostatic tension and a meniscus forms
- The water exerts a corresponding hydrostatic compression on the pore walls, perhaps inducing a reduction in pore size
- Stress induced is related to the RH; higher stresses as RH approaches 45%; no capillary stress beyond RH of 45% as menisci are not stable

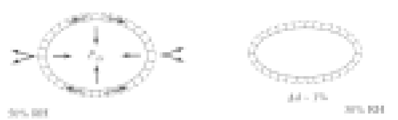


Disjoining Pressure

- Adsorption of water at the surface of the C-S-H layers creates a disjoining pressure
- The pressure increases with increasing RH (or water layer thickness)
- When the pressure exceeds the strength of the Van der Waals bonding between the C-S-H layers, the layers are forced apart, creating a dilation
- C-S-H exists in this dilated state after hydration
- On first drying, water is lost and the disjoining pressure decreases; layers of C-S-H are brought closer by Van der Waals attraction, resulting in a net volumetric shrinkage
- Occurs to RH ~45%

Surface Free Energy

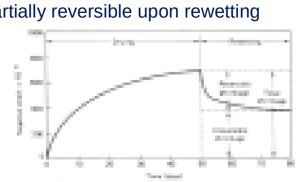
- Responsible for shrinkage below RH 45%; greatest below 20%
- As the most tightly held water is removed, the surface free energy of the C-S-H grows
- A pressure is generated, proportional to the surface free energy and the surface area
- This pressure leading to compression of the solid



Irreversible Shrinkage

- Drying shrinkage is only partially reversible upon rewetting

- Changes in structure
- Changes in bonding
- Microcracking



- Relative amounts of reversible/irreversible shrinkage are due to many factors, including w/c, cement composition, degree of hydration, use of SCMs, use of chemical admixtures, curing history (temperature, RH), drying history…

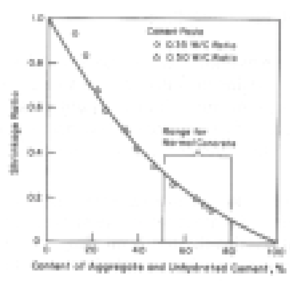
Shrinkage: Effect of Aggregate Content

Powers 1961:

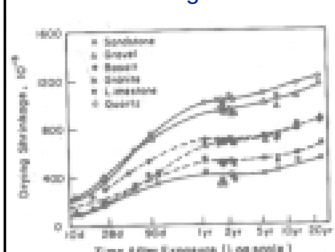
$\varepsilon_{concrete} = \varepsilon_{paste}(1-V_{agg})^n$

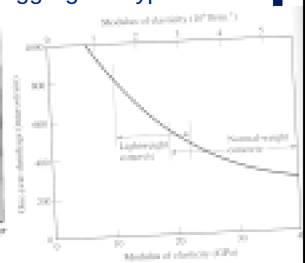
L'Hermite:

n 1.2-1.7, depending on E_{agg}

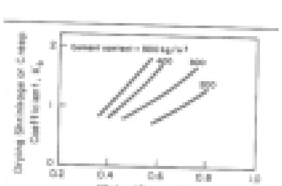


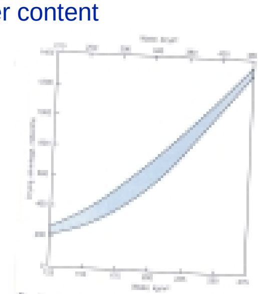
Shrinkage: Effect of Aggregate Type





Shrinkage: Effect of w/c, cement content, and water content

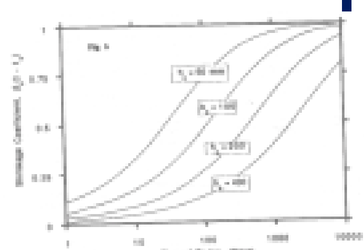




Shrinkage: Effect of Specimen Geometry

- Size and shape determine rate of moisture loss

h_o = theoretical thickness = area of section/semiperimeter in contact with atmosphere



Shrinkage: Effect of Specimen Geometry

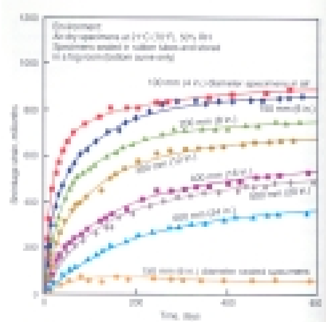
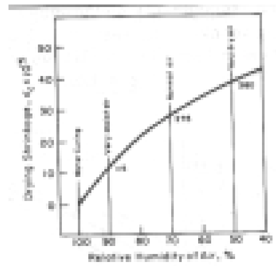
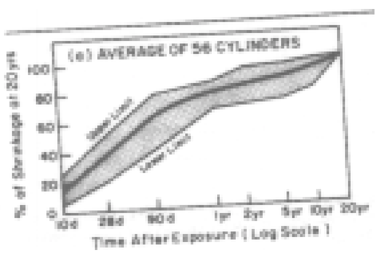


Fig. 10-12. Drying shrinkage of various sizes of cylindrical specimens made of Elgin, Illinois gravel concrete (Hansen and Mattock 1966).

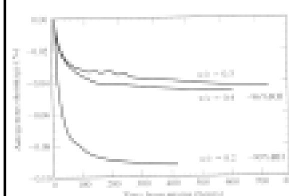
Shrinkage: Effect of RH



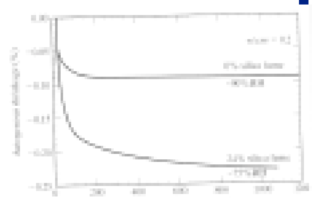
Shrinkage: Effect of Time



Autogenous Shrinkage



Previously discussed



Carbonation Shrinkage

Atmospheric CO_2 will react with hydration products leading to irreversible shrinkage due to water loss:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

C-S-H + $CO_2 \rightarrow$ C-S-H + $CaCO_3 + H_2O$

Note: the C/S ratio of the product C-S-H will be less than that of the reactant C-S-H

Probable mechanisms:

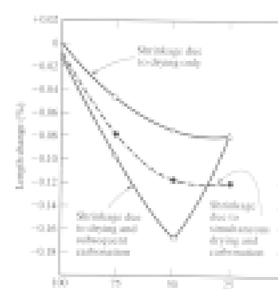
- Water loss
- Rearrangement of C-S-H structure

Can be used *advantageously* to prevent in service shrinkage

Carbonation Shrinkage

Depends on RH; worst at 50% RH

- <50% rate of carbonation is low due to lack of water
- >50% presence of water slows CO_2 ingress



Creep

Creep - time-dependent strain in hardened concrete results from applied stress

Similarities to shrinkage:
- Strain-time curves
- Magnitude of deformation
- Only partially reversible
- Paste related deformation
- Aggregate restrains deformation
- Mechanisms lie in changes in C-S-H
- Affected by largely the same parameters

Definitions

Basic creep – creep without drying (100%RH)

Drying creep – when concrete is under load and also exposed to low RH environment

total strain > elastic strain + shrinkage strain + creep strain
- the drying creep is the additional strain that occurs

Total creep – sum of basic and drying creep

Specific creep = creep strain/applied stress

10^{-6}/lb/in^2 or 150x10^{-6}/MPa are typical values

Creep coefficient = creep strain/elastic strain

Mechanisms

Like drying shrinkage, creep in concrete likely results from loss/movement of adsorbed water in the HCP, leading to a rearrangement of the C-S-H structure and porosity.

Driving force IS different!

In addition, with creep there may be some additional factors which contribute to the deformation:
- effects of microcracking in TZ
- additional effects of drying during creep
- delayed elastic strain in the aggregate (which may receive more of the load over time)

Mechanisms

Role of Moisture in Creep:
- The presence of a sufficient amount of adsorbed water between C-S-H layers may allow for slip to occur under shear stress
- With applied stress, water held in micropores may migrate to larger capillary pores, resulting in a net contraction
- New bonds may form in the C-S-H due to moisture migration and slip

Creep: Effect of Time

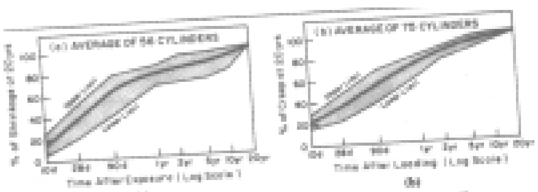


Figure 6-13 The time dependency of (a) drying shrinkage and (b) creep. (From G. E. Troxell et al., Proc. ASTM, Vol. 58, 1958. Reprinted with permission from ASTM. Copyright, ASTM, 1916 Race Street, Philadelphia PA 19103.)

For a wide range of concrete mixtures, drying shrinkage and creep show a similar time dependency.

Creep: Effect of Aggregate Content

$\varepsilon_{concrete} = \varepsilon_{paste}(1-V_{agg})^{\alpha}$

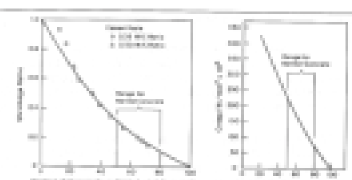


Figure 6-[illegible] Influence of aggregate content on (a) drying shrinkage and (b) creep. ((a), From ACI Monograph 6, 1971, p. 126; (b), from Concrete Society (London), Technical Paper 101, 1973.)

Aggregate content in concrete is the most important factor affecting drying shrinkage and creep. Unhydrated cement does not shrink and therefore may be included in the aggregate.

Creep: Effect of Aggregate Type

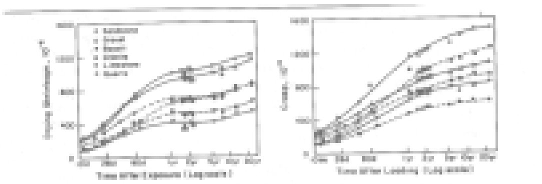


Figure 4–18 Influence of aggregate type on drying shrinkage and creep. (From G. E. Troxell et al., Proc. ASTM, Vol. 58, 1958; and ACI Monograph 6, 1971, pp. 128, 151. Reprinted with permission from ASTM Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103.

The modulus of elasticity of aggregate can affect the magnitude of ultimate drying shrinkage and creep up to 2-1/2 times. Generally, dense limestones and quartz have higher elastic moduli than sandstones and gravel.

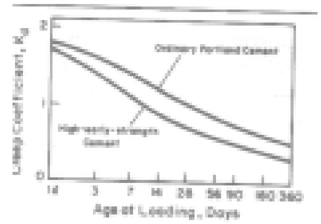
Creep: Effect of Cement Type

Creep increases with:

- Increasing C_3A
- Decreasing C_3S
- An optimal gypsum content seems to exist

Similar effects are seen with shrinkage

Poorly understood



Creep: Effect of Stress Magnitude

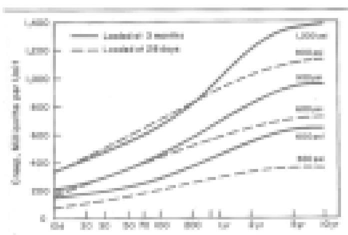


Figure 4–16 Effect of magnitude of sustained stress on creep. (From G. E. Troxell et al., Proc. ASTM, Vol. 58, 1958. Reprinted with permission, from ASTM, 1916 Race Street, Philadelphia PA 19103.)

Creep is directly proportional to the magnitude of sustained stress. With 90-day-old concrete specimens, the amount of ultimate creep doubled when the loading stress was increased from 600 psi to 1200 psi. Because of the effect of strength on creep, the figure shows that, at a given stress level, lower creep values were obtained for the longer period of curing before application of the load.

Creep: Effect of Age

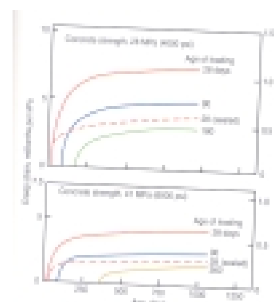


Fig. 18-25. Relationship of time and age of loading to creep of two different strength concretes. Specimens were allowed to dry during loading, except for those labeled as sealed (Russell and Corley 1977).

- At early ages, porosity is greater
- At later ages, even though porosity does not decrease appreciably, creep does; perhaps due to aging of C-S-H which may improve its resistance to stress

Creep: Effect of Curing Method

Curing at high Temperatures may accelerate C-S-H aging

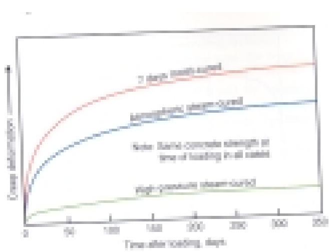


Fig. 18-28. Effect of curing method on magnitude of creep for typical normal-density concrete (Hanson 1964).

Creep: Effect of Temperature

Although creep develops faster at higher temperature, there is some evidence that long term creep may be lower due to aging of C-S-H

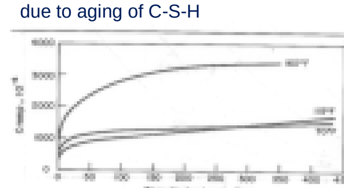
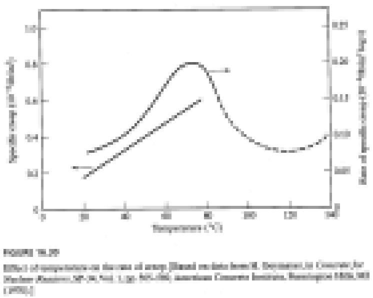


Figure 4–15 Effect of concrete temperature on creep. (From K. W. Nasser and A. M. Neville, J. ACI, Proc., Vol. 64, No. 2, 1967; and ACI Monograph 6, 1971, p. 162.)

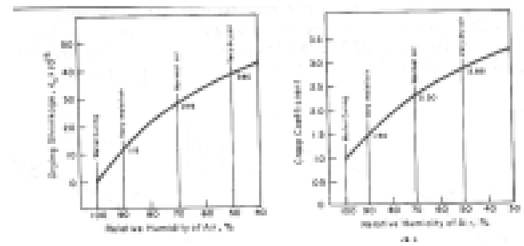
At a stress-strength ratio of 70 percent, the 350-day creep can increase 3.5 times if the surrounding temperature is raised from 70°F to 160°F.

Creep: Effect of Temperature

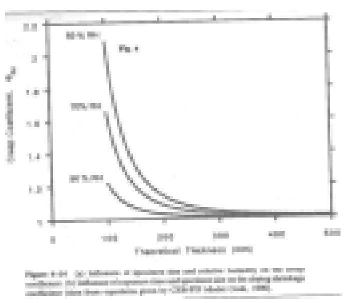
- Creep may increase linearly with temperature to 175F(80C)
- Above 175F(80C), some report continued linear increase in creep, while other report a maximum at 175F(80C)



Creep: Effect of RH

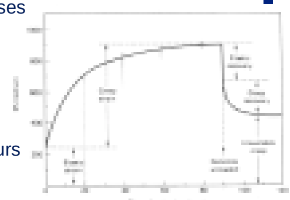


Creep: Effect of Specimen Size and RH



Creep Recovery

- Only a small portion (perhaps 10-20%) of creep strain is recovered upon unloading
- Portion of irreversible creep increases with duration loading
- Pre-loading exposure to higher temperature may decrease the proportion of the irreversible component (aging effect)
- Also, the age at which loading occurs can influence the proportion of irreversible creep



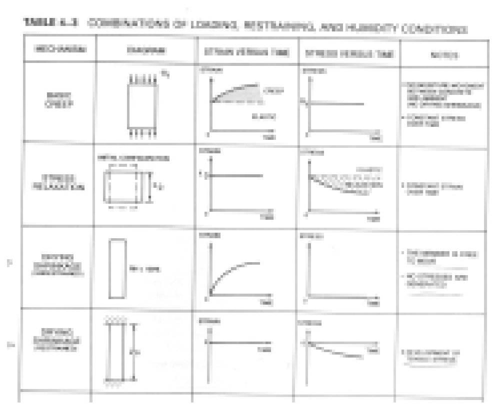
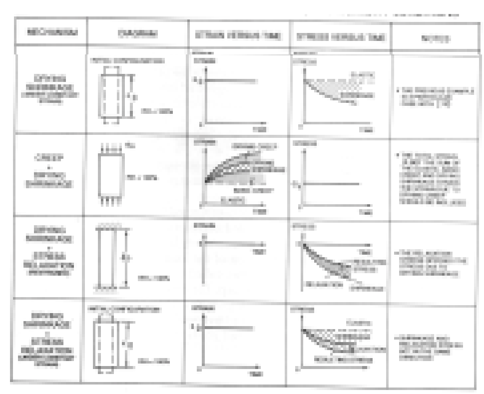


TABLE 6.3 COMBINATIONS OF LOADING, RESTRAINING, AND HUMIDITY CONDITIONS

MECHANISM	DIAGRAM	STRAIN VERSUS TIME	STRESS VERSUS TIME	NOTES
BASIC CREEP	[illegible]	[illegible]	[illegible]	[illegible]
STRESS RELAXATION	[illegible]	[illegible]	[illegible]	[illegible]
DRYING SHRINKAGE [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DRYING SHRINKAGE [illegible]	[illegible]	[illegible]	[illegible]	[illegible]



MECHANISM	DIAGRAM	STRAIN VERSUS TIME	STRESS VERSUS TIME	NOTES
DRYING SHRINKAGE [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CREEP + DRYING SHRINKAGE	[illegible]	[illegible]	[illegible]	[illegible]
DRYING SHRINKAGE + STRESS RELAXATION [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DRYING SHRINKAGE + STRESS RELAXATION [illegible]	[illegible]	[illegible]	[illegible]	[illegible]