Concrete dimensional stability

1. Introduction

- To calculate the long-term deformation and deflection of structural concrete member for its design life, stress-strain relationship, time and temperature are required.
- For all engineering materials, dimensional instability occur due to high load in the form of time-dependent failure or creep rapture. However, this can be avoided by keeping the stresses <~60% of short-term strength.

2. Dimensional stability

Short and long term deformation of concrete structures are affected by many factors, as below, and there are four types of deformation: elastic strain, creep, shrinkage and thermal movement.

2.1 Elasticity

The elastic properties (elasticity) of the engineering materials can be divided into four as shown in the next slide

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- Types of deformations and their significance (mehta P. 86)

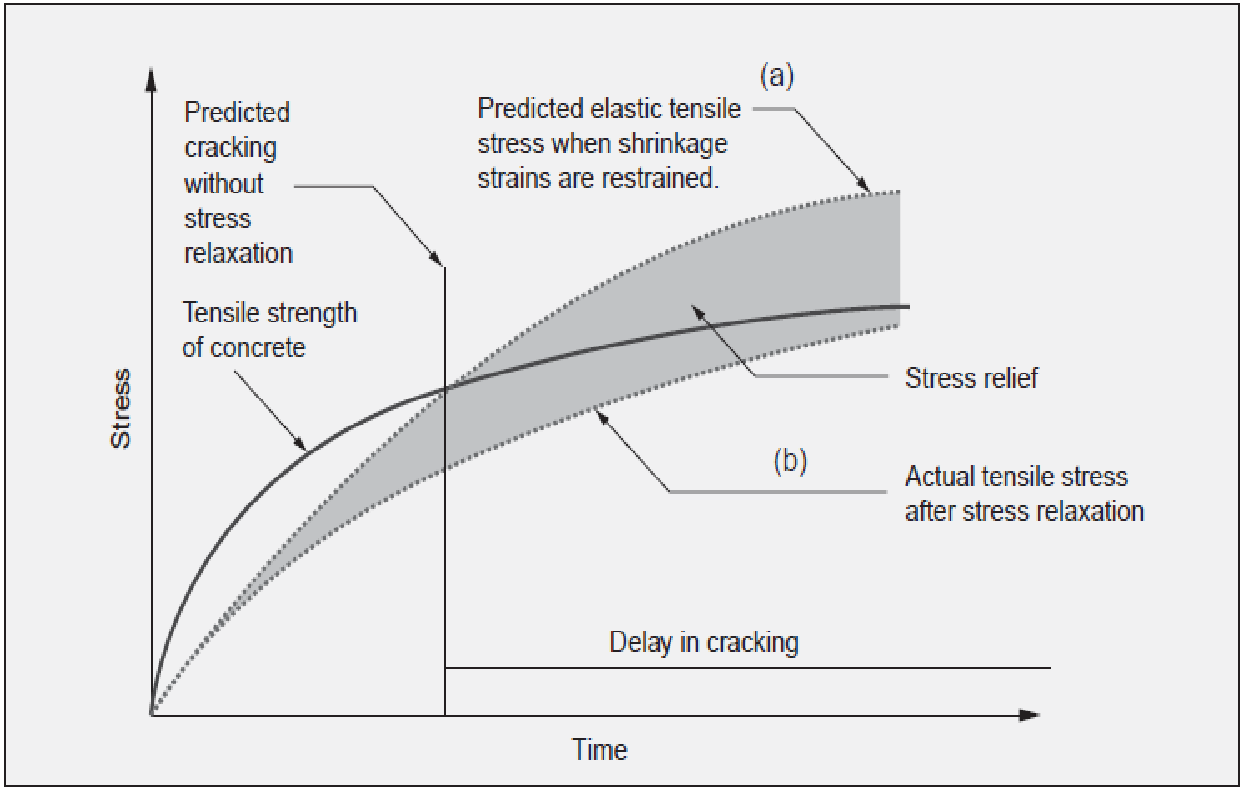

Figure 4-1 Influence of shrinkage and creep on concrete cracking. (Troxell, G.E., H.E. Davis, and J.W. Kelly, *Composition and Properties of Concrete*, McGraw-Hill, New York, p. 342, 1968.)

Under restraining conditions in concrete, the interplay between the elastic tensile stresses induced by shrinkage strains and the stress relief due to the viscoelastic behavior is at the heart of deformations and cracking in most structures.

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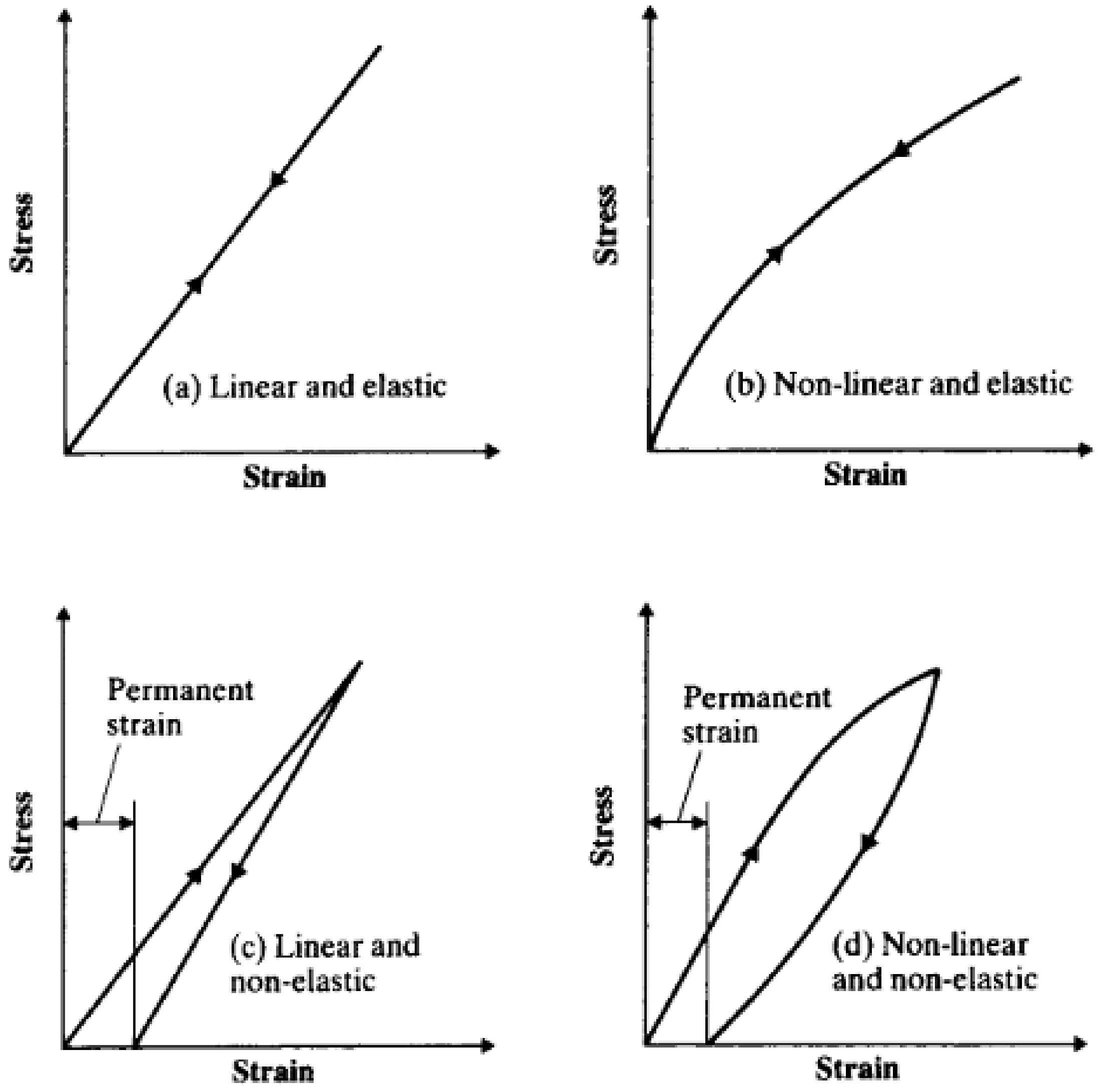
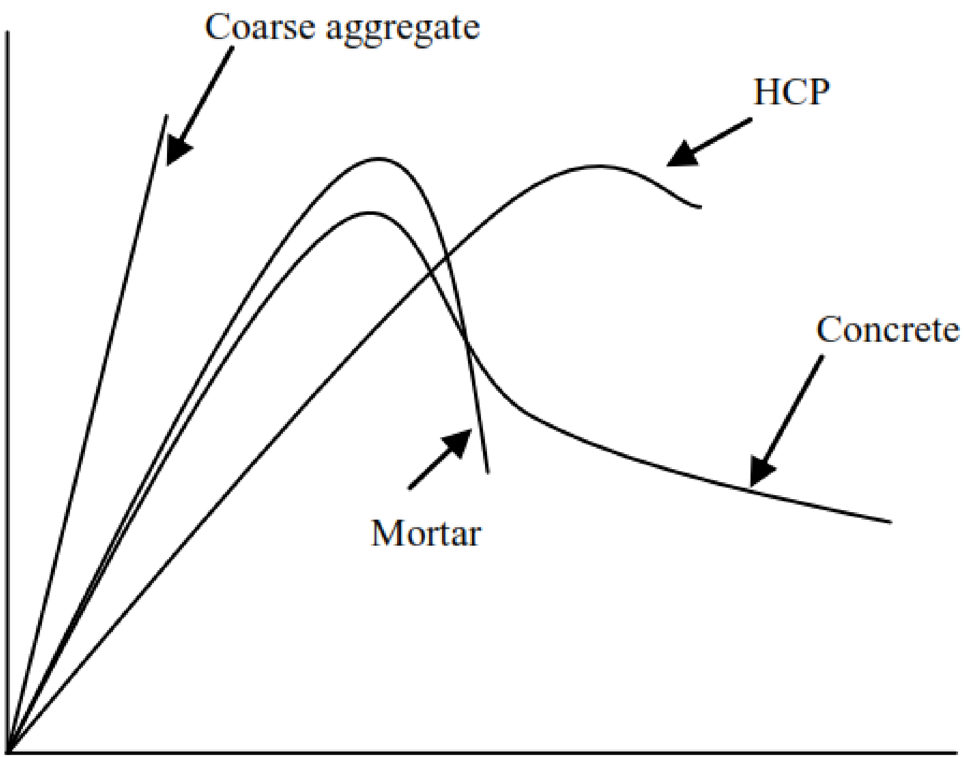


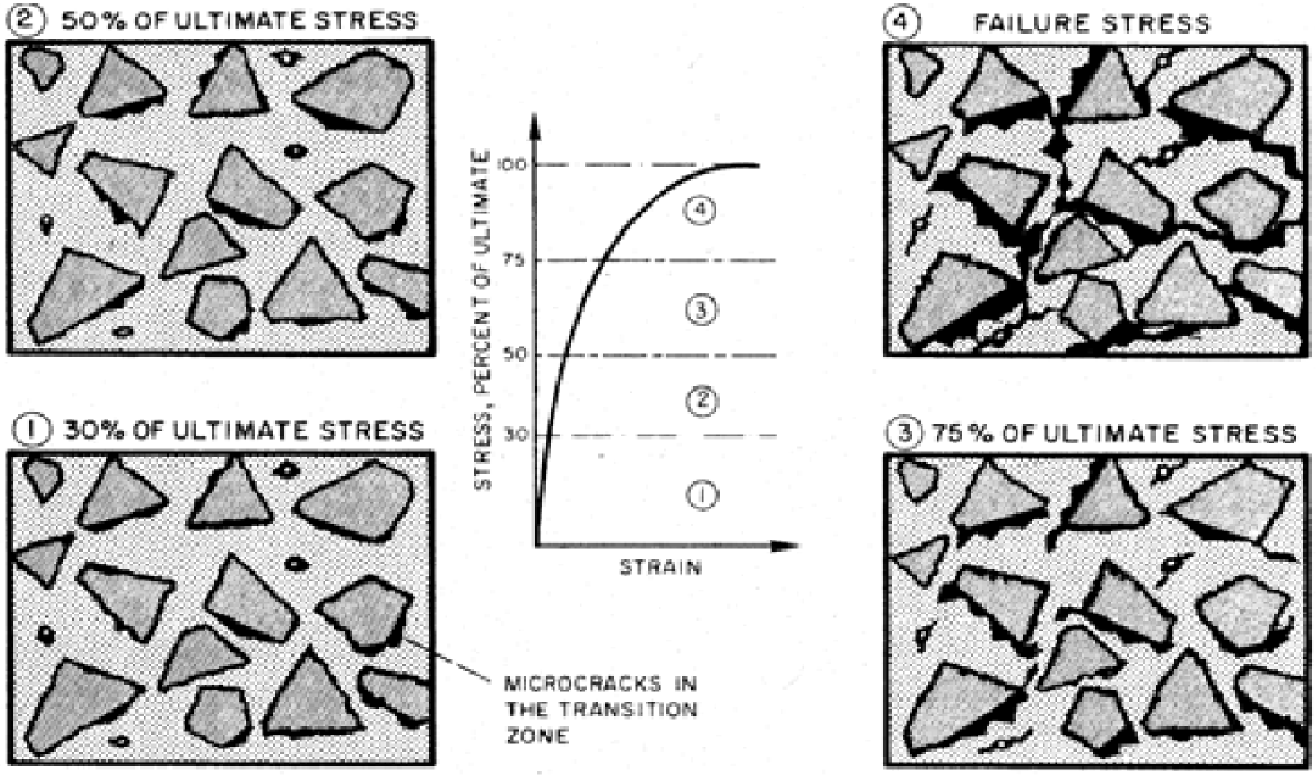
- **Concrete as a Composite Material (Three phase)**
- Cement paste and aggregates show linear elastic properties.
- The non-linear portion of the stress-strain curve for concrete is due to cracking of the cement paste/ ITZ



Typical stress-strain behavior of cement paste, aggregate, mortar and concrete.

Concrete Behavior under uniaxial load

- The stress-strain behavior of concrete under uniaxial compression can be schematically represented as below:



J. Glucklich, Proc. Int. Conf. on the Structure of Concrete, Cement and Concrete Association, Wexham Springs,Slough, U.K., 1968, pp. 176-85

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- The progress of internal micro-cracking in concrete goes through various stages, which depend on the level of applied stress. These stages can be summarized as:
- Stage one: stress (load) < 30% of ultimate load, the ITZ cracks remain stable and the strain-stress curve remain almost linear.
- Stage two: stress > 30% , cracks begin to increase in length, width and number, causing non-linearity, but still stable and confined to ITZ.
- Stage three: load >50%, cracks start to spread into the matrix and become unstable at loads approaching 75% of ultimate load, resulting further deviation from linearity.
- Stage four: > 75% spontaneous and unstable crack growth becomes increasingly frequent, leading to very high strain.

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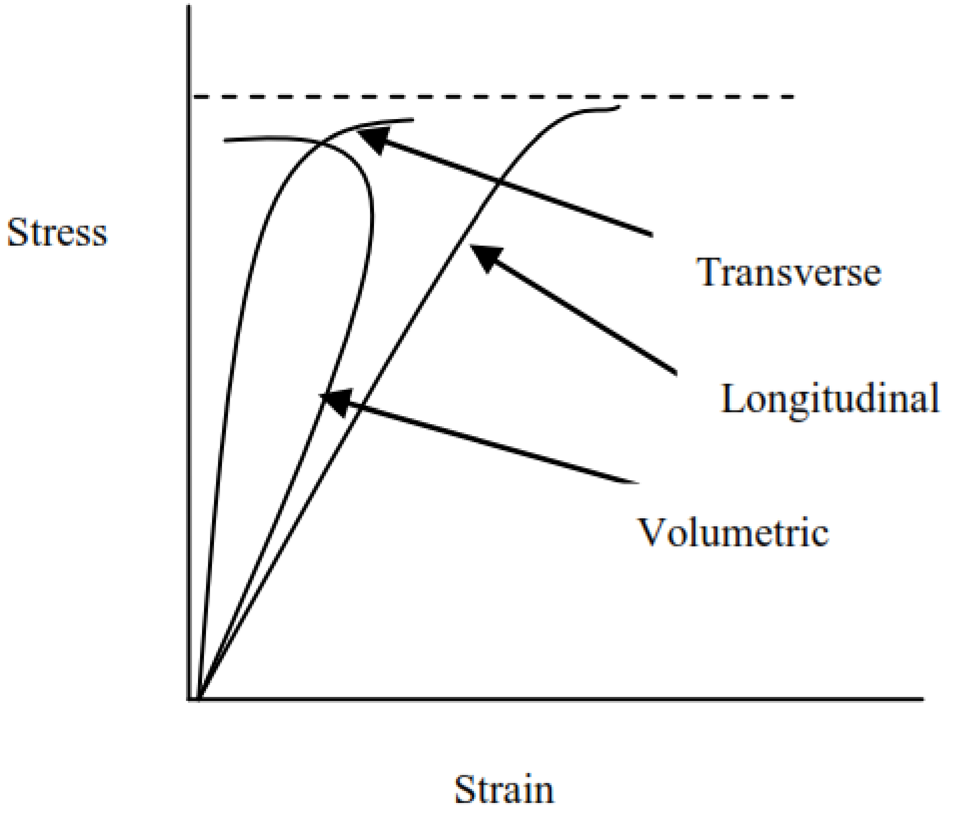
- Also at stage four, excessive cracking results in transverse strains increasing at a faster rate than longitudinal strains, resulting in an overall increase in volume as below:



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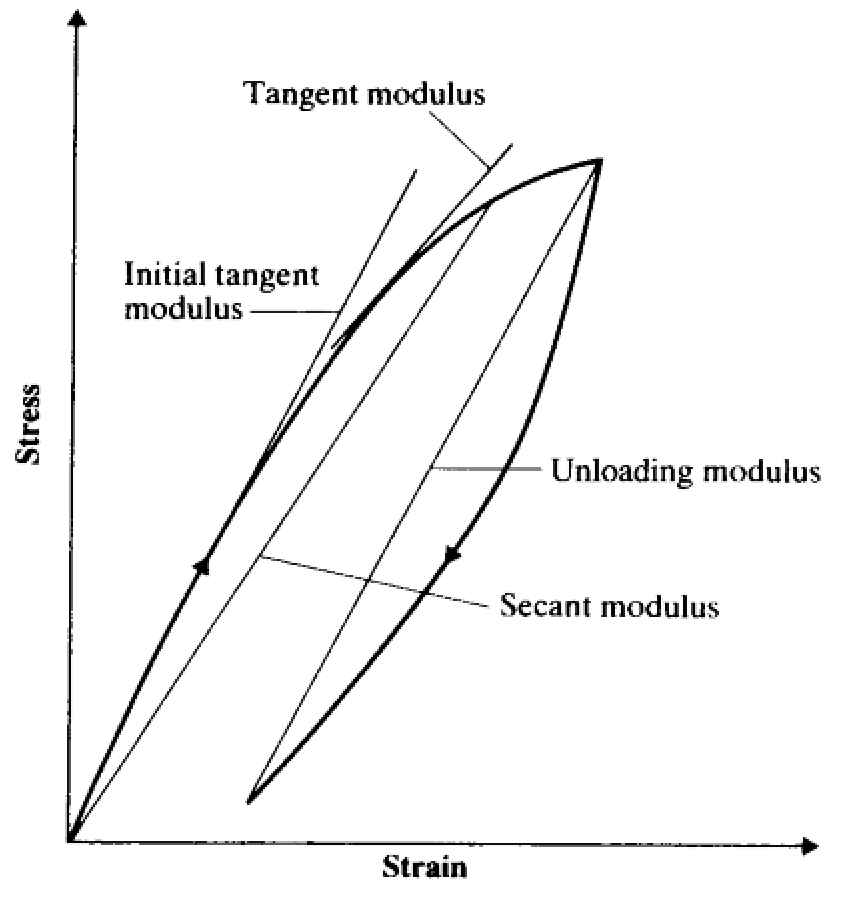
- What is Modulus of elasticity E? How does it measure?
- It is regarded as a key factor for predicting the deformation of building/structural element.
- E generally follows the pattern of strength (not always).
- Wet concrete tends to have a greater E than dry one, while strength varies in the opposite sense. WHY?
- What factors do influence E of
- concrete?



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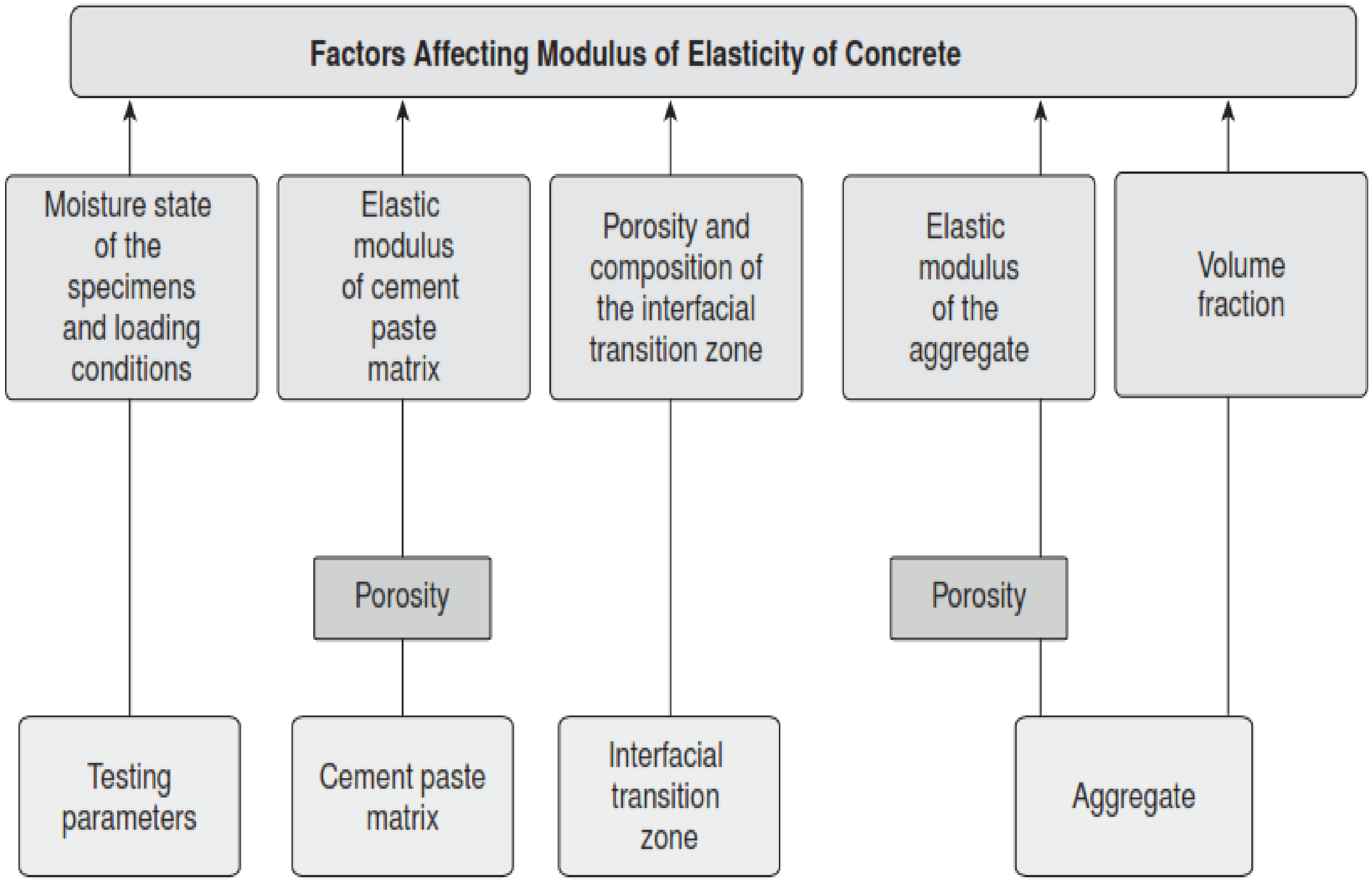
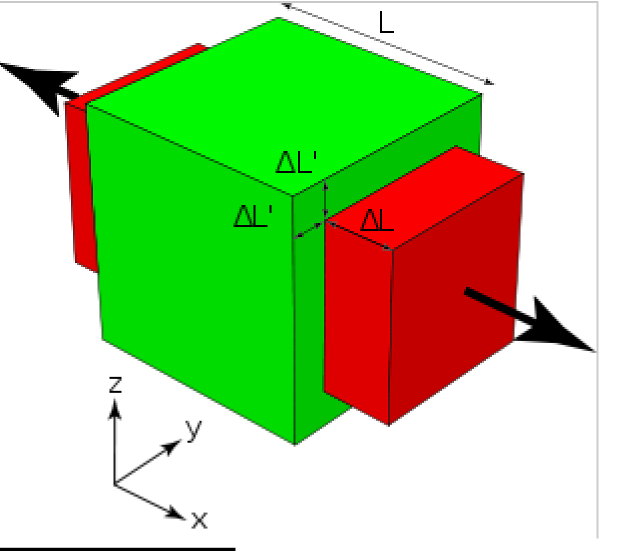


2.2 Poisson's ratio v

- In design and analysis some types of concrete structures, the volume change in a member subjected to an external loads is required.
- The ratio of lateral strain to the axial strain resulting from the axial load WITHIN ELASTIC RANGE.
- With concrete the values of Poisson's ratio generally vary between 0.15 and 0.20.
- Stress approaches failure, v increases rapidly due to vertical cracking and volumetric strain changes from a contraction to an extension.



2.3 Shrinkage and swelling

- The moisture movement during the drying of concrete is often described by a diffusion process where the diffusivity depends highly on the moisture content
- Water evaporation is a phase transition process by which molecules are converted from the liquid state into the vapor state
- In mass transfer problems, the air near the surface may be regarded as a boundary layer

Shrinkage

- Shrinkage is caused by loss of water by evaporation or hydration of cement
- The reduction in volume as a fraction of original volume i.e. volumetric strain is equal to three times of linear strain
- In practice, shrinkage simply measured as a linear strain, micro-strain (10^{-6})

Shrinkage types

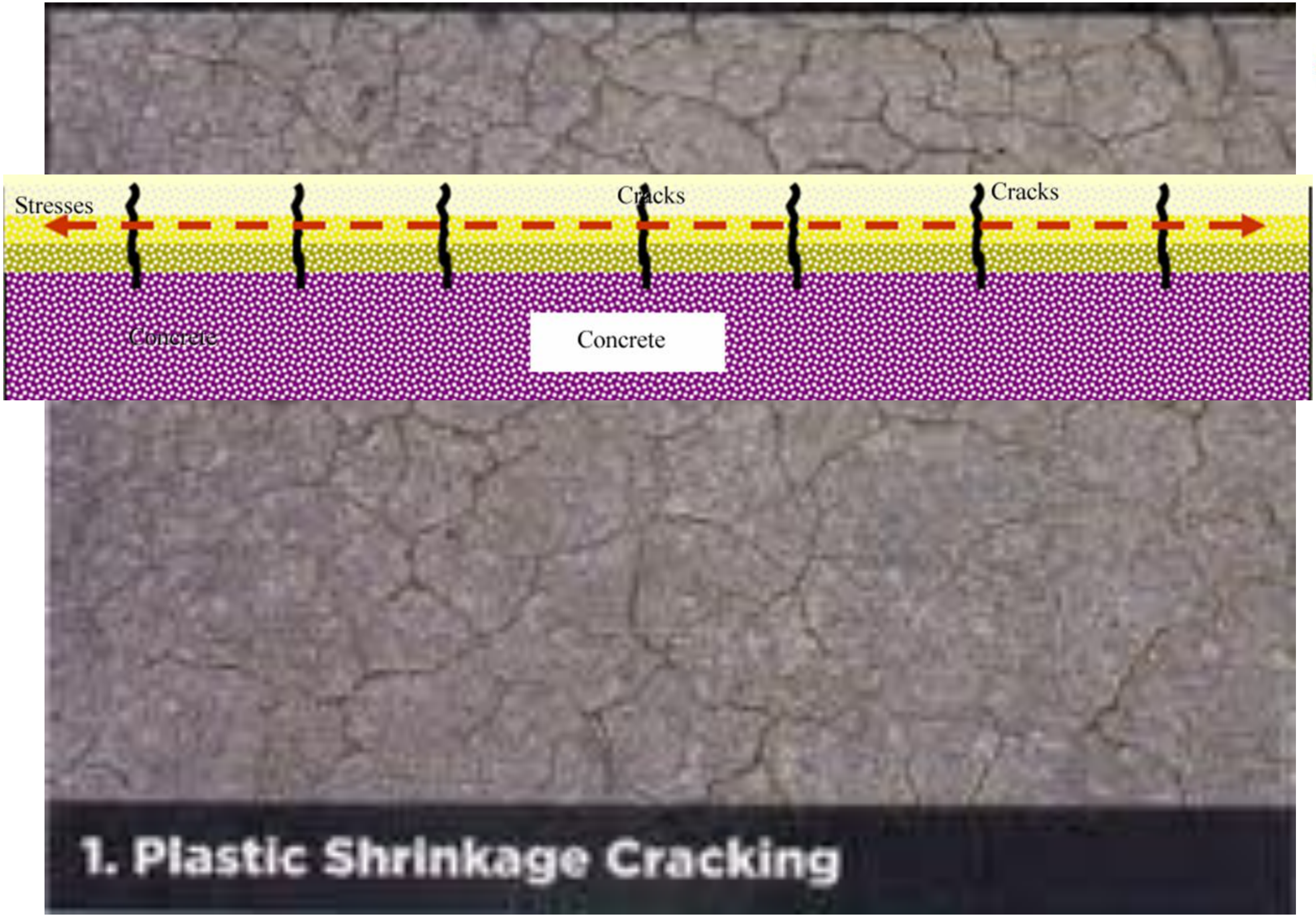
- **Plastic shrinkage**: occurs due to rapid loss of water from the surface before it has set (plastic state)……leads to plastic cracking

Plastic shrinkage cracking steps

- Bleed water appears on concrete surface
- Rate of evaporation exceeds bleed rate
- Concrete surface dries due to ambient conditions
- Concrete surface tries to shrink
- Moist concrete resists shrinkage
- Stress develops in soft “plastic” concrete
- Plastic” shrinkage cracks form

Plastic shrinkage increases with cement content, it can be minimized by preventing water evaporation immediately after casting

Concrete dimensional stability



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- **Autogenous shrinkage**: occurs due to the loss of water used by cement hydration

- It is not distinguished from drying shrinkage except for mass concrete? WHY?
- It is small (50-100 $\times 10^{-6}$), but this increases in HPC. WHY?
- Using mineral and chemical admixtures produces a finer pore structure than NC that causing a high early autogenous shrinkage at initial set, but that smaller at >28days
- **Swelling**: the expansion due to absorbing water during water-curing (continuously stored in water)

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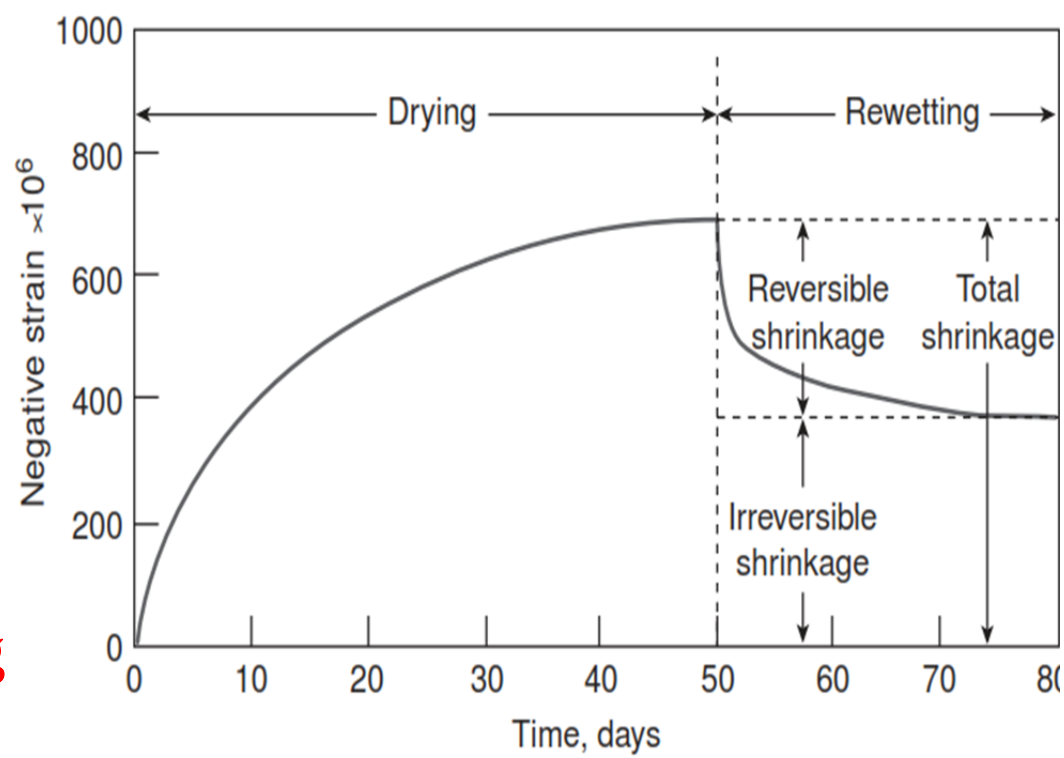
- **Drying shrinkage**: causes by loss of water from **hardened** concrete stored in dry air.

To some extent the process is reversible i.e. re-absorbing water will cause expansion of the concrete, but no back to the original volume

In NC, the reversible shrinkage 40-70% of drying shrinkage depending on Concrete age when first drying Occur



Drying slower than wetting

Mechanisms responsible for reversible drying shrinkage

- ❖ Capillary tension
- ❖ Disjoining pressure
- ❖ Changes in surface energy

Capillary tension: water evaporation from larger capillaries of cement paste to the dried outer air causes little shrinkage, but this distributes the internal equilibrium so that water is transferred from smaller capillaries to larger ones. HOW?

- When capillaries empty, a meniscus forms and a surface tension is developed that induces a balancing compressive stress in C-S-H resulting a volume contraction/shrinkage.
- Stresses are higher in smaller capillaries (WHY?) more reading is required

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Disjoining pressure theory: With the disjoining pressure theory, the adsorption of water on the C-S-H particles affects the Van der Waals surface forces of attraction between adjacent particles in areas of hindered adsorption. The adsorbed water creates a disjoining pressure, which increases with the thickness of the adsorbed water. When the disjoining pressure exceeds the Van der Waals forces the particles are forced apart and swelling occurs. Conversely, as the pressure decreases due to a reduction in relative humidity, the particles are drawn together and drying shrinkage occurs.

Change in surface energy: The change in surface energy is thought to be responsible for drying shrinkage at <40% humidity when capillary stress and disjoining pressure are no longer present.

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Solid particles are subjected to a pressure due to surface energy and the pressure is decreased by water adsorbed on the surface. Loss of water will allow the surface energy pressure to increase, resulting in further shrinkage.

- A significant part of the initial drying shrinkage is irreversible and this is explained by the changes that take place in the C-S-H. When adsorbed water is removed on first drying.
- Additional physical and chemical bonds are formed as the particles become more closely packed.
- Additional bonds can occur due to hydration and carbonation, Consequently, the porosity and connectivity of the pore system of the C-S-H change with drying, which reduces ingress of water on re-wetting

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- There are many factors affecting drying shrinkage, however the main ones as recognized by code of practice are: W/C, aggregate, RH, size of member, time, and admixtures.

- Drying shrinkage of a large member is less than that of a small member because it is more difficult for water to escape from the former, which has a longer drying path.
- The effect of size is expressed as the volume/surface area ratio(V=S) or effective thickness (2V=S), the surface area being that exposed to drying.
- The member shape has a secondary influence drying shrinkage (neglected)

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- **The effect of chemical and mineral admixtures:**
- Shrinkage-reducing admixtures are available, which appear to reduce shrinkage by suppressing cement hydration.
- For a constant water/cementitious materials ratio, increasing the level of cement replacement by silica fume and metakaolin reduces both autogenous and drying shrinkage of high performance concrete. For example, drying shrinkage is reduced by approximately 25% for a 10% replacement of cement.
- Drying shrinkage causes loss of prestress in prestressed concrete, increases deflections of asymmetrically reinforced concrete and, together with differential temperature, contributes to the warping of thin slabs.
- Restraint of shrinkage often leads to cracking.

- The importance of shrinkage in concrete structures is largely related to cracking as the shrinkage-induced cracking that is caused by different mechanisms negatively affects the serviceability and durability of the concrete
- **Shrinkage measurement**

It is measured according to BS ISO 1920-8:2009

- ✓ vertical comparator
- ✓ digital indicator with an accuracy of 0.001 mm
- ✓ 13.66 mm total range
- ✓ sample prism of 280 × 75 × 75 mm
- ✓ fixed steel pin at each end
- ✓ Change in samples' length (shrinkage)
- ✓ Mass loss were recorded.

- **Carbonation shrinkage** : caused by the reaction between calcium hydroxide and carbon dioxide, the process of this reaction results a volume contraction known as carbonation shrinkage that depends on

❖ Concrete permeability

❖ Moisture content

❖ Relative humidity (severest at 55%)

Carbonation shrinkage is usually small (accompanies drying shrinkage) as it restricted to the outer layer, but can cause warping of thin panels.

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- The ratio of concrete shrinkage (S_c) to cement paste shrinkage (S_p) can be related exponentially to the volume fraction of aggregate (g) in concrete

$$\frac{S_c}{S_p} = (1 - g)^n$$

Creep: the gradual increase in strain with time for a constant applied stress after accounting for other time-dependent deformations not associated with stress i.e. shrinkage or swelling and thermal strain.

- Creep is determined from the elastic strain at loading, which depends upon the rate of application of stress so that the time taken to apply the load should be quoted.
- Since the secant modulus of elasticity increases with time, the elastic strain decreases so that creep should be taken as the strain in excess of the elastic strain at the time in question.
- Concrete can suffer a time-dependent failure, which is known as creep rupture or static fatigue.
- In the case of concrete, the stress needs to exceed approximately 0.6 to 0.8 of the short-term strength for creep rupture to occur in either compression or tension

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- Very high rate of loading produces a near linear stress-strain curve with a higher strength than in the usual standard test
- decreasing the rate of loading or increasing the test duration produces non-linear curves due to creep and micro-cracking with a lower strength (creep rupture).
- The creep rupture envelope tends to a constant limit of between 0.6 and 0.8 of the usual short-term strength, depending on the type of concrete and mode of loading.
- With sustained stresses below approximately 0.6 of short-term strength, creep rupture is avoided and time-dependent strain due to primary and some secondary creep takes place for several years.
- Depending on the type of mix and other factors, creep of dry-stored concrete can be between two and nine times the elastic strain at loading, with around 70% occurring after one year under load

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- In the case of sealed concrete, which represents mass or larg volume concrete where little or no moisture is lost, only basic creep occurs, but when the concrete is allowed to dry additional drying creep occurs even though drying shrinkage has been deducted from the measured strain; the sum of basic and drying creep is sometimes called total creep.
- Creep is a partly reversible phenomenon.
- When the load is removed, there is an immediate, almost full, elastic recovery of the initial elastic strain, followed by a gradual decrease of strain called the creep recovery.
- The recovery quickly reaches a maximum and is only small, e.g. 1-25% of the 30-year creep
- Consequently, creep is mostly irreversible in nature.

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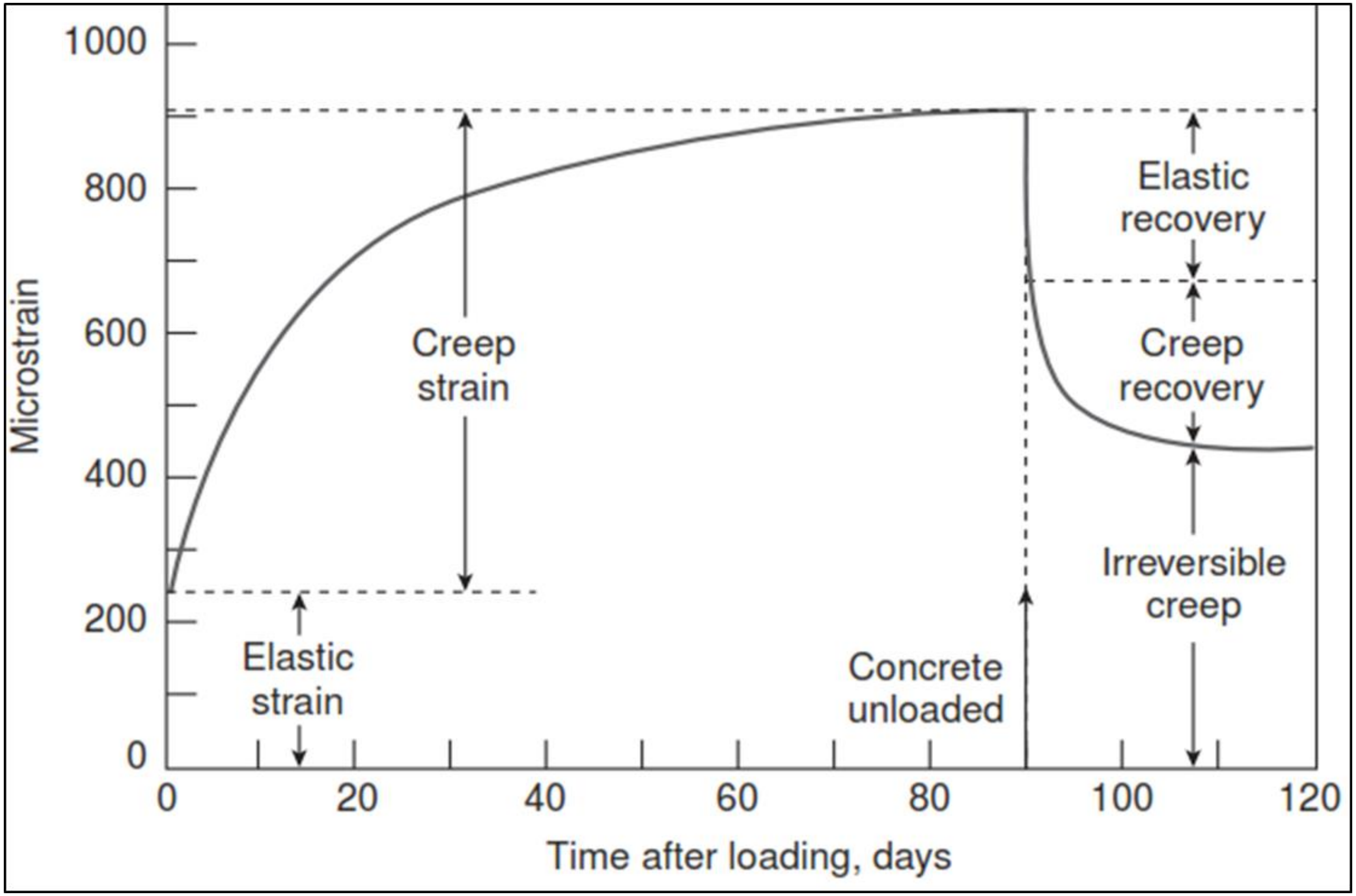

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- Like shrinkage, creep can be expressed in units of micro-strain (10^{-6}), but because of the dependency on stress, specific creep (C_s) is often used with units of 10^{-6} Per MPa.

- Other terms are creep coefficient (Ø), sometimes called the creep factor, and creep compliance (ϕ). The creep coefficient is defined as the ratio of creep to the elastic strain on loading and for a unit stress:

$$\phi = \frac{C_s}{\frac{1}{E \times 10^3}} = C_s E \times 10^3$$

Where E =modulus of elasticity at the age of loading (GPa).

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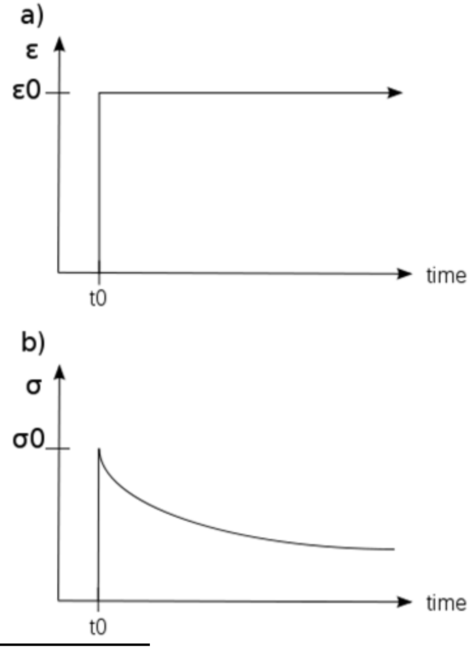
- The creep compliance is the total loading strain per unit of stress (10^{-6} per MPa) i.e. the sum of the elastic strain per unit of stress and specific creep so that:

$$\Phi = \frac{1}{E \times 10^3} + C_s = \frac{1}{E \times 10^3}(1+\phi)$$

- Stress relaxation (gradual decrease in creep)



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- ASTM C512 (1987) is used to determine creep
- Creep at normal stress is caused by internal movement of water adsorbed or heal within C-S-H
- Creep of concrete occurs in hydrated cement paste
- Aggregate plays an important role in restraining cement paste through its K (E) and volume
- What is the relation between strength and creep?
- What is the relation between creep and humidity?
- What is the relation between creep and member shape?

- Total creep increase as the volume/surface ratio or size increase
- At very high temperature (fire), very high creep occur (transient thermal strain)

The story has not finished yet

Thermal shrinkage