고성능 콘크리트 공학

High Performance Concrete Engineering

<Time dependent behavior>

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Plastic Shrinkage

Time – Dependent Deformation

- Concrete undergoes volume changes during service
 - Applied stresses
 - Changes in moisture content
 - Changes in temperature
- Response of concrete
 - Complex (reversible, irreversible, and time-dependent deformations)
- Structural elements of hardened concrete are always under restraint, usually from
 - sub-grade friction
 - end members
 - reinforcing steel
 - differential strains between the interior and exterior of concrete
- When the strain in a material is restrained, it develops stresses



Plastic Shrinkage

Plastic Shrinkage Cracks

- When? Usually in 30 minutes to 6 hours
- Where?
 - Random pattern
 - Diagonal cracks to the edges of the slabs
 - Cracks following the pattern of reinforcement or other physica l aspects





Plastic Shrinkage



(Portland Cement Association USA)



Plastic Shrinkage

Plastic Shrinkage Cracks (cont'd)

• Why?

- Rapid moisture loss from fresh concrete due to
 - high temperature of concrete and air
 - low relative humidity of air
 - high wind velocity over the concrete surface
- Likely to occur when evaporation rate > bleeding rate



Bleeding Rate





Evaporation Rate

(Jason Weiss)



Plastic Shrinkage Cracks (cont'd)

• Size

- fairly wide at the surface (up to 2-3 mm), diminish rapidly with depth
- range from a few cm to several m in length
- begin as shallow cracks but can become full-depth cracks
- Consequence
 - Destroy the integrity of surface
 - Reduce durability
- How to control
 - Minimize moisture loss by initiating early curing
 - Fog slab immediately after placing
 - Limitations of curing compounds
 - Reduce the amount of silica fume if used
 - Reduce initial concrete temperature
 - Use polypropylene fibers
 - Erect temporary windbreaks and sunshades





Plastic Settlement Cracking

Plastic Settlement Cracking

• When?

- 10 minutes to 3 hours
- Where?
 - Over reinforcement
 - Over changes in cross section
 - Deep sections
- Why?
 - Excessive bleeding, low stiffness
 - Hindered downward movement of fresh concrete
- How to control?
 - Re-vibrate before initial setting
 - Revise concrete mix proportion

Plastic Settlement Cracking

Plastic Settlement Cracks



Section (showing top layer of bars) Downward movement of concrete hindered by reinforcing bars

Crack pattern reflecting position of top bars



Plan (Top View) (Showing crack pattern)

Tam)

Surface cracks permit ingress of chemicals and moisture, promoting corrosion

Void below bars reduces bond

Repair to both defects needed



Plastic Settlement Cracking

Plastic Settlement Cracks (cont'd)

Column Head - Flat Slab



Arching at reduction of section

Waffle Slab



Differential settlement at change in depth

(C T Tam)



Shrinkage due to Temperature Change

- Strain associated with change in temperature depends on
 - coefficient of thermal expansion of material
 - magnitude of temperature drop or rise
- Except under extreme climate conditions, ordinary concrete structures generally suffer little or no distress from changes in ambient temperature
- In massive structures
 - large rise in concrete temperature within a few days after placing due to
 - heat produced by cement hydration
 - poor heat dissipation
- subsequent cooling to the ambient temperature often cause the concrete to crack



Shrinkage due to Temperature Change (Example)

• Assume

- thermal expansion coefficient $\alpha = 10x10^{-6}/^{\circ}C$
- temperature rise from heat of cement hydration $\Delta T = 15 \ ^{\circ}C$
- elastic modulus E of concrete = 20GPa
- concrete member is fully restrained $(K_r = 1)$
- Then
 - thermal shrinkage ϵ caused by a 15 °C temperature drop = $\alpha\Delta T$ = 150x10⁻⁶
 - cooling would produce tensile stress of $\epsilon E = 3$ MPa if concrete is fully restrained.
 - tensile strength of concrete at early ages is usually less than 3 MPa, concrete is likely to crack if no relief due to stress relaxation



Shrinkage due to Temperature Change (cont'd)

- However, there is always some relaxation.
- When the creep coefficient is known, tensile stress can be calculated

 $\sigma_t = K_r [E / (1+\phi)] \alpha \Delta T$

where

- σ_t = tensile stress
- K_r = degree of restraint
- E = elastic modulus
- ϕ = creep coefficient
- α = coefficient of thermal expansion, 10x10⁻⁶/°C
- ΔT = temperature change



Shrinkage due to Temperature Change

Factors Affecting Thermal Stresses

• Degree of restraint K_r



Internal restraint



External restraint (Bamforth 2007)



Factors Affecting Thermal Stresses (cont'd)

- Temperature change ΔT
 - Cement hydration exothermic, generates heat, increases concrete temperature
 - Heating causes expansion, and expansion under restraint results in compressive stress (relatively low at early ages because E is low)
 - ΔT is affected by
 - placement temp of fresh concrete
 - adiabatic temp rise
 - temp drop due to heat loss
 - ambient temp





Factors Affecting Thermal Stresses (cont'd)

- Placement temperature
 - Effect of placement temperature
 - Reducing placement temperature is one of the best ways to avoid crack
 - Use cooled mixing water
 - Use crushed or flaked ice as all or part of the required water
 - Cool aggregates
 - Whenever possible, place concrete in coolest part of the day

(Bamforth 2007)



Figure 4.4The effect of placing temperature on the temperature rise in a 500 mm
thick wall using concrete with 350 kg/m³ CEM I cast in steel formwork



Effect of Temperature of Materials on Concrete Temperatures

• Contribution of each constituent to concrete temperature is determined by its temperature, specific heat, and weight fraction.

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + T_{wa} W_{wa} - F_i W_i}{0.22(W_a + W_c) + W_w + W_{wa} + W_i}$$

T = temperature of the freshly mixed concrete, °C

 T_a , T_c , T_w , and T_{wa} = temperature in °C of aggregates, cementing materials, added mixing water, and free water on aggregates, respectively W_a , W_c , W_w , W_{wa} and W_i = weight, kg, of aggregates, cementing materials, added mixing water, free water on aggregates, and ice, respectively F_i = function of the latent heat of fusion, specific heat, and freezing temperature of water (76.6 °C)

 $S = \text{specific heat} (c = 0.88 \text{ J/g}^{\circ}\text{C}, a = 0.75 \text{ J/g}^{\circ}\text{C}, w = 4.18 \text{ J/g}^{\circ}\text{C})$



Shrinkage due to Temperature Change

Factors Affecting Thermal Stresses

- Adiabatic temperature rise
 - Is a function of the amount, composition, and fineness of cement, and its temperature during hydration
 - Reduce adiabatic temperature rise reduces the risk of thermal cracking
 - Use as low cement content as possible
 - Use Low heat cement (Type IV)
 - Use fly ashes or slags

(Bamforth 2007)





Shrinkage due to Temperature Change

Factors Affecting Thermal Stresses (cont'd)

• Heat loss

- depends on
 - thermal properties of concrete
 - construction technology adopted
- is a function of the type of environment in immediate contact with the concrete surface

TABLE 4-4COEFFICIENT OF HEAT TRANSMISSIONOF DIFFERENT ISOLATION ENVIRONMENTS

Type of isolation	Surface transmission coefficient (kcal/m2.h.C)				
Concrete-air	11.6				
Concrete-curing water	300.0				
Concrete-wood-air	2.6				
Concrete-metal-air	11.6				
Concrete-isolant-air	2.0				

(Mehta & Monteiro 1993)

reduce heat loss on surface until concrete developed sufficient strength



Shrinkage due to Temperature Change

Concreting in Hot Weather

- Hot weather (high T, low RH, high wind velocity, high solar radiation) results in
 - Slump loss ↑
 - Plastic shrinkage cracking ↑
 - Setting time ↓
 - Early strength ↑, long-term strength may ↓
 - Mixing water requirement ↑
- Control concrete temperature
- Protect concrete after casting
 - Prevent moisture loss (water, curing membrane)



Drying Shrinkage

- Drying shrinkage: loss moisture to environment (the term is generally used for hardened concrete)
- Special cases of drying shrinkage
 - Autogenous shrinkage: loss of moisture due to self-desiccation during cement hydration
 - Carbonation shrinkage: loss of moisture due to carbonation



• Drying shrinkage is a paste property, aggregate has restraining effect on shrinkage



Provide adequate contraction joints in pavements & slabs

Drying Shrinkage

Behavior of Concrete on Drying & Rewetting



• Part of the total shrinkage that occurs on the first drying is irreversible



Cause of Drying Shrinkage: Moisture Loss

- Five domains

 (1) Loss of water from large capillary pores (macropores)
 - (2) Loss of water from mesopores and micropores (finer capillary pores and pores in C-S-H gel)
 - (3) Loss of adsorbed water on solid surface
 - (4) Loss of water from the interlayers of C-S-H gel
 - (5) Loss of water due to decomposition of C-S-H at T > 105 °C

shrinkage-weight loss curve for cement paste



Shrinkage in Domain 5 will only occur in concrete exposed to fire.

TABLE 4.6 Classification of Pore Sizes in Hydrated Cement Pastes

Designation	Diameter	Description	
Capillary Pores	10,000–50 nm	large capillaries	
	$(10-0.05 \mu m)$	(macropores)	
	50–10 nm	medium capillaries	
		(large mesopores)	
Gel Pores	10–2.5 nm	small isolated capillaries	
		(small mesopores)	
	2.5–0.5 nm	micropores	
	$\leq 0.5 \mathrm{nm}$	interlayer spaces	(Mino

(Mindess 2003)

TABLE 4.7 Influence of Pore Sizes on Properties of the Hydrated Paste

	Category	Role of Water	Properties Affected
Capillary 🚽	Macropores	Behaves as bulk water	Permeability; diffusivity
oores	Large mesopores	Small surface tension forces generated	Permeability in the absence of macropores; shrinkage above 80% RH
Col poros	Small mesopores	Large surface tension forces generated	Shrinkage between 80% RH and 50% RH
sei pores	Micropores	Strongly adsorbed water; no menisci form	Shrinkage at all RH; creep

Drying shrinkage

Model of C – S – H Structure

- Layered structure
- C-S-H

"bread" – calcium silicate sheets "filling" – Ca⁺⁺, H₂O

- Sheets are distorted and randomly arranged.
- Space between the calcium silicate sheets is the intrinsic porosity:
 - I interlayer pores
 - M micro pores
 - P isolated capillary pores





Mechanisms of Shrinkage

- Capillary stress (when RH > 45%) (Domains 1 & 2)
 - Water within a capillary pore is partially under the influence of surface int eractions exerted by pore walls, and is in a state of hydraulic tension P_{cap}
 - Water cannot be removed by evaporation unless RH is lowered by an amount depending on pore radius r and surface free energy γ

$$\ln(RH) = K(\frac{2\gamma}{r})$$

$$P_{cap} = \frac{2\gamma}{r} = \frac{\ln(RH)}{K}$$

$$100\% \text{ RH}$$
Wet
$$Dry$$

$$\int_{P_{cap}} \int_{P_{cap}} \int_{-1 \mu \text{m}} \int_{0.1 \mu \text{m}} \int_{0.1 \mu \text{m}} \int_{0.0\% \text{ RH}} \int_{0.0\%$$

(Mindess et al 2003)

- Water can only be lost by the creation of air-water interface (meniscus) which require energy
- Internal particles rearrange, pores become smaller
- Capillary stresses cannot exist when RH < 45% since menisci are no longer stable



Mechanisms of Shrinkage (cont'd)

- Disjoining pressure (only significant when RH is down to ~45%)
 - An assembly of C-S-H particles has van der Waals' forces attracting adjacent particles and bringing them in close contact
 - Water is adsorbed on the surface of C-S-H at all RH
 - Adsorption of water between C-S-H surfaces creates a disjoining pressure which ↑ with the increase in thickness of adsorbed water layer (& RH)
 - When the disjoining pressure exceeds van der Waals' attraction, particles will be forced apart \rightarrow dilation
 - C-S-H is formed in dilated state during hydration. On drying, the decreasing disjoining pressure causes the particles to be drawn together by van der Waals' force, and there is a net volume ↓
 - Disjoining pressure also depends on RH



d~10Å 60% RH

(Mindess et al 2003)



Mechanisms of Shrinkage (cont'd)

Change in surface free energy

- Relevant to RH < 45%, when capillary stress and disjoining pressure are n o longer operating
- As the most strongly adsorbed water is removed, the surface free energy of solid begins to increase significantly
- A solid particle is subjected to a mean pressure







Δd~1%

30% RH

where γ - surface energy S - specific surface area of solid - γ depends on RH RH>45%, $\Delta \gamma$ negligible 20%<RH<45%, $\Delta \gamma$ linearly \propto RH RH<20%, $\Delta \gamma$ has the greatest effect (Mindess et al 2003)

For C-S-H, S is large (400 m²/g), P_{sfe} can be large and cause compression on the solid



Irreversible Drying Shrinkage

- Irreversible shrinkage occurs only on first drying
- Deformations on subsequent wetting and drying are essentially reversible
- Origin of irreversible shrinkage
 - unstable amorphous nature of C-S-H
 - removal of water ⇒ rearrange of packing ⇒ alteration of bonding between C-S-H sheets & creation of new mesopores
 - Microcracking

Schematic representation of drying shrinkage of cement paste



Drying Shrinkage

Factors Influencing Drying Shrinkage

- Effect of aggregate
 - Volume: increase aggregate content, reduce shrinkage
 - Modulus of elasticity of aggregate
 - Stress at ITZ due to drying shrinkage ↑ as the max. aggregate size ↑

$$\varepsilon_{\rm con} = \varepsilon_{\rm p} (1 - V_{\rm a})^{\rm r}$$

where

n = factor depending on the elastic properties of the aggregate, vary 1.2 - 1.7

(Mindess et al 2003)





Factors Influencing Drying Shrinkage (cont'd)

Specimen Geometry

- At a constant RH, both the size and shape of a concrete element determine the magnitude of drying shrinkage
- Volume-to-surface area ratio is important, a higher ratio will lead to less shrinkage
- Rate of moisture loss depends on total surface area & the average length of the diffusion path





Factors Influencing Drying Shrinkage (cont'd)

- Materials and mix proportions
 - Water content
 - for a given cement content, drying shrinkage ↑ with water content
 - Cement content
 - for a given w/c, drying shrinkage ↑ with cement content



Fig. 9.12 The pattern of shrinkage as a function of cement content, water content, and water/cement ratio; concrete moist-cured for 28 days, thereafter dried for 450 days^{9.76}

(Shoya 1979)



Factors Influencing Drying Shrinkage (cont'd)

• Time

- For a wide range of concrete mix proportions, aggregate types, and environmental and loading conditions
 - 20-25% of 20-year drying shrinkage occurs in 2 weeks
 - 50-60% in 3 months
 - 75-80% in 1 year



(Troxell et al 1958)

- Curing history
 - Longer moist curing reduce drying shrinkage



Autogenous Shrinkage

Autogenous Shrinkage

- Definition (ACI 116)
 - Shrinkage produced by the continued hydration of cement, exclusive of the effects of applied load and change in either thermal condition or moisture content

Cause

- Chemical shrinkage
 - volume of hydration products is less than the volume of cem ent and water before hydration
- · Formation of a skeleton of cement paste after initial setting
- Formation of capillary pores
- Continued cement hydration leads to self desiccation
- Increase in capillary tension \Rightarrow autogenous shrinkage
- Restraint of this shrinkage leads to internal microcracking



Chemical Shrinkage

Chemical Shrinkage

Calculation of chemical shrinkage •

 $\epsilon_{Ch} = 1 - (V_c + V_w + V_h) / (V_{ci} + V_{wi})$

where V_{c} , V_{w} , V_{h} – volume of cement, water, hydration products, V_{ci} , V_{wi} – initial volumes of cement, water

(Mehta & Monteiro 2006)

At time t = 0, ϵ_{Ch} = 0, ϵ_{Ch} increase with hydration time

		Hydration						Chemical shrinkage (%)
	C ₃ S	+	5.3 H	\rightarrow	$C_{1.7}SH_4$	+	1.3 CH	7.2
Molar mass (g/mol)	228.32		18.02		227.2		74.09	
Mass (g)	1.00		0.418		0.995		0.422	
Density (g/ml)	3.15		0.998		2.01		2.24	
Volume (ml)	0.317		0.419		0.495		0.188	
	$2 C_3 S$	+	6.5 H	\rightarrow	$C_{3}S_{2}H_{3.5}$	+	3 CH	8.5
Molar mass (g/mol)	228.32		18.02		351.49		74.09	
Mass (g)	1.00		0.257		0.770		0.487	
Density (g/ml)	3.15		0.998		2.50		2.24	
Volume (ml)	0.317		0.257		0.308		0.217	

SOURCE: Adapted from Justnes, H., E. Sellevold, B. Reyniers, D. Van Loo, A.V. Gemert, F. Verboven, and D.V. Gemert, Autogenous Shrinkage of Concrete, Tazawa, E., ed., E & FN Spon, London, pp. 71-80, 1998.



Chemical Shrinkage

Chemical Shrinkage and Autogenous Shrinkage - volume changes of fresh and hardened paste (not to scale)



While autogenous shrinkage is due to the chemical shrinkage, the magnitude of autogenous shrinkage is less than the chemical shrinkage after setting occurs, because the aggregate particles and the hydrated cement paste network restrain the shrinkage.

Chemical Shrinkage

Autogenous Shrinkage (AS)

- Typical value for ordinary concrete
 - 40x10⁻⁶ at 1 month
 - 100x10⁻⁶ after 5 years
 - Relatively low compared with drying shrinkage, ignored for practical purposes
- For high-performance concrete with low w/c, AS is of magnitude similar to drying shrinkage
 - AS \uparrow with the \downarrow in w/c
 - AS \uparrow with the incorporation of SF
- How to control AS?
 - Use shrinkage reducing admixtures
 - Add porous fine particles soaked with water
 - Water ponding at early age (reading materials)



(Ai 2000)



Chemical Shrinkage

Reading Materials

- Internal curing: A 2010 State-of-the-Art Review <u>http://concrete.nist.gov/~bentz/NISTIR7765.pdf</u>
- R. Morin, G. Haddad, and P.C. Aitcin (2002). Crack-free, high-performance concrete structures. Concrete International, n.9 pp. 43-48

Carbonation Shrinkage

Carbonation Shrinkage

$CH + CO_2 \rightarrow CaCO_3 + H_2O$

- Irreversible
- Affected by RH, and is the greatest when RH is ~50%
- CO₂ also reacts with C-S-H, loses water and ↓ C/S of C-S-H, change the bonding characteristics of C-S-H
 - $\begin{array}{l} C-S-H + CO_2 \rightarrow \\ C-S-H + CaCO_3 + H_2O \end{array}$



(Verbeck 1958)



Expansive Cement & Shrinkage Compensating Concrete

• Shrinkage: when restrained, it may lead to cracking



(Polivka & Wilson 1973)



Expansive Cement & Shrinkage Compensating Concrete (cont'd)

- Volume expansion at early age can be used to offset shrinkage
- Steel reinforcement restrains the overall expansion, converts expansion into slight prestress in concrete
 - Steel in tension
 - Concrete in compression (typically 0.2 – 0.7 MPa)
 - Subsequent drying will reduce the compressive stress, thus reduce or eliminate the risk of shrinkage cracking





 Based on the formation of ettringite in considerable quantities during the 1st week of cement hydration

Calcium aluminate $+\overline{S} + H \rightarrow ettringite$

- Type K contains $C_4A_3\overline{S}$ and $C\overline{S}$, and free lime
- Type M Use monocalcium aluminate (CA) with gypsum
- Type S high C₃A content (~20% wt)
- Calcium silicates control long-term properties
- Type O expansive cement (Japan)
 - Contains specially processed CaO
 - Derive its expansion from the slower hydration of the specially processed CaO

Expansive Cements (cont'd)

Time-dependence

- Exact prestress depends on the amount of expansive components and the amount of reinforcement.
 - Amount of reinforcement should be > 0.15%
 - Lack of sufficient restraint will provide little protection against shrinkage cracking
 - Beyond a certain point, additional restraint becomes wasteful
 - Correct positioning of the steel is important to provide restraint.



("New Materials in Concrete Construction", U of Illinois, 1972)

Expansive Cements

Control of Expansion

- For given reinforcement, expansion †, compressive stress †
- Concrete mix design and curing
 - w/c ↑, expansion ↓,
 w/c < 0.6 is recommended
 - Moist curing is important
 - Formation of ettringite combines large amounts of water, which cannot be completely provided by the mixing water
 - Curing compound, ASTM C309 specifies that water loss should not exceed 0.55 kg/m² in the first 72 hrs



Expansive Cements

Control of Expansion (cont'd)

- Ettringite can only contribute to volume expansion, and to prestress when it is formed after the concrete has gained rigidity through hydration of C₃S
 - Effect of temperature
- Control the time of ettringite formation
 - Delayed formation of ettringite may be disruptive.
 - ASTM C 845 specifies that the expansion at 28-d should not exceed 7-d expansion by more than 15%.





Properties & Applications

- The physical & engineering properties of expansive cement concretes are comparable to Type I OPC concrete
- Some differences
 - Higher compressive strength than OPC concrete (~3.5 to 7.0 MPa higher)
 - Higher rate of heat evolution
 - Lower workability & greater slump loss
 - Generally not resistant to sulphate attack
- Applications
 - Airport pavement
 - Parking structures
 - Industrial warehouse
 - Liquid storage tanks, swimming pools, etc.

Expansive Cements

Strain Rate Effects

- Behavior of concrete depends on the rate of load application
- Causes of strain rate sensitivity
 - Time-dependent movement of free water through voids & pores
 - Importance of moisture condition of concrete on strain rate sensitivity
 - Dry concrete: strength affected by strain rate
 - Time-dependent nature of crack growth relative to the load rate
 - Cracks require time to propagate
 - At high rates of loading, when crack propagates much more slowly than applied stress, the crack path is altered and the crack length is shortened



(McHenry & Shideler 1955)

Strain Rate Effects (cont'd)

• Influence of strain rate on the compressive strength of concrete



(McHenry & Shideler 1955)



Expansive Cements

Strain Rate Effects (cont'd)

- At high strain rate loading
 - Crack go through coarse aggregate
 - Increase strength
 - Increase E as well
 - Effect of moisture movement and creep plays a ↓ role
 - A greater portion of strain is accounted for by mortar cracking or microcracking within the cement paste; bond cracking appears to be largely unchanged
- Weaker concrete tends to be more strain rate sensitive than high-strength concrete

Cement paste w/c=0.4



(Harsh et al1989)