Early-Age Cracking
(temperature, shrinkage, strength)

National Concrete Pavement Technology Center

Iowa's Lunch–Hour Workshop

In cooperation with the Iowa DOT

and the Iowa Concrete Paving Association

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(IMCP—pages 148–164)

Early-Age Cracking

1. Concrete cracks when tensile stresses exceed tensile strength.
2. The challenge is to control the number and location of cracks
   - Construct proper and timely joints
   - Use good curing practices
   - Understand that concrete needs to gain strength to resist random cracking
3. Cracking is generally due to a combination of several factors.

(IMCP—pages 116, 125–130)

Facts

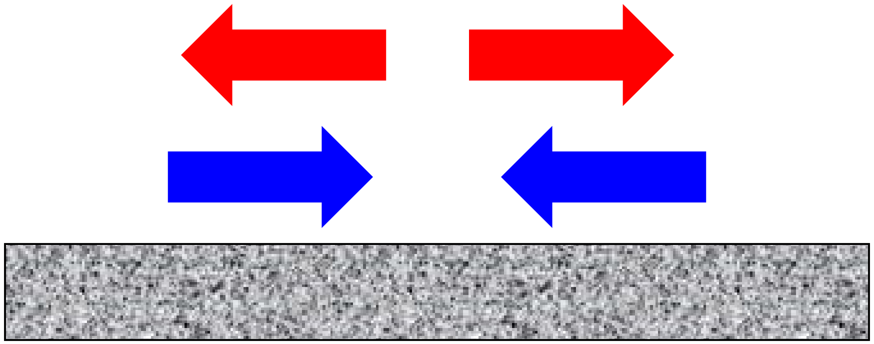
Fresh concrete always shrinks. This shrinkage leads to cracking. Cracking is not necessarily bad and can be controlled. A number of factors affect early age cracking:

- Volume changes and restraint
- Curling and warping
- Strength gain during the stages of hydration
- Subgrade support
- Early loading

(IMCP—page 149)

Primary Factors of Early-Age Cracking

- Concrete expands as **temperature** rises and contracts as **temperature** falls



- Concrete expands as **moisture** increases and contracts as **moisture** decreases

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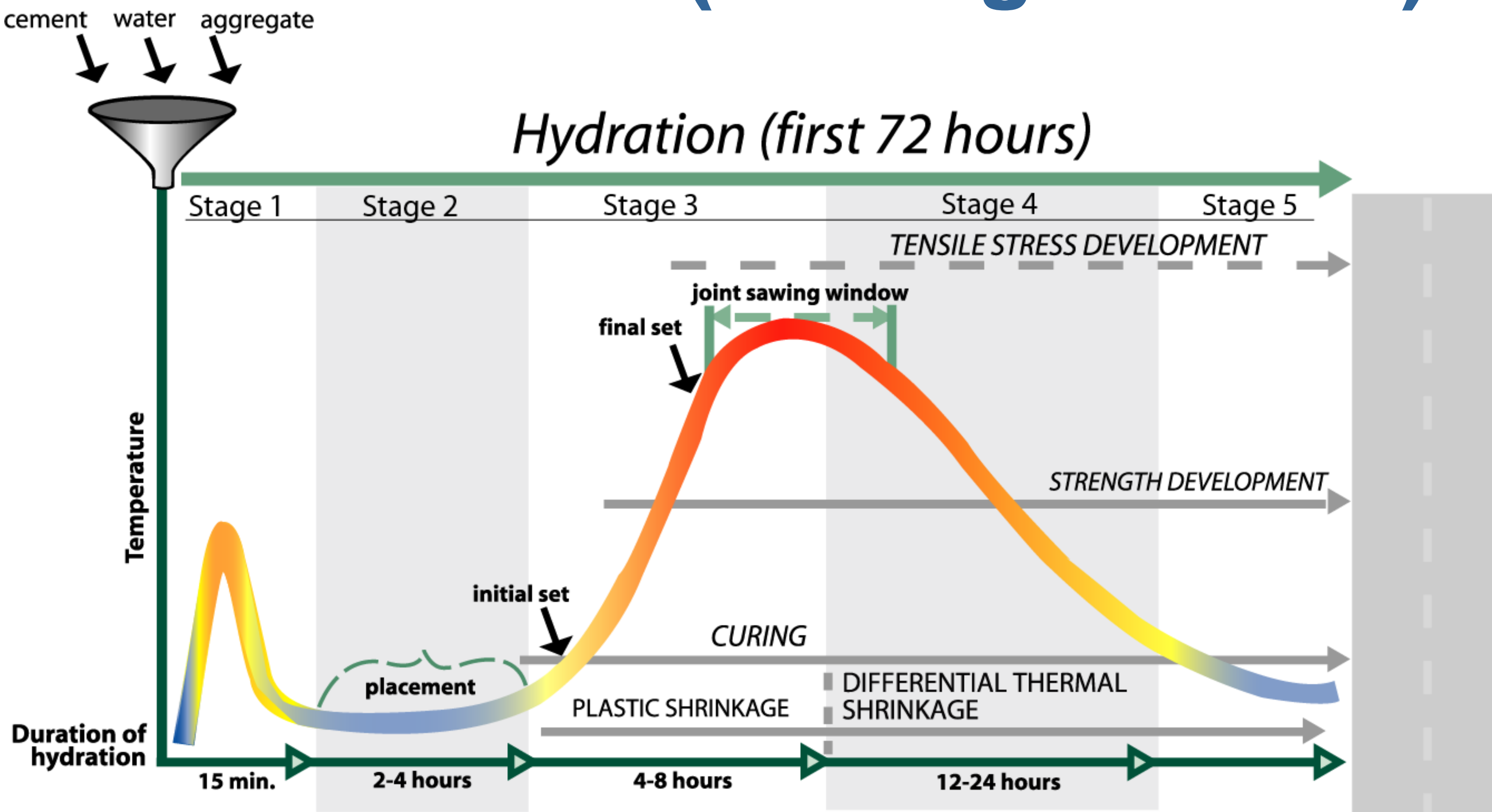
Strength and Stiffness

Strength: The greater the concrete strength, the greater stress it can withstand.

- Early-age concrete has not gained all its potential strength
- Stresses in early-age concrete can surpass the concrete's strength

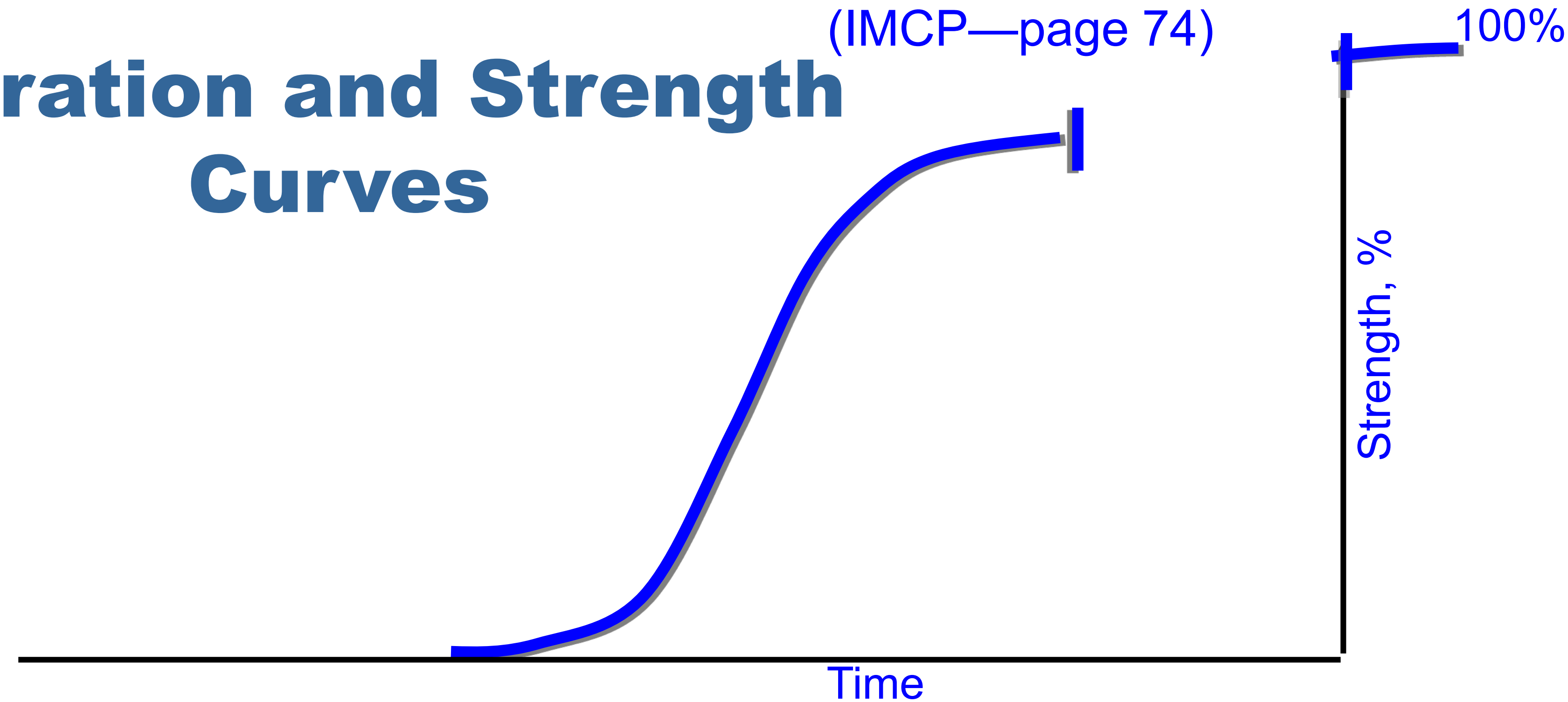
Construction (Sawing Window)

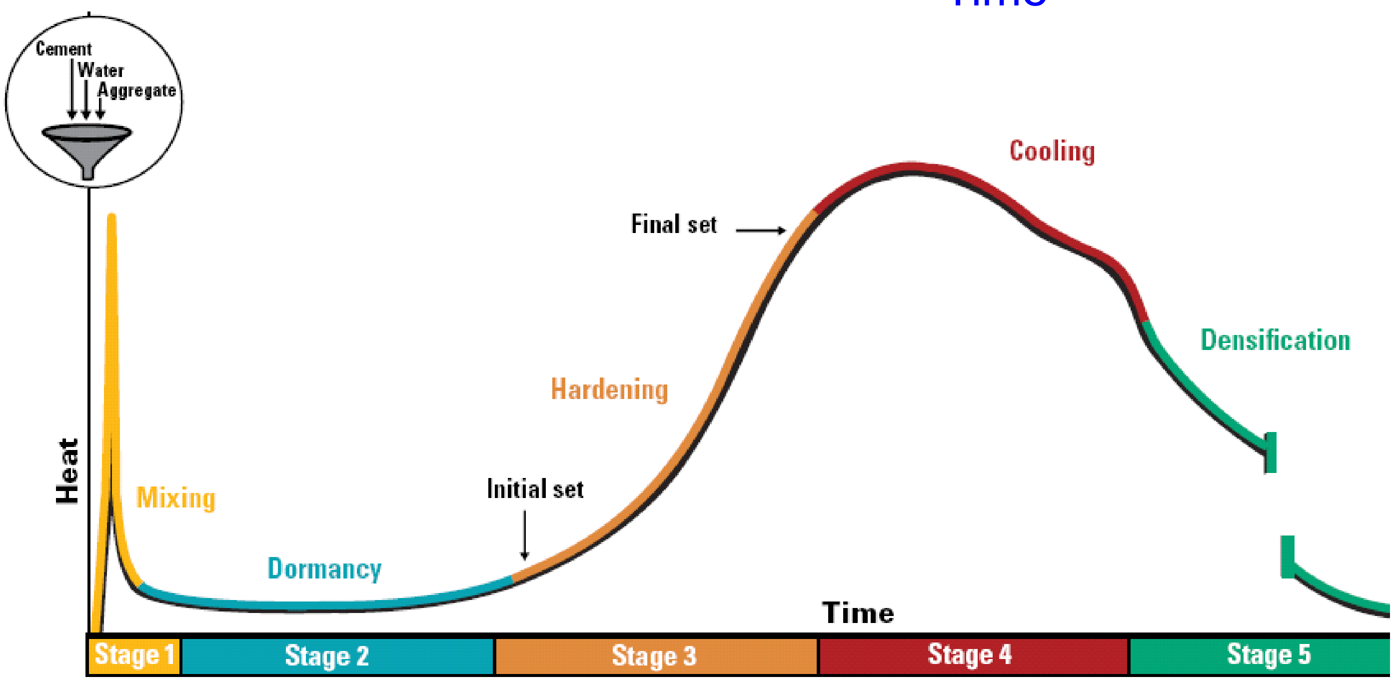


Initial Mix	Dormancy	Acceleration	Deceleration	Slow Hydration
(15 minutes)	*(24 hours)*	*(4-8 hours)*	*-24 hours)*	*(Indefinitely)*
High heat followed by rapid cooling	Cool, plastic, workable	Significant heat, less workable, begins to harden	Becomes hard and dense	70 – 75%hydrated after 28 days
	Transport and Place	Begin curing Cut joints	Continue curing	Can continue indefinitely, as long as water can reach un-hydrated particles

Hydration and Strength Curves

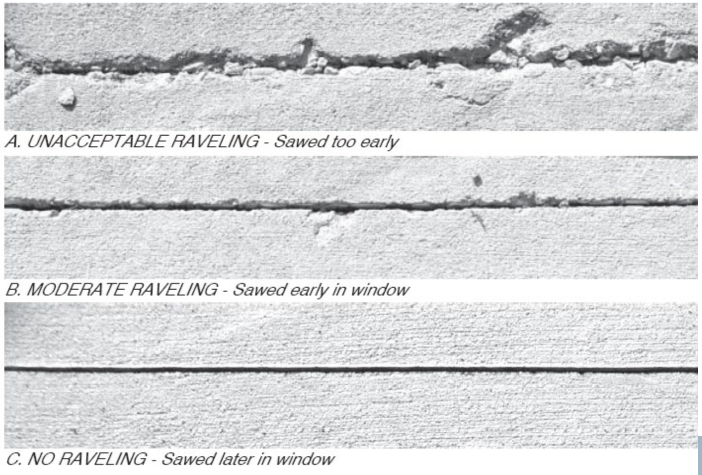
(IMCP—page 74)





Factors Affecting Sawing Window

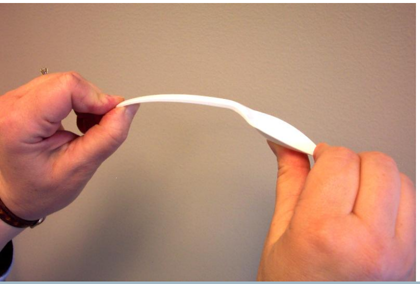
- Weather:
  - Sudden temperature drop or rainshower
  - Sudden temperature rise
  - High winds & low humidity
  - Cool & cloudy
  - Hot & sunny
- Concrete Mixture:
  - Rapid early strength
  - Retarded set
  - Supplementary cementing materials



Strength and Stiffness

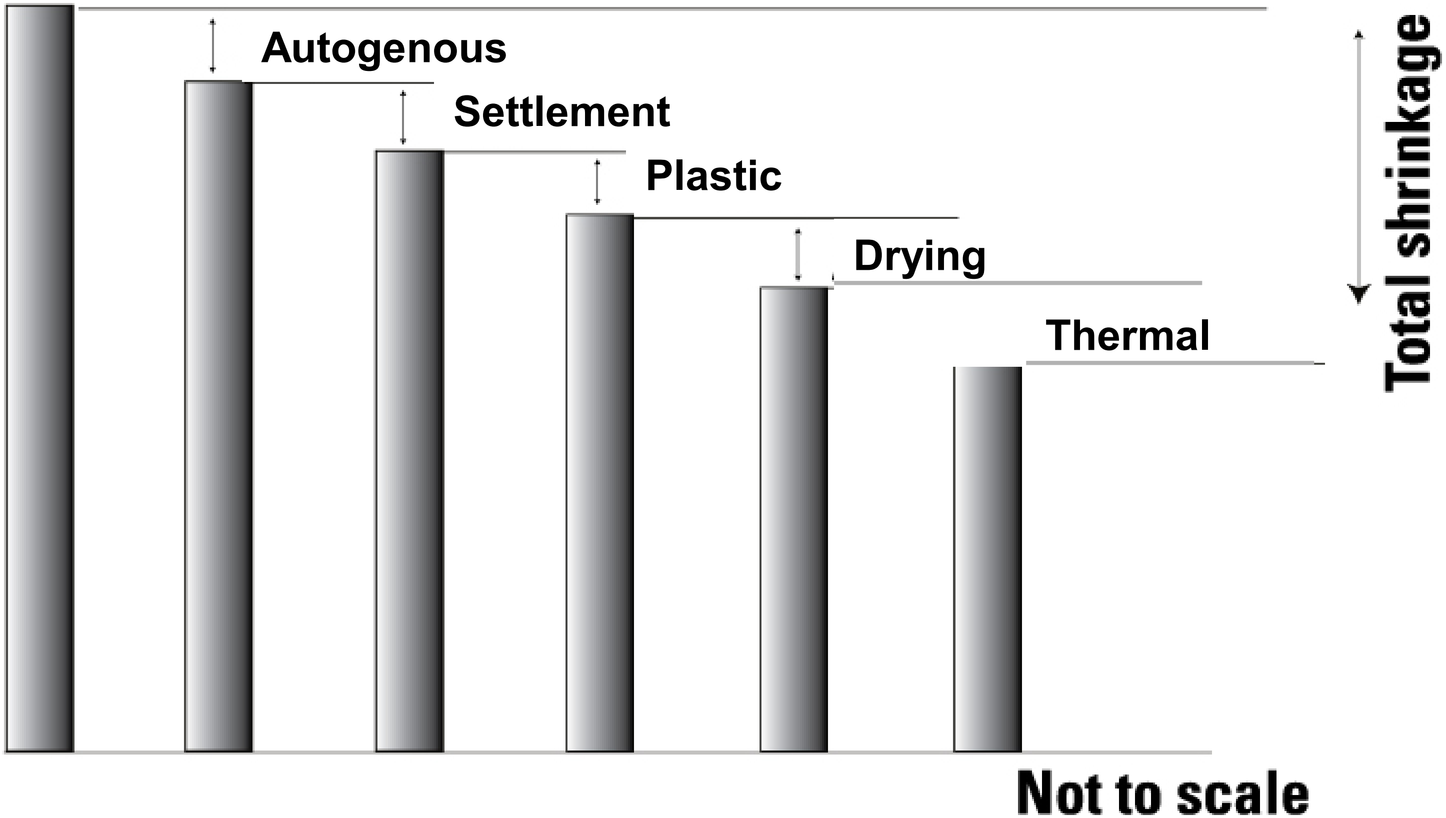
Stiffness: The stiffer the concrete (as indicated by modules of elasticity), the greater the stresses resulting from volume change.

- Unfortunately, stiffness increases faster than strength for the first few hours after setting
- First few hours
  - Minimize temperature & moisture change
  - Minimize the build up of stresses when the concrete has not gained sufficient strength



Volume Shrinkage

Total shrinkage is the sum of individual shrinkage mechanisms. Minimizing any or all mechanisms will reduce the risk of cracking.



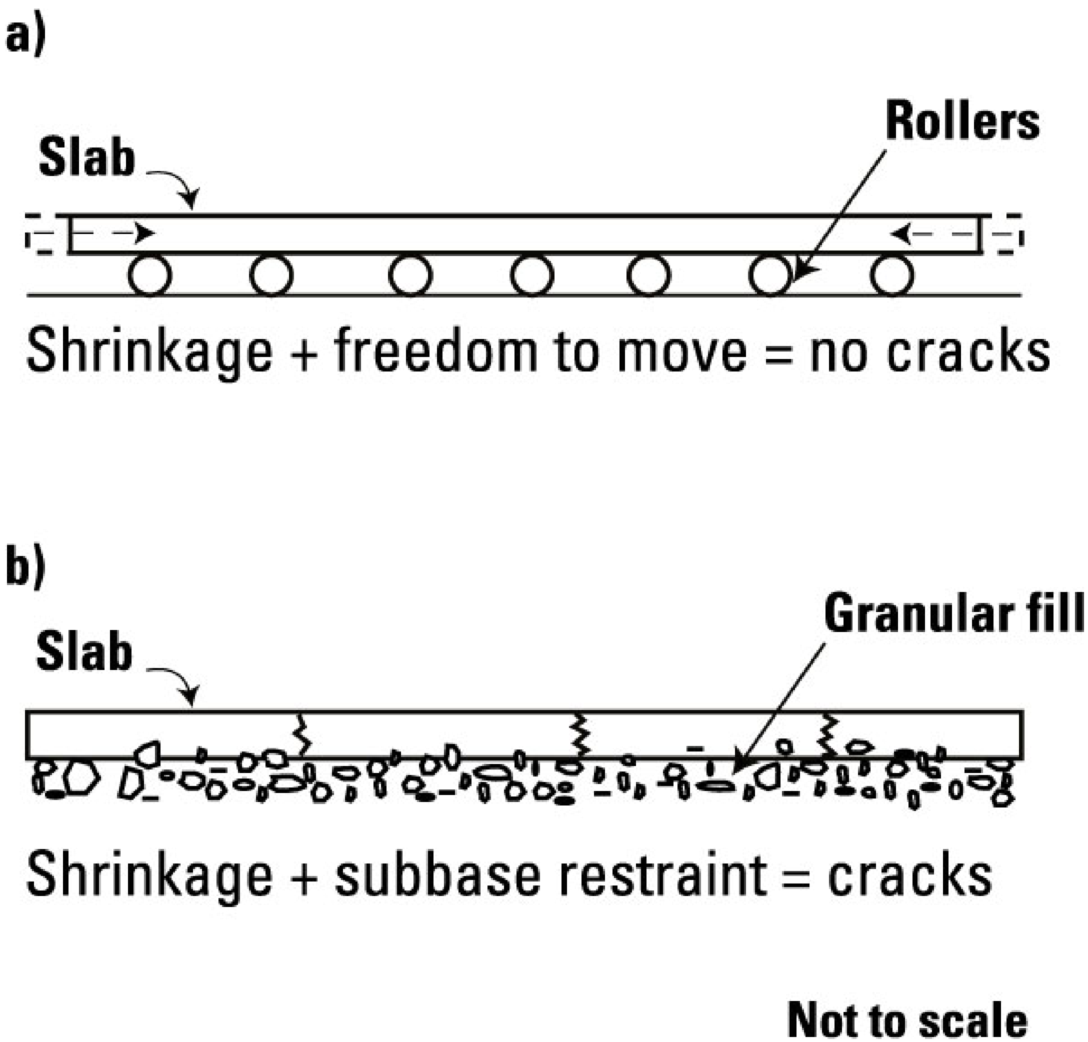
Restraint

External Restraint: A bonding or friction between a slab and the base or an abrupt change in the slabs cross-section.

Internal Restraint: The outer concrete shrinks or expands and the core does not.

(IMCP—page 150)

Shrinkage/Cracking



(a) Cracks generally do not develop in concrete that is free to shrink.

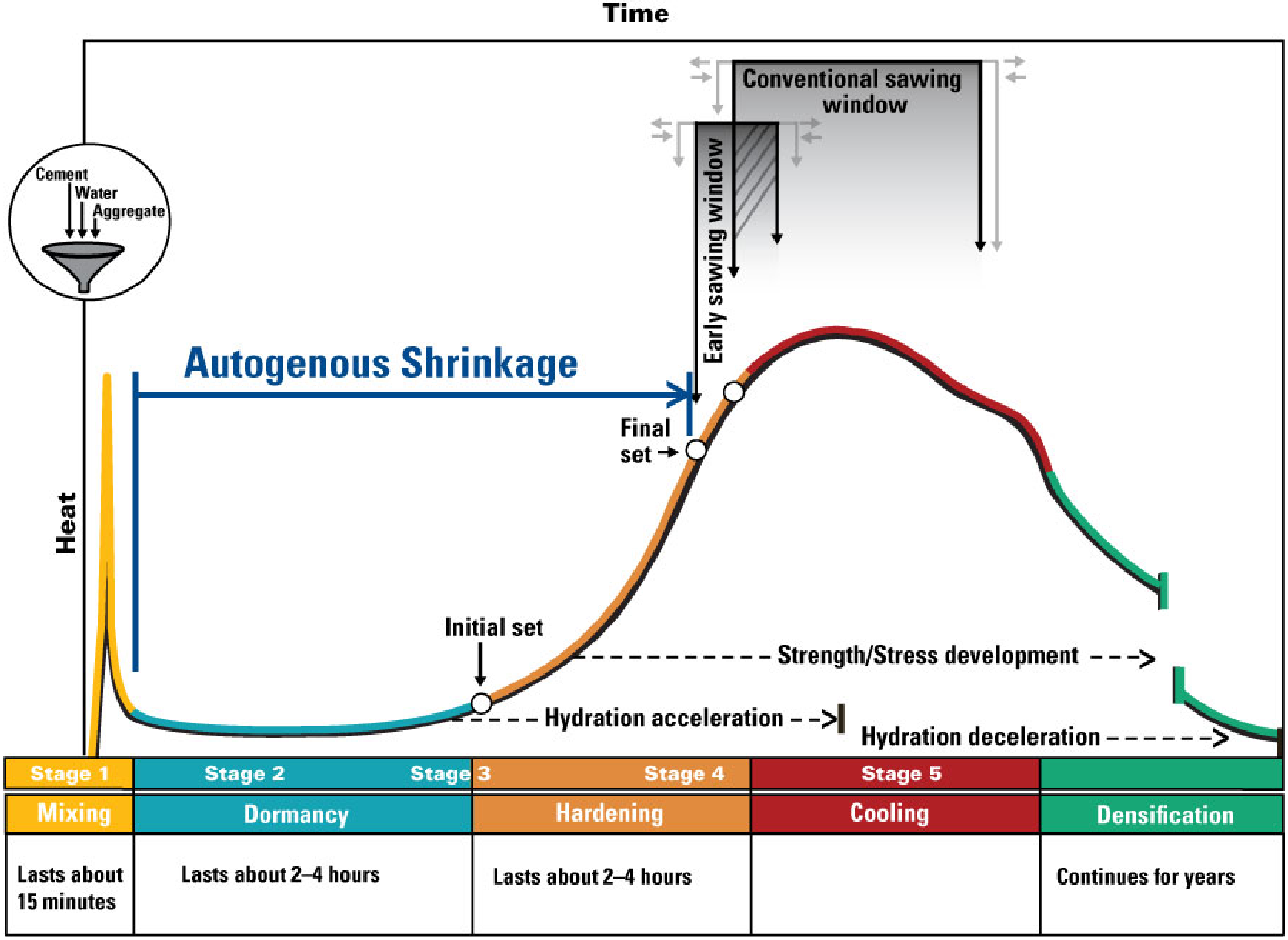
(b) Slabs on the ground are restrained by the subbase, creating tensile stresses that result in cracks.

Autogenous Shrinkage

The amount of chemical shrinkage that can be measured in a sample.

- Chemical shrinkage is a reduction of volume
- Results from hydration products occupying less space than the original materials
- Typically only significant for W/C less than 0.42

Autogenous Shrinkage



Settlement Shrinkage

- Bleeding is the development of a layer of water at the top or surface of freshly placed concrete.
- It is caused by sedimentation (settlement) of solid particles (cement and aggregate) and the simultaneous upward migration of water.
- Some bleeding is normal. It should not diminish the quality of properly placed concrete.

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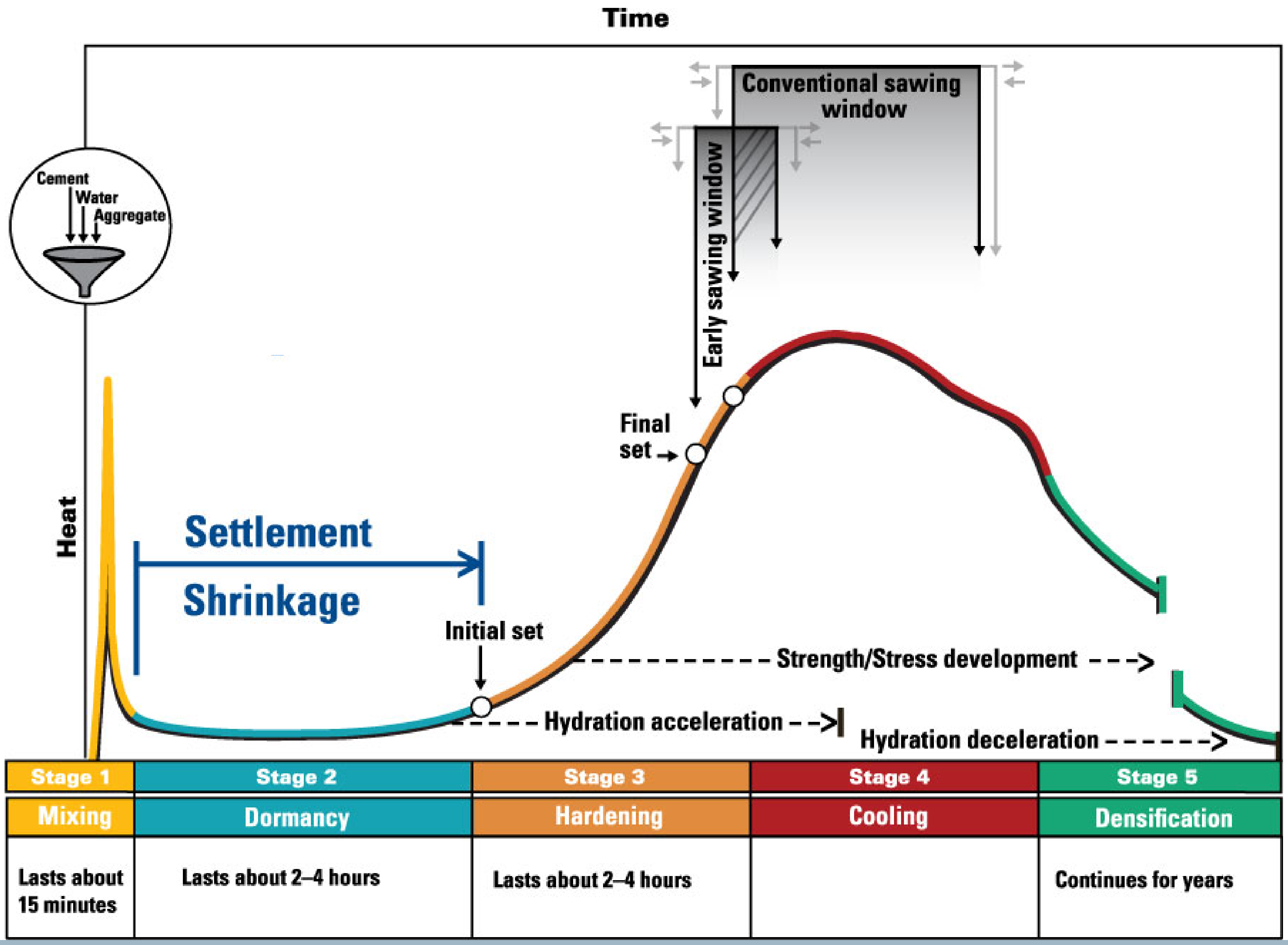
Settlement Shrinkage



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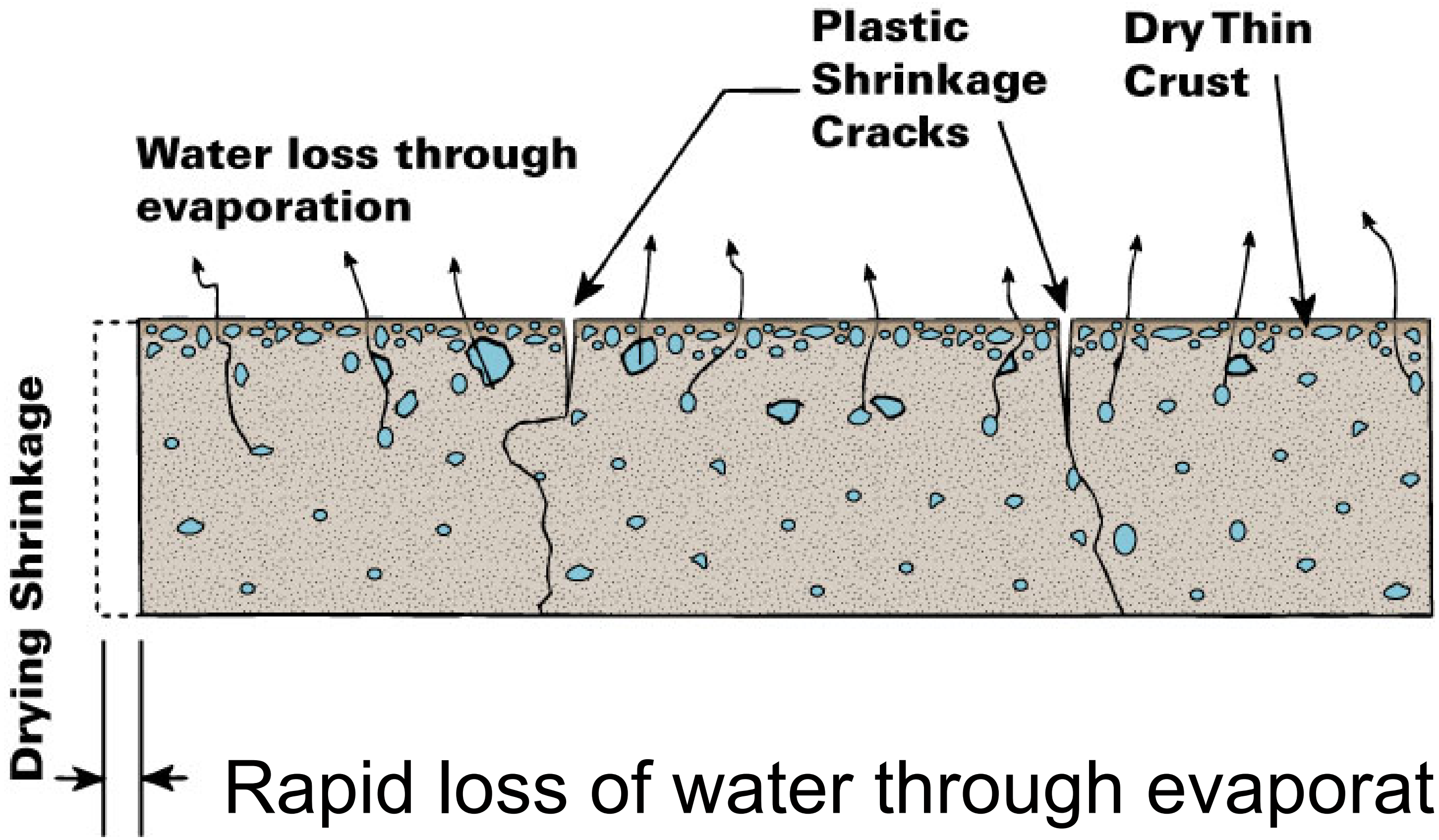
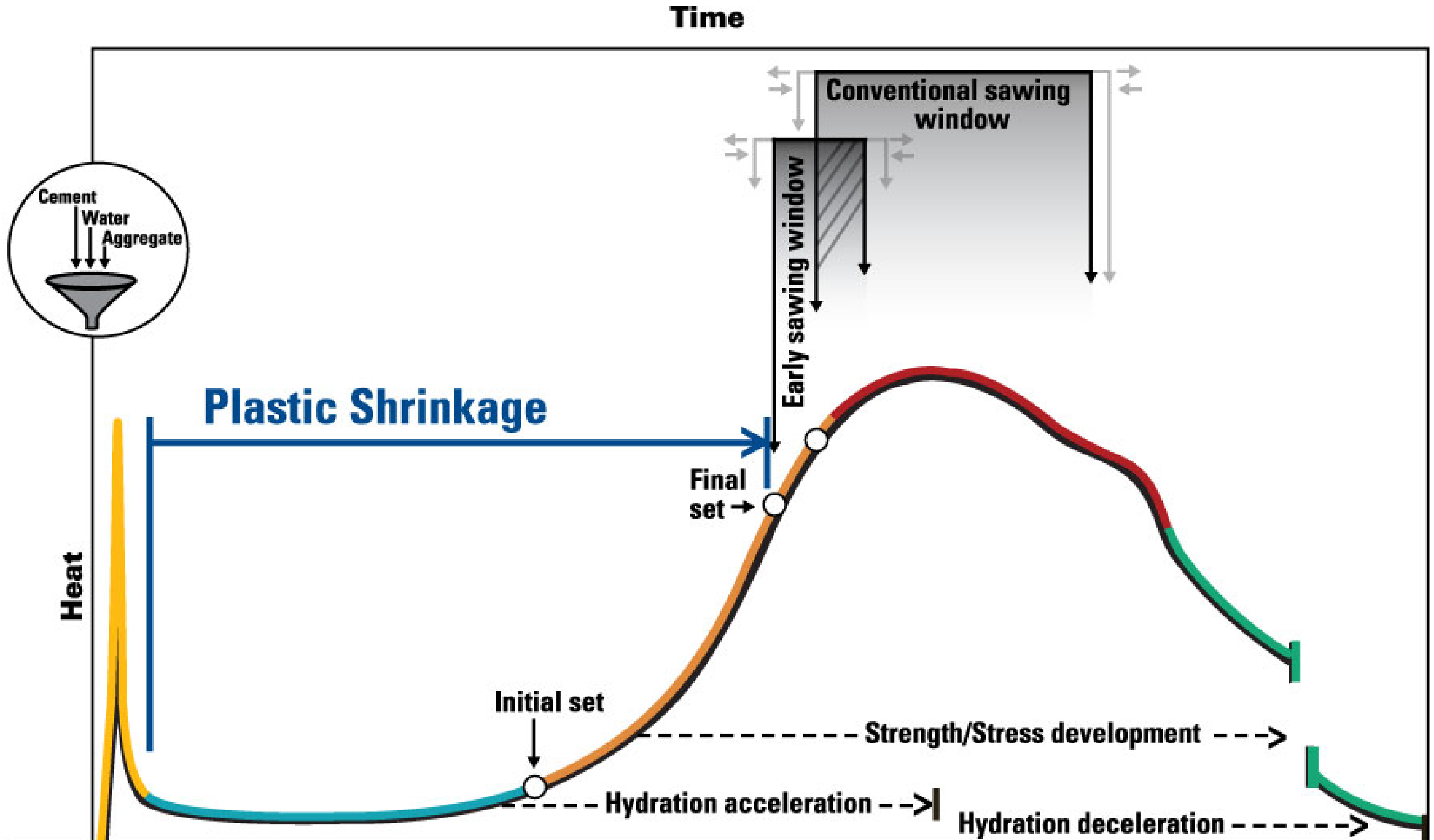
(IMCP—pages 125, 158, 159)

Plastic Shrinkage



Rapid loss of water through evaporation causes concrete **on the surface** to shrink. If shrinkage is restrained, tension develops, which may cause cracking.

Plastic Shrinkage



Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Mixing	Dormancy	Hardening	Cooling	Densification
Lasts about 15 minutes	Lasts about 2–4 hours	Lasts about 2–4 hours		Continues for years

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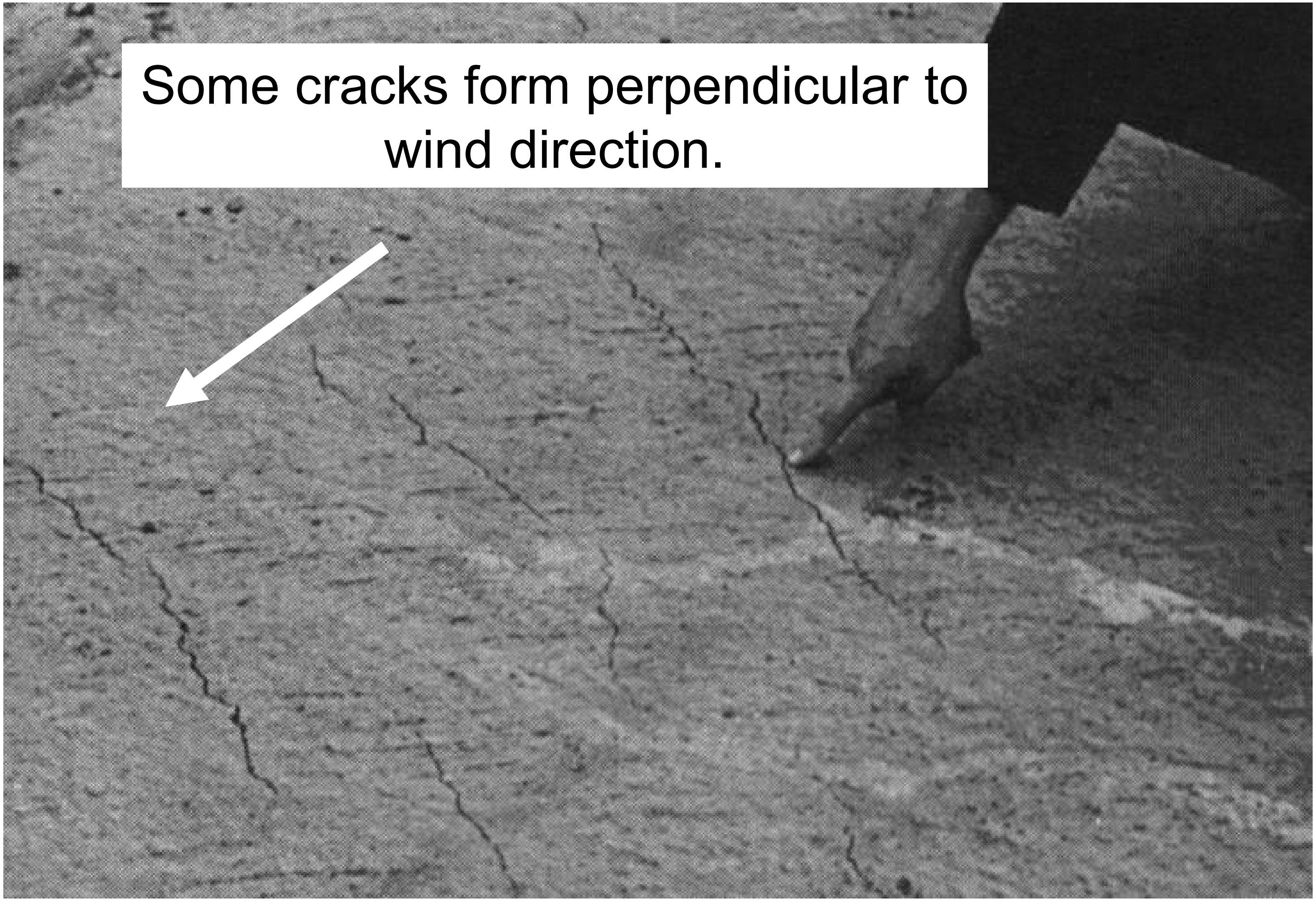
Plastic Shrinkage Cracks



(IMCP—pages 125–126)

Drying and Thermal Shrinkage

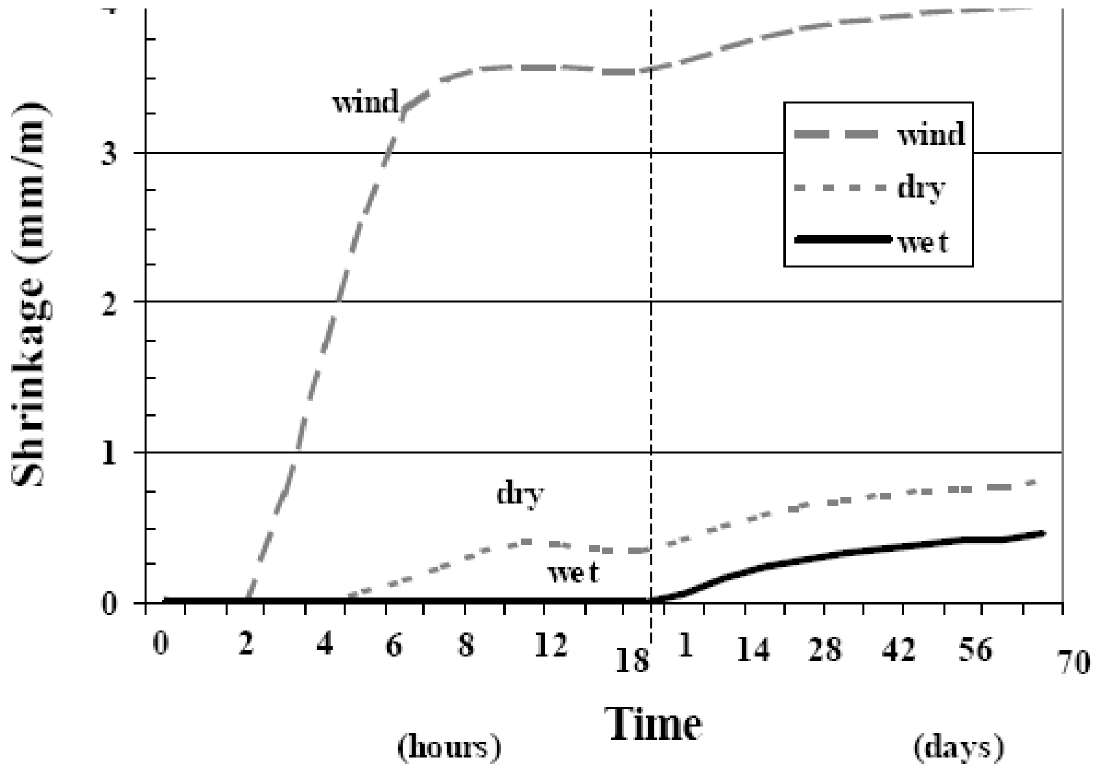
- Drying and thermal contraction shrinkage
  - Most frequent causes of early-age cracks
  - Thermal-related cracks
    - Normally observed in the first day
  - Drying-related cracks
    - May appear over a longer period

(IMCP—pages 161–162)

Drying Shrinkage

- Loss of mixing water through hydration and evaporation
  - Overall volume contracts
  - Greater paste content results in greater drying shrinkage and higher tensile stress
  - Low relative humidity of air can affect shrinkage diffusion

Wind on Shrinkage



IGURE 6 Combined early age and long-term shrinkage for three different curi
environments (Holt and Leivo, 2000). [1 mm/m = 1,000 µm/m (0.001 in./in.).]

From: Transportation Research Circular E-C107, October, 2006

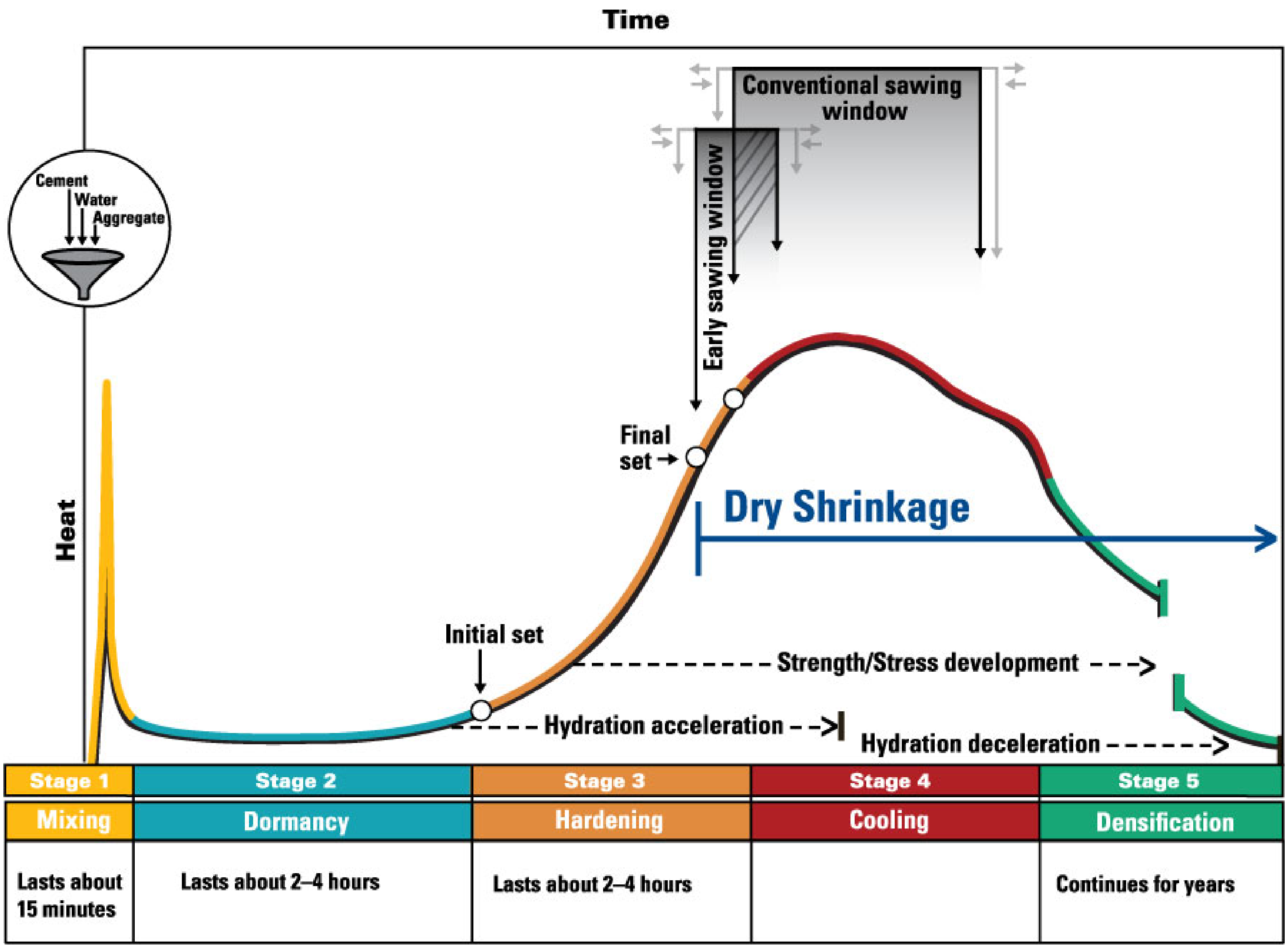
Drying Shrinkage

More Cement = More Water

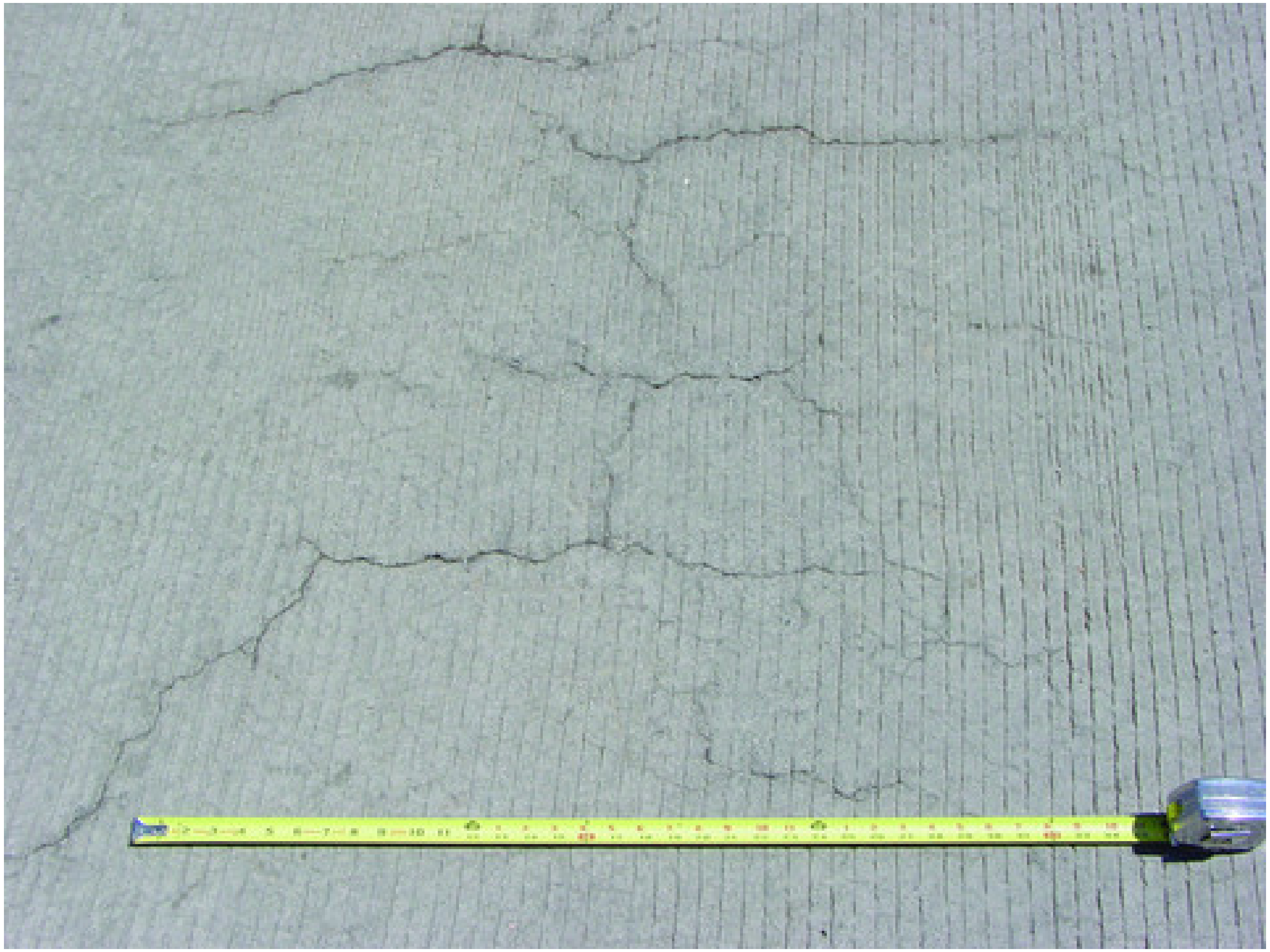
(W/C)

More Water = More Shrinkage

Drying Shrinkage



Drying Shrinkage



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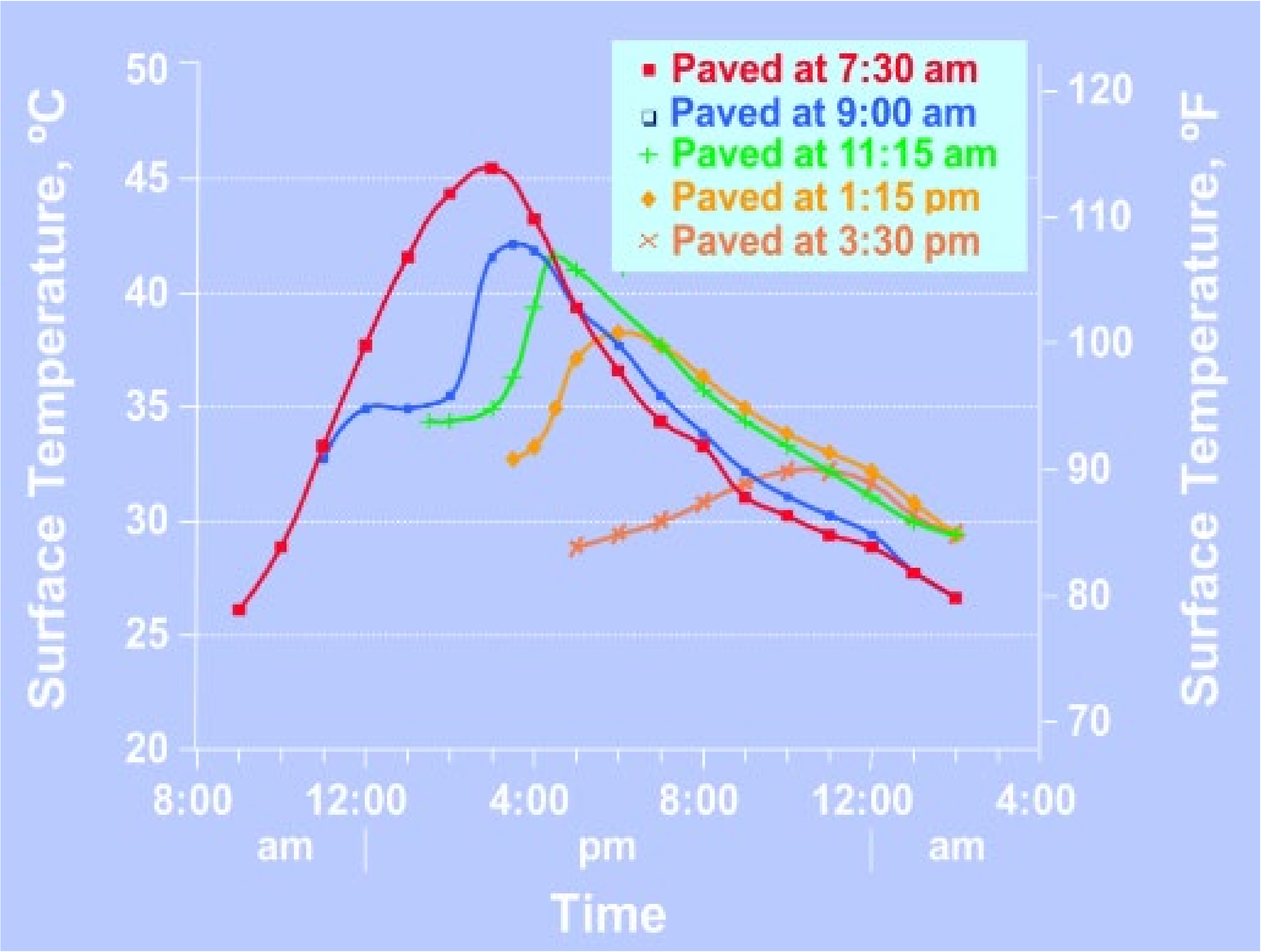
(IMCP—pages 125, 127–130, 149)

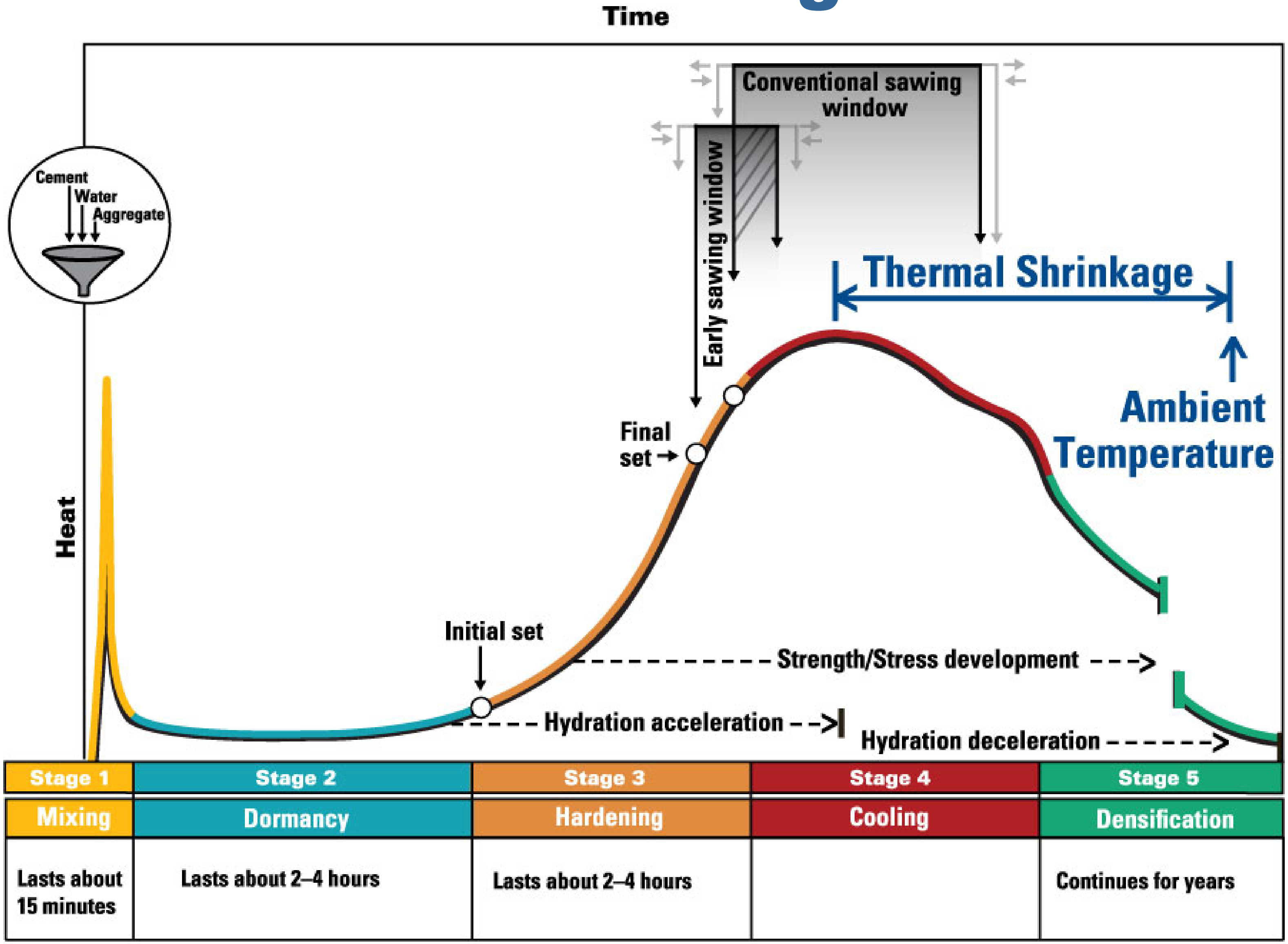
Thermal Shrinkage

- Air temperature can cause significant changes in shrinkage and expansion rates
- Hydration peaks within the first 12± hours after the concrete is placed
  - Volume starts to contract as hydration slows and concrete temperature drops
  - Movement of slab is constrained by subgrade
  - Contraction produces tension
  - Accelerated contraction (such as cold front) can cause thermal shrinkage cracking

Thermal Shrinkage



Thermal Shrinkage



Thermal Shrinkage

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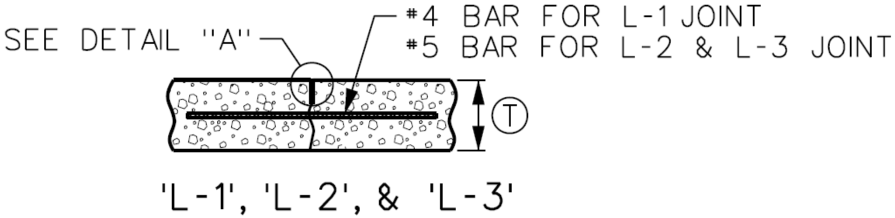
Longitudinal Cracking

Early entry saw, not deep enough



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Longitudinal Cracking

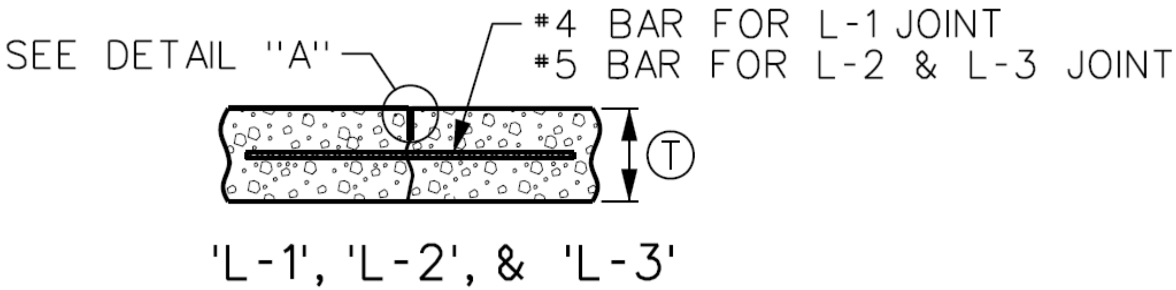
Late sawing or not deep enough

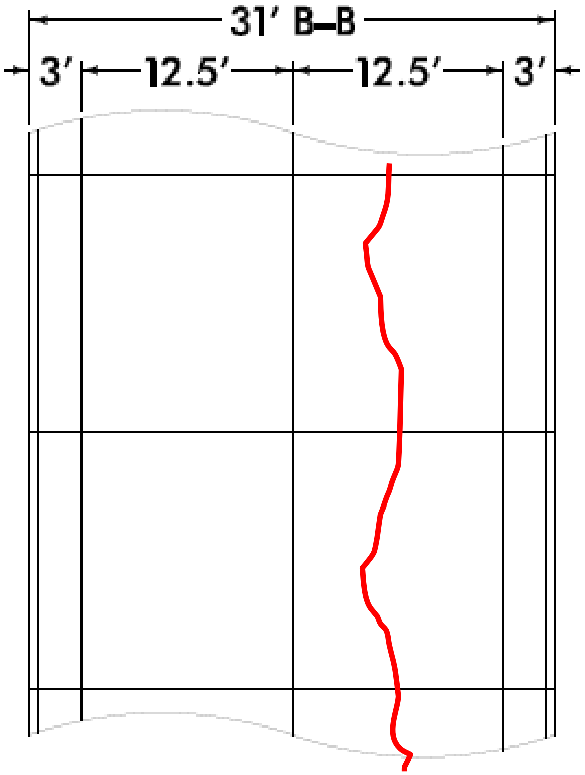
Need min. 6” embedment

Longitudinal Cracking (Not Sawing Deep Enough)

- Use of gutter joints not recommended for T < 9"
- Thinner pavements may not crack at gutter joint, causing longitudinal cracks at mid-panel
- Saw depth must be T/3

Longitudinal Spacing	
6.5' min. -12.5' max.	for T < than 9"
14.5' max.	for T > 9"



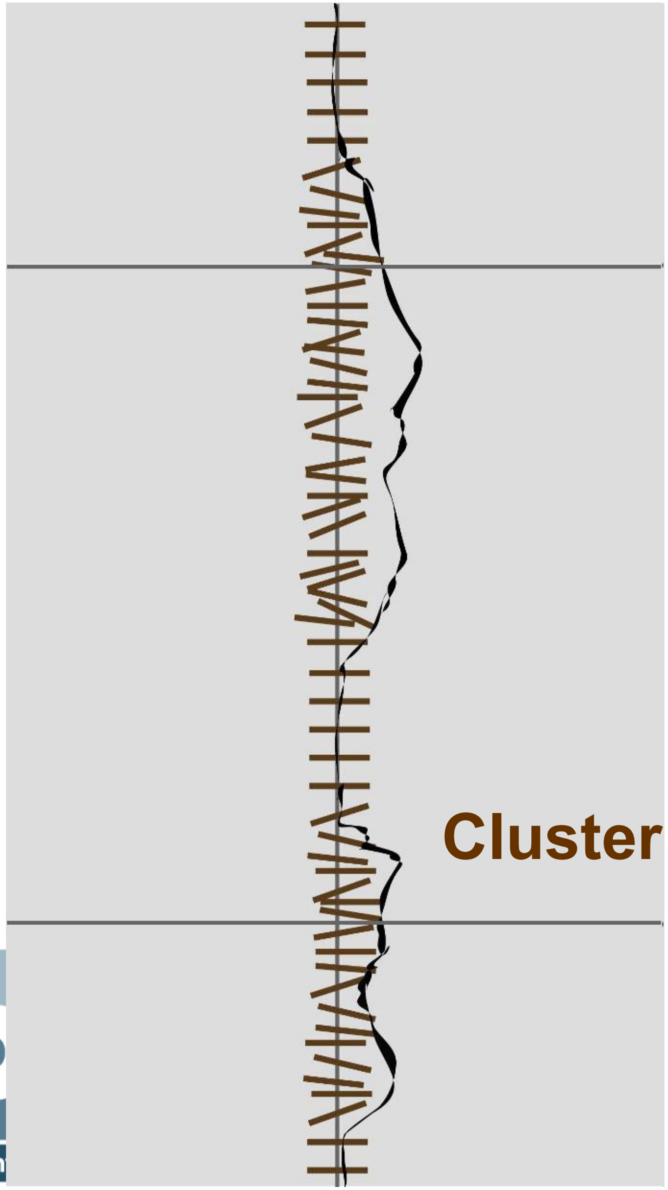


Gutterline Jointing

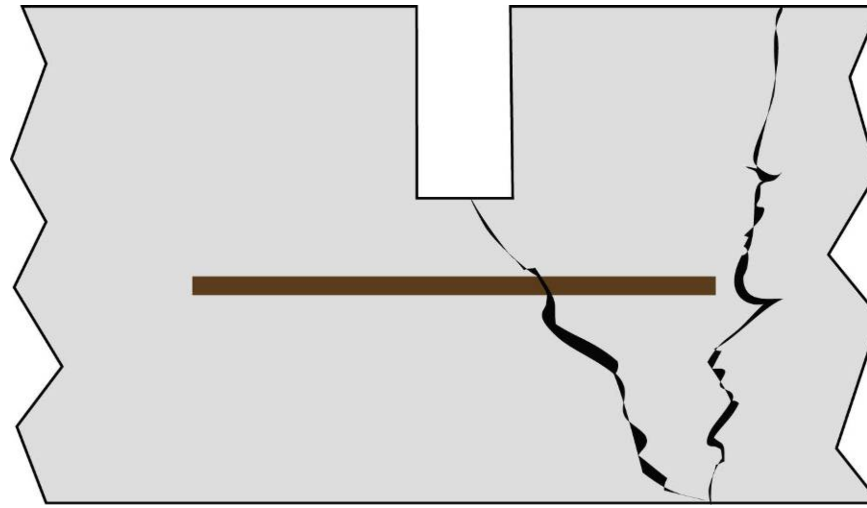
Longitudinal Cracking

Saw too late or not deep enough

Longitudinal Cracking



What happened?



Cluster of tie bars

2 lane roadway

Longitudinal Cracking

Panel too wide

Transverse Joints

Table 5G-2.01: Transverse Joint Requirements

Pavement Thickness	Transverse Joint Type	Transverse Joint Spacing
6"	C	12'
7"	C	15'
8"	CD[1]	15'
9"	CD[1]	15'
≥ 10"	CD[1]	20'

[1] No dowels within 24" of the back of curb

Source: SUDAS Specifications Figure 7010.901

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Transverse Cracking

Sawed too late

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Diagonal (Random) Cracking

Very poor subgrade

Diagonal (Random) Cracking

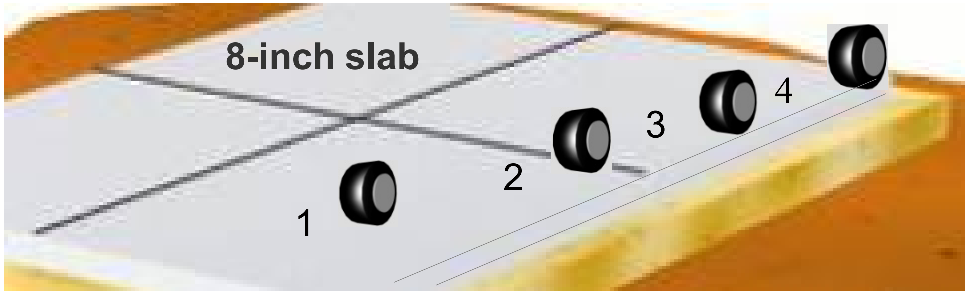
Very poor subgrade

Early Loading Stress – Corner Cracking

- Subgrade pressures are widely distributed, except at the edges and corners of the slab.
- Shoulders/curbs help
  - Equal to 2′ offset

Loading position *	Maximum subgrade pressure	
	psi	tons per square foot.
1. Slab interior	3	0.22
2. Transverse joint edge	4	0.28
3. Outside edge	6	0.43
4. Outside corner	7	0.50

* 12,000 lb. Load on a 12-in plate (~100 psi)



(IMCP—page 152)

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(IMCP—pages 150–151)

Curling and Warping

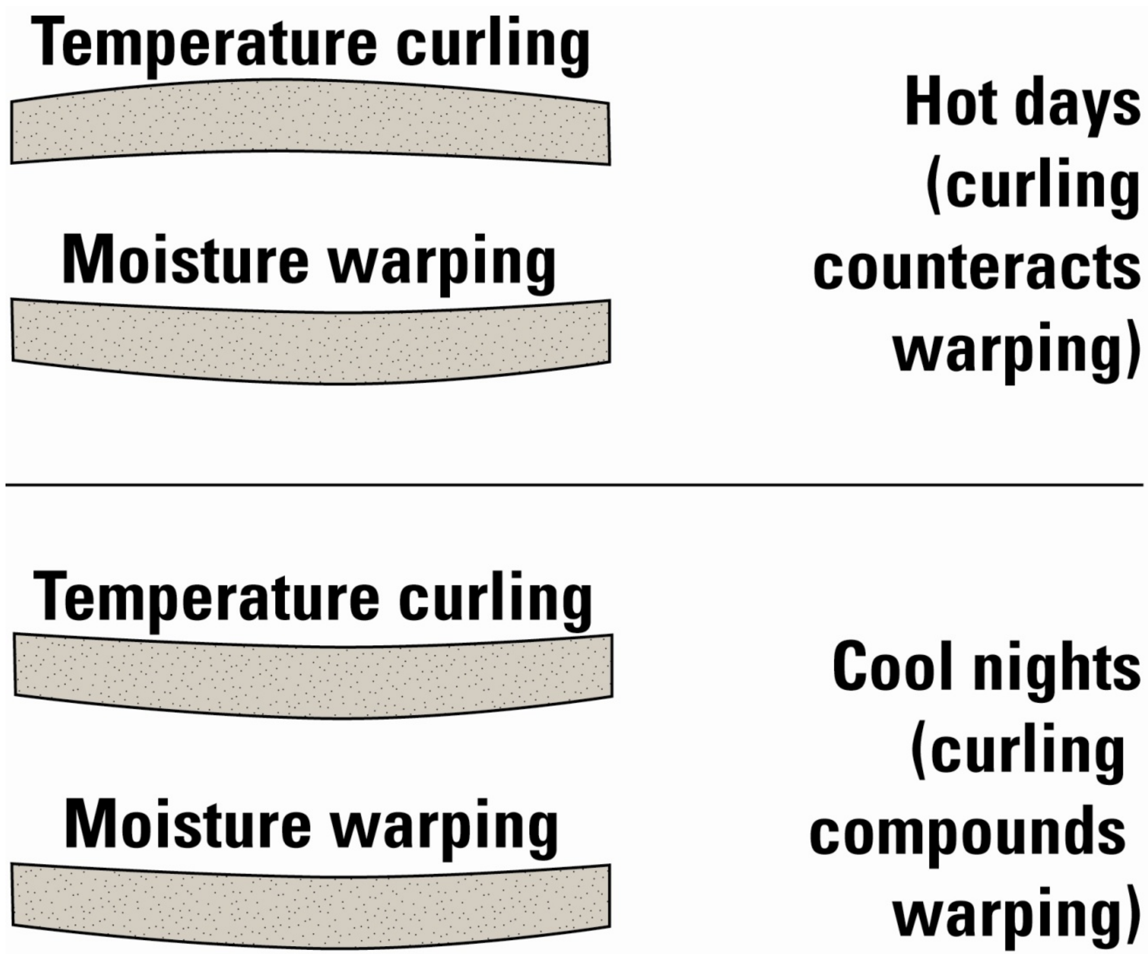
- Differential temperature and moisture levels throughout slab depth typically occur during the first 72 hours
- Variations in contraction and expansion cause differential, non-uniform movements

Curling => Change in **Temperature**

Warping => Change in **Moisture**

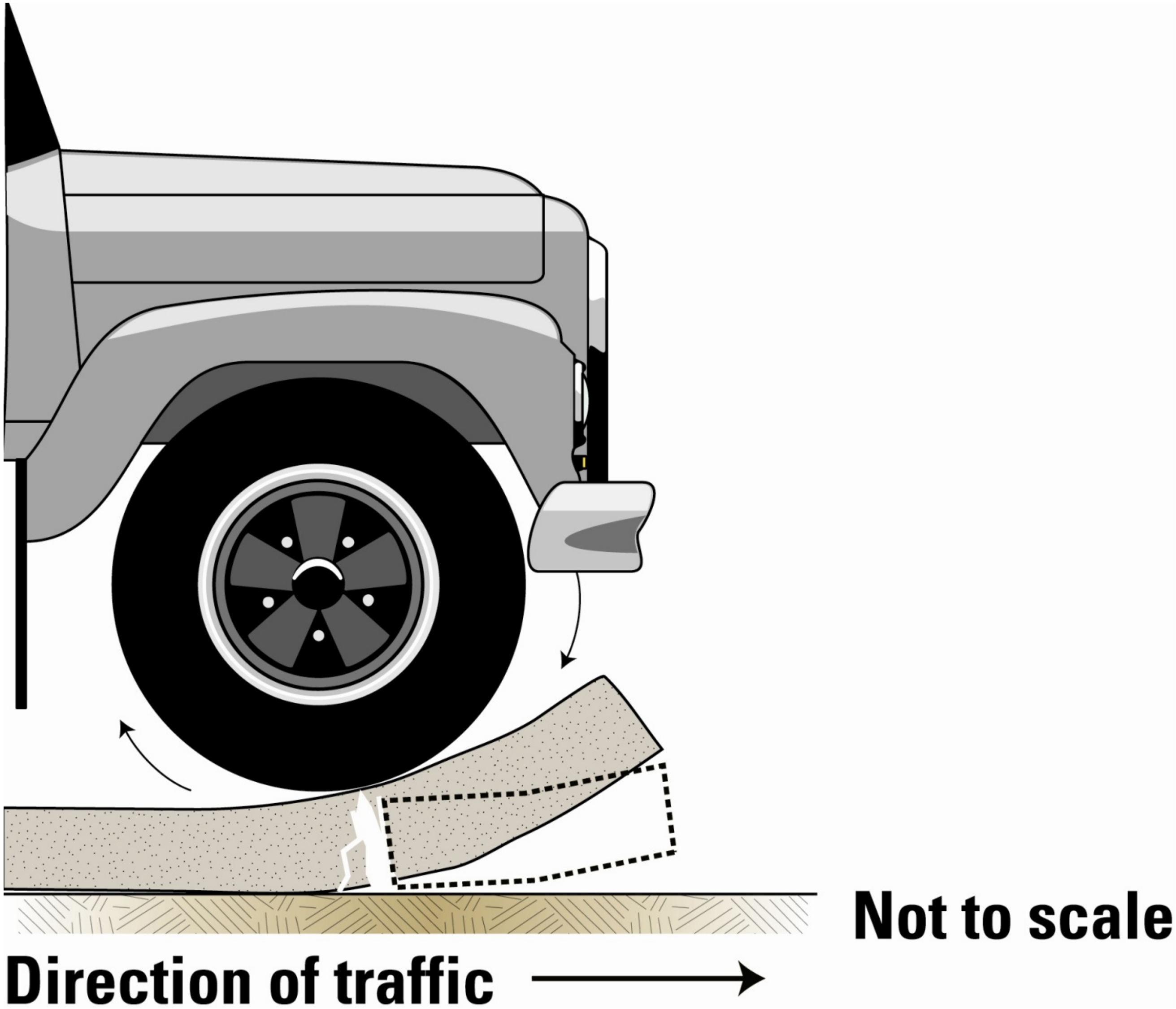
- These movements, especially when restrained, can cause cracking

Curling and Warping of Slabs



Curling

(IMCP—pages 150–151)



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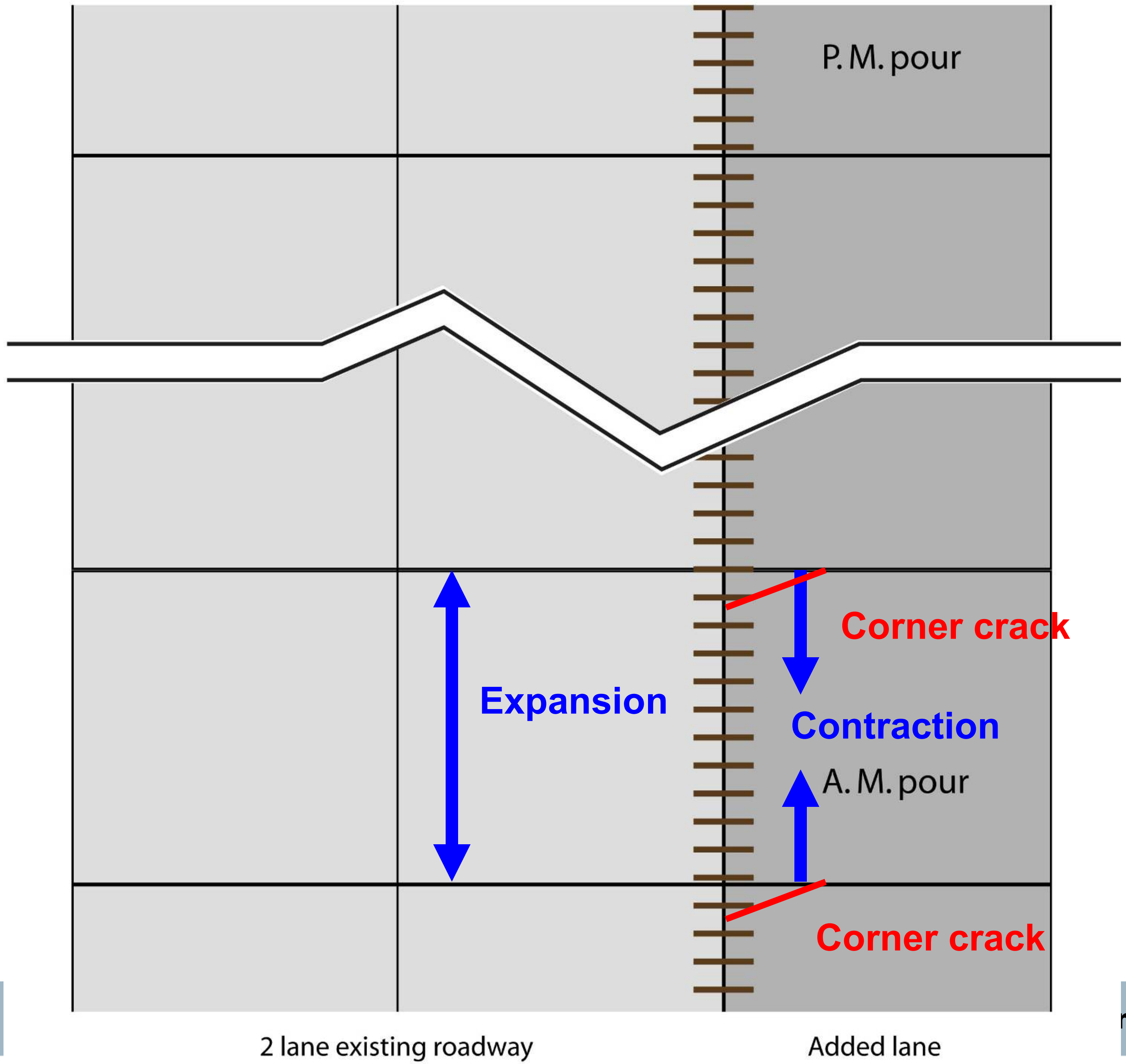
Corner Cracking

Pavement too thin & saturated subgrade



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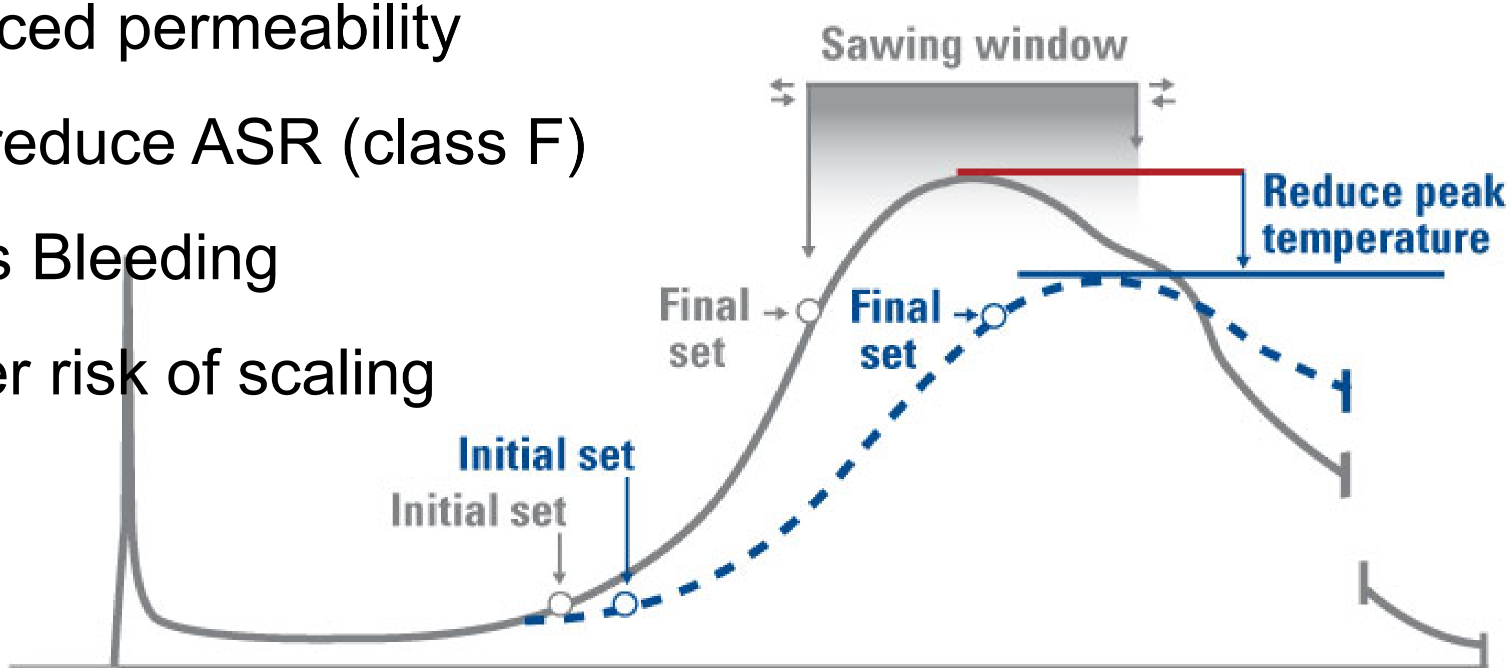
(IMCP—page 78)

SCM Effects

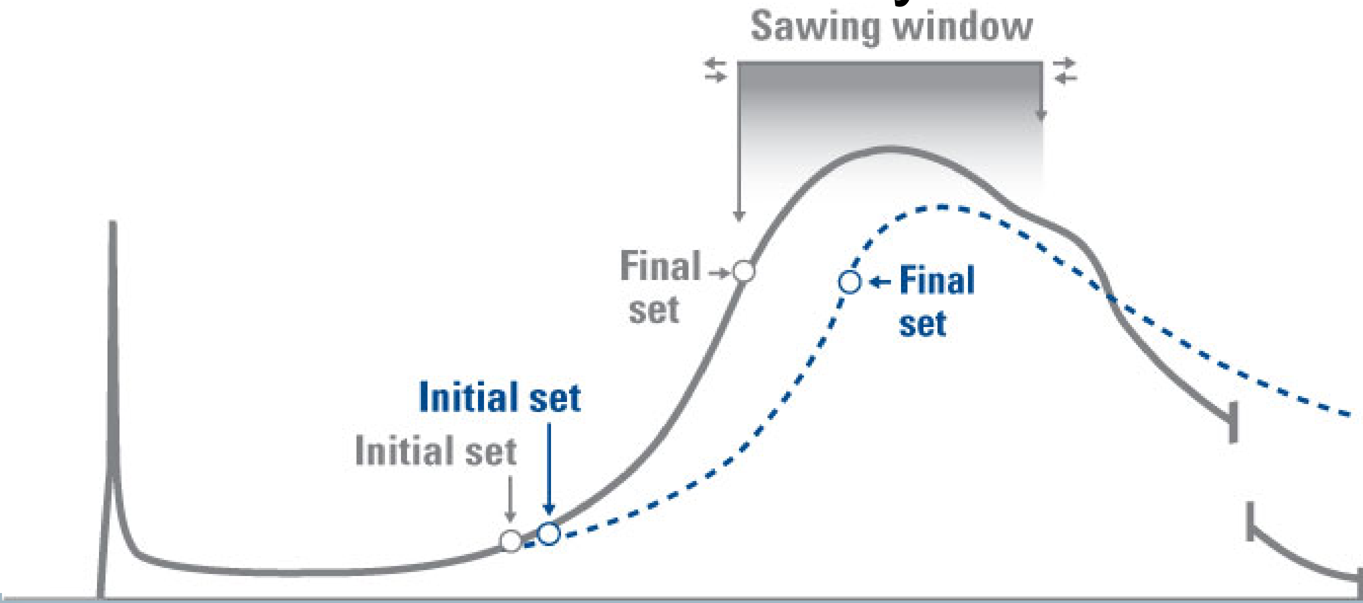
- Delayed final set
- Reduced heat peak
- Extended heat generation
- Increased long-term strength
- Reduced permeability
- May reduce ASR (class F)
- Slows Bleeding
- Higher risk of scaling



(IMCP—pages 79, 99)

Water Reducers' Effects

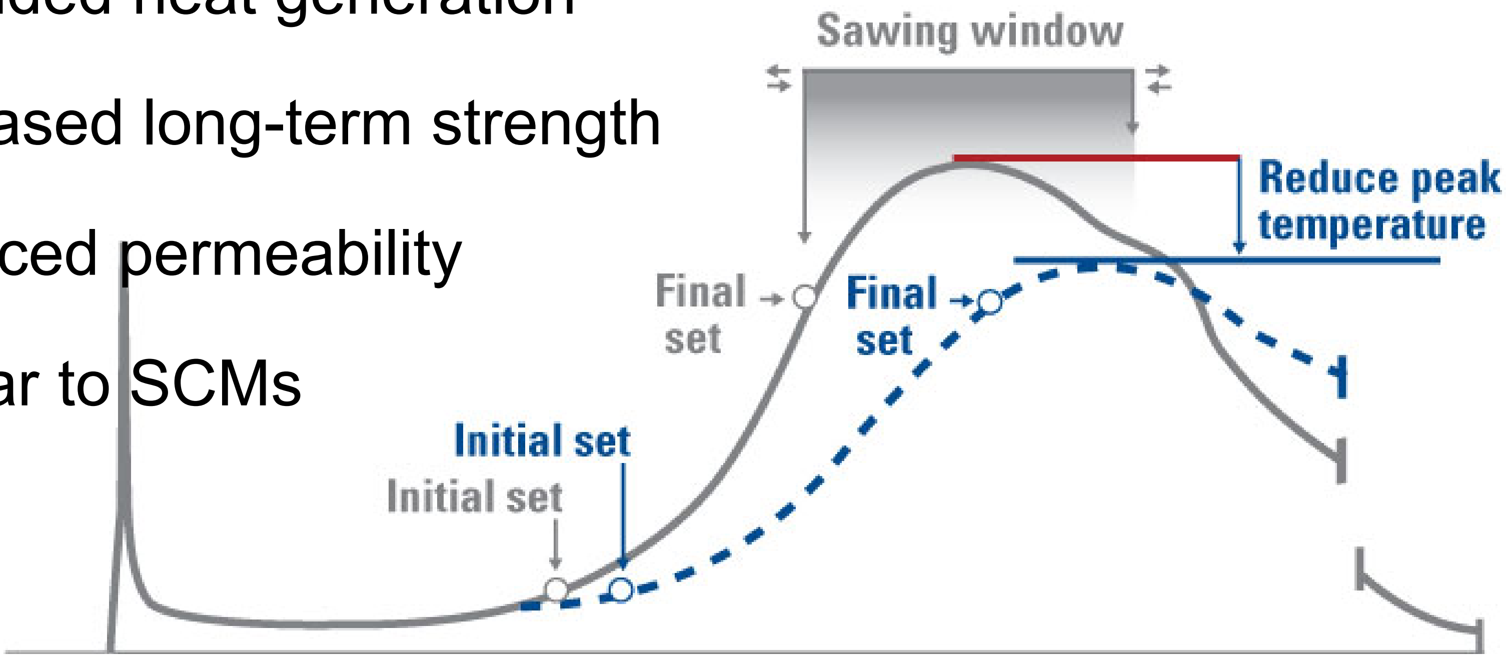
- Possibly slower strength gain (slows rate of alite reactions)
- Possibly faster aluminate reactions (and risk of flash set)
- More mix water available for hydration



(IMCP—page 79)

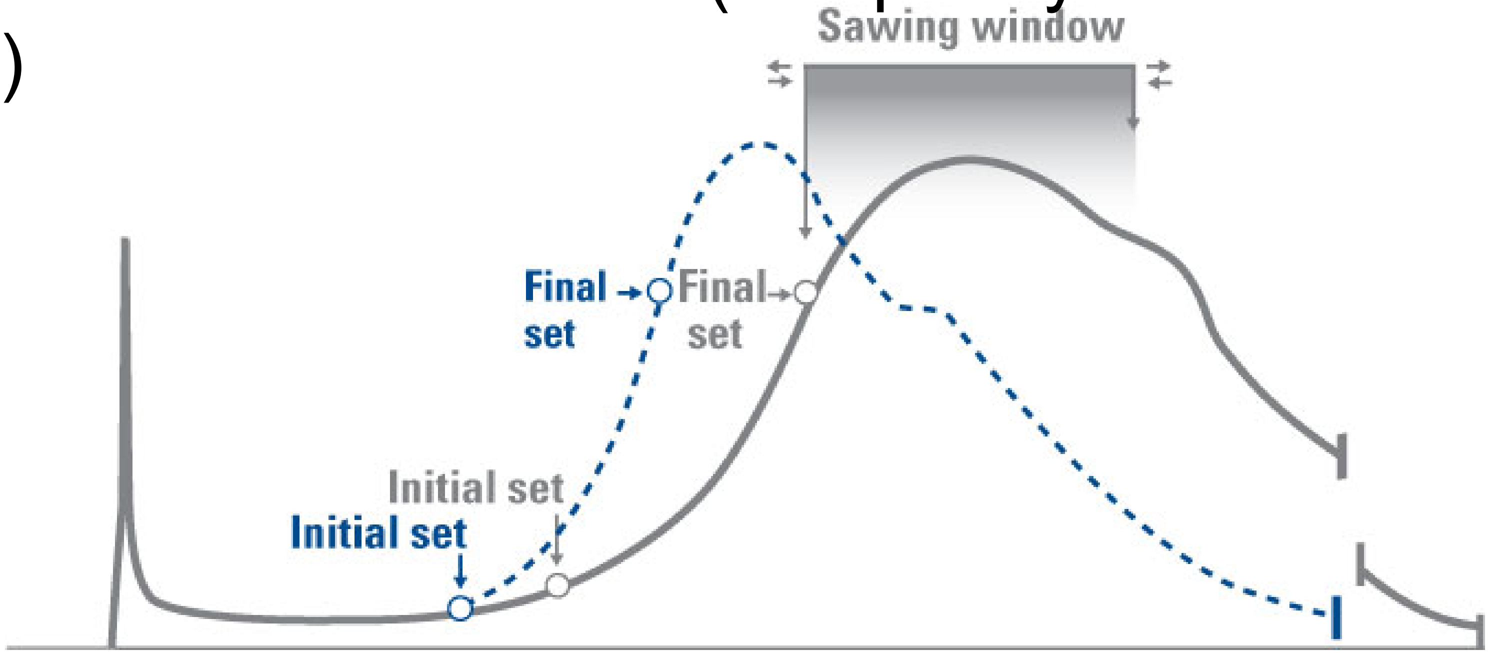
Retarders' Effects

- Lengthened dormancy
- Slowed hydration
- Reduced heat peak
- Extended heat generation
- Increased long-term strength
- Reduced permeability
- Similar to SCMs

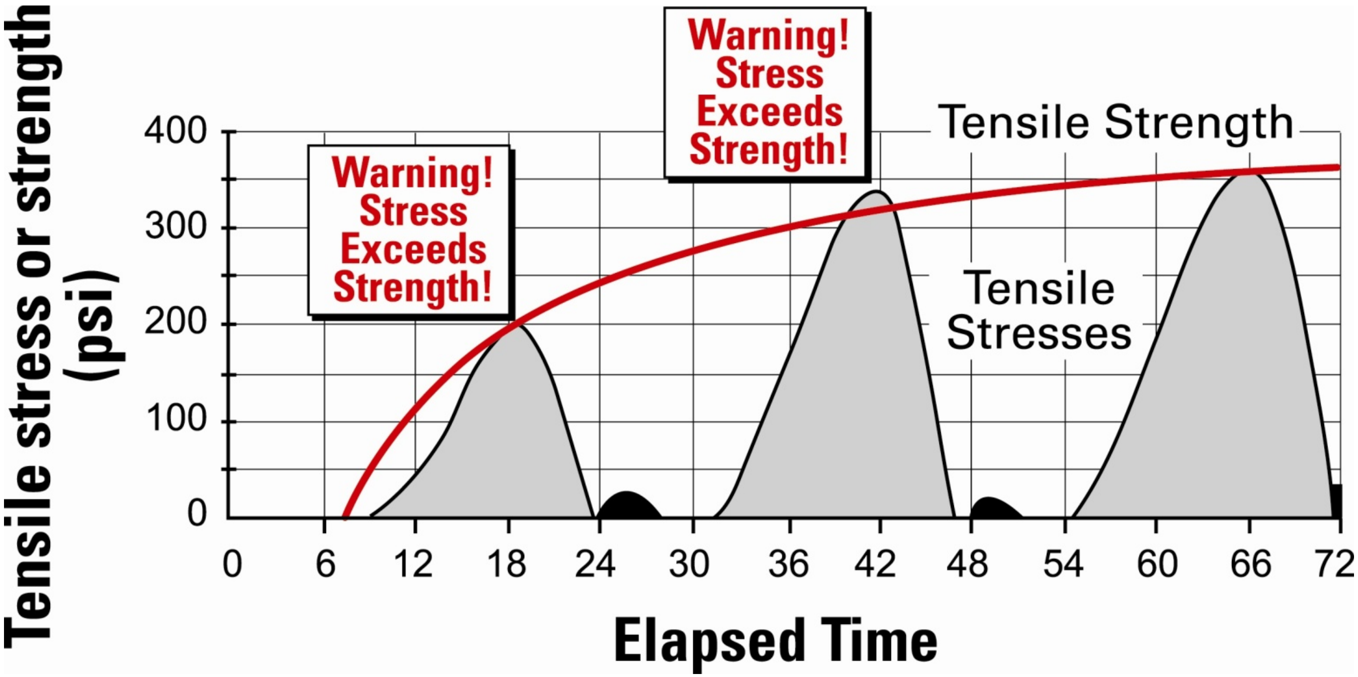


Accelerators' Effects

- Calcium Chloride
- Shortened dormancy (increased rate of ion saturation)
- Earlier initial and final sets (steeper hydration curve)



Combined Shrinkage and Curling Stresses



HIPERPAV curve

If the sum of stresses exceeds established strength, cracks can develop.

www.hiperpav.com

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Troubleshooting

MIX DESIGN

Method of Control or Prevention	Why This Works
Avoid using high early strength cements (Type III cements) unless for special conditions.	High early strength cements increase shrinkage potential by generating hear at a faster rate.
Use aggregate with low coefficient of thermal expansion (CTE).	Minimize aggregate expansion to help control volume change.
Use W/C ratio 0.42 to 0.45.	High paste and, thus, high water content increases shrinkage potential.
Consider using a water-reducing admixture.	Reduces paste content and helps reduce shrinkage. Typically reduces water requirements by 5% to 10% and may increase air content by 1%.
In very hot weather, consider using a set-retarding admixture.	Reduces heat generated, thus reducing thermal contraction.
In cold weather consider using a accelerating admixture.	Increases the rate of strength development. However excess acceleration may result in cracking before joint sawing.

Method of Control or Prevention	Why This Works
Incorporate fly ash or ground, granulated blast furnace (GGBF) slag.	Reduces thermal shrinkage. In comparison to portland, these materials lower the amount of heat generated while extending the hydration process. Also improves long term density and strength and helps with control of deicing scaling.
During extreme hot weather, consider using pre-cooled materials in the batch (e.g., shade and dampen aggregates, use chilled water or ice in the mix).	Lowers the temperature of the mix and, thus, minimizes the amount of cooling and shrinkage after final set.
Use saturated, surface dry aggregates.	Dry aggregates absorb moisture meant for cement hydration out of the mix. Wet aggregates add water to the mix, which can increase the water/cement ratio and reduce durability.
Use well-graded aggregates.	Requires less paste and thereby less water, which leads to a lesser potential for shrinkage.

RESTRAINED VOLUME CHANGE

Mechanism	Method of Control or Prevention	Why This Works
Restrained volume change	Dampen the pavement subgrade.	Dry subgrade pulls moisture out of the pavement.
Restrained volume change	Do not spray water on the slab to facilitate finishing. Do not finish the surface while bleed water is present.	Such actions lead to weakening of the pavement surface and can lead to scaling.
Restrained volume change	Avoid paving when weather conditions may cause rapid drying. (e.g., try to avoid final set at the peak day temperature).	Such weather conditions can increase potential for plastic or drying shrinkage cracks.
Restrained volume change	During extremely hot weather, consider paving in late afternoon, early evening, or at night.	Minimize the amount of thermal shrinkage after final set.
Restrained volume change; Curling and/or warping	Avoid significant concrete temperature changes as concrete is placed and cured (e.g., protect the surface if exposed to cold fronts within the first two nights).	Such weather conditions can increase differential concrete temperature and volume changes throughout the slab depth, thus resulting in a buildup of stresses from the top to bottom of the slab, causing cracking.

RESTRAINED VOLUME CHANGE, BASE SUPPORT & EARLY LOADS

Mechanism	Method of Control or Prevention	Why This Works
Restrained volume change	Cure properly and promptly. (Immediately after finishing, cover surface thoroughly with white-pigmented curing compound and cure for 72 hours without traffic.	Protects surface from high evaporation rates that can lead to shrinkage cracks and loss of water for hydration.
Restrained volume change; Loads	Construct joints properly with regard to type, timing, spacing and depth. Make sure spacing of longitudinal joints do not exceed 12.5' for pavements < 9" thick and 14.5' for pavement ≥ 9.0".	Directs cracks to joint locations and prevents random cracking.
Restrained volume change	Do not tie too many lanes together with tiebars. Do not tie lanes together when the weather is excessively hot or cold.	The new (weaker) pavement does not move the same as the existing (stronger) pavement, particularly under high temperature changes.
Uniformity of subgrade/base support	Ensure a uniformly stable subgrade and base.	Prevents the stress buildup that results from different support conditions.
Loads	Keep construction traffic away form the pavement slab edges when opening strength has not been obtained.	Allows concrete to develop the strength and stiffness necessary to support and distribute loads.
Other	Do not overwork or over-finish.	Leads to bleeding and map cracking

How to Avoid Random Cracks

Manage Change!

Thank you

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