during setting, the greater the shrinkage that accompanies cooling. Excessive temperature changes thereby contribute to high cracking risk during early age.

To adjust to extreme environmental conditions, the following actions can be taken:

- At high temperatures, pave at night or use pre-cooled materials in the batch.
- At low temperatures, take steps to prevent concrete from freezing while it gains strength.

To control the heat curve, note how the following factors influence concrete temperature:

- Increasing cement fineness increases the rates of hydration and heat generation.
- Concrete's thickness, temperature, and degree of insulation affect the rate of heat loss to the environment.

Controlling Shrinkage

Shrinkage is the reduction in volume or length of concrete that occurs with moisture loss. High shrinkage leads to low strength, increased stress, and increased cracking risk.

The primary factor affecting shrinkage is the water/paste content. However, total shrinkage is result of shrinkage from five different, independently occurring, mechanisms, as follows:

- Autogenous shrinkage (chemical reaction).
- Settlement shrinkage (bleeding).
- Plastic shrinkage (evaporation before set).
- Drying shrinkage (evaporation after set).
- Thermal shrinkage (evaporation due to environmental factors).

To control the collective amount of shrinkage, take the following precautions:

- Keep water content as low as possible.
- Maximize the total aggregate content (while maintaining workability and avoiding segregation).
- Avoid aggregates with excess clay or high coefficients of thermal expansion.

Also note how other factors influence shrinkage:

- Aggregate type is the primary factor influencing a concrete system's overall coefficient of thermal expansion.
- Uncontrollable weather factors also influence the rate of hydration and temperature effects and, thus, shrinkage.

National Concrete Pavement Technology Center

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This technical summary is based on chapter 5 of the IMCP Manual (Taylor, P.C., et al. 2006. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual*, Ames, Iowa, Iowa State University [FHWA HIF-07-004] [www.cptechcenter.org/publications/imcp/]) and was sponsored by the Federal Highway Administration. (References for any citations in this summary are at the end of the chapter.)

For More Information

Marcia Brink, Managing Editor
CP Tech Center, Iowa State University
2711 S. Loop Drive, Suite 4700
Ames, IA 50010-8664
515-294-8103, mbrink@iastate.edu
www.cptechcenter.org/

Center for Transportation Research and Education
Iowa State University

5a

A summary of chapter 5 (pages 105–170) of the *IMCP Manual* (reference information on page 4)

Plastic (Fresh) Concrete Properties

This document is one of a set of technical summaries of chapters 1 through 10 of the *Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Practice Manual* (IMCP manual). The summaries provide an overview of the manual and introduce its important concepts. To be useful for training, the summaries should be used in conjunction with the manual.

This summary covers the first sections of chapter 5. It briefly describes the properties of plastic concrete and how various properties should be optimized.

What are Plastic Concrete Properties?

Plastic concrete properties are those manifested from mix to setting. To successfully construct pavements that achieve all the desired properties, the designer, ready mix provider, contractor, and owner need to understand how their decisions can affect the many interrelated properties of the concrete system.

Plastic properties, such as uniformity, workability, segregation, bleeding, and setting, affect the ease of placement. Therefore, contractors need to control these properties by

- Maximizing uniformity.
- Maximizing workability.
- Minimizing segregation.
- Controlling bleeding.
- Controlling setting.

Early-age cracking can be highly influenced by controlling additional fresh concrete properties (see Technical Summary 5c):

- Optimizing strength gain.
- Understanding modulus of elasticity.
- Controlling temperature.
- Controlling shrinkage.

Optimizing Fresh Concrete Properties

See table 1 for plastic concrete properties test methods.

Maximizing Uniformity

Excellent uniformity means that concrete maintains consistent properties from batch to batch, even though the materials and processes are variable and the test results have scatter. Uniform concrete prevents the need for adjustments in the paver and helps create concrete that is consistently acceptable.

To ensure sufficient uniformity, take the following precautions:

- Minimize segregation in the aggregate stockpile (figure 1).
- Batch by mass rather than by volume.
- Follow mixer guidelines (such as loading capacity and speed).
- Inspect and maintain equipment regularly.

Figure 1. Good stockpile management is important for minimizing aggregate segregation (photo by American Concrete Pavement Association).

Table 1. Testing for Fresh Concrete Properties

Property	Methods	Comments
Uniformity	ASTM C 172 / AASHTO T 141	Ensure representative sample
Workability	Most common = Slump test Others = Compaction factor, Vebe, penetration, and rheology tests	No existing test directly and comprehensively measures workability.
Segregation	No standard test for segregation	Easily recognizable with visual inspection
Bleeding	ASTM C 232 / AASHTO T 158	Includes two test methods
Setting	ASTM C 403 / AASHTO T 197 Temperature or P-wave for initial set	Initial set occurs at 500 lb/in^2; final set occurs at 4000 lb/in^2
Temperature	ASTM C 186 ASTM C 1064 / AASHTO T 309 AASHTO TP 60	Heat of hydration Uses embedded sensors Coefficient of thermal expansion
Strength/ Strength Gain	ASTM C 39 / AASHTO T 22 ASTM C 42 / AASHTO T 24	Measures compressive strength of cylinders (mix design and acceptance testing). Measures cores extracted from the field (when disputes about ASTM C 39 data).
Shrinkage	ASTM C 157 / AASHTO T 160	Specimen size affects rate and magnitude.
Modulus of Elasticity	ASTM C 469 ASTM C 215	Dynamic modulus

Maximizing Workability

Workability refers to the ease of mixing, placing, consolidating, and finishing concrete. It can also serve as a rough measure of uniformity. While considered a fresh concrete property, good workability also benefits the hardened concrete system by allowing adequate consolidation, thus reducing concrete voids and contributing to strength.

To achieve good workability, follow these guidelines:

- Follow proper mix proportioning (especially regarding water content).
- Carefully select and proportion aggregates (with consideration given to gradation, particle size, texture, and porosity).
- Include supplementary cementitious materials (SCMs) with spherical shapes or glassy surfaces (such as fly ash and slag).
- Incorporate water-reducing admixtures.
- Do not exceed the established water-to-cementitious materials (w/cm) ratio.
- Ensure adequate air entrainment.

Evaporation rate and, thus, workability are also influenced by temperature and amount of time elapsed.

Minimizing Segregation

Segregation occurs when aggregate and mortar separate, causing some areas to have too little coarse aggregate and others to have too much (figure 2):

- Low-aggregate / high-paste zone—Increased shrinkage and cracking; poor abrasion resistance.
- High-aggregate / low-paste zone—High permeability; low strength.

To mitigate segregation, take the following actions:

- Increase the amount of fines.
- Ensure a well-graded system.

Controlling Bleeding

Bleeding refers to the water moving to the concrete surface due to the settlement of heavier solids. Although some bleeding reduces plastic shrinkage cracking, excessive bleeding has many negative effects (figure 3):

- Reduces strength, surface durability, and abrasion resistance.
- Delays finishing work (can cause blisters if prematurely sealed).
- Results in voids below steel and aggregate that can affect concrete strength or lead to corrosion.

To control bleed rate and total bleed amount, the following steps can be taken:

- Increase fines.
- Include air-entraining and water-reducing admixtures.
- Minimize w/cm ratio (higher ratio provides more water for potential bleeding).
- Account for the varying effects that different supplementary cementitious materials (SCMs) have on the total bleed volume and rate.

Controlling Setting

Setting is the transformation of concrete from a workable plastic to a solid. Initial and final setting times dictate the timing of saw cutting and finishing work.

To ensure timely setting of concrete, note how the following aspects influence set time:

- Temperature (affects setting speed and hydration).
- System chemistry (type of cement, cement content, w/cm ratio, and SCMs).
- Admixtures (provide accelerating or retarding effects; timing of addition may influence setting).

Figure 2. Segregated concrete (photo by Iowa Department of Transportation)

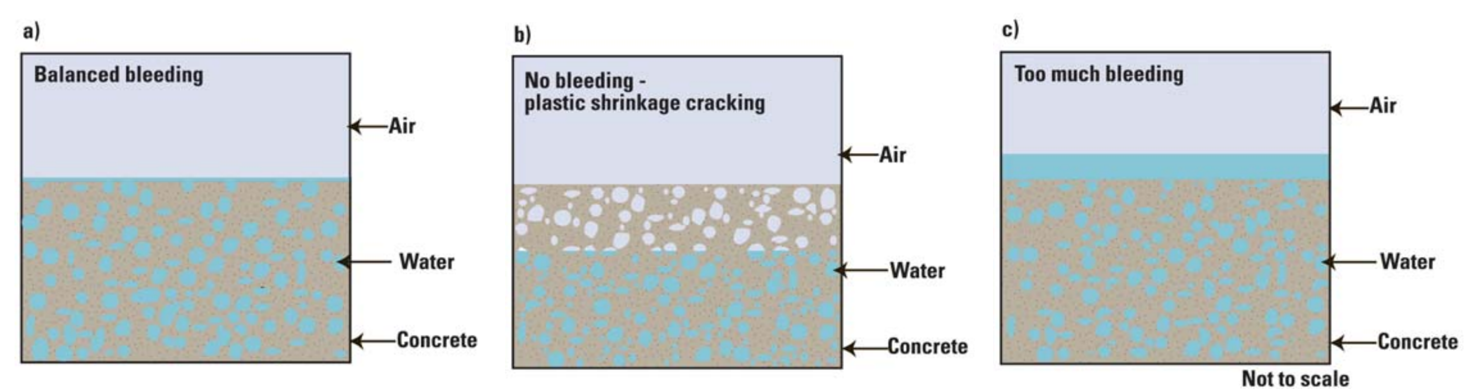

Figure 3. Bleeding

- Mixing (improved mixing accelerates hydration and setting).

Optimizing Strength Gain

Strength is a measure of concrete's ability to resist compressive and flexural stresses, a property that increases over time (strength gain).

Although often interpreted as an assessment of concrete quality, there is no direct correlation between strength and some other important quality characteristics, such as durability and abrasion resistance. However, strength gain can influence susceptibility to early-age cracking (see Technical Summary 5c).

Strength gain is primarily influenced by w/cm ratio and degree of hydration. To ensure maximum concrete strength, follow these recommendations:

- Keep w/cm ratio as low as possible.
- Ensure adequate compaction.
- Incorporate SCMs.

Understanding Modulus of Elasticity

The stiffness, or modulus of elasticity, indicates how much the hardened concrete moves under load. This value generally correlates with concrete strength (modulus of elasticity increases with compressive strength) and is used as an indicator of the risk of cracking.

The following factors affect modulus of elasticity:

- The aggregates' modulus of elasticity and proportions.
- The same factors that affect strength, such as w/cm ratio, kinds of cementitious materials, etc.

Controlling Temperature Effects

Concrete hydration generates heat, and the placement temperature of material affects the rate of hydration and, thus, strength gain. The hotter (and more expansive) the mix is