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Concrete Pavement Mixture Design and Analysis (MDA): Factors Influencing Drying Shrinkage

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Abstract

This literature review focuses on factors influencing drying shrinkage of concrete. Although the factors are normally interrelated, they can be categorized into three groups: paste quantity, paste quality, and other factors.

Keywords

Admixtures, Cement paste, Concrete pavements, Highways, Literature reviews, Mix design, Pavement design, Shrinkage, Mixture Design and Analysis, MDA, Paste quality, Paste quantity

Disciplines

Civil Engineering

Concrete Pavement Mixture Design and Analysis (MDA): Factors Influencing Drying Shrinkage

National Concrete Pavement
Technology Center



**Literature Review
October 2014**

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CONCRETE PAVEMENT MIXTURE DESIGN AND ANALYSIS (MDA): FACTORS INFLUENCING DRYING SHRINKAGE

**Literature Review
October 2014**

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INTRODUCTION

This literature review focuses on factors influencing drying shrinkage of concrete. Although the factors are normally interrelated, they can be categorized into three groups: paste quantity, paste quality, and other factors.

Mechanisms of Shrinkage

Concrete shrinkage can be separated into different forms, depending on the mechanisms causing it. These include plastic shrinkage, chemical shrinkage (autogenous shrinkage), and drying shrinkage (Tia et al. 2005). In addition, shrinkage can be considered over early and later ages that together contribute to the total shrinkage. Early age of shrinkage is normally defined as that occurring during the first day after batching, while long term refers to concrete at 24 hours and older.

Plastic Shrinkage

Plastic shrinkage occurs before setting due to moisture loss.

Chemical Shrinkage

Chemical shrinkage is also an early age behavior, especially in the first hour after mixing. It occurs because the volume of the hydrated system is lower than the volume of the ingredients. (Boivin et al. 1999, ACI 2005) This is exacerbated in low w/cm systems because desiccation of the pores can lead to significant volume reductions. Autogenous shrinkage is a subset of chemical shrinkage in that it is the amount of movement that can be measured in a given sample. The difference is because while shrinking, some internal voids open up in the microstructure, meaning that a length measurement across a dimension of a sample will indicate slightly less movement that has occurred.

Drying Shrinkage

Drying shrinkage is also due to moisture loss, but after setting. The differentiation is made between plastic and drying shrinkage because the form of cracking that occurs is different, and preventative actions are also different. American Concrete Institute (ACI) Committee 209 (2005) defined drying shrinkage as “Shrinkage occurring in a specimen that is exposed to the environment and allowed to dry is called drying shrinkage. For normal-strength concrete, it is usually assumed that the entire shrinkage strain is from drying shrinkage, and any contribution from autogenous shrinkage is neglected.” Drying shrinkage makes up a portion of the total deformation that can be observed in a concrete member.

Water Movement

All of these shrinkage mechanisms, then, are related to water movement. Water can exist in many forms—interlayer water, capillary water, and physically adsorbed water—in hydrated cement paste and is classified based on the ease with which it can be removed from the paste (Feldman and Serada 1970).

capillary voids are the voids not filled by solid hydration products, but are instead filled initially with excess unreacted water. Such voids will retain water by capillary tension. Water in the larger voids (>50 nm) is considered to be “free water” because its removal does not result in volume change. These voids are influential in determining the strength and impermeability characteristics of the mixture.

However, water in small capillary voids (5 to 50 nm) may play an important part in drying shrinkage when water is forced to leave the system (Malhotra and Mehta 1996). The size and volume of the capillary voids are controlled by the initial w/cm ratio and the degree of cement hydration. At a constant w/cm ratio, increasing the degree of hydration decreases the size and volume of the capillary voids. Subsequent drying, then, will result in reduced shrinkage strain (Malhotra and Mehta 1996).

Adsorbed water is the water bonded to but not reacted with the surface of hydration products. Water molecules are physically adsorbed onto the surface of solids in hydrated cement by the influence of attractive forces such as hydrogen bonding. The removal of adsorbed water will result in shrinkage strains, but such removal will not occur unless the relative humidity (RH) of the pore system is less than about 40% (Idiart 2009).

Interlayer water is the water held within the calcium silica hydrate (CSH) nanostructure. The water in the interlayer space of CSH voids is held by Van der Waals forces (Raki et al. 2010). Because of the extremely small size of the so-called gel pores, removal of interlayer water will only occur under very dry conditions (about 10% RH) (Malhotra and Mehta 1996, Idiart 2009). The size and volume of gel pores vary depending on the Ca/Si ratio, type of molecules (non-ionic, anionic, or cationic), concentration, and pH, while they are independent of the initial w/cm ratio and degree of hydration (Raki 2010, Selvam et al. 2009). Therefore, increasing the Ca/Si ratio may decrease the size and volume of gel pores and so increase resistance to water removal (Taylor 1997).

The predominant drying shrinkage mechanisms, therefore, are driven by moisture transport within the porous solid combined with surface tension (Khatri et al. 1995).

Capillary tension is a well-documented drying shrinkage mechanism in drying porous media. Tensile stresses in the capillary water in the high RH range (up to approximately 50% RH) are subjected to capillary tension. These tensile stresses bring up elastic shrinkage strains in small capillaries (5 to 50 nm) (Malhotra and Mehta 1996, Idiart 2009)

Surface tension is another important mechanism for adsorbed water removal. Due to lack of symmetry of molecules lying on the surface of the material, a resultant force perpendicular to the surface that provokes contraction is referred as surface tension. It is suggested that this mechanism is only valid in the low RH regime (up to 40% RH) (Idiart 2009).

Another mechanism, movement of interlayer water, is attributed to the layered structure of the CSH. This phenomenon may migrate the interlayer water out of the CSH sheets when RH drops below 10%, yielding a considerable shrinkage (Idiart 2009).

FACTORS AFFECTING SHRINKAGE

The following factors are reported to contribute to the degree of shrinkage in a mixture. The factors have been categorized in terms of the quantity of the paste and the quality of the paste, primarily because it is the paste in the system that is subject to moisture-related movement and aggregates tend to be dimensionally stable.

Paste Quantity

At a given w/cm ratio, drying shrinkage almost linearly increases with higher paste content/volume in a concrete mixture (Pickett 1956, Bissonnette et al. 1999, Hooton 2000, Darwin et al. 2004, Roziere et al. 2007, Hale et al. 2008, Wang 2011, Wang et al. 2012).

Paste Quality

The quality of paste may be considered to include the parameters that are based on the composition and amounts of ingredients, including cementitious materials, w/cm, and admixtures.

Cement Chemistry

It has been generally concluded that the composition of cement can affect drying shrinkage (Cement Concrete and Aggregates Australia 2002). The C₃A and alkali content have been evidenced to have a dominant effect on shrinkage behavior, i.e., higher C₃A and alkali content increase shrinkage (Nakajo et al. 1950, Hamada and Hujimatsu 1958, Roper 1974).

Some specifications in Australia specify limits on the chemical composition of cement as a means to control shrinkage of concretes in field applications. These specifications require a maximum C₃A content of 7% and a minimum SO₃ content of 1.8% (Cement Concrete and Aggregates Australia 2002).

Lower sulfate content will increase shrinkage. In turn, shrinkage of cements of the same C₃A content differs for different gypsum content; therefore, shrinkage is influenced as well (Pickett 1947). It is possible to reduce the drying shrinkage by increasing the gypsum content in cement (Tsuruta et al. 2004).

Cement Fineness

The rate of hydration of portland cement depends on the surface area of the clinker particles, with increasing fineness leading to more rapid strength gain. On the other hand, a finer pore structure leads to a higher early age shrinkage (Bennett and Loat 1970). Research has indicated that, for given w/cm and aggregate-cement ratios, finer cement results in an increase in drying shrinkage. It was attributed to the higher water demand of finer cements with equal workability,

which resulted in increased shrinkage. The greater water requirement of the finest cement resulted in about 200×10^{-6} greater strain at the same workability level (Vebe time of 7 seconds) (Bennett and Loat 1970).

Supplementary Cementitious Material Types

In modern concrete, different supplementary cementitious materials (SCMs) are often used to improve the performance of the mixture. Theoretically, one might expect an increase in drying shrinkage due to the increased proportion of CSH and the finer pore structure (Mindess et al. 2003). However, the findings from various studies are mixed, as discussed below.

Fly Ash

ACI Committee 232 (2005) on the use of fly ash in concrete reported that shrinkage may be increased slightly with the addition of fly ash with a constant water content. This finding is attributed to the increased paste volume in a concrete mix. Meanwhile, if the water content is reduced, shrinkage should be about comparable to concrete without fly ash. Class F fly ash used in binary mixtures may reduce drying shrinkage with increasing replacement dosages compared to plain portland cement concrete. However, Class C fly ash has reportedly caused more shrinkage than control concrete mixtures in most cases, most likely due to its low alkali contents and higher Ca/Si ratios (Deshpande et al. 2007).

A decrease in drying shrinkage from using fly ash was reported by Atis (2003). A low-calcium Class F fly ash was used to replace ordinary cement by 50% and 70% by mass. In order to maintain the same workability, the actual w/cm ratios for the fly ash mixtures were less than those for the control mixtures. Also, the paste volume in fly ash mixes was a little higher (27.3% in 50% fly ash mixture and 26.9% in 70% fly ash mixture as compared to 25.9% in the control mixture) due to varied specific gravity. After curing in the same condition, significantly lower shrinkage was observed for the high-volume fly ash concrete than for the control concrete at the first day. At an age of six months, the 70% fly ash mixture showed the lowest shrinkage compared to the control mixture.

Gesoğlu et al. (2009) replaced portland cement with Class F fly ash at dosages of 20%, 40%, and 60%. It was observed that drying shrinkage was reduced by using Class F fly ash, and this beneficial effect appeared to be more pronounced with increasing replacement levels. A similar conclusion was drawn in another investigation of fine Class F fly ash effects on shrinkage (Haque and Kayali 1998).

Slag Cement

ACI Committee 233 (2000) on use of slag cement in concrete and mortars reported that shrinkage is reduced when lower paste contents are used with slag mixes. The committee stated that published data on the effects of slag on shrinkage indicated conflicting results, and, overall,

drying shrinkage was comparable in portland cement concrete and concrete mixtures containing slag cement.

Gesoğlu et al. (2009) concluded that the shrinkage decreased with increased amounts of slag cement, while Collins and Sanjayan (2000) stated that alkali-activated slag concrete had higher drying shrinkage than plain concrete by 1.6 to 2.1 times. Similarly, Khatri et al. (1995) also found that the drying shrinkage values of all slag mixtures were higher than those for the mixes prepared from ordinary cement. Deshpande et al. (2007) studied a 30% volume replacement of portland cement by slag cement without changing the water or aggregate content in concrete. An increased early age shrinkage was observed, although the ultimate shrinkage did not appear to be significantly affected. In order to assess the influence of slag cement on drying shrinkage behavior, the Slag Cement Association (SCA) conducted a critical review based on published shrinkage research. They concluded that for a similar mixture, slag cement appears to have a marginal effect on increasing drying shrinkage.

Silica Fume

For binary blends of portland cement and silica fume, ACI Committee 234 (1995) on the use of silica fume in concrete reported that shrinkage in mixtures containing silica fume is generally comparable to that of portland cement concrete, but slightly higher shrinkage may be expected at early ages for mixtures with a w/cm ratio of more than 0.60 and for concrete containing more than 10% silica fume dosage.

Khatri et al. (1995) reported an increase in early age shrinkage for concrete containing silica fume compared to the control mixture, but long-term shrinkage was less for the concrete using silica fume. Alsayed (1998) monitored the drying shrinkage of silica fume concrete for three years subjected to controlled laboratory or hot-dry field conditions. The author similarly concluded that 10% silica fume greatly reduces the three-year drying shrinkage, the stress due to shrinkage strain, and the rate of first-month drying shrinkage of concrete. In addition, adding 10% of cement weight as silica fume to a concrete mix greatly reduces the influence of curing conditions on the rate of drying shrinkage.

Silica fume concrete had lower shrinkage than normal portland cement concrete with the same w/cm ratio but marginally lower binder content (Tazawa and Yonekura 1986). The lower drying shrinkage of silica fume concrete could be attributed to the lower w/cm ratio used in the study (Khatri et al. 1995).

However, Rao (2000) conducted a project on shrinkage behavior with silica fume replacement rates from 0% to 30% by weight. A constant w/cm ratio of 0.5 and cementitious material to sand ratio of 1 to 3 by mass were used. The results indicated a significant increase in shrinkage with the use of silica fume, which further increased with the replacement dosage of silica fume. The author concluded that the addition of silica fume increases the content of C-S-H, which is an important factor causing shrinkage at an age of 28 days. Whiting et al. (2000) studied the effects of silica fume on drying shrinkage and the cracking tendency of concrete bridge decks. They

recommended a silica fume dosage of less than 8% unless demanded by the situation but did not give clear justification.

The drying shrinkage of silica fume–incorporated concrete was 10% to 22% higher than that of ordinary portland cement with the same w/cm ratio and same binder content for the short term (Hooton 1993).

Ternary Mixtures

For ternary blends of portland cement, slag cement, and silica fume, the adverse effect of the silica fume on the early age was reduced, and the shrinkage values compared to the control mixture were reduced (Gesoglu et al. 2009). It was reported that drying shrinkage was caused by the removal of adsorbed water, and the addition of silica fume to slag cement concrete refined the pore size distribution of the cement paste (Khatri et al. 1995).

For ternary blends of portland cement, slag cement, and Class F fly ash, reduced shrinkage can be observed when using 10% slag cement and 10% Class F fly ash, 20% slag cement and 20% Class F fly ash, and 30% slag cement and 30% Class F fly ash (Gesoglu et al. 2009).

A study by Wang et al. (2012) focused on the drying shrinkage behavior of mortars made with ternary blends. The amounts of slag cement, fly ash, and silica fume ranged from 15% to 35%, 13% to 30%, and 3% to 10% by mass of cementitious materials, respectively. The analysis from statistical models indicated that slag cement has a dominant effect on increasing mortar shrinkage for a ternary blend system. The contribution of Class C fly ash to the shrinkage was slightly less than that of slag. An increase in silica fume or in Class F fly ash content slightly increased drying shrinkage.

Water to Cementitious Material Ratio

Hindy et al. (1994) investigated the effects of w/cm ratio, curing time, and silica fume content on concrete shrinkage. According to the authors, “an increase in the w/cm ratio increases the total drying shrinkage and the rate of shrinkage of the cement paste by providing more space for free water diffusion and reducing the rigidity of the solid matrix to resist deformation.” Concrete with a low w/cm ratio was found to be less susceptible to expansion. However, this study varied the w/cm ratio by reducing the water content and increasing the cementitious material content, yielding a change of paste volume, which may have a more significant effect on shrinkage.

There are contradictory conclusions from other researchers. Bissonnette et al. (1999) found that the w/cm ratio effects on shrinkage were relatively small. An average reduction in shrinkage for w/cm ratios from 0.35 to over 0.50 was only 7% to 10% for a given paste content. No clear trend of w/cm effects on shrinkage was observed in the study by Bloom and Bentur (1995). Concrete with a 0.5 w/cm ratio showed the highest shrinkage, the 0.4 w/cm concrete showed the lowest, and the 0.33 w/cm concrete was in between. Deshpande et al. (2007) concluded that no clear effect of w/cm ratio on shrinkage was observed.

Superplasticizers

ACI Committee 212 (2010) reported that superplasticizers may increase concrete drying shrinkage with a given w/cm ratio and cement content. Less shrinkage may be expected when there is a simultaneous reduction in cement content and w/cm ratio.

Phelan and Martin (1995) proposed different opinions regarding the effect of superplasticizers on shrinkage. Phelan stated that a good superplasticizer can reduce the water content of concrete by 10% to 18%, and this reduction in water will lead to reduced shrinkage. However, Martin, one of the authors in the same article, argued that many chemical admixtures will indeed reduce the mix-water content but will not reduce the shrinkage. Similar results were shown in other references (Whiting 1979, Rixom and Waddicor 1981, Gebler 1982).

Most researchers have found that drying shrinkage increases when water reducer agent dosage increases regardless of the curing conditions (Alsayed 1998, Kosmatka et al. 2002). However, Qi et al. (2002) reported a reduction in drying shrinkage with the use of high superplasticizer contents. The authors explained that the action of high-range water reducers mainly derives from better particle dispersion as admixture is adsorbed on the cement particles, leading to a reduction in the surface tension of water and yielding a lower capillary pressure.

Johnston et al. (1979) investigated the effects of four types of superplasticizers on fresh and hardened concrete properties. The superplasticizers were used to reduce the cement content while maintaining the w/cm ratio at 0.5 with constant workability. The authors concluded that melamine formaldehyde condensate and high-molecular weight sulfoaryl alkylene had little effect on drying shrinkage, but sulfonated polymer and polymerized naphthalene condensate increased shrinkage. It should be noted that the results could have been significantly affected by varied paste contents, which was not mentioned by the authors.

As concluded in a study by Alsayed (1998), replacing superplasticizer with plasticizer increases the three-year drying shrinkage, the stress due to shrinkage strain, and the rate of the first-month drying shrinkage of concrete cured under controlled laboratory or hot-dry field conditions.

Shrinkage-Reducing Admixtures

Shrinkage-reducing admixtures (SRAs) have been shown to reduce drying shrinkage of concrete (Sato et al. 1983, Shah et al. 1992, Ai and Young 1997, Berke et al. 1997, Brooks and Jiang 1997, Folliard and Berke 1997, Weiss and Shaw 1997, Nmai et al. 1998, Shah et al. 1998, Weiss et al. 1999, Bentz et al. 2001, D'Ambrosia et al. 2001).

SRAs function by reducing capillary tension of pore water, which is a primary cause of drying shrinkage, resulting in a reduced loss of concrete volume (Ai and Young 1997, Berke et al. 1997, Bentz et al. 2001). Shah et al. (1992) and Weiss et al. (1999) stated that the reduced shrinkage of mixtures containing SRAs can also increase the time to cracking for mixtures and reduce the corresponding crack width. The addition of SRAs has shown to reduce the pore size distribution

as measured by a mercury intrusion porosimeter (Shah et al. 1992), but contradictory results were reported by Ai and Young (1997).

OTHER FACTORS

Aggregate

The volume, type, gradation, texture, and fines content of aggregate are other factors that affect the shrinkage of concrete. Aggregates restrain the shrinkage of cement paste; therefore, an increase in aggregate volume and the commensurate reduction in the volume of paste should result in a reduction in shrinkage (Deshpande et al. 2007).

Type

Different types of coarse aggregate, including quartzite, limestone, dolomite, granite, and feldspar along with several types of natural sand and gravel, have been evaluated (Calson 1938). Due to the physical nature of the aggregate itself, some aggregates required more mixing water than others to reach a 3 in. slump. The texture of the aggregates was found to be a critical factor in drying shrinkage: natural sands and gravel, including sandstone and dolomite pebbles, had higher shrinkage than crushed aggregates, such as granite, limestone, and quartz. Among the crushed aggregates, shrinkage was higher for concretes containing aggregates with higher absorptions.

By studying the effects of 23 aggregates types, Alexander (1996) found that the aggregate influenced shrinkage in two ways: through the mixing water demand and the stiffness of the aggregates. The paste content of a given mix for a given strength grade could be decided by the mixing water demand, and aggregates with more water demand tended to have higher shrinkage. The author controlled the paste volume by using Pickett's equation (1) (Pickett 1956) to normalize the measured shrinkage values, which were affected by varied aggregate types.

$$\frac{S_{c1}}{S_{c2}} = \left[\frac{V_{p1}}{V_{p2}} \right]^{1.5} \quad (1)$$

where S_c is the shrinkage of concrete and V_p is the volume fraction of paste. The subscript 2 is a mean paste volume, and each individual result is normalized to the mean paste volume. It was found that concretes containing higher elastic modulus aggregate exhibit lower shrinkage.

Meininger (1966) reported that the source of coarse aggregate may effect concrete shrinkage. The shrinkage measured on test prisms ranged from 5.3% for quartz gravel to 9.9% for a sandstone-greywacke gravel at 182 days.

Gradation

The gradation, maximum size, shape, and texture of aggregate seem to indirectly affect shrinkage. In practice, any variations in these properties can lead to a change in the water demand and/or paste content, both of which directly affect the drying shrinkage (Cement Concrete and Aggregates Australia 2002). Increasing the size of aggregate while decreasing the paste content will decrease the drying shrinkage (ACI 209 2005).

Fines

Aggregate can be contaminated by other fines, such as silt, clay, coal, or organic matter. Most of these fine materials increase the shrinkage, especially in cases where the clay absorbs moisture and causes considerable shrinkage during the drying process. Clays, such as illite and kaolinite with a stable lattice, may be present in some aggregates, and these will cause large moisture related movements in concrete (Grieve 2001). Some specifications set maximum limits on the fine materials content, and this can be achieved by washing the aggregate (Cement Concrete and Aggregates Australia 2002). Also, some tests, such as Methylene Blue Index test, used as an indicator of clay content in fine aggregate, were demonstrated to be linearly correlated to shrinkage (Wang et al. 2012).

Air Content

As long as the air content is less than 8%, there is no significant effect on the magnitude of drying shrinkage (Davis and Troxell 1954).

Curing

An extended curing period will normally reduce drying shrinkage by 10% to 20% (Perenchio 1997). Powers (1959) stated that prolonging the curing period reduces the amount of unhydrated cement, which partly restrains the cement paste. This restraint is supposed to increase the amount of shrinkage in cement paste. However, the overall shrinkage might be diminished by prolonged moist curing because it makes the paste more prone to internal cracks when severely restrained, and if the cracking relieves the stress around the aggregate, overall shrinkage might thus be reduced.

Four curing methods were studied to assess their influence on drying shrinkage of concrete (Alsayed and Amjad 1994): sprinkling with water twice a day, covering with burlap and sprinkling with water twice a day, covering with an impervious polyethylene sheet, and exposing to air without curing. The conclusion was drawn that the intermittent wet curing reduces the ultimate shrinkage of concrete and increases the exposure time needed to develop it, but none of these methods can effectively reduce the rate of shrinkage development at an early age (less than 30 days) of curing. Another three curing methods, air curing, air curing after coating with a curing compound, and moist curing with wet burlap, were evaluated by Nassif et al. (2003). The shrinkage of concrete mixtures cured in the air was the highest, followed by the specimens

coated with the curing compound, and then the burlap-wrapped specimens. The authors concluded that an effective curing method could dramatically reduce shrinkage. Klieger (1960) showed that heat and steam curing can reduce drying shrinkage by as much as 30%. One explanation is that most of the water released during the chemical reaction may evaporate during the curing process, and the remaining amount of water contained in the micro-pores of the hardened concrete is small (Wallah 2009).

The concept of internal curing to improve mixture properties, including reduced shrinkage, was first proposed by Philleo (1991). It is achieved by including some fine lightweight aggregate (LWA) in concrete mixtures that provide curing water throughout the system. Materials normally used for internal curing purposes include LWA, super-absorbent polymers (SAPs), perlite, and wood pulp. Internally cured concrete has been shown to exhibit reduced shrinkage under drying conditions (Jensen and Hansen 1995, Maruyama and Sato 2005) and when autogenous shrinkage is a concern (Schwesinger and Sickert 2000, Mechtcherine et al. 2006).

Environment and Construction Practice

Relative humidity around concrete can increase shrinkage dramatically, especially when the relative humidity is lower than 10%. It is agreed that the interlayer water may migrate out of CSH sheets to reduce the distance between these layers, causing macroscopic shrinkage strain (Malhotra and Mehta 1996).

Generally, higher relative humidity yields a lower shrinkage of concrete mixtures because it slows the relative rate of moisture flow from the interior to the outer surfaces of the concrete (Mehta and Monteiro 2006). Higher ambient temperature and wind velocity can accelerate the hydration process and moisture loss, yielding a higher shrinkage (Malhotra and Mehta 1996, Neville 1998).

SUMMARY AND CLOSING

A summary table (Table 1) is provided to give a general sense of the factors influencing concrete shrinkage.

In summary, factors that appear to influence shrinkage of a given element include the following:

- Paste content of the mixture
- SCM selection and dosage
- Aggregate quality, in particular the clay content
- Admixture type and dosage
- The environment to which the concrete is exposed

Table 1. Summary of influence factors on concrete shrinkage

Categories	Factors	Specific factors	General findings and conclusions on shrinkage
Paste quality	Cement characteristics	Chemistry	Higher sulfate and gypsum content may reduce shrinkage
		Fineness	Through change of the rate of hydration and water demand, finer cement leads to higher shrinkage
	Supplementary cementitious material	Fly ash	Class F fly ash potentially decreases shrinkage; Class C fly ash increases shrinkage with increasing dosage
		Slag cement	Conflicting results, depending on paste content; overall, comparable to ordinary PCC mixtures
		Silica fume	Conflicting results; depending on w/cm, curing period, and paste content; limited replacement may reduce long-term shrinkage
		Ternary mixtures	Normally, adverse effect can be diminished (i.e., PC+slag cement+silica fume) or even reduced (i.e., PC + slag cement + F fly ash)
	Chemical admixtures	Superplasticizers	May increase concrete shrinkage with a given w/cm ratio and cement content; dependent on admixture chemistry
Air content		No significant effect on the magnitude of drying shrinkage if it is less than 8%	
Paste quantity	w/cm		Influence is relatively small with a constant paste content for w/cm > 0.40
	Paste content		For a given w/cm ratio, shrinkage linearly increases with increasing paste content/volume
Other factors	Aggregate	Type	Influenced by mixing water demand and the stiffness of the aggregate
		Gradation	Indirect influence through the change of water demand and paste content; increased size results in decreased paste content, so decreased shrinkage
		Fines	Most fines increase shrinkage
	Curing	Duration	Increasing curing period reduces the amount of unhydrated cement, resulting in reduced overall shrinkage
	Environment	Relative humidity	Higher relative humidity leads to lower shrinkage
		Temperature	High temperatures accelerate moisture loss leading to higher shrinkage
		Wind	Similar to temperature effect
	Construction		Improper addition of water during finishing, and poor curing will increase shrinkage
Geometry		Increasing the volume-to-surface area ratio decreases shrinkage	

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