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Concrete Technology in Focus

Shrinkage of Concrete

Introduction

Concrete continues to be the most widely used construction material in the world because of the ease with which it can be formed into a variety of shapes and sizes, its potential durability and its relatively low cost. Also contributing to the popularity of concrete as a construction material is the ready availability of its most basic constituents, namely, portland cement, aggregates, water and admixtures.

The need for adequate workability to facilitate placement and consolidation of concrete often necessitates the use of a greater amount of mixing water than is needed for the hydration process (reaction with portland cement). The loss of some of this excess "water of convenience" from a concrete matrix as it hardens results in a volume reduction that is known as shrinkage. If the volume reduction occurs before the concrete hardens, it is called plastic shrinkage. The volume reduction that occurs primarily due to moisture loss after the concrete has hardened is known as drying shrinkage.

In addition to drying shrinkage, hardened concrete can also experience volume reductions such as thermal contraction, autogenous shrinkage and carbonation shrinkage. Due to the hydration process, the temperature of fresh concrete in the hours after batching is often higher than the ambient temperature. The magnitude of the temperature rise is dependent on, among other things, the type and amount of cement used, the use of pozzolans or slag cements, the size of the concrete member, and the ambient temperature. As the hot concrete cools to the ambient temperature, it contracts and it is this volume reduction that is referred to as thermal contraction.

Autogenous shrinkage occurs as a result of the chemical reactions that take place during cement hydration. It can be significant in concrete with a very low water-cementitious materials ratio. It is possible for such concrete to shrink without the loss of any water to the environment. Fortunately, the magnitude of autogenous shrinkage is not significant in the majority of concrete placed where shrinkage is a concern.

As implied by the name, carbonation shrinkage occurs when concrete becomes carbonated, that is, when the calcium hydroxide in the hardened matrix reacts chemically with carbon dioxide present in the atmosphere. This leads to the formation of calcium carbonate and water and, consequently, a reduction in volume.

The major concern with regard to the shrinkage of concrete is the potential for cracking either in the plastic or the hardened state. In most situations, the likelihood of plastic and drying shrinkage is often greater than that of the other types of shrinkage mentioned above. Therefore, further details on the mechanisms by which these two types of shrinkage occur and the influences of concrete mixture ingredients, ambient conditions, design and construction practices are presented in the sections that follow.

Effects of Environmental Factors and Time

As mentioned earlier, the loss of moisture from hardened concrete, and hence drying shrinkage, is inevitable unless the concrete is in an environment with 100 percent relative humidity. This scenario of course is rarely the case unless the concrete is completely submerged in water.

The magnitude of drying shrinkage is greatly affected by the relative humidity of the surrounding environment. The lower the relative humidity, the higher the magnitude of drying shrinkage. The magnitude of drying shrinkage is, however, not influenced by the rate of drying. The rate of drying is in turn not affected by wind or forced convection except during the early stages of exposure. This is because of the very low moisture conductivity of concrete that allows for only a very small rate of evaporation.

The magnitude of drying shrinkage is also time dependent. Though the bulk of drying shrinkage occurs within the first few months of drying, the process continues for years. Data from a comprehensive study spanning a period of nearly 30 years showed that, on average, nearly 50 percent of the drying shrinkage obtained at 20 years occurred within the first 2 months of drying, and nearly 80 percent within the first year [15].

Effects of Shrinkage

As stated earlier, the major concern with regard to the shrinkage of concrete is the potential for cracking. Other potential issues are curling of slabs, dimensional stability of concrete members and loss of prestress in prestressing applications. Dimensional stability and loss of prestress are typically taken into consideration during design, and unless the actual shrinkage far exceeds the design value, there should be no problems.

Cracking due to shrinkage occurs mainly because of restraint. The restraint can be externally applied as with a bonded overlay or due to internal factors, such as reinforcement or nonuniform shrinkage within the thickness of the concrete member. Concrete that is unrestrained, for example a 4 x 8 in. (100 x 200 mm) cylinder, will not crack due to shrinkage. The modulus of elasticity and creep characteristics of concrete also affect its cracking tendency.

The mechanism by which cracking occurs is quite simple. In a given environment, concrete that is unrestrained has the potential to shrink a given amount. If all or a portion of that shrinkage is restrained, tensile stresses will develop. When the induced tensile stresses exceed the tensile strength of the concrete, cracking occurs. Cracks provide easy access for oxygen, moisture, chlorides and other aggressive chemicals into the matrix, and can therefore impact the long-term durability of concrete. In this regard, the width and orientation of the crack become important factors.

Curling is the uplifting of a slab at its edges. It is caused by differential shrinkage between the top surface and the bottom of the slab due to moisture and temperature changes. In addition to being unsightly, the potential for cracking due to traffic loads, and in some instances the self-weight of the slab, is created. Curling can be reduced or eliminated by minimizing moisture and temperature related volume change differentials within a slab. Therefore, among other things, techniques that lead to a reduction of drying shrinkage are desirable.

Recommendations

Shrinkage of concrete, in particular drying shrinkage, is inevitable; and because of restraint, cracking can occur. However, with good concreting and construction practices, shrinkage and subsequent cracking can be minimized.

To control plastic shrinkage, the surface of fresh concrete should be prevented from drying out until finishing operations have been completed, and curing initiated. The use of ice or chilled water to reduce the batched concrete temperature and MasterFiber polypropylene fibers can be beneficial. Temporary windbreaks should be erected on windy days, if possible, to reduce wind velocity. To reduce concrete surface temperatures, temporary sunshades may be used. In arid regions where conditions for plastic shrinkage are prevalent, the use of accelerating admixtures and MasterKure ER 50 evaporation reducer should be considered.

To minimize drying shrinkage, the total water content of the concrete mixture must be kept as low as is practically possible for the intended application. This can be achieved by using a high content of hard, rigid aggregates that are free of clay coatings, and by using mid-range or high-range water-reducing admixtures. In addition, the concrete should not be retempered at the jobsite.

Use of a shrinkage-reducing admixture or a crack-reducing admixture will reduce the drying shrinkage and the rate of drying shrinkage of concrete. In addition, their use will improve cracking resistance, reduce curling heights and rate of curling, and reduce joint opening and rate of joint opening. As stated earlier, MasterLife CRA 007 crack-reducing admixture also provides better performance under restrained shrinkage.

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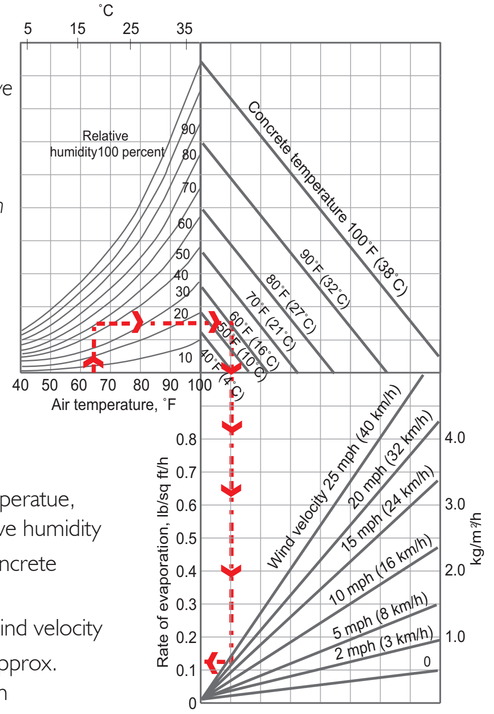
Plastic Shrinkage

Loss of water from fresh concrete, which leads to plastic shrinkage, can occur in a couple of ways. The predominant mode is, however, through evaporation from an exposed surface. Concrete can also lose water through suction by the subbase or, depending on the type of material used in its manufacture, the formwork. Such loss of water can aggravate the effects of surface evaporation. It is generally accepted that the loss of water from the paste fraction of concrete due to external factors generates negative capillary pressures that cause the volume of the paste to contract, hence the shrinkage.

The rate of water evaporation is usually aggravated by a combination of high wind speed, low relative humidity, and high ambient and concrete temperatures. Though these conditions are most likely during the summer months, they can occur at any time. The rate at which bleed water is transported to the concrete surface will impact the potential for the phenomenon or form of cracking commonly referred to as plastic shrinkage cracking. It has been reported that if the rate of surface evaporation exceeds about 0.1 lb/ft²/h (0.5 kg/ m²/h), the loss of moisture may exceed the rate at which bleed water reaches the surface, thereby setting into motion the mechanisms that cause plastic shrinkage [1].

FIGURE 1. *Effect of Concrete and Air Temperatures, Relative Humidity, and Wind Velocity on the Rate of Evaporation of Surface Moisture from Concrete [1].*



To use this chart:

1. Enter with air temperatue, move **up** to relative humidity
2. Move **right** to concrete temperature
3. Move **down** to wind velocity
4. Move **left**; read approx. rate of evaporation

In ACI 305R [2], it is recommended that precautions against plastic shrinkage cracking should be taken if the evaporation rate from the exposed concrete surface is expected to approach 0.2 lb/ft²/h (1.0 kg/ m²/h). The evaporation rate for a prevailing ambient condition can be estimated by using the nomograph shown in Fig. 1.

Precautionary measures to control plastic shrinkage include adjustments to the concrete mixture and the use of proven construction techniques. Reducing the temperature of a concrete mixture, particularly in hot weather, or increasing its rate of setting can be beneficial. The latter is one of the primary reasons why accelerating admixtures, such as MasterSet® FP 20 (formerly Pozzutec 20+) admixture, are increasingly being used in the arid Southwest Regions, where conditions for plastic shrinkage are prevalent. The use of microsynthetic fibers, such as MasterFiber® M or F series, has also been reported to be beneficial in controlling plastic shrinkage cracking.

Effective construction practices to control plastic shrinkage include the use of temporary windbreaks and sunshades to reduce wind velocity and concrete surface temperatures, respectively, and placing concrete at the coolest time of the day. But by far, the most effective control method is to prevent the concrete surface from drying out until finishing operations have been completed and curing initiated. The use of an evaporation reducer such as MasterKure® ER 50 (formerly Confilm), temporary wet coverings, waterproof sheeting or a fog spray can be beneficial in this regard.

Drying Shrinkage

The loss of moisture from concrete after it hardens, and hence drying shrinkage, is inevitable unless the concrete is completely submerged in water or is in an environment with 100 percent relative humidity. Thus, drying shrinkage is a phenomenon that routinely occurs and merits careful consideration in the design and construction of concrete structures.

The actual mechanisms by which drying shrinkage occurs are complex, but it is generally agreed upon that they involve the loss of adsorbed water from the hydrated cement paste [3-5]. When concrete is initially exposed to a drying condition – one in which there is a difference between the relative humidity of the environment and that of the concrete – it first loses free water. In the larger capillary pores this results in little or no shrinkage. In the finer water-filled capillary pores (2.5 to 50 nm size) due to loss of moisture, curved menisci are formed, and the surface tension of water pulls the walls of the pores. Thus, internal negative pressure develops when the meniscus forms in the capillary pores. This pressure results in a compressive force that leads to shrinkage of concrete. Continued drying also leads to the loss of adsorbed water, a change in the volume of unrestrained cement paste and an increase in the attraction forces between the C-S-H hydration products that leads to shrinkage [5]. The thickness of the adsorbed water layer has been reported to increase with increasing humidity [5]. Therefore, it is conceivable that a higher water content would lead to a thicker layer of adsorbed water, and hence, more drying shrinkage.

The drying shrinkage of concrete can be determined in the laboratory by using ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" [6], and it is usually expressed as a percent or in millionths (x 10^{-6}).

Physically, concrete that experiences a drying shrinkage of about 0.05 percent (500 millionths or 500 x 10^{-6}) will shrink approximately 0.6 in. per 100 ft (50 mm for every 100 m). In more graphic terms, that is about two inches for the length of a football field.

There are several factors that affect drying shrinkage. These include the characteristics of the concrete mixture ingredients and their proportions, design and construction practices, and environmental influences.

Effects of Concrete Mixture Ingredients

There are conflicting data in the literature on the effects of concrete mixture ingredients on its drying shrinkage. However, without question the constituents of a concrete mixture that influence drying shrinkage the most are the water and the coarse aggregate, because both have a profound effect on minimizing the paste content.

Graphical data from Reference 7 for a large number of concrete mixtures with various proportions are replotted in Fig. 2 to illustrate the effect of total water content on drying shrinkage. The data show that the total water content of a concrete mixture has a significant effect on its drying shrinkage. For example, assume that a concrete mixture has a cement factor of 708 lb/yd³ (420 kg/m³) and a water-cement ratio of 0.45 – that is, a water content of about 320 lb/yd³ (190 kg/m³). **The figure shows that, on average, this concrete will have a drying shrinkage of about 0.06 percent and that this shrinkage value can be reduced by 50 percent by reducing the water content to 244 lb/yd³ (145 kg/m³), which translates into a water-cement ratio of 0.35.** Therefore, to minimize the drying shrinkage of concrete the total water content must be kept as low as is practically possible.

Contrary to common belief that shrinkage increases with cement content, data complied in Reference 7 for concretes with cement contents ranging from 470 to 750 lb/yd³ (280 to 445 kg/m³) showed that cement content had little effect on concrete shrinkage. The total water contents for these mixtures range from 338 to 355 lb/yd³ (200 to 210 kg/m³) and slumps were between 3 and 4 in. (75 and 100 mm).

For practical purposes, the type, composition and fineness of cement have also been found to have relatively little effect on drying shrinkage.

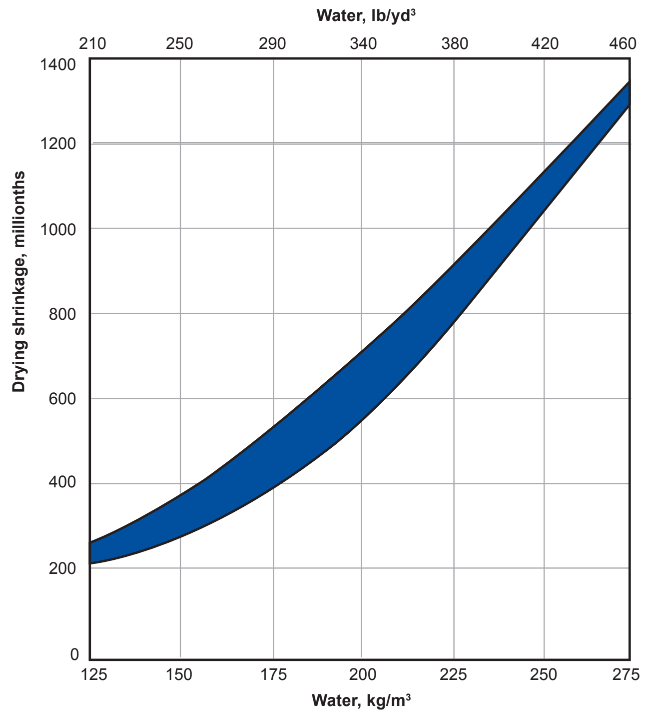


FIGURE 2. *Effect of Total Water Content on Drying Shrinkage [7]. (Shaded area represents data from a large number of mixtures of various proportions.)*

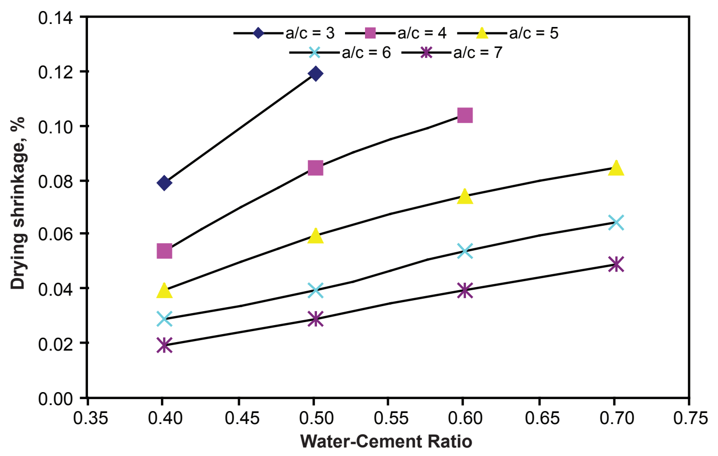


FIGURE 3. *Effect of Aggregate-Cement Ratio (a/c) and Water-Cement Ratio on Drying Shrinkage [8]. [Data from 5 in. (125 mm) square mortar and concrete specimens exposed to a 70 °F (21 °C), 50 percent relative humidity environment for six months.]*

The effect of coarse aggregate on drying shrinkage is twofold. First, the use of a high coarse aggregate content will minimize the total water and paste contents of the concrete mixture and, therefore, drying shrinkage. The effects of aggregate-cement ratio and water-cement ratio on drying shrinkage are illustrated in Fig. 3. The figure clearly shows that, at a given water-cement ratio, drying shrinkage is reduced as the aggregate-cement ratio is increased. For example, at a water-cement ratio of 0.40, a 50 percent reduction in drying shrinkage was obtained when the aggregate-cement ratio was increased from 3 to 5 (and also from 5 to 7).

Second, drying shrinkage of the cement paste is reduced by coarse aggregate because of its restraining influence. As to be expected, the amount of restraint provided by the coarse aggregate is dependent on the type of aggregate and its stiffness, the total amount of the aggregate used and the topsize. Hard, rigid aggregates, such as dolomite, feldspar, granite, limestone and quartz, are difficult to compress and will provide more restraint to the shrinkage of the cement paste. These aggregates should therefore be used to produce concrete with low drying shrinkage.

The use of sandstone and slate should be avoided if low drying shrinkage is desired. Also to be avoided are aggregates with clay coatings. This is because in addition to its inherent shrinkage and effect on water demand, clay will reduce the restraining effect of aggregate on shrinkage.

Admixtures form an integral part of concrete mixtures produced today. Their addition to concrete typically increases the volume of fine pores in the cement hydration product. As a result, studies have shown increased drying shrinkage when admixtures such as calcium chloride, slag cement and some pozzolans are used. With regard to water-reducing admixtures, ACI 212 reports that information on their effects is conflicting [9], but that long-term shrinkage may be less depending on the degree to which the water content of the concrete is reduced. Reductions in drying shrinkage have been obtained in instances where significant reductions in total water content were realized through the use of high-range water-reducing admixtures [10, 11]. Similar results may be obtained with mid-range water-reducing admixtures.

A specific example of reduced drying shrinkage with a high-range water-reducing admixture is shown in Table 1 for concrete mixtures with a nominal cement factor of 600 lb/yd³ (356 kg/m³) and slump of 9 in. (225 mm). **The data show that at 84 days a decrease in drying shrinkage of about 30 percent was obtained with a 18 fl oz/cwt (1170 mL/100 kg) dose of MasterRheobuild® 1000 (formerly Rheobuild 1000) admixture. The water reduction at this dose was approximately 30 percent**. Therefore, mid-range and high-range water-reducing admixtures can be beneficial if they are used to obtain significant reductions in total water content.

TABLE 1

Drying Shrinkage Data for MasterRheobuild 1000 Admixture-Treated Concrete

	Mixture #1	Mixture #2
Type I Cement, lb/yd³ (kg/m³)	595 (353)	603 (358)
Water Content, lb/yd³ (kg/m³)	325 (193)	222 (132)
HRWR, fl oz/cwt (mL/100 kg)	—	18 (1170)
Slump, in. (mm)	9 (225)	9.75 (245)
Air Content, %	6.4	5.6
Age, days	Drying Shrinkage,* % (ASTM C157/C157M)	
28	—	—
35	0.020	0.014
42	0.031	0.022
49	0.035	0.024
56	0.036	0.024
84	0.045	0.031

**Samples cured in saturated lime water for 28 days and then at 50% relative humidity and 73±3 °F (23±1.7 °C). Ambient and concrete temperatures during mixing were 72 °F (22 °C).*

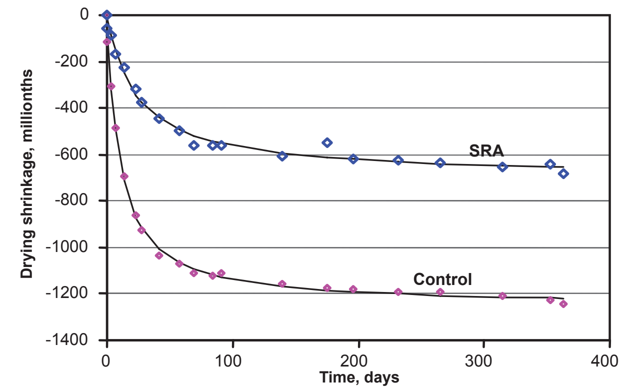


FIGURE 4. *Drying Shrinkage of Concrete with and without MasterLife SRA 20 admixture.*

Air-entraining admixtures have been shown to have little or no effect on drying shrinkage.

The magnitude of drying shrinkage can be reduced significantly through the use of a shrinkage-reducing admixture. Shrinkage-reducing admixtures function by reducing the surface tension of water within the pores of concrete. This leads to a reduction in the capillary tension and pull on the walls of the pores and, consequently a reduction in drying shrinkage. MasterLife® SRA 20 (formerly Tetraguard AS20) admixture was the first commercially available shrinkage-reducing admixture developed specifically to reduce the drying shrinkage of mortar and concrete (see Fig. 4) and the potential for subsequent cracking. MasterLife SRA 20 admixture has been successfully used in the Far East and North American construction markets since its introduction in 1985 (12).

The Master Builders Solutions family of durability-enhancing admixtures now includes MasterLife SRA 035 shrinkage-reducing admixture and MasterLife CRA 007 admixture, a first-of-its-kind crack-reducing admixture. Compared to conventional shrinkage-reducing admixtures, MasterLife CRA 007 admixture provides better performance under restrained shrinkage resulting in smaller initial crack widths (13), in addition to reducing the drying shrinkage of concrete.

Recent research (14) indicates that shrinkage-reducing admixtures may be used beneficially to reduce evaporative water loss from fresh concrete, to reduce autogenous shrinkage, and thus to reduce early-age cracking whether due to plastic shrinkage or autogenous deformation.

Effects of Design and Construction Practices

Design parameters that most influence drying shrinkage are the amount of reinforcement provided and the size, shape and surface area-to-volume ratio of the concrete member.

Steel reinforcement will reduce the drying shrinkage of concrete because of the restraint provided by the steel.

In the same ambient environment, a small concrete member will, because of its higher surface area-to-volume ratio, shrink more than a larger member. The greater the exposed surface area the greater the rate of moisture loss, and hence, the potential for drying shrinkage. Therefore, it should be recognized that the drying shrinkage that will be experienced in actual concrete structures will only be a fraction of that obtained in the laboratory with the ASTM C157/C157M test method.

Improper concreting practices such as retempering at the jobsite will increase drying shrinkage because of the increase in the water content of the concrete. Prolonged moist curing will delay the onset of drying shrinkage, but in general the length of curing is reported to have little effect on drying shrinkage [3]. Steam curing will, however, reduce drying shrinkage.