Technical Tip

Understanding and Controlling Shrinkage and Cracking in Shotcrete

by D.R. Morgan and C. Chan

Shrinkage is a potential problem in shotcrete construction in that it can lead to restrained shrinkage cracking. Cracking, in turn, can cause problems such as providing a path for ingress of aggressive chemicals, such as chlorides in marine structures, deicing chemical solutions, or salt spray in bridges and parking structures. This can lead to accelerated rates of corrosion in reinforcing steel in these types of structures, with consequent corrosion-induced shotcrete cracking, delamination, and spalling.

Shrinkage is also a potential problem in shotcrete repairs in that it can give rise to high interfacial bond stresses between the shotcrete and substrate. This can result in curling and peeling at repair edges and cracks and, ultimately, delamination of the shotcrete. Fig. 1 shows an example of such edge curling and delamination in a shotcrete-repaired bridge.[1] (Improper substrate preparation was a contributing factor to the problem in this bridge.)

Shrinkage induced cracking can also lead to problems in shotcrete-constructed water-retaining structures such as tanks, reservoirs, and swimming pools. Not only can the cracks allow leakage to occur, but they can also result in unsightly buildup of leachates and efflorescence at crack locations. This can be particularly problematic in architectural structures, such as artificial rockscapes, waterscapes, and theme parks, where it can negatively impact on aesthetics.

Fig. 1: Edge curling and delamination in a shotcrete-repaired bridge pier with improper surface preparation.

For all these reasons, it is desireable to minimize shrinkage and attempt to eliminate cracking. Is this possible? The *Technical Tips* that follow give guidance on measures that can be adopted towards achieving this goal. First, however, it is important to understand the causes of shrinkage and cracking, so that appropriate preventative measures can be applied.

What Causes Shrinkage?

The prime cause of shrinkage in concrete and shotcrete is a loss of water from the mix. There are various types of shrinkage:

Plastic Shrinkage: Shrinkage that occurs in the fresh shotcrete before it has set and hardened as a result of loss of moisture to the ambient environment.

Drying Shrinkage: Shrinkage that occurs in the hardened shotcrete as a result of loss of moisture to the ambient environment (drying shrinkage can continue for many years, although about 70% of it occurs within about three months).[2]

Autogenous Shrinkage: Also referred to as self-desiccation, is caused by the consumption of water by the cement hydration reactions (autogenous shrinkage is usually only about 10% of long-term drying shrinkage).[2]

Thermal Contraction: In addition to the various types of moisture-loss-related shrinkage described above, shotcrete can also contract as a result of thermal effects.

Hydrated portland cement in concrete or shotcrete has various types of pores within it. There are macropores such as voids of incomplete consolidation (called "bugholes" in concrete) and micropores such as capillary pores that range in size from about 2.5 to 50 nanometers. These capillary pores are initially filled with water. As water is lost by evaporation and cement hydration, the pores become less than fully saturated and a meniscus forms at the air-water interface, as shown in Fig. 2. The surface tension of the pore solution meniscus exerts an inward force on the sides of the pore walls, pulling the walls together. It is this force that causes the contraction that we describe as shrinkage.

What Causes Cracking?

Just as there are various types of shrinkage, there are also various types of cracking.

Plastic Cracking: This cracking is caused by plastic shrinkage and is the result of the freshly applied shotcrete drying excessively before it has had a chance to develop any significant tensile strength.

Drying Shrinkage Cracking: This cracking is caused by drying shrinkage in the hardened shotcrete and occurs when the tensile stress at the surface of the shotcrete exceeds the tensile strength of the shotcrete, as shown in Fig. 3. Shotcrete exposed to drying at an early age (say, 12 hours to 7 days) before it has had a chance to develop sufficient tensile strength, is vulnerable to drying-shrinkage cracking. Mixtures with high shrinkage capacity (for example, poorly designed mixtures with excessive water demand and/or overdosed with accelerator) may crack at later ages, even if they are initially properly cured (that is, protected from drying) as shown in Fig. 3.

Autogenous Shrinkage Cracking: This type of cracking is relatively rare in conventional shotcretes. It can, however, occur in very high strength, say, 70 MPa (10,000 psi) shotcretes, such as high-performance silica-fume-modified shotcretes, if they are not properly wet cured at early ages (12 hours to 3 days).[3]

Thermal Cracking: While not moisture related, shotcrete can crack if it is subjected to thermal shock. It is caused by exposure of freshly applied (warm) shotcrete to a cold ambient environment and development of a strong thermal gradient between the surface and interior of the shotcrete before it has developed sufficient tensile strength to resist the strains imposed by the thermal gradient.

Mixture Design Factors Affecting Shrinkage

Shotcrete, like concrete, is comprised of cementing materials (typically portland cement and supplementary cementing materials such as fly ash, silica fume, or sometimes blast furnace slag), as well as specially graded coarse and fine aggregates and water. In addition, wet-mix shotcrete may contain chemical admixtures, such as water reducers, superplasticizers, and sometimes hydration-controlling admixtures. Air entraining admixtures are frequently used in wet-mix shotcretes and sometimes in dry-mix shotcretes. Accelerators are sometimes added to both wet and dry-mix shotcretes, particularly in tunneling and mining applications.

All of these constituent ingredients have an effect on the amount of shrinkage experienced by the shotcrete, but it is mixtures with high water demand that experience the greatest shrinkage.

Cement Content

Shotcrete is typically a cement-rich material compared to common structural concretes. A cement content of 420 kg/m^3 (710 lbs/yd^3) is common in wet- and dry-mix shotcretes. This contrasts with a typical 30 MPa (4350 psi) structural concrete that would have a cement content of about 310 kg/m^3 (520 lbs/yd^3).

Water Content

The higher the cement content, the higher the water content of the mix to produce a mixture with a given consistency (slump). Thus, while a typical 30 MPa (4350 psi) concrete batched with a water-reducing admixture may have a water demand of about 150 L/m^3 (30 gal/yd^3), a typical wet-mix shotcrete containing a water-reducing admixture would have a water demand of about 180 L/m^3 (36 gal/yd^3). The consequence of these higher cement contents and water demands in shotcrete is that they typically have drying shrinkage at 90 days of about 700 microstrain in dry-mix shotcrete and 850 microstrain in wet-mix shotcrete, compared to shrinkage of about 500 microstrain in a typical 30 MPa (4350 psi) structural concrete.

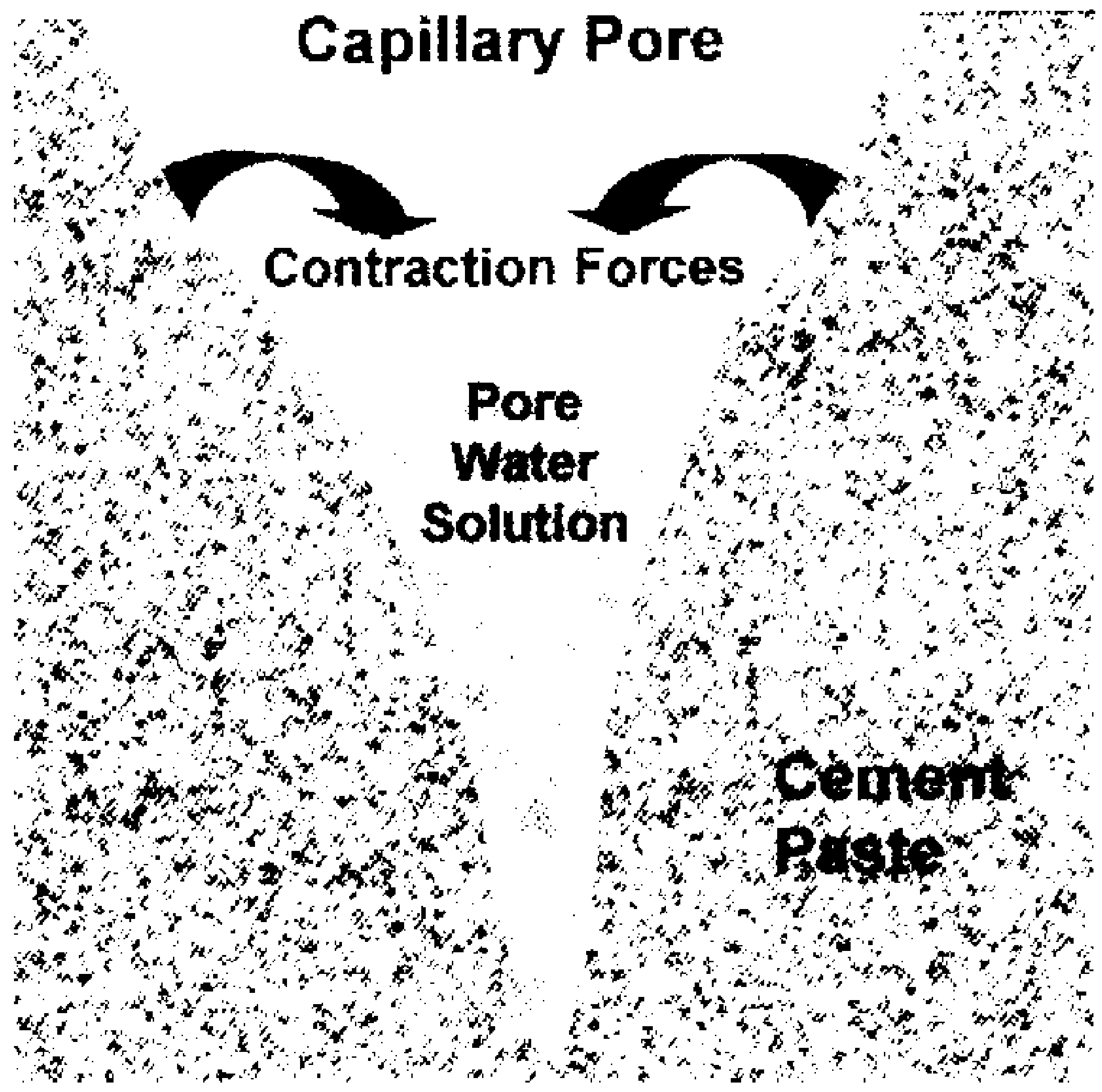


Figure 2. Meniscus forces in pore water solution in capillary pores in hydrated cement cause contraction and shrinkage.

Supplementary Cementing Materials

With regard to supplementary cementing materials, most fly ashes and blast furnace slags tend to reduce the water demand of the shotcrete mixture (compared to adding an equivalent amount of cement). By contrast, very finely divided materials such as silica fume tend to increase the water demand of the mixture.

Water Reducers and Superplasticizers

With silica fume modified wet-mix shotcrete, it is important to use mid- or high-range water-reducing admixtures (superplasticizers) to control the water demand and, consequently, the amount of shrinkage. A word of caution: Do not add dry powdered superplasticizers to dry-mix shotcrete, as they can activate on the wall, causing sagging.

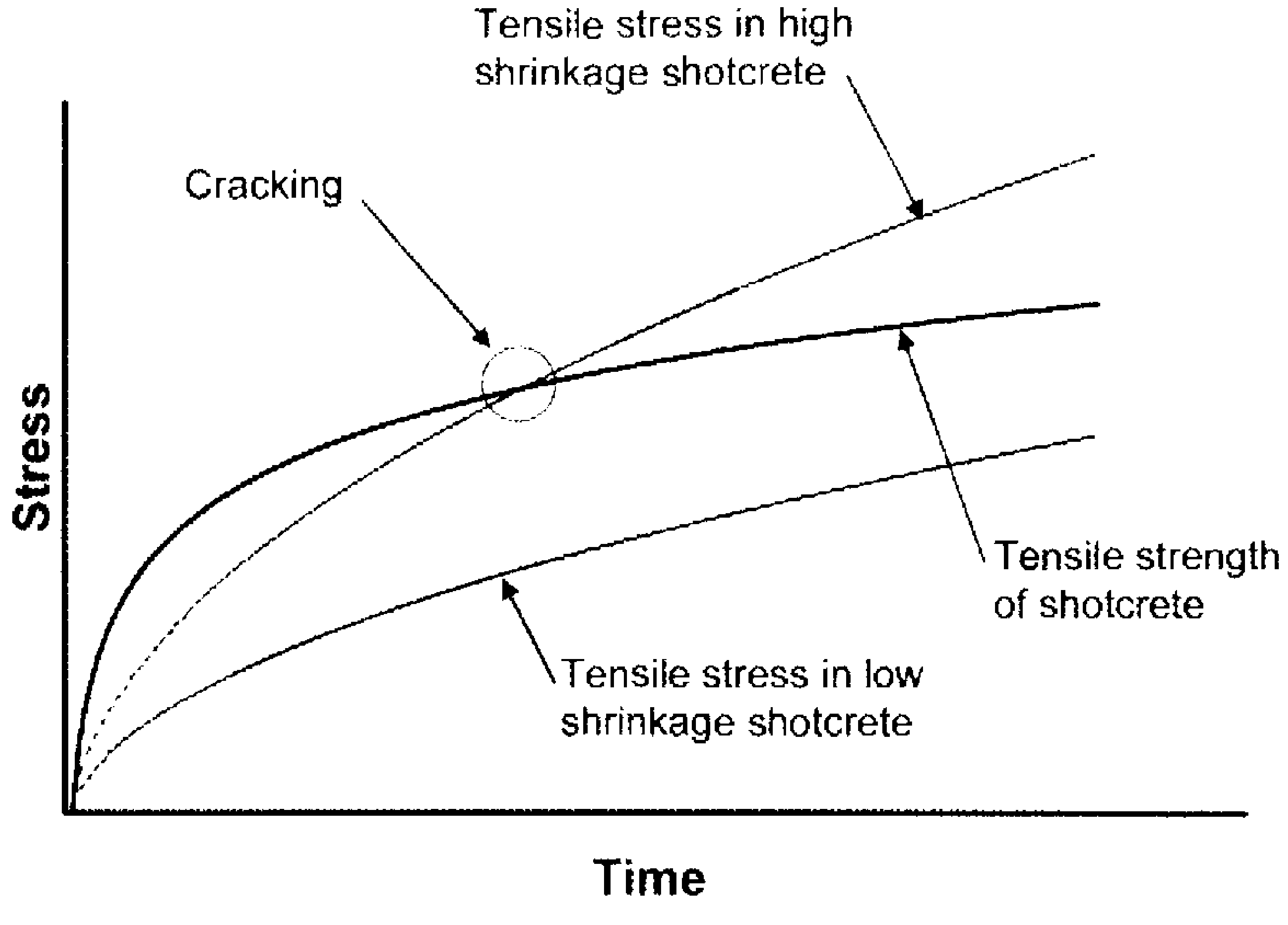
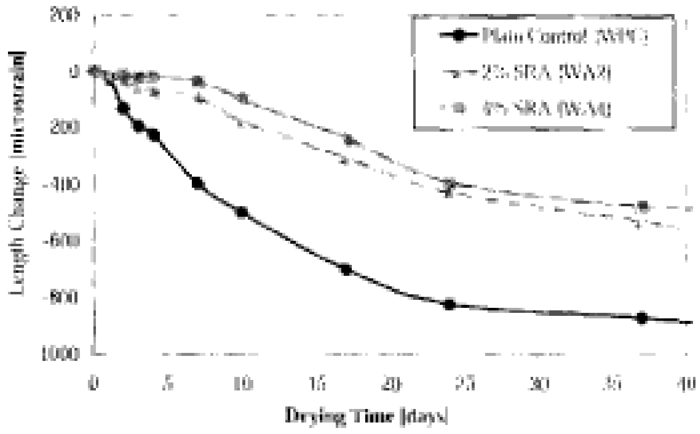


Figure 3. Cracking occurs when shrinkage-induced tensile stress exceeds tensile strength of shotcrete.



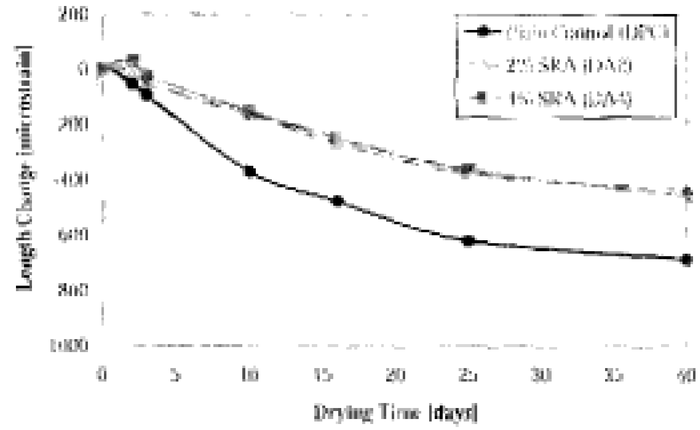


Figure 4 (top). Drying shrinkage in wet-mix shotcretes produced with and without shrinkage reducing admixtures (SRAs).

Figure 5 (bottom). Drying shrinkage in dry-mix shotcretes produced with and without shrinkage reducing admixtures (SRAs).

sloughing, and fallout of the applied shotcrete.

Shrinkage Reducing Admixtures

Alternatively, shrinkage can be controlled using shrinkage reducing admixtures (SRAs). They act by reducing the surface tension in the pore water solution. This reduces the contraction forces exerted by the pore water menisci on the capillary pore walls, which in turn reduces shrinkage and cracking. Figure 4 and 5 show the drying shrinkage in wet- and dry-mix shotcretes produced with and without SRAs. Note the marked reduction in unrestrained drying shrinkage.[4] In this study, plain shotcretes under restrained conditions cracked extensively on exposure to harsh drying in an environmental chamber, whereas shotcretes with SRAs added at 2% by mass of cement developed no plastic or restrained drying shrinkage cracking.[4]

Air Entraining Admixtures

Air entraining admixtures can be helpful with respect to minimizing water demand and hence controlling cracking. It can be demonstrated that as the air content increases, the slump of the shotcrete increases. Thus for a given slump, air entrainment can enable a pumpable and shootable mix to be produced with a reduced water demand. Air entrainment also has an additional benefit: a so-called slump-killing effect. Wet-mix shotcretes can be batched at 7 to 10% air contents, producing very workable, easily pumped mixtures with about 100 mm (4 in.) slump. As the shotcrete hits the wall, the air content is reduced to about 4% and the slump is instantly reduced to about 40 mm (1.5 in.). This is very beneficial for shotcrete adhesion and cohesion and thickness of build-up.[5]

Accelerators

Research and practical experience have shown[1,6] that most accelerators will increase the shrinkage of concretes and shotcretes, particularly at early ages. This, in turn, can lead to shrinkage-induced cracking. Fig. 6 shows a photo of a bridge pier repaired with a dry-mix steel-fiber-reinforced shotcrete, which contained an accelerator. It cracked extensively, in spite of being moist cured. When the accelerator was eliminated from the mix, the companion shotcrete-repaired bridge piers were essentially crack free (they were properly moist cured). A word of caution: NEVER use calcium chloride as a shotcrete accelerator. One bridge owner made a shotcrete contractor add calcium chloride to the mix water added to a dry-mix shotcrete (for electrochemical reasons in a cathodic repair application). The results were disastrous. The shotcrete cracked, curled, and delaminated, in spite of rigorous surface preparation and curing by the contractor. Calcium chloride can increase early age (3 day) drying shrinkage by as much as 50%.[6]

Fiber Reinforcement

Steel and synthetic fibers, while not necessarily reducing the amount of drying shrinkage (as measured in an unrestrained free shrinkage test), can be very beneficial in controlling or even eliminating plastic and restrained drying shrinkage crack-

Figure 6. Bridge pier repaired with an accelerated, steel-fiber-reinforced shotcrete with drying shrinkage cracking.

Figure 7. Littlerock Dam seismic retrofit with crack-free, wet-mix, steel-fiber-reinforced silica fume shotcrete. Note: curing blankets.

Figure 8. Fogging freshly applied shotcrete at Littlerock Dam using water pressure sprayer.

ing in shotcrete. Low volume addition rates of about 1 kg/m³ (1.7 lb/yd³) of monofilament or collated fibrillated synthetic fibers have been demonstrated to be very effective in mitigating plastic shrinkage cracking.[7] High volume addition rates of synthetic fibers of about 7 to 10 kg/m³ (12 to 17 lb/yd³) have been demonstrated to be effective in mitigating restrained drying shrinkage cracking.[8] Similarly, high volume addition rates of steel fiber reinforcement of about 40 to 60 kg/m³ (67 to 100 lb/yd³) have been demonstrated to be effective in controlling drying shrinkage cracking.[9] For example, in the seismic retrofit of the Littlerock Dam near the Edwards Air Force Base in California, 4680 m² (48,000 ft²) of silica-fume modified wet-mix shotcrete with 60 kg/m³ (100 lb/yd³) of steel fiber was applied with virtually no cracking. This was achieved in spite of the shotcrete being constructed in a desert environment, with up to 37 C (100 F) ambient temperatures with hot drying winds. Rigorous moist curing was, of course, adopted, as shown in Fig. 7 and 8.

Control of Shrinkage Induced Cracking

The following is a brief summary of the most important points for controlling shrinkage-induced cracking in shotcrete.

- Select aggregates with appropriate shape, texture, quality, and gradation (ACI 506R-90 gradation No. 2 is the preferred grading, although gradation No. 1 aggregate may also be used).
- Carefully design the shotcrete mixture to avoid excessive cement contents and water demand. Cement contents in excess of 450 kg/m³ (760 lbs/yd³) are seldom justified, and water demands in excess of 200 L/m³ (40 gal/yd³) should be avoided.
- Keep water demand of wet-mix shotcrete to a minimum using chemical admixtures such as water reducers, superplasticizers and/or hydration-controlling admixtures. Do not retemper aging shotcrete with water.
- Take advantage of the water reduction and slump killing effects provided by the use of air entraining admixtures.
- Do not use accelerators unless essential to the construction process.
- Never use calcium chloride as an accelerator.
- Give consideration to the use of a shrinkage reducing admixture.
- Use a low volume addition rate of about 1 kg/m³ (1.7 lb/yd³) of a synthetic microfiber for control of plastic shrinkage cracking.
- Consider the use of a high volume steel or synthetic fiber reinforcement, in lieu of mesh, if warranted by the design.
- Use windscreens or sunshades in harsh environmental exposure conditions, if required.
- Use fogging/misting to protect the freshly applied shotcrete from drying (see Fig. 8).[9]
- As soon as the shotcrete has hardened sufficiently, cure for at least 4 days and preferably 7 days using one of the following methods:

  (a) Plastic coated synthetic fabric kept saturated throughout the curing period;

  (b) Saturated burlap, covered with plastic sheets to prevent drying; or

  (c) Soaker hoses, sprinklers, or water ponding where appropriate.

  Note: Curing compounds can be used, but they are second best to water curing methods, as they do not provide the external moisture the shotcrete needs to mitigate autogenous shrinkage.
- Finally, protect the shotcrete against thermal-shock-induced cracking if necessary using thermal curing blankets placed on top of the moist curing.

Numerous large and small shotcrete construction projects, some of them in onerous environmental exposure conditions, have demonstrated that if the above good design and construction practices are followed, it is possible to construct high quality, durable, aesthetically pleasing shotcrete structures that are largely crack-free.

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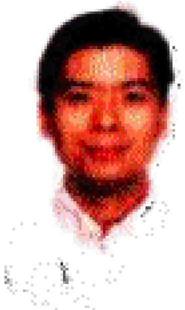

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