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REACT: Reducing Early-Age Cracking Today

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Abstract

Concrete is generally viewed as a durable and long-lasting construction material. However, the long-term performance of a concrete structure can be greatly compromised by early-age cracking. One recent informal estimate from the industry places this as a $500 million problem in the U.S. alone, with some ready-mix companies experiencing early-age issues on as many as 70 % of their jobs. As is often the case, as a problem intensifies, mitigation strategies are developed and promoted from the research laboratory to the field. This paper will briefly review the most common non-structural causes of early-age cracking and present an introduction to various mitigation strategies. These strategies are being further investigated as part of a newly formed university/industry/government collaboration under the acronym of REACT: Reducing Early-Age Cracking Today.

Introduction

Viewpoints on concrete cracking vary as widely as potential applications for this century-old construction material. At one end of the spectrum lies the commonly heard statement "all concrete cracks." At the other end, there are numerous real world examples of crack-free (at least to the naked eye) concrete construction. As is usually the case, the truth likely lies between these two extremes, perhaps with a statement like "all concrete can be made to crack when proper design and construction practices are not followed." However, when proper materials selection and placement procedures are followed, crack-free concrete can be a reality. Early-age cracking is a particular concern for the industry, both for aesthetic reasons and for its potentially detrimental impact on the service life performance of concrete facilities.

While the causes of early-age cracking can be numerous (e.g., improper design, structural issues such as early-age loading beyond capacity), the remainder of this paper will focus on three of the principal non-structural causes: plastic shrinkage, thermal deformations, and autogenous shrinkage. Of course, these three may act separately, in sequence, or concurrently at a job site. Plastic shrinkage cracking occurs as a combination of differential settlement and excessive evaporation of water from a fresh concrete surface. In the U.S., a nomograph has been used for over fifty years that relates the air temperature, relative humidity, wind speed, and concrete temperature to the evaporation rate from a water surface. Recently, an internet accessible system that computes this expected rate of evaporation has been developed.[1] When this rate exceeds the bleeding rate, the susceptibility for plastic shrinkage cracking may be greatly increased. Specifically, when the evaporation rate exceeds 1.0 $kg/(m^2 \cdot h)$ [0.2 $lb/(ft^2 \cdot h)$], it has historically been recommended that precautions (curing procedures) be taken to reduce the potential for cracking. However, the increasing fineness of cement and other binders and the use of lower water to cement ratio (*w/c*) systems may require even more stringent evaluation criteria.

Thermal cracking is largely due to the considerable heat generated by the cement hydration reactions. Especially in mass concrete construction, this heat generation will produce a significant temperature rise (and subsequent fall) within the concrete element. Heat generation will depend on the binder characteristics of the concrete (cement content, cement chemistry and fineness, mineral admixture additions), while its dissipation will depend on the thermal conductivity and heat capacity of the concrete, along with the geometry and boundary conditions of the constructed element. The coefficient of thermal expansion of the concrete is equally important, especially since it may vary significantly at early ages, leading to a permanent finite expansion/contraction during heating/cooling (from and back to ambient temperature).

Autogenous shrinkage is caused principally by chemical shrinkage, which is the reduction in volume due to the hydration reaction, and the self-desiccation or internal drying that accompanies it under partially saturated or sealed curing (hydration) conditions. The magnitudes of the stresses that produce autogenous shrinkage are directly proportional to the surface tension of the pore solution (consisting of water, ions, and admixtures in the concrete) and inversely proportional to the radius of the partially-filled pores. As will be illustrated later in this paper, both of these parameters can be engineered to one's advantage in reducing and even eliminating autogenous shrinkage. While autogenous shrinkage is present in all concretes, it can be particularly prominent in high-performance concretes, due to the small interparticle spacing (pores) produced by a combination of a low *w/c* and the addition of very fine pozzolans such as silica fume.

It should be emphasized that hydration rates critically influence both thermal and autogenous deformation characteristics. Faster hydration rates, as produced by finer cements, for example, increase the heat generation rate and accelerate the self-desiccation process, as smaller and smaller pores sequentially empty within the hydrating microstructure.

Measurement Techniques

Thermal Properties

While the fundamental thermal properties of a concrete, such as thermal conductivity, heat capacity, heat of hydration, and coefficient of thermal expansion, can be readily assessed in the research laboratory, a simple measurement with perhaps more applicability to real field exposures is semi-adiabatic calorimetry. For this measurement, the temperature of a well-insulated specimen of fresh cement paste, mortar, or concrete is monitored during its first few days of curing. As shown in Figure 1, the magnitude of the measured temperature rise (T_{max}) and the rate at which the temperature decays after reaching a peak (*dT/dt)* are indicative of the relative potential of the field concrete to: 1) achieve high internal temperatures that may lead to instability of hydration products such as ettringite and 2) develop large temperature gradients. Both of these conditions may contribute to early-age cracking. No elaborate experimental setup is required to develop a practical semi-adiabatic calorimeter, as test setups can range from a simple "coffee cup" calorimeter for pastes and mortars to insulated coolers for mortars and concretes. If one has a thermocouple and a well insulated container (Figure 2), a semi-adiabatic response can be measured to compare the performance of various mixture proportions. Of course, numerous semi-adiabatic calorimeters are commercially available to facilitate comparisons between testing groups, if one prefers not to construct their own unit.

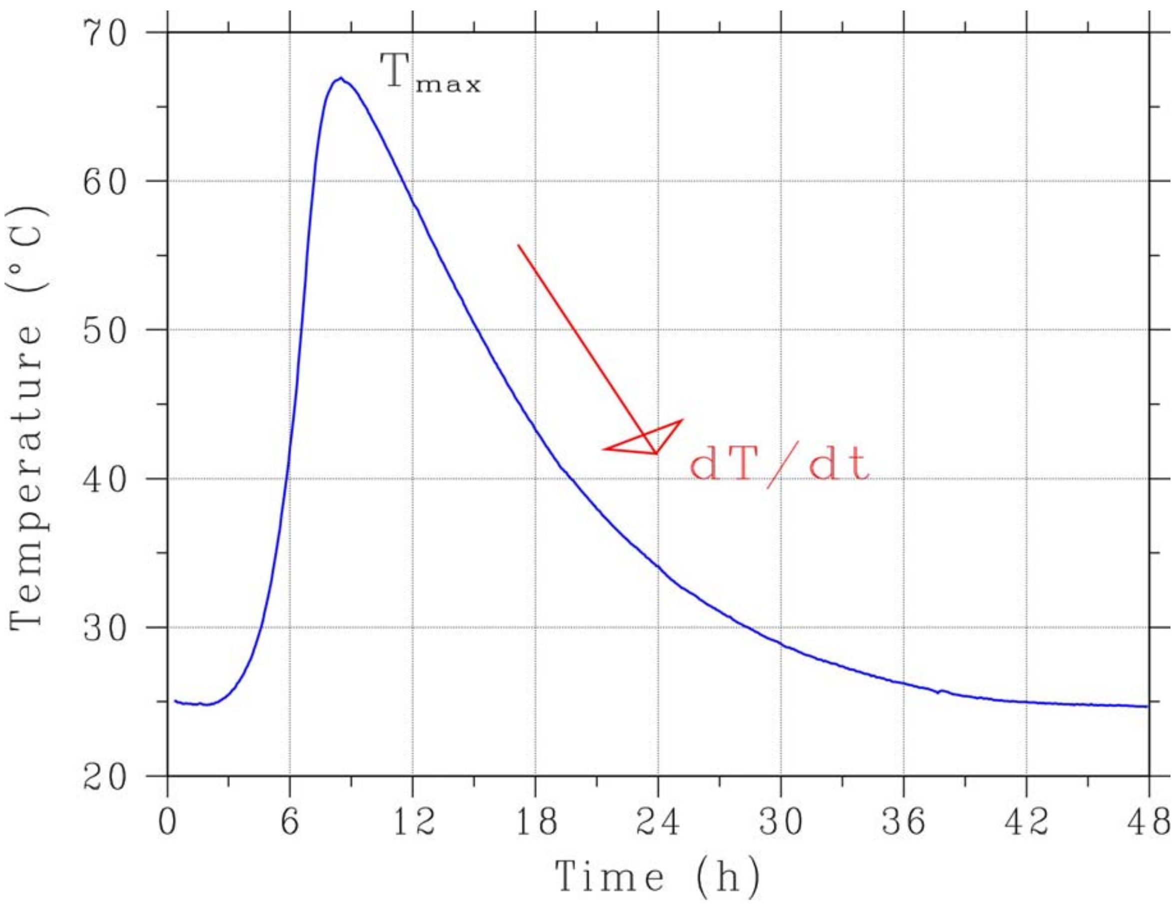

Figure 1. Typical semi-adiabatic temperature rise curve for a portland cement paste specimen.

Autogenous Stresses and Strains

Chemical shrinkage can be assessed using the American Society for Testing and Materials (ASTM) C1608 standard test method,[2] or other similar standardized techniques,[3] and provides both a quantitative indication of hydration rates and a measure of the "curing water demand" of a concrete mixture (e.g., how much curing water must be supplied to maintain saturated conditions within the hydrating cement paste). Autogenous deformation of pastes and mortars can be evaluated from the time of set using commercially available sealed corrugated tubes (Figure 3).[4] For concretes, an equivalent system based on larger diameter corrugated tubes has been developed by Prof. Jensen at the Technical University of Denmark, while Craeye and DeSchutter[5] have successfully employed a vertical dilatometer that could be practically implemented using standard concrete cylinder (plastic) molds. Temperature control becomes an issue when evaluating the larger concrete specimens, as early-age autogenous shrinkage can be easily confounded with thermal expansion/contraction when isothermal conditions are not maintained.

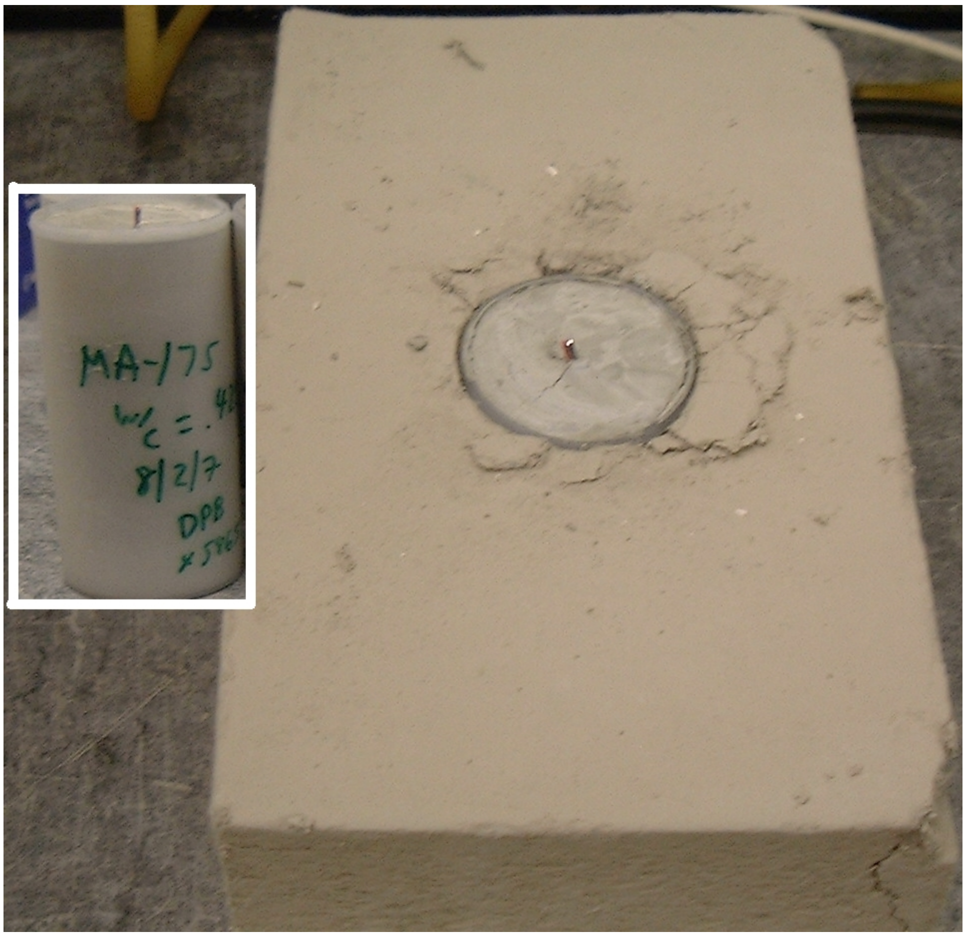

Figure 2. Custom-built semi-adiabatic calorimeter, with a typical size (48 mm diameter by 96 mm length cylinder) paste or mortar specimen (inset), embedded in microporous insulation. Top insulating panel is not shown.

Autogenous deformation of a sealed paste or mortar specimen is often characterized by an initial expansion followed by shrinkage, as shown in Figure 4. Cusson[6] has suggested that one metric of the propensity for early-age cracking due to autogenous shrinkage can be obtained from the net autogenous shrinkage at 7 d, determined as the difference between the maximum expansion, ε_{max} (ε_{max}=0 if no expansion is measured), and the subsequent minimum deformation (shrinkage), ε_{min}, achieved during the first 7 d of testing, as indicated in Figure 4.

Figure 3. Typical equipment for measuring autogenous deformation of paste and mortar specimens.[4]

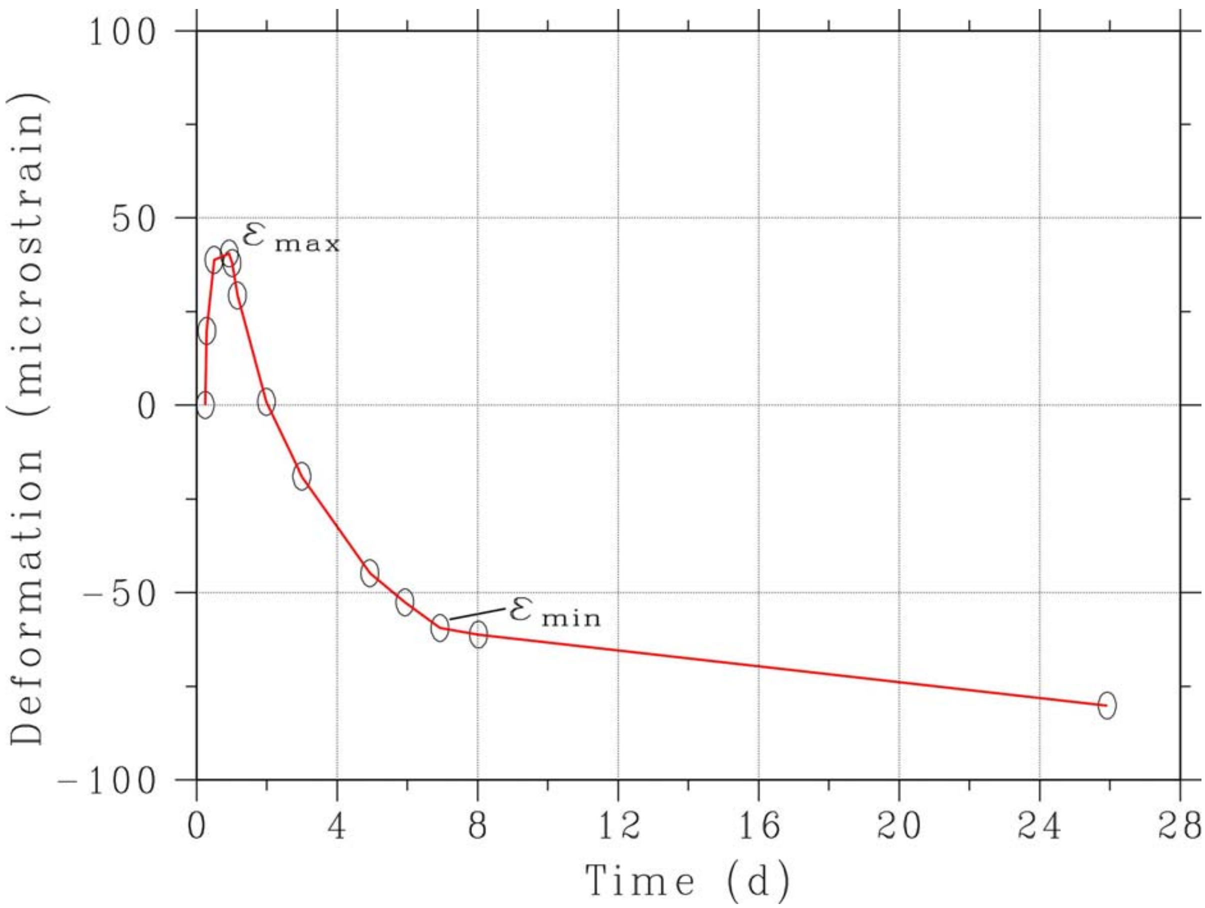

Figure 4. Typical autogenous deformation curve for a mortar specimen.

Stresses, strains, and cracking potential can be evaluated simultaneously using a restrained ring shrinkage test with sealed or exposed curing conditions.[7] The restrained ring is shown in Figure 5 while typical results are shown in Figure 6 for sealed and unsealed mortars. The ring test is based on the principle that the steel restrains or resists the shrinkage. As the concrete attempts to shrink, it compresses the steel ring and the ring pushes back, thereby placing the concrete in tension. By monitoring the strain that develops in the steel ring, an indication of the level of stress caused by restraint can be obtained.[8] The sudden decrease in strain, as shown in Figure 6, is associated with the development of a visible through crack. Results from the ring specimen can be related to the behavior of slab specimens.[9] The efficiency of mitigation strategies such as shrinkage reducing admixtures (SRAs)[7] and internal curing with saturated lightweight aggregates (LWA)[10] can be conveniently evaluated using ring testing (Figure 6).

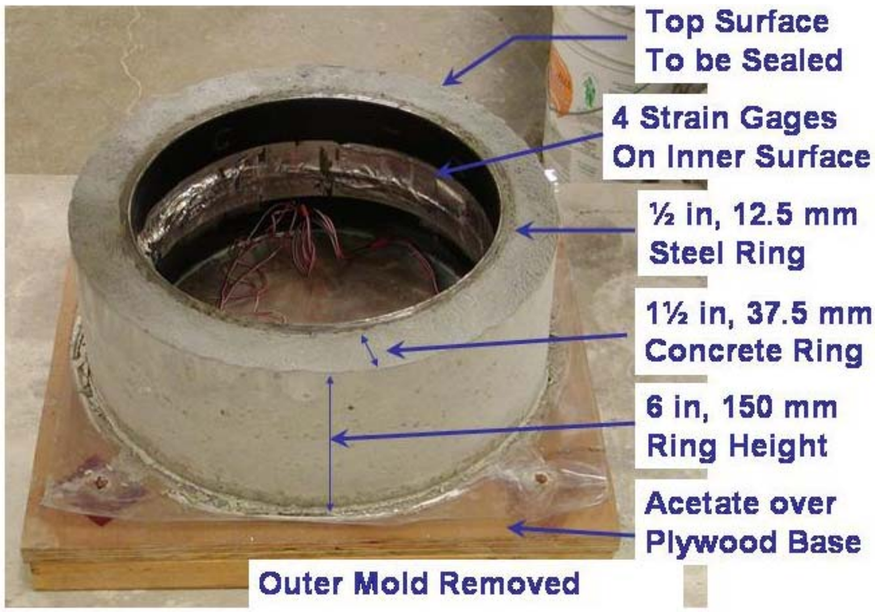

Figure 5. Typical equipment for measuring restrained shrinkage and cracking potential for mortar and concrete specimens (as per ASTM C 1581).

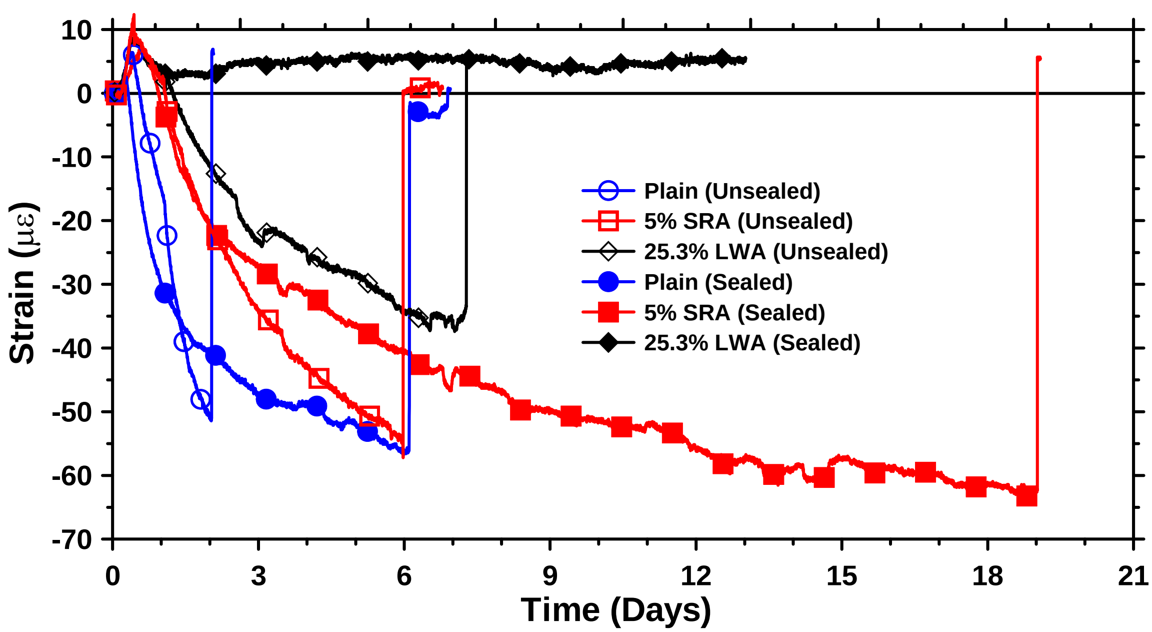

Figure 6. Restrained ring strain measurements for mortar specimens (*w/c*=0.30) with different curing conditions and mitigation strategies.[10] Sharp vertical lines indicate crack formation.

Innovative Concrete Technologies

Shrinkage-Reducing Admixtures (SRAs)

SRAs are generally organic chemical compounds that have been conventionally employed to reduce drying shrinkage. SRAs significantly reduce the surface tension of the pore solution,[11,12] generally increase its viscosity,[13] and modify the drying profile to decrease drying rates of cement-based materials.[11,12] The reduction in surface tension should lower capillary stresses and reduce sorption rates,[14,15] while an increase in viscosity will decrease transport rates, whether by diffusion, sorption, or flow under pressure.[16]

Internal Curing (IC)

IC provides extra water to maintain the cement paste under saturated conditions by distributing reservoirs of curing water throughout the three-dimensional concrete structure. Reservoirs may be provided by pre-wetted lightweight aggregates,[10,17] superabsorbent polymers,[17,18] saturated wood fibers, or pre-wetted crushed returned concrete aggregates.[19] These reservoirs will sacrificially empty during the cement hydration, as the water they contain will be imbibed by the surrounding hydrating cement paste, as long as the pores in the cement paste are substantially smaller than those in the reservoirs. Since these reservoirs typically contain much larger radius pores, much lower capillary stresses will be created and autogenous shrinkage can be effectively eliminated.[10,17] Practical guidelines for mixture proportioning with IC have been presented previously.[20]

Mixture Proportioning

SRAs and IC mainly address the plastic and autogenous shrinkage components of early-age cracking. Additionally, modifications to the mixture proportions can reduce both the thermal and autogenous contributions to early-age cracking. These include a decrease in cement content, utilization of a coarser cement, an increase in *w/c* ratio, and replacement of a portion of the cement by a coarse limestone powder.[21] The latter three of these effectively increase the interparticle spacing within the paste (binder) fraction of the concrete. High volume fly ash mixtures that slowly hydrate and develop strength can also substantially reduce semi-adiabatic temperature rise and early-age autogenous shrinkage.[22,23]

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Plastic Shrinkage

Proper curing can effectively eliminate plastic shrinkage and its associated cracking. Extra insurance is sometimes provided by the incorporation of polymeric fibers into the concrete mixture. More recently, field and laboratory evidence suggest that both SRAs and IC, in addition to substantially reducing autogenous shrinkage, can also effectively reduce plastic shrinkage, the former by reducing both evaporation rates and the stresses that develop during drying,[12] and the latter by providing an extra source of sacrificial water so that once again the cement paste portion of the concrete can remain saturated and crack-free (longer) during initial curing.

Autogenous Shrinkage

Clear reductions in autogenous shrinkage can be provided by either SRAs or IC,[10,11,17-19] as shown in Figure 7, for example. Because commonly employed SRAs can reduce the surface tension of the pore solution by a factor of two at most, they can reduce but not eliminate net autogenous shrinkage (Figure 7). At sufficient addition levels, however, internal curing reservoirs can effectively eliminate net autogenous shrinkage, and, as exemplified by the results in Figure 7, may even produce an autogenous expansion at ages of 7 d and beyond.[17]

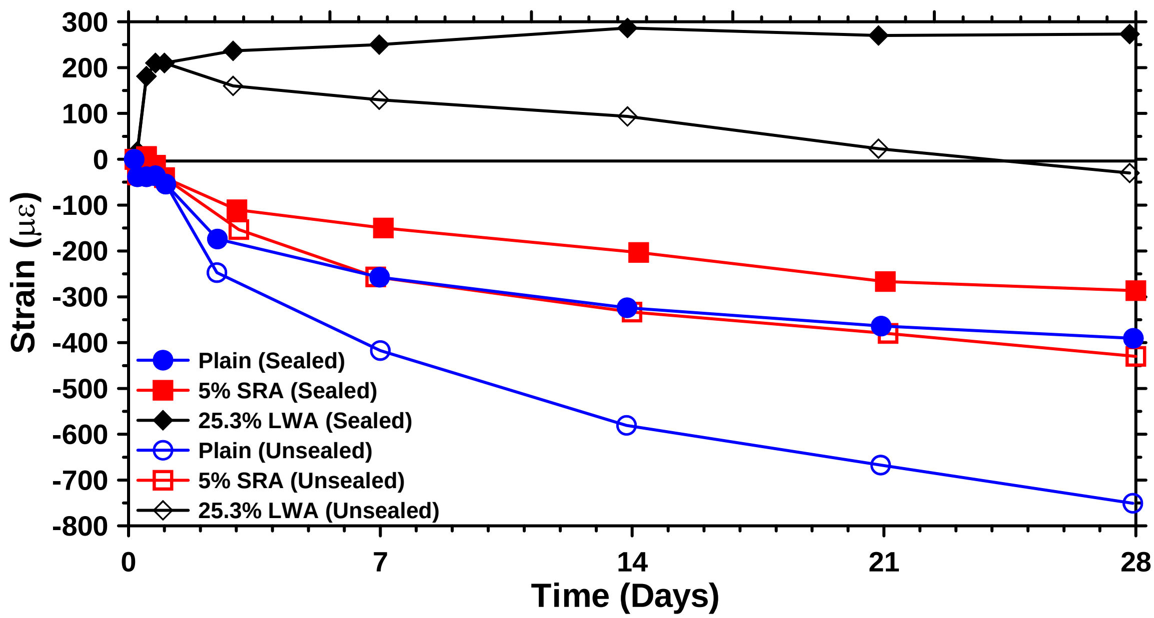

Figure 7. Autogenous deformation measurements for mortar specimens (*w/c*=0.30) with different curing conditions and different mitigation strategies.[10]

Thermal Gradients

A variety of proven technologies are available for reducing maximum temperature rise and temperature gradients in mass concrete construction, including the use of ice as part of the mixing water, chilled aggregates, cooling pipes, night time pours, fly ash additions, and the incorporation of phase change materials into the concrete mixture.[24] These approaches generally reduce the hydration rates or increase the thermal capacity of the concrete such that the heat generated by the hydration reactions results in a smaller temperature rise within the concrete element.

Thermal and Autogenous

In addition to the mitigation strategies discussed above, modifications to the mixture proportions have the potential to reduce both thermal and autogenous contributions to early-age cracking. As one example of this, Table 1 presents the measured strength reductions at 28 d, maximum temperature rise, and net autogenous shrinkage at 7 d for cement pastes and mortars with various modifications to an initial *w/c*=0.35 mixture design.[21] Modifications included the replacement of the initial cement (Blaine fineness of 380 m^2/kg) with a coarser one (Blaine fineness of 311 m^2/kg), an increase in *w/c* to 0.40, and the substitution of either a fine (modal diameter of 28 μm) or a coarse (modal diameter of 107 μm) limestone powder for the cement at a 10.2 % mass fraction. Among these modifications, the greatest reductions in maximum temperature and decreases in autogenous shrinkage are provided by the utilization of the coarser cement, but with a significant reduction (≈ 25 %) in strength development. With a lesser decrease in compressive strength of about 7 %, the 10 % coarse limestone addition still provides a substantial reduction in both maximum temperature and autogenous shrinkage. As noted previously,[25] high early-age strengths and avoidance of early-age cracking are often conflicting goals that must be carefully balanced to achieve acceptable performance.

Table 1. Relative mortar cube compressive strength at 28 d, maximum temperature achieved in semi-adiabatic testing of pastes, and (ε_{min}-ε_{max}) at 7 d for mortars.[21]

Cement paste or mortar	**Relative strength at 28 d**	**Maximum temperature (% Reduction vs. control)**	**(ε_{min}-ε_{max}) at 7 d and (% Reduction vs. control)**
w/c = 0.35 fine cement	100 %	66.9 °C (---)	-127 microstrains (---)
w/c = 0.35 coarse cement	74 %	47.4 °C (43 %)	-49 microstrains (61 %)
w/c = 0.40 fine cement	93 %	59.8 °C (16 %)	-100 microstrains (21 %)
w/cm = 0.357 fine cement/10 % fine limestone	93 %	58.8 °C (18 %)	-163 microstrains (**-28** %)
w/cm = 0.357 fine cement/10 % coarse limestone	93 %	57.8 °C (20 %)	-88 microstrains (31 %)

Prospectus

This paper has illustrated several mitigation strategies for decreasing the contributions of plastic, thermal, and autogenous shrinkage to non-structural early-age cracking. These strategies are currently being employed in practice at an increasing number of job sites. In 2008, the measurements and mitigation strategies presented in this paper are being extended in the newly formed collaborative research effort, REACT, between Purdue University, NIST, and interested industrial members. Interested parties may contact the authors for more details.

References

1) Munir, A., and Snell, L., "Evaluating Concrete Curing Conditions," available at http://construction.asu.edu/cim/curing/curingfirstpage.htm (access verified April 2008).
2) ASTM C1608-05, Test method for chemical shrinkage of hydraulic cement paste, Volume 04.01, ASTM International, West Conshohocken, PA, 2005.
3) E. Tazawa, Ed., Autogenous Shrinkage of Concrete, E&FN Spon, London, 1999, pp. 53-55.
4) Jensen, O.M., and Hansen, P.F., "A Dilatometer for Measuring Autogenous Deformation in Hardening Portland Cement Paste," *Materials and Structures*, **28**, 406-409, 1995.
5) Craeye, B., and De Schutter, G., "Experimental Evaluation of Mitigation of Autogenous Shrinkage by Means of a Vertical Dilatometer for Concrete," in Proceedings of the International

RILEM Conference - Volume Changes of Hardening Concrete: Testing and Mitigation, Eds. O.M. Jensen, P. Lura, and K. Kovler, RILEM Publications S.A.R.L., 21-30, 2006.
6) Cusson, D., "Effect of Blended Cements on Efficiency of Internal Curing of HPC," ACI-SP, Internal Curing of High-Performance Concretes: Laboratory and Field Experiences, American Concrete Institute, Farmington Hills, MI, 2008.
7) Weiss, J., Lura, P., Rajabipour, F., and Sant, G., "Performance of Shrinkage Reducing Admixtures at Different Humidities and at Early Ages," *ACI Materials Journa*l, in press.
8) Hossain, A.B., and Weiss, W. J., "Assessing Residual Stress Development and Stress Relaxation in Restrained Concrete Ring Specimens," *Cement and Concrete Composites*, **26** (5), 531-540, 2004.
9) Weiss, W. J., Yang, W., and Shah, S. P., "Shrinkage Cracking of Restrained Concrete Slabs," *Journal of Engineering Mechanics*, American Society of Civil Engineering, **124** (7), 765-774, 1998.
10) Henkensiefken, R., Nantung, T., and Weiss, J., "Reducing Restrained Shrinkage Cracking in Concrete: Examining the Behavior of Self-Curing Concrete Made using Different Volumes of Saturated Lightweight Aggregates," in Proceedings of Concrete Bridge Conference, St. Louis, May 2008.
11) Bentz, D.P., Geiker, M.R., and Hansen, K.K., "Shrinkage-Reducing Admixtures and Early Age Desiccation in Cement Pastes and Mortars," *Cement and Concrete Research*, **31** (7), 1075-1085, 2001.
12) Lura, P., Pease, B., Mazzotta, G., Rajabipour, F., and Weiss, J., "Influence of Shrinkage-Reducing Admixtures on the Development of Plastic Shrinkage Cracks," *ACI Materials Journal*, **104** (2), 187-194, 2007.
13) Bentz, D.P., "Influence of Shrinkage-Reducing Admixtures on Drying, Autogenous Shrinkage, and Freezable Water Content of Cement Pastes at Early Ages," *Journal of Advanced Concrete Technology*, **4** (3), 423-429, 2006.
14) Sant, G., Eberhardt, A., Bentz, D., and Weiss, J., "The Influence of Shrinkage-Reducing Admixtures (SRAs) on Moisture Absorption in Cementitious Materials at Early Ages," submitted to *ASCE Journal of Materials in Civil Engineering*, 2008.
15) Weiss, W. J., and Berke, N.S., "Admixtures for Reduction of Shrinkage and Cracking," Early Age Cracking In Cementitious Systems – RILEM State of the Art Report TC-EAS, ed. A. Bentur, Chapter 7.5, 2002.
16) Bentz, D.P., Peltz, M.A., Snyder, K.A., and Davis, J.M., "VERDiCT: Viscosity Enhancers Reducing Diffusion in Concrete Technology," submitted to *Concrete International*, 2008.
17) Geiker, M.R., Bentz, D.P., and Jensen, O.M., "Mitigating Autogenous Shrinkage by Internal Curing," in ACI SP-218, High Performance Structural Lightweight Concrete, Eds. J.P. Ries and T.A. Holm, American Concrete Institute, Farmington Hills, MI, 143-154, 2004.
18) Jensen, O.M., and Hansen, P.F., "Water-Entrained Cement-Based Materials: II. Experimental Observations," *Cement and Concrete Research*, **32** (6), 973-978, 2002.
19) Kim, H., and Bentz, D.P., "Internal Curing with Crushed Returned Concrete Aggregates," to be published in NRMCA Technology Forum: Focus on Sustainable Development, 2008.
20) Bentz, D.P., Lura, P., and Roberts, J.W., "Mixture Proportioning for Internal Curing," *Concrete International*, **27** (2), 35-40, 2005.
21) Bentz, D.P., and Peltz, M.A., "Reducing Thermal and Autogenous Shrinkage Contributions to Early-Age Cracking," *ACI Materials Journal*, in press.

22) Mehta, P.K., “High-Performance, High-Volume Fly Ash Concrete For Sustainable Development,” in Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China, 3-14, 2004.
23) Houk Jr., I.E., Borge, O.E., and Houghton, D.R. “Studies of Autogenous Volume Change in Concrete for Dworshak Dam,” *ACI Journal*, **66** (45), 560-568, 1969.
24) Mihashi, H, Nishiyama, N, Kobayashi, T, Hanada, M. “Development of a Smart Material to Mitigate Thermal Stress in Early Age Concrete,” in Control of Cracking in Early Age Concrete, Eds. H. Mihashi & F. H. Wittmann, Balkema, Rotterdam, 385-392, 2002.
25) Mehta, P.K., and Burrows, R.W., “Building Durable Structures in the 21st Century,” *Concrete International*, **23**, 57-63, 2001.