Improving Watertightness of Reinforced Concrete Structures With Shrinkage-Reducing Admixtures

by

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Abstract

Drying shrinkage cracking can adversely affect the aesthetics, durability, and serviceability of reinforced concrete structures, thereby negating some of the benefits provided by high-performance concretes. Developed years ago but relatively new to the construction industry, shrinkage-reducing admixtures (SRAs) have been shown to provide significant reductions in concrete drying shrinkage and subsequent cracking. The potential benefits that SRAs provide have resulted in increased use of these products in the past few years.

In this paper, data from laboratory testing and field investigations of SRA-treated concrete mixtures and their use in a few projects where watertightness was desired are presented and discussed. The findings of visual inspections of the projects performed shortly after construction and after a year in service will also be presented. The information to be presented verify the drying shrinkage reduction characteristics of SRAs and show that these innovative admixtures can provide substantial benefits with regards to improving watertightness and overall serviceability of reinforced concrete structures.

Keywords: Concrete, Cracking, Drying Shrinkage, Durability, Shrinkage-Reducing Admixture, Polyoxyalkylene Alkyl Ether

INTRODUCTION

Durability refers to the ability of concrete to maintain its integrity in service. "Corrosion of steel reinforcement, freeze/thaw damage, salt scaling, alkali aggregate reactions, and sulfate attack, all of which can result in cracking and spalling of the concrete cover, are the major problems."[1] If concrete is properly designed for the environment to which it is to be exposed, and is properly placed and cured; it should last for many decades without costly repairs.

Engineers are currently shifting towards durability-based designs in an effort to extend the useful service lives of reinforced concrete structures in aggressive environments. The effectiveness of measures that are typically implemented to improve the resistance of concrete to these deterioration forces can be reduced by cracks in the hardened concrete. As a result, drying shrinkage is beginning to receive more consideration in the design and construction of concrete structures.

In an effort to meet the demands of the concrete construction industry, manufacturers of specialty construction materials have developed and introduced shrinkage-reducing admixtures (SRAs) that can be used to produce low shrinkage, high-performance concretes. SRAs are being studied and gaining acceptance within the world-wide concrete industry, especially in the United States.[2-7] In this paper, structures fabricated and repaired with SRA treated concrete are reviewed for their watertightness and overall serviceability.

Drying Shrinkage

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 of 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 due to moisture loss after the concrete has attained final set is known as drying shrinkage.

Drying shrinkage is the decrease in the volume of a concrete element when it loses moisture by evaporation. Drying shrinkage is inevitable unless the concrete is either completely submerged under water or is an environment that has 100 percent relative humidity. Therefore, drying shrinkage is a phenomenon that occurs routinely in concrete constructed works. With adequate restraint, drying shrinkage can cause cracking if the induced tensile stresses exceed the tensile strength of the concrete. Cracks provide easy access for oxygen, moisture, chlorides and other aggressive chemicals and agents into the concrete matrix, and can therefore impact long-term durability of concrete. Differentials in drying shrinkage between the top and bottom surfaces of slabs cause curling and possible cracking.

Shrinkage-Reducing Admixtures

SRAs were first developed in Japan in 1982 in a partnership between Nihon Cement Co., Ltd., now Taiheiyo Cement Corporation, and Sanyo Chemical Industries, Ltd.[2, 3] On October 15, 1985, U.S. Patent number 4,547,223 was granted to Goto et al. for the invention, the main component being a polyoxyalkylene alkyl ether, a lower alcohol alkylene oxide adduct.[8] Since, this invention interest in this technology has grown [9-12] and on September 17, 1996, U.S. Patent Number 5,556,460 was granted to Berke et al. for an SRA with a similar base composition.[13] Several low viscosity, water soluble SRAs have been developed by Taiheiyo Cement and Sanyo Chemical Industries. These admixtures function by reducing capillary tension and the tensile forces that develop within the concrete pores as it dries.[2-7] They are primarily used as integral admixtures, but some can be applied topically to concrete surfaces.[5]

Design and Construction Practice

Parameters that most influence drying shrinkage include the amount and size of reinforcement provided, and the size and shape, as well as the surface area-to-volume ratio of the concrete member. Steel-reinforced concrete will shrink less than plain concrete and the relative difference is a function of the reinforcement percentage providing restraint. In the same ambient condition, a small concrete member will shrink more than a larger member because of its higher surface area-to-volume ratio. The greater the area of area of exposure, the greater the rate of moisture loss, and hence the potential for drying shrinkage.

Improper concreting practices, such as job-site re-tempering, will increase drying shrinkage because of the increase in 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.[14] Steam curing will, however, reduce drying shrinkage.

Liquid containment is typically a design consideration in water-treatment plants, wastewater-treatment facilities, tanks, and reservoirs. The concrete used for these facilities should be of good quality to provide resistance to environmental effects such as freezing and thawing and must be watertight to minimize or eliminate leakage or groundwater contamination. ACI 350 recommends the following to minimize leakage: a) well proportioned and consolidated concrete; b) minimization of crack widths; c) proper joint spacing; d) impervious protective coatings or barriers where required; and e) provision of adequate reinforcement.[15]

Although proper design, such as specifying control joints and reinforcing steel is important, the most effective way of minimizing water leakage is by reducing the permeability and the drying shrinkage of concrete. ACI 350 recommends a maximum water-to-cementitious materials ratio of 0.45 and minimum cement contents based upon coarse aggregate topsize.[15] Drying shrinkage and hence drying shrinkage cracking can be reduced further through the use of SRAs.

In the case studies that follow, laboratory and field data is presented that show the effectiveness of an SRA in reducing drying shrinkage cracking thereby improving the watertightness of the structures.

Case Study #1: The Burbank Water Treatment Facility, Burbank, California

Three water tanks were erected to increase capacity of the Burbank Water Reclamation Plant in Burbank, California. The engineer specified typical containment structure concrete mixture parameters with 1.0-inch maximum aggregate size for pumpability, a slump of 7 ± 1 inches, an air content of 4 ± 1%, a 28-day compressive strength of 4000 psi and a maximum drying shrinkage of 0.042% at 28 days. Four concrete mixtures were studied for use on the project, a reference concrete mixture and three SRA-treated mixtures. The concretes were tested in accordance with applicable ASTM Standards.[16] The concrete mixture design, fresh concrete properties and hardened concrete performance data are included in Table I.

Table I. Concrete Mixture Proportions Burbank Water Treatment Facility

Materials	Reference	Mixture 2	Mixture 3	Mixture 4
Type II Cement, lb/yd^3	649	649	649	649
Sand, lb/yd^3	1289	1289	1289	1289
3/8" Aggregate, lb/yd^3	334	334	334	334
1" Aggregate, lb/yd^3	1432	1432	1432	1432
Total Water, lb/yd^3	292	292	292	292
Water/Cement Ratio	0.45	0.45	0.45	0.45
Admixture				
Superplasticizer, fl oz/cwt	5.0	5.0	5.0	5.0
Air Entrainer, fl oz/cwt	0.40	0.40	0.40	0.40
SRA, gal/yd^3	0.0	0.50	0.75	1.0

Plastic Properties of Concrete Mixtures				
Mixture	**Slump (in)**	**Air Content (%)**	**Plastic Unit Weight (lb/ft^3)**	**Concrete Temperature °F**
Reference	9.75	4.9	148.9	66
Mixture 2	9.25	5.0	148.7	67
Mixture 3	9.75	5.0	153.5	69
Mixture 4	10.25	3.8	152.9	70
Average Compressive Strength (psi)				
Mixture	**1-day**	**3-day**	**7-day**	**28-day**
Reference	2340	4270	4740	4900
Mixture 2	2640	3770	5210	5860
Mixture 3	2670	4690	5100	6210
Mixture 4	2890	4650	5410	6450
Average Length Change, % (negative sign denotes shrinkage)				
Mixture	**7-day**	**14-day**	**21-day**	**28-day**
Reference	-0.023	-0.033	-0.044	-0.049
Mixture 2	-0.011	-0.018	-0.027	-0.034
Mixture 3	-0.009	-0.014	-0.024	-0.028
Mixture 4	-0.007	-0.012	-0.020	-0.023

All three SRA treated concrete mixtures met the 28-day compressive strength and drying shrinkage requirements. For economic reasons "Mixture 2" was used in the construction of the water treatment tanks. The constructed tanks were filled with water and hydrostatic tested. Scrutinizing visual examinations for leakage specifically associated with drying shrinkage cracking were also conducted. All three tanks passed hydrostatic testing on the first trial and visually did not exhibit any leakage.

Case Study #2: The Los Angeles Metro Rail Red Line Tunnels, Los Angeles, California

The Metro Rail Red Line tunnels are parallel twin portals that link Hollywood to Universal City. The tunnels are part of a 6 1/2-mile-long rail line that starts in North Hollywood and will end in downtown Los Angeles.

Most of the 10,000 lineal feet of railway grade had a final elevation in bedrock that was stable enough to use standard 4,000-psi concrete for the cast-in-place tunnel lining. However, 2500 feet of the tunnel's path was located in an unstable stratum of friable sandstone with high permeability. Without structural support, the exposed sandstone would erode from groundwater infiltration. Additionally, local environmental concerns of potential groundwater contamination due to the porosity of the strata had to be addressed. With these design considerations a monolithic tunnel lining was proposed. The tunnel lining concrete mixture required a low water-to-cement ratio for permeability reduction and had a maximum shrinkage requirement of 0.040% at 28 days to be watertight and durable to meet long service-life requirements.

The mixture proportions and hardened properties for the Metro Red Line Tunnel are tabulated in Tables II and III below. This data was obtained from testing laboratories used on the project and can be found elsewhere.[17] Visual examination of the concrete showed no cracking after one year.

Table II. Concrete Mixture Proportions, Metro Rail Red Line Tunnels

Materials	**6000 psi**
Type II cement, lb/yd^3	700
Class F pozzolan, lb/yd^3	123
Sand, lb/yd^3	1242
3/8" gravel, lb/yd^3	243
1" gravel, lb/yd^3	1544
Water, lb/yd^3	267
Water, gal/yd^3	32
Water/cement ratio	0.32
Admixtures	
Superplasticizer, fl oz/cwt	5.0
SRA, gal/yd^3	0.75
Hydration Control, fl oz/cwt	1.0 - 8.0
Water Reducer, fl oz/cwt	8.0
Slump, in	6.0 – 9.0
Air Content, %	2.0

Table III. Hardened Properties for the Metro Rail Red Line Tunnels

ASTM C157 Shrinkage Test Data				
Age of Sample after (air storage)	**Sample 1**	**Sample 2**	**Sample 3**	**Average**
5 days	-0.000%*	-0.001%	-0.000%	-0.000%
7 days	-0.001%	-0.001%	-0.000%	-0.001%
14 days	-0.011%	-0.001%	-0.010%	-0.007%
21 days	-0.013%	-0.008%	-0.013%	-0.011%
28 days	-0.020%	-0.013%	-0.019%	-0.017%
* Negative sign denotes shrinkage				
Compressive Strength , psi				
Age	**Strength (psi)**		**Age**	**Strength (psi)**
7 days	6170		28 days	7060
	6070			7290
	6260			7460
Average	6170		Average	7270

Case Study #3: Dupont Circle Parking Garage Full-Depth Repair, Washington, D.C.

The drying shrinkage of repaired concrete is one of the important factors that influence the dimensional behavior. Bond failures and cracking generally result from dimensional incompatibility between the repair material and the existing substrate. The existing concrete substrate has already experienced most of its time-dependent volume change such as drying shrinkage and creep. However, the repair concrete must also undergo volume changes after placement. Consequently, it is very important to identify and select a low shrinkage repair material. Additionally, the durability of the concrete repair must be considered so that it may resist structural loading and environmental conditions (i.e. deicing salts) without degradation and deterioration.

A SRA was evaluated in the full-depth repair of the Dupont Circle Parking Garage through the use of vibrating wire strain gauges to examine the dimensional stability of the in situ concrete. This repair was necessitated by corrosion of the reinforcing steel and electrical conduits within the 11-inch thick flat slab. The repair concrete mixture proportions are in Table IV. Companion length change test specimens were fabricated. Two sets of ASTM C157 specimens were cast with one set cured under job site conditions (Reference and SRA 4-6) and the other set was cured under standard laboratory conditions (Reference and SRA 1-3) for twenty-eight days, thereafter both sets were placed in the standard laboratory environment. This allowed for examination of the relationship between drying shrinkage measurements in situ and traditional test specimens used for ASTM C 157.

Table IV. Repair Mixture Proportions for Dupont Circle Parking Garage

	Reference	**SRA Treated**
Type I cement, lb	705	705
Sand, lb	1428	1428
#8 aggregate, lb	1650	1650
Water, gal.	34	34
Water/cement ratio	0.40	0.40
Admixtures		
Water Reducer, fl oz/cwt	3.0	3.0
Superplasticizer, fl oz/cwt	8.0	8.0
SRA, gal/yd^3	N/A	1.5
Air Entrainer, fl oz/cwt	0.70	0.70
Calcium Nitrite Corrosion Inhibitor, gal/yd^3	3.0	3.0
Slump, in	6-9	4
Unit Weight, lb/ft^3	145.2	148.4

Table V. ASTM C157 Laboratory Results (μstrain)

Date **Age (days)**	**9/28/98** **3**	**10/2/98** **7**	**10/9/98** **14**	**10/15/98** **20**	**10/23/98** **28**	**01/18/99** **115**	**08/11/99** **320**	**01/12/00** **474**
Reference 1	50	-280	-490	-590	-650	-920	-1020	-1090
Reference 2	30	-280	-480	-590	-660	-850	-930	-980
Reference 3	40	-280	-500	-630	-680	-980	-1060	-1120
Reference 4	50				-680	-890	-990	-1070
Reference 5	30				-640	-880	-960	-1030
Reference 6	40				-640	-840	-900	-970
Lab Avg. (1 - 3)	**40**	**-280**	**-490**	**-603**	**-663**	**-917**	**-1003**	**-1063**
Field Avg. (4 - 6)	**40**				**-653**	**-870**	**-950**	**-1023**
SRA 1	40	-190	-300	-400	-440	-660	-780	-780
SRA 2	20	-190	-290	-360	-410	-650	-730	-800
SRA 3	60	-140	-260	-340	-410	-580	-650	-750
SRA 4	40				-370	-580	-670	-720
SRA 5	40				-370	-650	-720	-730
SRA 6	40				-370	-630	-710	-790
Lab Avg. (1 - 3)	**40**	**-173**	**-283**	**-367**	**-420**	**-630**	**-720**	**-777**
Field Avg. (4 - 6)	**40**				**-370**	**-620**	**-700**	**-747**

Table VI. In Situ Volume Change Measurements

Date	Age (days)	Reference Repair Vertical (μstrain)	SRA Repair Vertical (μstrain)
9/25/98	0	0	0
9/26/98	1	-91.35	-65.23
9/28/98	3	-98.68	-65.58
10/23/98	28	-196.43	-92.66
01/18/99	115	-348.57	-160.61
08/11/99	320	-586.24	-297.73
01/12/2000	474	-688.46	-361.82

Temperature and Relative Humidity Measurements in Garage

Date	**9/26/98**	**9/28/98**	**10/23/98**
Dry Bulb (F)	78	78	55
Wet Bulb (F)	69	72	45
Relative humidity (%)	64	74	45

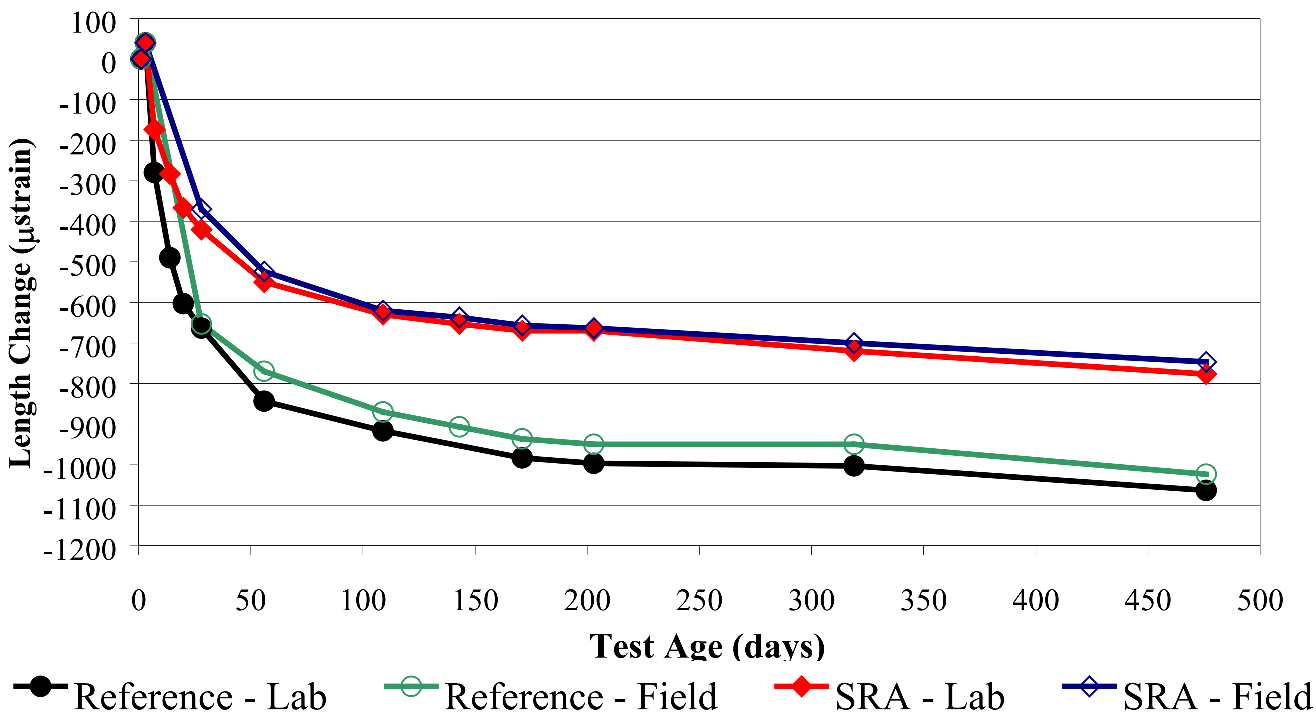

Fig. 1 ASTM C 157 Shrinkage Data for Dupont Circle Full Depth Repair

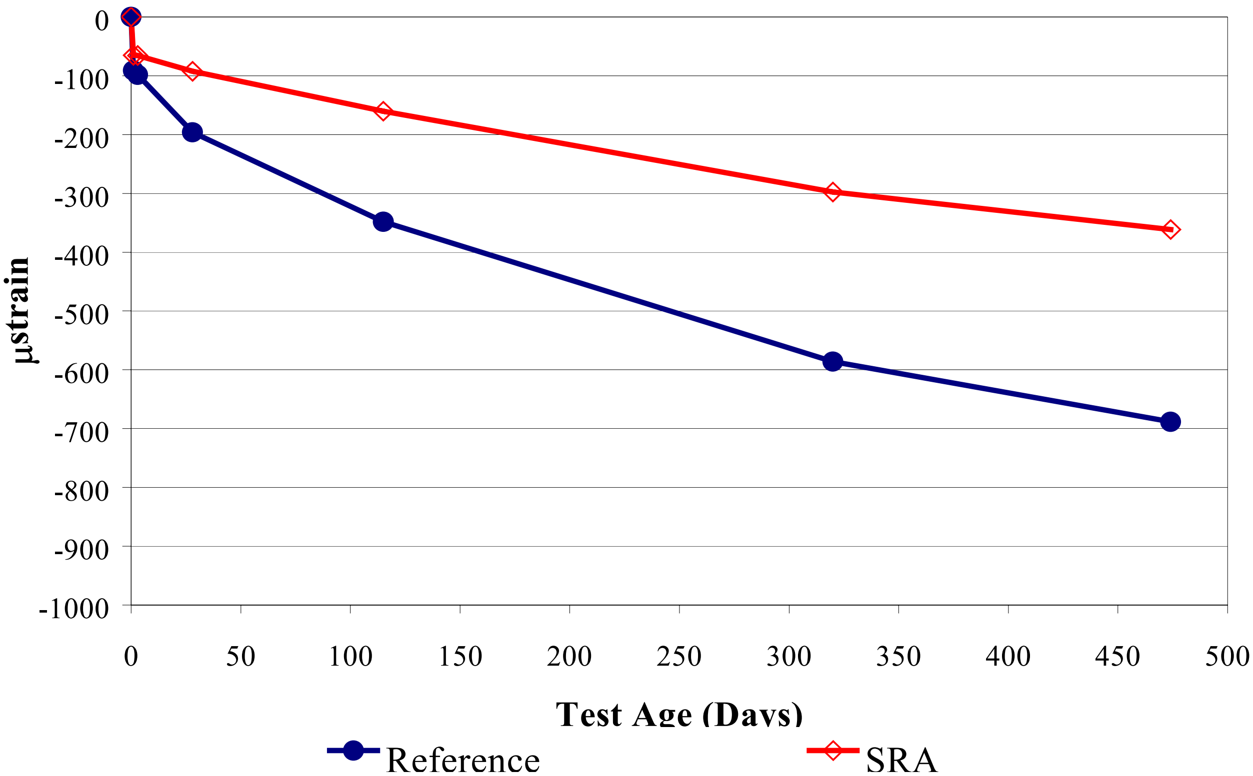

Fig. 2 In situ Shrinkage Data for Dupont Circle Full Depth Repair

Figs. 1 and 2 show the laboratory and in situ drying shrinkage from the Dupont Circle Parking Garage case study. Both figures illustrate the significant reductions in drying shrinkage that can be obtained with SRA treated concrete.

The Dupont Circle Parking Garage case study provides insight into the differences between laboratory and in situ measurements. The data presented in Tables V and VI show that the SRA significantly reduced drying shrinkage in both the standard test conditions and in the structure. The data also show that drying shrinkage results produced from ASTM C 157 testing are significantly greater than that experienced in situ. However, the 28-day laboratory results were similar to the drying shrinkage strains experienced in situ after fifteen months in the heated, underground parking garage. This may not be true for the other structures due to environmental and other differences.

The data shown in Fig. 3 illustrates the reduction of drying shrinkage with SRA in comparison to reference concrete mixtures in laboratory and field conditions at both early and late ages. For example, drying shrinkage reductions of 37 and 27% were obtained at 28 and 474 days respectively for laboratory test specimens. Reductions of 53 and 47% were observed at the same ages in situ (Fig. 3).

The surface to volume ratio is a significant factor when estimating the volume change in real structures from laboratory drying shrinkage data. Fig. 4 presents the in situ drying shrinkage in Table VI as a ratio of the laboratory drying shrinkage in Table V. At 28 days, the structure experienced 22-30% of the shrinkage experienced in laboratory specimens and after fifteen months, this ratio increased to 47-65%. The difference in magnitude seen in these percentages can be attributed in part to the larger surface to volume ratio in the small, slender laboratory specimens and environmental differences such as relative humidity (Table VI). The larger surface to volume ratio accelerates moisture loss from the specimens. This is confirmed by comparing the slopes of the drying shrinkage curves in Figs. 1 and 2. Fig. 1 shows that most of the drying shrinkage of the ASTM C157 specimens occurred in the first 180 days, whereas the in situ measurements have yet to reach equilibrium. Since drying shrinkage occurs in the structure at a slower rate, the effect of creep reduces the induced tensile stress and thereby the cracking potential. Therefore, by reducing the early age drying shrinkage with a SRA the overall cracking potential is reduced for the life cycle of the structure.

Fig. 5 illustrates the visual inspection of the repairs after fifteen months. The SRA treated repair was well bonded and showed no evidence of cracking within the body of the repair. In contrast, the reference concrete showed visible hairline cracking within the body of the repair and along one edge. The absence of cracking in the SRA treated repair will improve the corrosion resistance of the concrete by minimizing the ingress of water, oxygen and chloride ion from deicing salts.

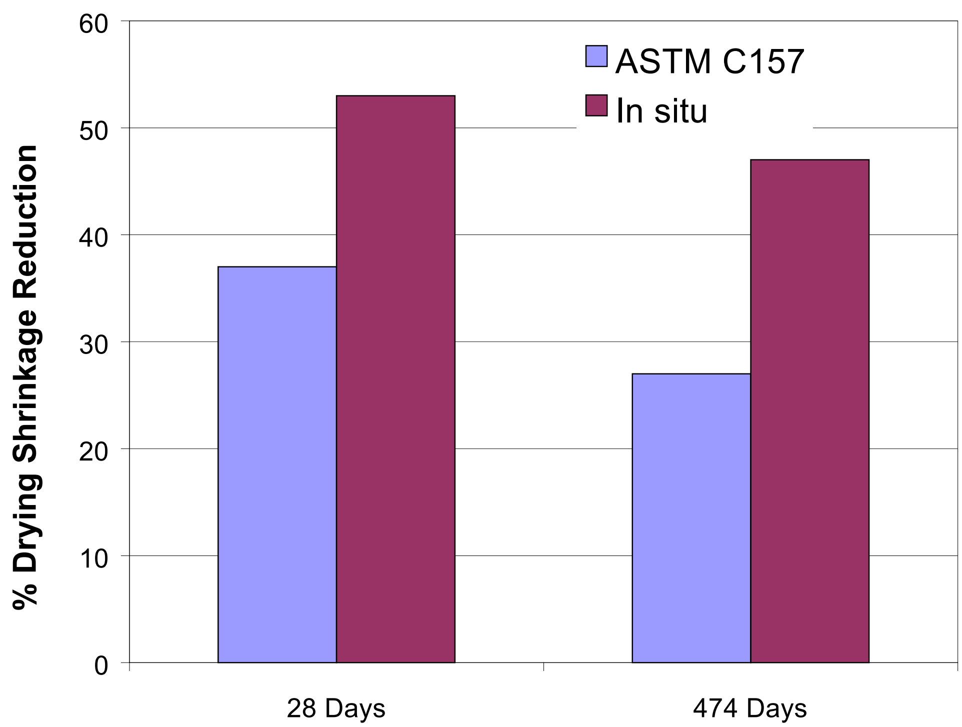

Fig. 3 Shrinkage Reduction with SRA

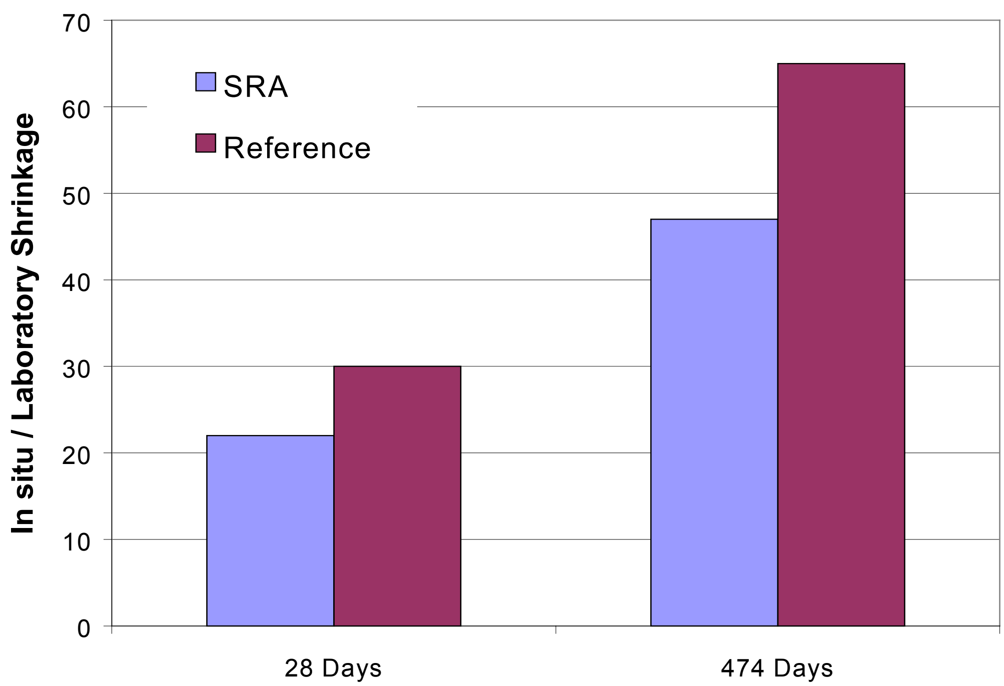

Fig. 4 Drying Shrinkage Test Method Comparison

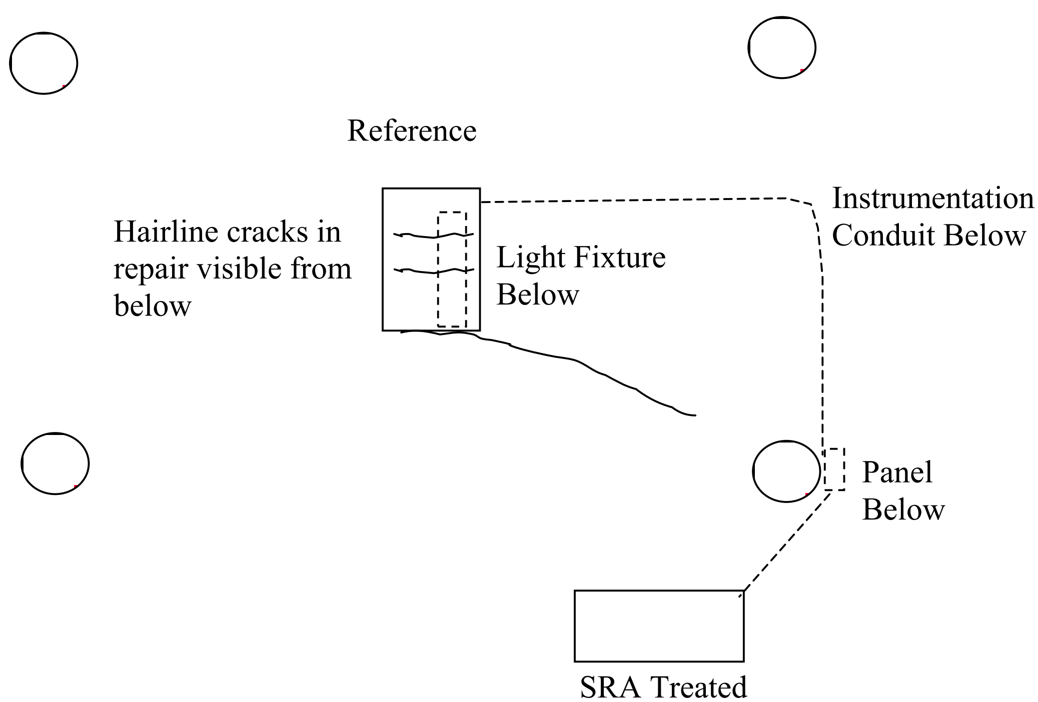

Fig. 5 Sketch of Cracks Found in Repairs After Fifteen Months

Conclusions

Drying shrinkage is an inherent and unavoidable property of concrete, including high-performance concrete, and can detrimentally impact the aesthetics, durability, and serviceability of reinforced concrete structures. However, with implementation of durability-based designs and good concrete construction practices, drying shrinkage and subsequent cracking can be minimized to extend the useful service lives of reinforced concrete structures.

The shrinkage-reducing admixture described in this paper has provided significant reductions in drying shrinkage and subsequent cracking in both laboratory and field investigations. This novel admixture has provided substantial benefits with regards to improved watertightness, aesthetics and overall serviceability of reinforced concrete structures. The inclusion of shrinkage-reducing admixtures can be used to great advantages in slabs, bridge decks, liquid containment structures and repair work where cracking can lead to steel reinforcement corrosion and decreased resistance to other aggressive species. Inherently, improving durability has "…perhaps the highest potential of all for achieving remarkable cost-saving benefits in the infrastructure."[18]

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References

1. Hanson, C.M., "Concrete: The Advanced Industrial Material of the 21st Century", The 1993 Edward DeMille Campbell Memorial Lecture ASM International, *Metallurgical and Materials Transactions A*, Volume 26A, June 1995, pp. 1321-1341.

2. Sato, T., Goto, T., and Sakai, K., "Mechanism for Reducing Drying Shrinkage of Hardened Cement by Organic Additives," *Cement Association of Japan (CAJ) Review*, 1983, pp. 52-54.

3. Tomita, R., Takeda, K., and Kidokoro, T., "Drying Shrinkage of Concrete Using Cement Shrinkage Reducing Agent," *Cement Association of Japan (CAJ) Review*, 1983, pp. 198-99.

4. Berke, N.S., Dallaire, M.P., Hicks, M.C., and Kerkar, A., "New Developments in Shrinkage-Reducing Admixtures," Superplasticizers and Other Chemical Admixtures in Concrete, SP-173, American Concrete Institute, Farmington Hills, MI, 1997, pp. 971-998.

5. Nmai, C., Tomita, R., Hondo, F., and Buffenbarger, J., "Shrinkage-Reducing Admixtures for Concrete," *ACI Concrete International*, Vol. 20, No. 4, April 1998, pp.31-37.

6. Nmai, C., Mullen, B., Fletcher, K., "Comparative Evaluation of Shrinkage-Reducing Admixtures for Concrete," *Concrete99*, Concrete Institute of Australia 19th Biennial Conference Proceedings, D. Baweja, S. Bernard, P. Shea and R. Wheen, eds., May 1999, pp. 84-90.

7. Nmai, C. and Seow, K.H., "Shrinkage-Reducing and Other Durability-Enhancing Admixtures for Concreting in the 21st Century,

8. United States Patent Number 4,547,223, Goto et al., October 15, 1985.

9. EP 0 359 068 A2, Okuno et al., March 21, 1990.

10. United States Patent Number 5,326,396, Abdelrazig et al., July 5, 1994.

11. United States Patent Number 5,389,143, Abdelrazig et al., February 14, 1995.

12. United States Patent Number 5,498,665, Schulze et al., March 12, 1996.

13. United States Patent Number 5,556,460, Berke et al., September 17, 1996.

14. Neville, A.M., *Properties of Concrete*, 3rd Edition, Pitman Publishing, Inc., MA, 1981, p. 779.

15. ACI 350R, "Environmental Engineering Concrete Structures," *ACI International*, Farmington Hills, MI.

16. *Annual Book of ASTM Standards*, Vol. 04.02 - Concrete and Aggregates, ASTM, West Conshohocken, PA, 1997.

17. Yelton, R., "Special-effects concrete in Hollywood," *The Concrete Producer*, February 2000, pp.41-44.

18. CERF Report #94-5011, "Materials for Tomorrow's Infrastructure: A Ten-Year Plan for Deploying High-Performance Construction Materials and Systems – Technical Report," Civil Engineering Research Foundation, Washington, D.C., December 1994, p. 150.