IN Ci

Working Knowledge

Concrete shrinkage is not a new problem. J.B. Johnson discussed it in *A Treatise for Engineers on the Strength of Engineering Materials* in 1897. But shrinkage continues to be a timely topic.

Low-shrinkage mixtures are used to minimize curling and thereby help meet the increasing demand for very flat and level industrial floors. As McKinney and Neuber report (p. 29), mixtures with very low paste fractions are common. Combined with highly efficient placing and finishing technologies, however, such mixtures may be contributing to isolated instances of surface distress. Solutions are proposed.

Low-shrinkage mixtures are also used to minimize cracking in bridge decks, with the ultimate goal of boosting service life. As Maggenti, Knapp, and Fereira (p. 36) report, California's department of transportation, Caltrans, has successfully instituted specifications defining shrinkage limits. On the numerous projects cited, contractors have selected shrinkage reducing admixtures to help meet the performance requirements. Both the means and the end are notable.

Many of the factors affecting shrinkage are discussed further in documents produced by ACI committees (Concrete Q&A, p 64). Combined, these articles and documents demonstrate that multiple parameters must be considered toward minimizing shrinkage. No one party can control such complexity, so collaboration among the owner, engineer, supplier, and contractor is essential.

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Controlling Shrinkage Cracking

Available technologies can provide nearly crack-free concrete bridge decks

by Ric Maggenti, Craig Knapp, and Sonny Fereira

It's widely accepted that the durability of structures—particularly concrete bridge decks—will be compromised by the presence of cracks. It's also widely accepted that a major source of cracking is concrete shrinkage. Although research on concrete shrinkage started well over a century ago,[1] our industry has yet to establish a standard and accepted practice for consistently, reliably, and predictably producing concrete structures with minimal or no cracking due to shrinkage stresses. We believe, however, that the industry is on the verge of establishing an accepted practice, coupling newly available tools with an understanding of how various factors impact shrinkage.

Shrinkage Cracking

Shrinkage cracking can have many causes, including:

- Restraint of autogenous and chemical shrinkage strains;
- Strain gradients induced after hardening by hydration heat and surface cooling (thermal strains);
- Strain gradients caused by loss of water to the environment while concrete is fresh (plastic shrinkage); and
- Restraint of drying shrinkage after concrete has hardened (drying shrinkage).

In bridge decks, autogenous, chemical, and thermal effects are generally minor. Also, it's well-established that eliminating evaporation of water from the concrete during and immediately following placement will control and prevent plastic shrinkage. For these reasons, our article focuses solely on drying shrinkage.

Drying Shrinkage Cracking

In his President's Address at ACI's 27th Convention in 1931, Duff A. Abrams observed, "…we shall never have adequate basis for specifications, design, and construction in concrete and reinforced concrete until we develop a sound theory.…[With] a complete theory of concrete we should be able to calculate in advance all properties…"[2] Much has been done toward developing sound theory on drying shrinkage, so we should be able to calculate shrinkage in advance and work to avoid the associated cracking.

In 1930, Davis summarized investigations, dating from the nineteenth century, on moisture and thermal volume changes in concrete.[3] Of the 11 factors he identified as important, many were functions of testing methods, including sample size, durations of wetting and drying, and storage environment for the sample. Five of the 11 factors are most pertinent to modern-day concrete practice:

- Composition and fineness of cement;
- Proportions of cement and aggregate;
- Type and gradation of aggregate;
- Consistency of the mixture (well before today's admixtures, this was a measure of water content); and
- Amount and distribution of reinforcement.

More recent observations have provided detailed evaluations of parameters such as water and paste contents, characteristics of the aggregates, and admixtures.

Water and paste contents

As reported by Carlson,[4] E.N. Vidal and D.O. Ehrenburg at the Denver Laboratory of the Bureau of Reclamation made an early observation that drying shrinkage could be correlated with water content, irrespective of aggregate source, aggregate gradation, cement content, water-cement ratio (*w/c*), or curing duration. Graphs of shrinkage versus water content have since been reprinted in editions of the *Concrete Manual* (at least as early as the sixth edition published in 1956[5]) produced by the Bureau of Reclamation of the U.S. Department of the Interior (Fig. 1).

Tests reported in 1963 by Tremper and Spellman[6] of the California Division of Highways Transportation Laboratory verified Carlson's work. In their tests, mixtures with consistent water content and cement contents ranging from 496 to 754 lb/yd^3 (five to eight sacks or 294 to 447 kg/m^3) exhibited similar shrinkage. The same trend was also shown when comparing mortar containing 752 to 1053 lb/yd^3 (eight to 11 sacks or 446 to 625 kg/m^3) of cement. "Slightly higher" shrinkage was reported only with mixtures with 1270 lb/yd^3 (13.5 sacks or 753 kg/m^3) cement content. The authors also reported that curing beyond 3 days did not

reduce shrinkage—verifying Carlson's findings.[7] It's important to keep in mind, however, that the slumps used in the studies reported in References 4 and 6 were limited by the contemporary placement capabilities and admixtures.

The correlation of water content with drying shrinkage, almost exclusive of other factors, does not conflict with the maxim that concrete shrinkage originates in the paste. It also does not conflict with the observation that paste shrinkage is proportional to the water-cementitious material ratio (*w/cm*) (Fig. 2).

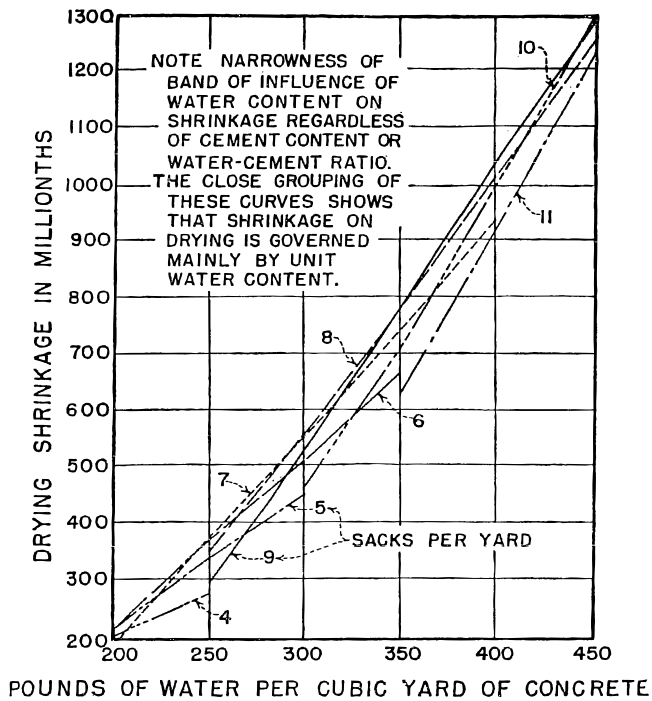

Fig. 1: Influence of water content on drying shrinkage of concrete mixtures with various cement contents[5] (Note: 1 lb/yd³ = 0.6 kg/m³, one sack = 94 lb = 43 kg)

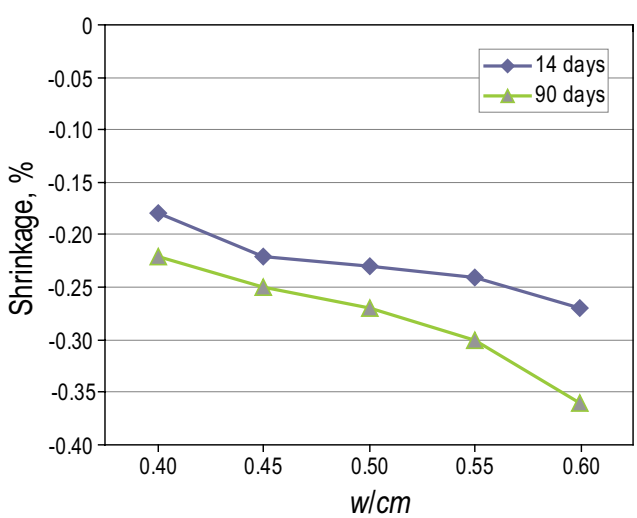

Fig. 2: Effect of *w/cm* on paste shrinkage *(Source: Unpublished Caltrans data used in internal presentations)*

For any given aggregate, slump is a characteristic of water content (excluding the use of admixtures), regardless of paste content. So, if slump is to be held constant, the water must also be held constant. An increase in cement content will thus decrease the *w/c*, paste shrinkage will decrease, and this will offset the increased concrete shrinkage due to the increased paste content (Fig. 3). If more water is added to increase slump and more cementitious material is added to maintain constant *w/cm*, the increased paste content will increase the concrete shrinkage.

Aggregates

Aggregates directly influence drying shrinkage by restraining shrinkage of the paste. This has been verified using concrete specimens with nonabsorbent rubber particles as aggregate having no or little restraint capacity (resulting in shrinkage equal to that of the neat cement).[8] Shrinkage will be a function of the aggregate's stiffness (for a given aggregate size, concrete shrinkage will decrease with increasing aggregate modulus of elasticity) and drying shrinkage (concrete shrinkage will increase with increasing aggregate drying shrinkage). This is not new information. In 1938, for example, Carlson listed the following aggregate types in increasing order of influence on concrete shrinkage: quartz, limestone, granite, basalt, and sandstone.[4,7]

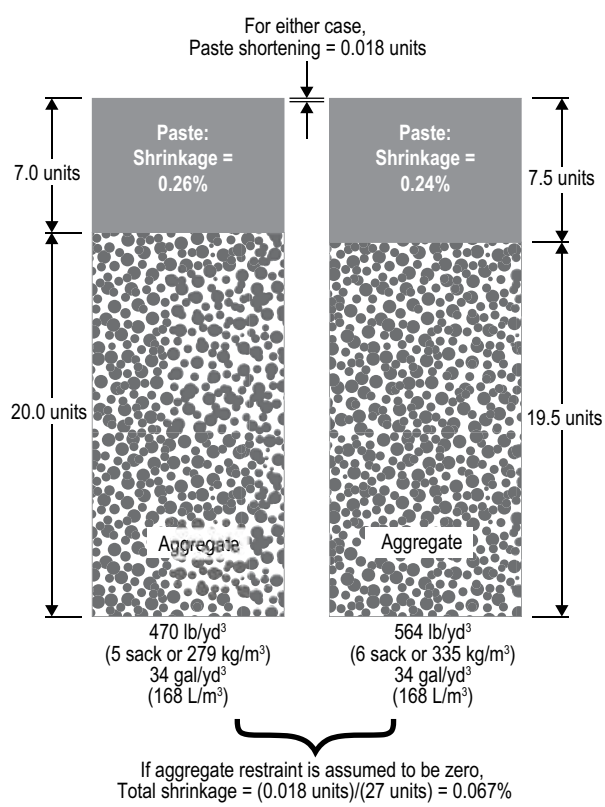

Fig. 3: A hypothetical example showing the counteracting effects of increased cement content with constant water content

The size, shape, and gradation of the aggregates in a mixture also indirectly influence shrinkage by affecting water content and volume of paste in the concrete. Maximizing the amount of aggregate per unit volume of concrete reduces the amount of paste, minimizing the drying shrinking component. Additionally, the aggregate shape affects the amount of water necessary to accomplish the required consistency. For any given *w/c* or *w/cm*, water demand clearly dictates the paste content.

Contamination of aggregate particles with substances such as clay particles can affect water demand and thus increase drying shrinkage. Contamination can also affect the bond of the paste at the aggregate paste interface, directly influencing the aggregate's ability to restrain paste movement.

Setting limits

There has long been evidence suggesting that a target 28-day shrinkage value below 0.030% would significantly limit or eliminate early-age shrinkage cracking. It has also long been known, however, that it would be difficult to achieve a 28-day shrinkage value below 0.030% without transporting specific aggregates to areas where they are not readily available. An 8-year-long study of the Webber Creek Bridge on SR 50 east of Sacramento, CA,[9] for example, evaluated concrete deck sections constructed on steel plate girders with 137 ft (42 m) simple spans.

After 8 years in service, a deck section comprising Type II cement and quartz aggregate had very low amounts of cracking, with only 26 ft (8 m) of soffit cracking. None of these cracks exhibited signs of leakage. The 28-day shrinkage value for the mixture was 0.020% per ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete." In contrast, a similar section comprising a graywacke sandstone mixture exhibited 533 ft (162 m) of soffit cracking, with 18 leaking cracks. The 28-day shrinkage value for the mixture was 0.050% per ASTM C157/C157M.

In a March 1966 study,[7] the California Producers Committee on Volume Change reported that only 5% of the concrete produced would have a 28-day shrinkage value less than 0.030%. It also reported that a 28-day shrinkage value of 0.020% was about the lowest attainable. Even when using good-quality, large aggregate and minimizing water content, low shrinkage values could be achieved only in the best of circumstances.

Efficient means

Today, for a multitude of aggregates and mixture designs, shrinkage-reducing admixtures (SRAs) appear to be an economical and efficient means to achieve a 28-day shrinkage value below 0.030%. SRAs reduce capillary tension in the paste pore water, thereby decreasing shrinkage strains as paste dries.

In 2002, prior to the segmental construction of the Skyway portion of the new east spans of the San Francisco-Oakland Bay Bridge (SFOBB), San Jose State University began investigations of the influence of chemical admixtures on drying shrinkage in high-strength concrete. Testing was performed on over 40 concrete samples and over 80 paste samples, with some measurements continuing after 9 years.[10] Figure 4 summarizes data on 22 concrete mixtures from that investigation. All concrete had a *w/cm* of 0.33 and contained 631 lb/yd^3 (374 kg/m^3) of cementitious material (cement replacements of 20, 25, or 30% with fly ash and 5% with silica fume or metakaolin). Figure 5 illustrates results for paste consisting of portland cement with *w/c* of 0.33 and varying SRA dosages. The effect of SRA on shrinkage is apparent. To show the difference in magnitude

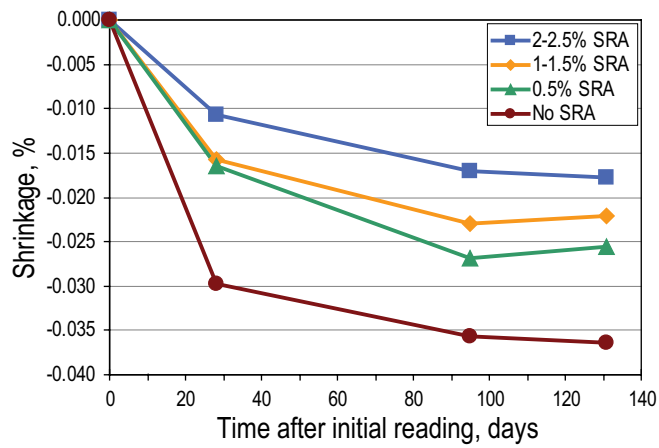

Fig. 4: Concrete shrinkage over time for mixtures with and without SRAs. Data for the control mixture (no SRA) are the averages of four batches. Data for the 0.5% SRA dosage are the averages of five batches. Data for the 1 to 1.5% and 2 to 2.5% SRA dosages represent averages of six batches each. Three shrinkage bars were tested per batch *(Source: Unpublished Caltrans data used in internal presentations)*

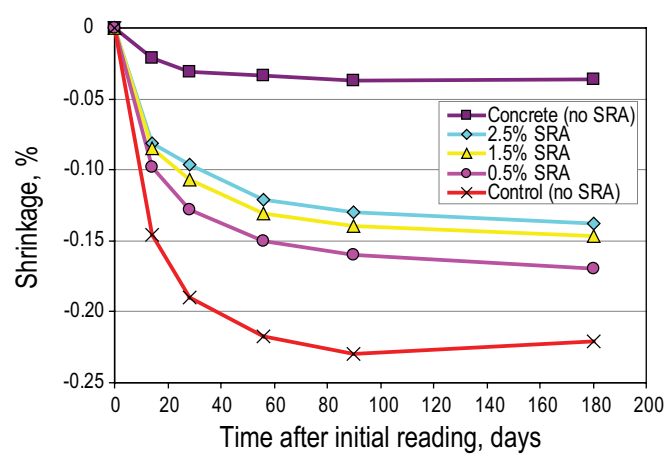

Fig. 5: Effect of SRA dosage on cement paste only, compared with a typical Caltrans high-performance concrete deck mixture *(Source: Unpublished Caltrans data used in internal presentations)*

of paste versus concrete, Fig. 5 includes data for a concrete mixture meeting the California Department of Transportation (Caltrans) bridge deck specification (*w/cm* of 0.34 and 675 lb/yd^3 [400 kg/m^3] of cementitious materials with cement replacements of 25% fly ash and 5% metakaolin).

Given the numerous successful case studies provided by SRA suppliers, and given the positive experiences of Caltrans and other agencies,[11,12] Caltrans has selected SRAs as a method of crack control in cast-in-place decks on precast girders.

Demonstrating success

Between 2001 and 2003, six new bridges with cast-in-place decks on spliced precast bulb-T girders were constructed on I-80 near Truckee, CA. The mixtures had *w/cm* of 0.36, cementitious material contents of 752 lb/yd^3 (446 kg/m^3) with 25% fly ash cement replacement), and 6% air content. Curing was performed according to the Caltrans standard requirements.

After the first few decks were constructed, multiple transverse cracks (on about 2 ft [0.6 m] centers) were visible. Beginning in late summer of 2002, deck mixtures were modified to include SRAs. As shown in Fig. 6, there was a dramatic reduction in cracking. The following construction season, the remaining structures were constructed using an SRA in the deck concrete. The decks constructed using SRAs have remained free of visible cracking.

Following this simple, yet effective, adjustment to the mixture design, specifications were written for the deck mixture for the Angeles Crest Bridge on SR 2 in Los Angeles County, in the mountains northeast of Los Angeles, CA. Specifications called for a 28-day strength of 5000 psi (34.5 MPa) and a 6% air content.

Construction was completed in 2008 using a deck mixture with 767 lb/yd^3 (455 kg/m^3) of cementitious material and SRA. This is a 208 ft (63 m) single-span bridge with the deck cast on six 8 ft (2.4 m) deep spliced precast/prestressed bulb-T girders spaced on 6.5 ft (2 m) centers. Upon later inspection, the bridge maintenance engineer reported: "You appear to have been successful in mitigating the cracking, as the only cracks I could find were some hairline shrinkage cracks at the westerly end." The same result has been achieved on several projects, including the 2007 emergency replacement of the fire-destroyed bridge spans at the MacArthur Maze in Oakland, CA. This replacement was completed in a mere 26 days using a deck mixture comprising SRAs, 800 lb/yd^3 (475 kg/m^3) of cementitious material, water reducers, and a Type C accelerating admixture. The deck was cast on steel girders with headed studs for composite action. No cracking has yet been reported on this replacement deck span, while transverse cracks have been noted every few feet on all adjacent deck spans. The original spans used a six-sack (564 lb/yd^3 [335 kg/m^3]) mixture with 1.5 in. (38 mm) maximum nominal aggregate. These projects demonstrated that SRAs could eliminate the need to specify low-strength concrete, long curing times, a low *w/cm*, or large aggregates.

"Deck-on-deck" rehabilitation of the Pit River Bridge on I-5 over Shasta Lake, CA, in 2007 permitted evaluation of several mixture designs, including combining SRA with fibers. Deck-on-deck construction is especially prone to cracking due to drying shrinkage stresses. Relying upon our earlier experience of using SRAs to reduce early-age deck cracking and several previous successful applications of synthetic polyolefin macrofibers to restrain plastic and drying shrinkage cracking, the two technologies were combined for a "crackless" concrete deck (771 lb/yd^3 [8.2 sacks or 457 kg/m^3] of cement, 6% air, *w/c* of 0.51, SRA at 0.75 to 1.5 gal./yd^3 [3.7 to 7.4 L/m^3], and fibers at 3 lb/yd^3 [1.8 kg/m^3]). After 5 years of service, sections of the deck comprising both SRA and fibers exhibited very limited cracking. Cores taken at cracked locations indicated that cracks were very thin and most were arrested near the surface. Two cores extracted at full-depth (4 in. [102 mm]) crack locations showed finelined cracks kept intact by the

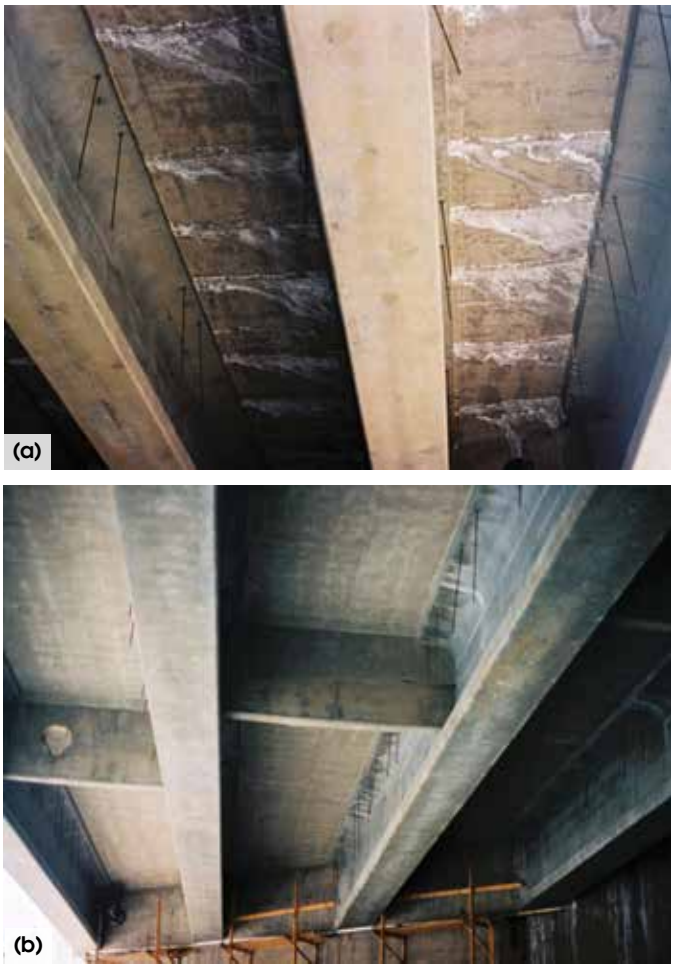

Fig. 6: Cast-in-place decks and spliced precast bulb-T girders on I-80 near Truckee, CA: (a) deck constructed without SRA; and (b) deck constructed with SRA *(photos courtesy of Ric Maggenti)*

fibers. In contrast, the control sections of the deck, placed without SRA and without fibers, exhibited substantial cracking within 6 weeks.

In 2011, a 5 in. (127 mm) "crack-free" deck was placed on precast box beams over Craig Creek on SR 99 near Red Bluff, CA. The concrete mixture was designed to develop a 3-day strength of 4000 psi (27.6 MPa), using 705 lb/yd^3 (418 kg/m^3) portland cement (*w/c* of 0.39), SRA (0.75 gal./yd^3 [3.7 L/m^3]), and synthetic macrofibers (3 lb/yd^3 [1.8 kg/m^3]). The project was used to study accelerated bridge construction via high-performance concrete and limited time (only 3 days) for moist curing. No visible cracking was noted during inspection after 14 months of service. It was concluded that a high-quality, durable deck can be successfully and rapidly constructed.

A concrete mixture comprising SRA and fibers was also used to construct the roof of a maintenance station on the Doyle Drive project in San Francisco, CA. The completed deck also serves as the invert of the project's tunnel. The deck was found to be crack-free 6 months after construction.

The effectiveness of SRAs in mitigating shrinkage cracking was also demonstrated on 1 ft (0.3 m) thick concrete encasement jackets placed around steel footing boxes on the Skyway portion of the new east spans of SFOBB. Impressively, there were no cracks, even at the reentrant corners (Fig. 7), several months after construction. SRA was also used successfully in the project's pile caps.

Fig. 7: Concrete footing jacket on the skyway portion of the new span for the SFOBB: (a) stay-in-place steel forms with headed studs; and (b) finished jacket, exhibiting no visible cracks *(photos courtesy of Bill Lee and Ric Maggenti)*

Ongoing Needs

Tens of thousands of cubic yards of high-strength concrete have been supplied with SRAs to meet the Caltrans shrinkage performance requirements of 0.030% at 28 days and 0.045% at 180 days. Segmental bridges such as Confusion Hill; Devil's Slide; the Spanish Creek Spandrel Arch Bridge in Plumas County, CA, on SR 70; and the two large box girder bridges of the east spans of the SFOBB have been constructed under a performance specification for shrinkage. In all cases, the contractors elected to use SRAs to meet the shrinkage performance requirements. In the latter case, only 0.5 gal./yd^3 (2.5 L/m^3) of SRA was used, yet the mixture exhibited 28-day shrinkage values of only about 0.020%.

It should be noted that the SFOBB projects were in an area with high-quality aggregates (which were absolutely necessary to produce the specified high-performance concrete). In locations where aggregate quality is very poor, it may be necessary to use SRAs in addition to other practices, such as using larger maximum size aggregate, to reduce water demand and control drying shrinkage.

While it is also possible to use methacrylate treatments to fill and seal cracks, the preparation and application costs for these treatments are more than double the costs for an effective dosage of SRA and fibers. Therefore, preventing cracks is a more cost-effective solution.

Bases for Success

As Bryant Mather wrote in 1951: "…concrete research has value and meaning only as it improves the quality, economy, and applicability of concrete for construction…"[13] Research and experience has convincingly demonstrated that early-age shrinkage cracking in concrete bridge decks can be significantly reduced if the mixtures have 28-day shrinkage values below 0.030%. While controlling drying shrinkage to these levels previously required use of low-slump mixtures and large, dense aggregates, it is now possible to do so using SRAs, water reducers, and fibers. With a sound theoretical basis, we believe that SRA mixtures satisfy Abram's key requirement for the control of concrete behavior. With the associated improvements in quality and economy, we also believe the research behind these mixtures meets Mather's requirements for value and meaning.

Acknowledgments

The authors wish to recognize the generation of leaders that we followed for their contributions to the body of materials science, immense construction engineering knowledge, and contagious knack for inspiring scientific study. While this list is large, some former

Caltrans engineers are at the top of our list: James E. Roberts, L. Edwin Dunn, Leo R. Ferroni, Bert P. Bezzone, Loren L. Krueger, and David K. DeFoe. Importantly in the civil service arena, they accomplished their missions and made their careers by balancing risks necessary for pioneering advancements in modern engineering methods with the responsibility and incontrovertible duty to keep and protect the public trust.

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