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## **Understanding Early-Age Shrinkage of High-Performance Concrete for Bridge Deck Applications**

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**ABSTRACT**

The paper discusses results and analyses from a series of early-age autogenous shrinkage measurements for several high performance concrete mixtures developed for bridge deck applications using fly ash and silica fume. These tests were performed under temperature-controlled conditions to investigate the influence of mixture proportions and binder composition on early-age shrinkage measurements.

For bridge decks, it is desirable to minimize autogenous shrinkage. Because autogenous shrinkage is due to self-desiccation, it cannot be mitigated with curing techniques. Rather it must be addressed during mix design. Excessively high autogenous shrinkage can lead to cracking that reduces the life span of bridge decks and negates the benefit of reduced permeability by providing a direct path for chlorides to reach reinforcing steel.

Corrections for measured strains resulting from temperature effects are also discussed. The problem of autogenous shrinkage measurement at early ages is complicated by the nebulous definition of strains during the transition from a semi-liquid to a solid. It is hence necessary to complement autogenous shrinkage measurements with measurements of concrete setting times. The presence of free water within the concrete matrix (as indicated by setting times) greatly influences the thermal expansion of concrete. In order to accurately represent very early-age measurement of autogenous shrinkage, the thermal expansion of the concrete due to heat of hydration must be corrected for. A tri-linear model was used where the coefficient of thermal expansion varies from initial to final set.

Results show that silica fume significantly increases autogenous shrinkage, and the fly ash reduces autogenous shrinkage slightly. Additionally, companion tests on chloride permeability show that silica fume causes a profound reduction in chloride penetration, while fly ash causes the permeability to increase significantly. Ternary blends of cement, fly ash, and silica fume are shown to take advantage of the best features of both silica fume and fly ash, offering the durability improvement typical of silica fume, along with the early-age shrinkage-reducing effects of fly ash.

## INTRODUCTION

Durability of bridge decks is of primary concern to transportation officials, especially those living in colder climates where de-icing salt can cause significant deterioration and rebar corrosion. (1) Concrete mixes with low water to binder (w/b) ratios incorporating supplementary cementitious materials (SCMs), particularly silica fume, are known to offer superior resistance to chloride permeability, as well as enhanced frost resistance. (1-4) In the past, such mixes offered very poor workability as a compromise. In recent years, however, improved superplasticizers have been developed specifically for high performance concrete. (5) These superplasticizers are more efficient, requiring lower dosages, and do not cause segregation, retardation, or raise the air content. (6)

Usage of high performance concrete for bridge decks was not always successful. It was discovered that the shrinkage of these mixes, especially those with silica fume, was enough to cause cracking. (3, 7) Large cracks in a bridge deck are not only an immediate maintenance concern, but they also negate any effects of lower permeability by providing a direct path for chlorides to attack reinforcing steel. The very low permeability of these mixes leads to much greater autogenous shrinkage than in traditional concrete mixes. Total shrinkage due to drying plus self-desiccation is essentially the same for HPC mixes, but a greater proportion of the total shrinkage is autogenous. (8) Silica fume decreases the porosity of the concrete such that it is not possible to introduce further water into the concrete matrix for cement hydration. The cement thus uses up the available water in the pore spaces, leading to shrinkage as negative pressures develop. (2) In addition, autogenous shrinkage begins shortly after the concrete is placed, well before wet curing can take place, or curing compound can be placed. It is desirable to minimize as much as possible the autogenous shrinkage as it cannot be mitigated, as can drying shrinkage, with proper curing.

There exists much research on the effects of single SCMs on autogenous shrinkage, but very little has been published regarding the autogenous shrinkage of ternary blends of cements. (9, 10) This paper presents a series of laboratory studies of the autogenous shrinkage of concrete mixes with varied water to binder ratio, and different replacement fractions of silica fume and fly ash. Test fixtures were designed such that shrinkage measurements could be made beginning immediately after placing concrete in the molds. Special attention was paid to isolate shrinkage measurements from thermal movements caused by the heat of hydration. A tri-linear model from Kada (11) is used to model the coefficient of thermal expansion (CTE) of the concrete.

Shrinkage measurements were carried out for 14 days. Due to the phase transition of concrete from liquid to solid, very early-age measurements of concrete strain are not meaningful. It has been suggested in the literature that only measurements after initial set are relevant. (12) Time-of-set tests were conducted and the time of initial set was used as the beginning of relevant shrinkage.

Results from these tests, as well as companion tests to measure chloride permeability, are similar to published results for control mixes containing only Portland cement, as well as for those mixes incorporating a single SCM. Results for mixes with ternary blends of binders show that autogenous shrinkage is similar to control mixes. These ternary blended mixes, however, exhibit improved durability compared to the control mixes.

## EXPERIMENTAL PROGRAM

The work presented here is part of a larger project where 32 concrete mixes were prepared and tested to measure the effects of water to binder ratio, paste content, and binder composition on time dependant and serviceability properties of concrete. Silica fume and class C fly ash are used a supplementary binder materials. Specimens were prepared for each mix to measure autogenous shrinkage, long-term creep and shrinkage, strength, modulus of elasticity, freeze-thaw resistance and permeability by rapid chloride ion penetration.

### Materials and Mixing

Thirty-two mixes were designed with varied paste content, water to binder ratio and binder composition. This paper focuses on w/b ratio and binder composition (24 mixes). The range of these parameters used in typical high performance mixes was noted from an extensive review of available literature (13), the following values were chosen: water to binder ratio: 0.25, 0.30, 0.35 and 0.40, fly ash replacement: 0%, 25%, and 50%, silica fume replacement: 0%, 5% and 10%. All mixes have 25% paste (water plus binder fraction by weight), and the combined aggregate is 50% fine aggregate by weight.

The cement is a Type I/II ordinary Portland cement, the fly ash is Class C ash from low sulfur coal conforming to ASTM C618, and the silica fume is dry, densified product conforming to ASTM C1240. The coarse aggregate is a crushed dolomite limestone, MoDOT Gradation E (14), with 80% to 100% passing a 1/2" inch sieve, and the fine aggregate is natural Missouri River sand meeting MoDOT gradation requirements for concrete sand (14).

All mixes were entrained with 4.5 % to 7.0 % air. A polycarboxylate superplasticizer was used to produce a slump of 4 in to 6 in. The superplasticizer dosage rate varied from 3 to 13 oz/cwt (oz / 100 lb binder) depending on the composition of the mix. Those mixes with more silica fume, or lower w/b ratio required more, while those with larger fly ash replacement required less superplasticizer.

A revolving drum mixer was used batch each mix. Aggregates and water were added initially and mixed for 3 to 5 minutes. Air entraining agent was added to the mix water. For mixes requiring a large dosage of superplasticizer, approximately 50% of it was added at this stage. After full incorporation of the aggregates, the combined binder was added gradually along with additional superplasticizer as needed to maintain plasticity of the concrete. After all constituents were added, the concrete was mixed for 3 to 5 additional minutes to ensure full incorporation of the binder and superplasticizer. If necessary, additional superplasticizer was added to produce the required workability and the concrete was mixed additionally for 3 to 5 minutes more.

The concrete was then discharged into pans and specimens prepared. Slump, unit weight and air content were determined 5 to 10 minutes after discharge of concrete. It was found that waiting after discharge produced more reliable air content values. Air contents taken immediately after discharge were often much higher. It is believed that this is due to entrapped air.

### Test Setup

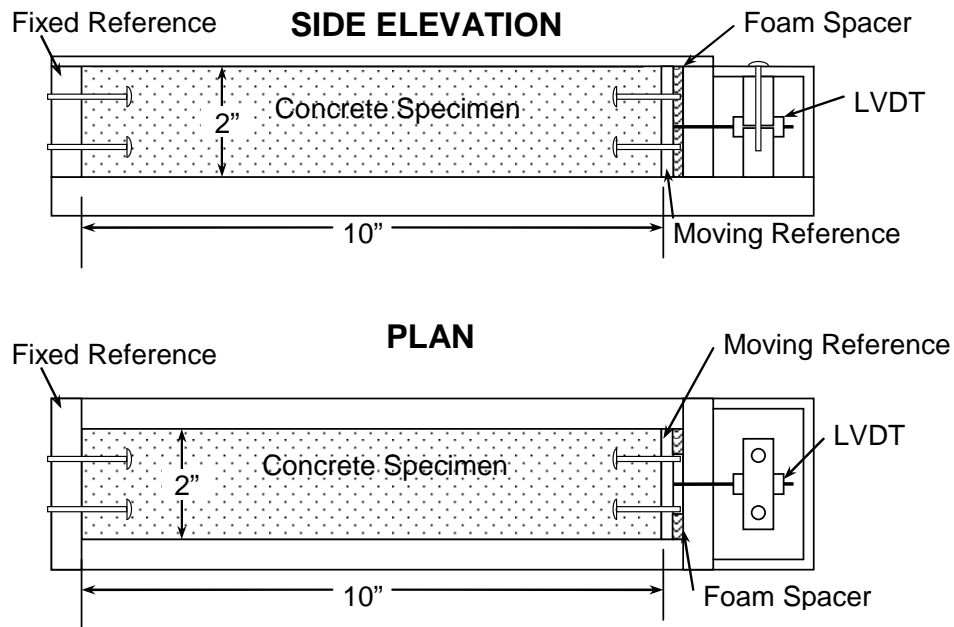
Test fixtures were constructed to allow deformation and temperature measurements of 2" by 2" by 10" concrete specimens immediately after casting (Fig. 1-Fig. 2). As can be seen in the following results, if one were to wait even 12 hours to demold specimens and begin measurements, a significant portion of the autogenous shrinkage would go unrecorded. This would lead

to substantial underestimation of the autogenous shrinkage. In order to reduce the potential for frictional restraint, the fixtures were constructed from PVC sheet. The fixtures have a fixed reference and a moving reference. Deformations are measured with an LVDT at the moving reference having a total range of  $\pm 0.1$  inches. Four #8 machine screws are embedded as studs at each reference to fix the references to the concrete. The studs protrude only 0.5" into the concrete to minimize their restraint on the free shrinkage of the concrete. The moving reference uses a foam spacer between it and the back of the mold to allow for expansion as well as contraction.

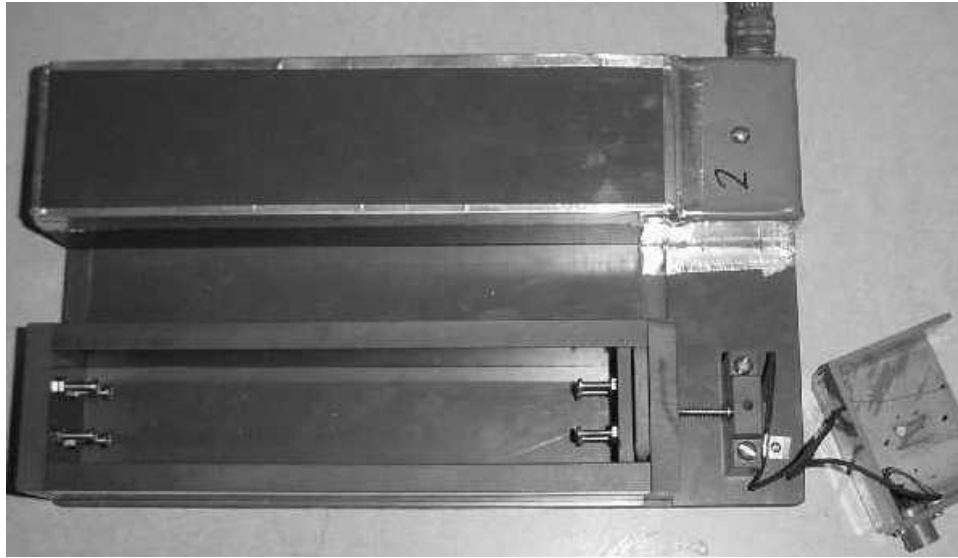
To prevent moisture loss, the molds have a PVC lid that is sealed with aluminum foil adhesive tape that is commonly used to seal ductwork (Fig. 2). Additionally, the LVDT is sealed to prevent moisture loss. Monitoring of the weight of a specimen during the test showed no weight loss within  $\pm 0.01$  lb, indicating the sealing is effective.

It was found after initial trials that PVC alone did not prevent the concrete from sticking. To reduce friction further, the molds were coated with a Teflon spray and then lined with Teflon film having a thickness of 0.002 inches. As a final measure to alleviate any possible restraint to free expansion "shims" of heavy paper were placed between the film and the mold during casting. These shims were removed prior to sealing the concrete specimens approximately 1/2 to 1 hour after mixing.

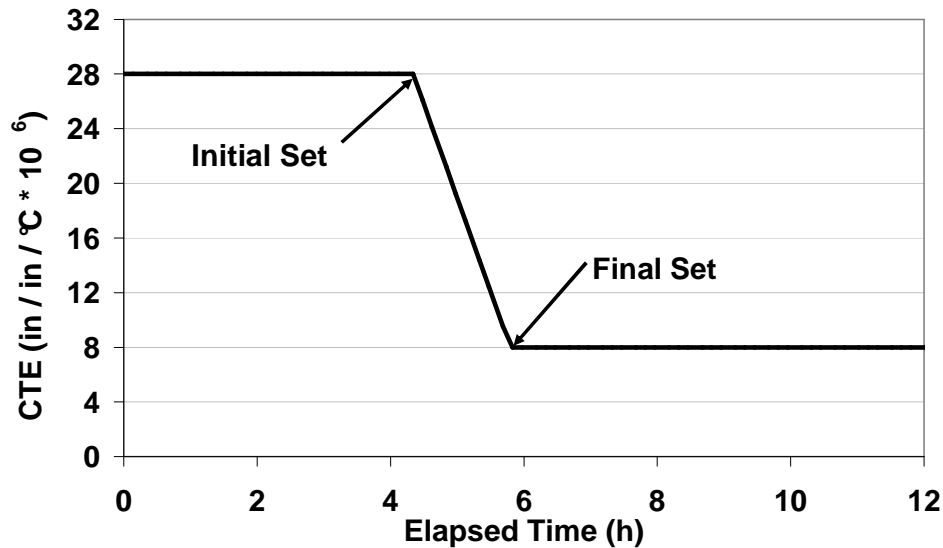
Two identical specimens are prepared for each mix by vibrating the concrete into the fixtures. Halfway through placement, a thermocouple is placed in the center of the specimen to monitor the internal concrete temperature. The specimens are only filled to approximately 1/8" from the top and the Teflon film is closed over the top of the fresh concrete. After removing the paper spacers, the specimens are immediately sealed and placed in a temperature-controlled chamber. A thermocouple is then fixed to the bottom surface of the mold to monitor the mold temperature.



**FIGURE 1 Autogenous Test Fixture Schematic**



**FIGURE 2 Autogenous Shrinkage Test Fixture Sealed (Top) and Open (Bottom)**



**FIGURE 3 CTE of Concrete During Curing (11)**

### Temperature Correction

Thermal expansion due to the heat of hydration must be compensated for because the tests are commenced immediately after casting (10). The fixtures used measure not only the concrete deformation, but also the thermal strain of the specimen and of the fixture itself.

Temperature corrections are complicated by the transition from a fluid to a solid during curing. The CTE of water is much greater than that of the hardened concrete. At early age, the concrete has free water that dominates the thermal behavior. As the cement begins to hydrate and consumes the water, the coefficient gradually approaches that of hardened concrete. Kada, et al. (11) studied the CTE of concrete at early age and proposed a model where the coefficient at early age varies from three to four times that of hardened concrete at and before initial set to the hardened value after final set. An average multiplier of 3.5 was used for all calculations in this study. Setting times were determined using resistance penetration according to ASTM C403 --

“Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance”. Weiss (15) indicates that this method is used widely, and that other methods that may be more accurate are not yet fully understood. He additionally states that this method is recommended by the Japanese Concrete Institute (JCI 12).

The CTE of hardened concrete was chosen as  $8 \times 10^{-6}$  in / in / °C based on a survey of values found in available literature for concrete with limestone aggregates. Because the coarse aggregates make up a majority proportion of the concrete volume, their thermal properties tend to dominate that of hardened concrete. The literature indicated a range of 6 to  $10 \times 10^{-6}$  in / in / °C for all concrete. Varying CTE in this range causes less than one percent variation in the calculated autogenous shrinkage at 14 days.

Due to the high CTE of PVC, it is also necessary to adjust the measured deformation to account for mold deformation. Calibration studies were done to measure the thermal expansion of the PVC mold. Fig. 4 shows the difference between the measured strain and the autogenous strain found by subtracting the thermal expansion of the concrete at the mold. Autogenous strain is found using Equation 1. It is necessary to compute the autogenous deformation using displacements because the mold and the concrete do not have the same gage length relative to the fixed end of the test fixture (Fig. 1). The CTE of the molds was experimentally determined using external dial gages to measure the length change as the molds were heated from ambient temperature to over 40 °C.

$$\epsilon_{shrink} = (\delta_{measured} - \delta_{T mold} + \delta_{T conc}) / L_{conc} \quad (1)$$

where:

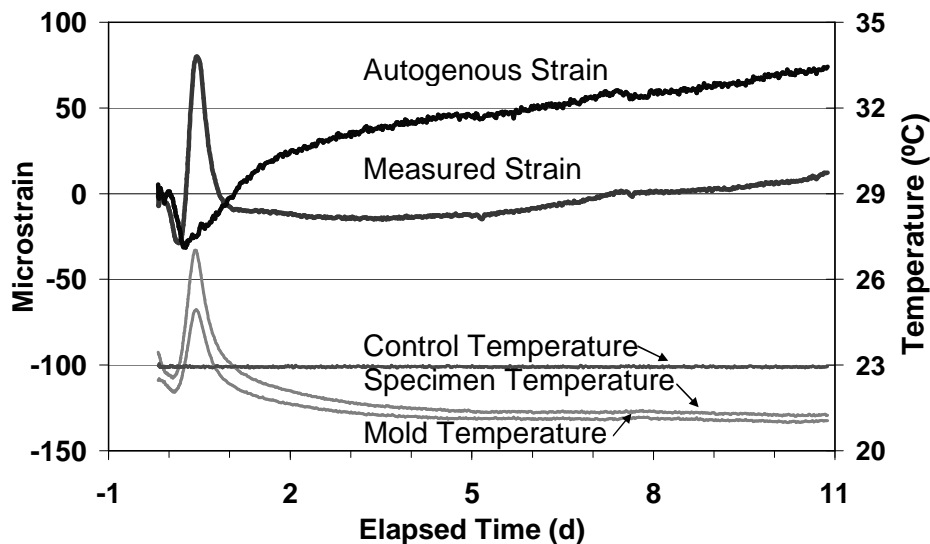
$$\delta_T = \alpha \times L \times \Delta T$$

$\alpha$  = CTE

L = gage length for displacement measurement

$\Delta T$  = change in temperature

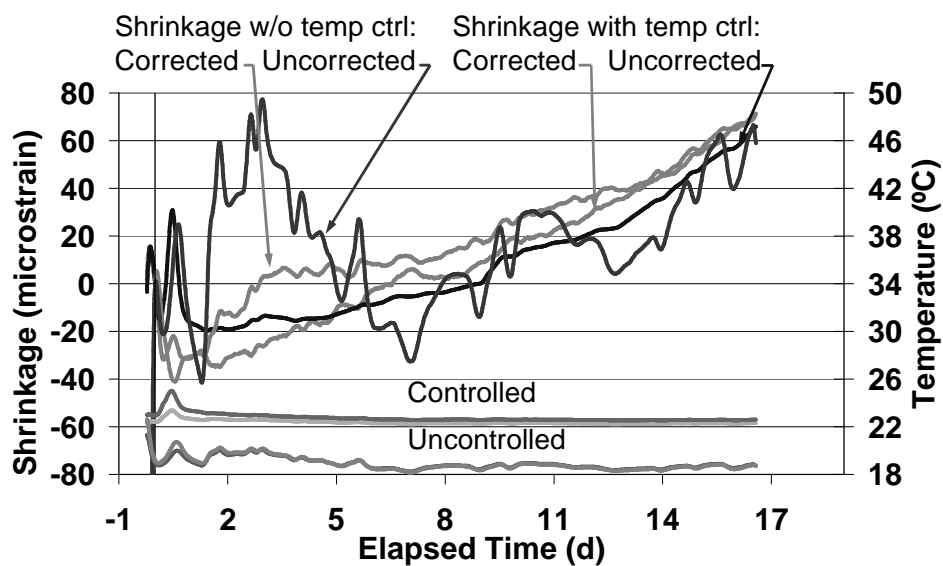
$\delta_{measured}$  = measured displacement.



**FIGURE 4 Measured and Adjusted Strain and Temperature History for Autogenous Shrinkage Measurements**

It can be seen in Fig. 4 that before the temperature correction is applied, the measured strain at early age actually appears to contract during a period where the temperature is increasing. This is a result of the mold having a higher CTE than the concrete, causing the LVDT to move away from the specimen.

Fig. 5 shows the results of a test done to verify the effectiveness of the temperature correction scheme. Four identical specimens were prepared and two were cured under controlled temperature while the remaining two were left in ambient temperature. It can be seen that despite varying measured strains and temperature histories, the thermal corrections produced nearly identical measurements for autogenous shrinkage, thus verifying the effectiveness of the correction scheme.

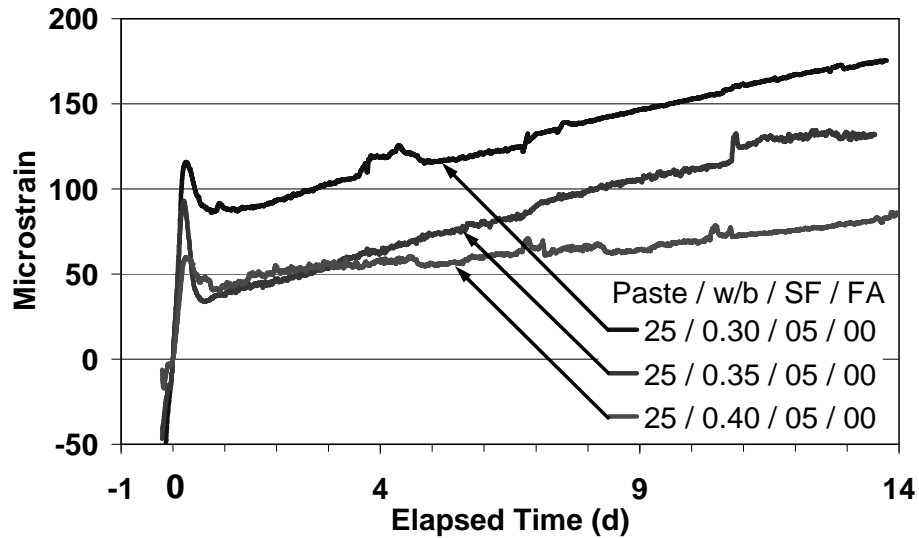


**FIGURE 5 Comparison of Autogenous Shrinkage with and without Correction for Temperature in Controlled and Uncontrolled Environments**

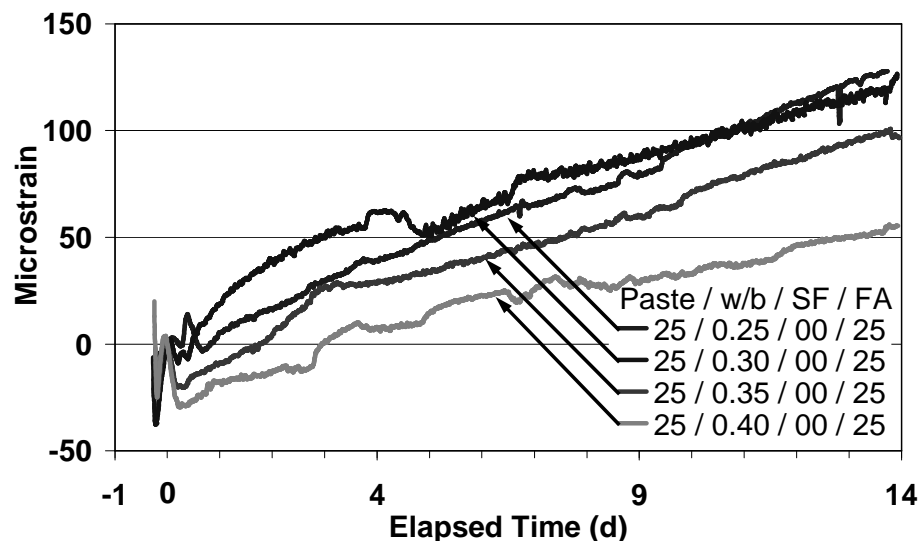
## TEST RESULTS

Volumetric autogenous shrinkage in concrete begins very soon after cement hydration. This shrinkage, however, cannot be reliably measured as a linear change due to the semi-solid nature of the concrete at this stage. Even if it were measurable, the very low stiffness of the concrete at this stage would preclude the creation of tensile stresses in the concrete.

It is suggested by JCI (12) and supported by others (15, 16) that only deformations occurring after initial set are of practical relevance. Many methods are proposed in the works cited above to determine when initial set has occurred -- some more easily determined than others are. Weiss (15) suggests that the initial set as defined by ASTM C403, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance" (17) is as good as any, and is easy to determine as well. All of the results presented below are adjusted such that the point of zero strain corresponds with the time of initial set per ASTM C403.



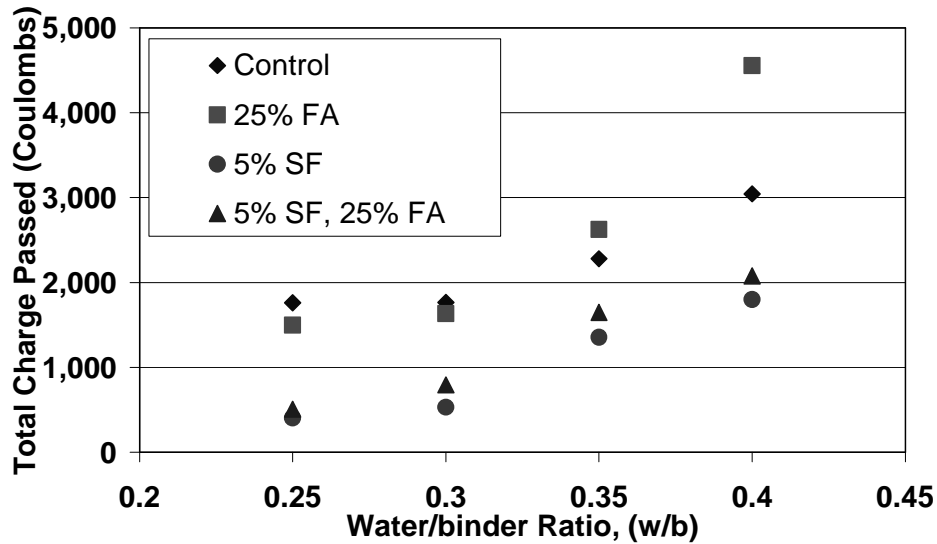
**FIGURE 6 Effect of W/B Ratio on Autogenous Shrinkage of Concrete with 5% Silica Fume**



**FIGURE 7 Effect of W/B on Autogenous Shrinkage Ratio of Concrete with 25% Fly Ash**  
**Effect of Water To Binder Ratio**

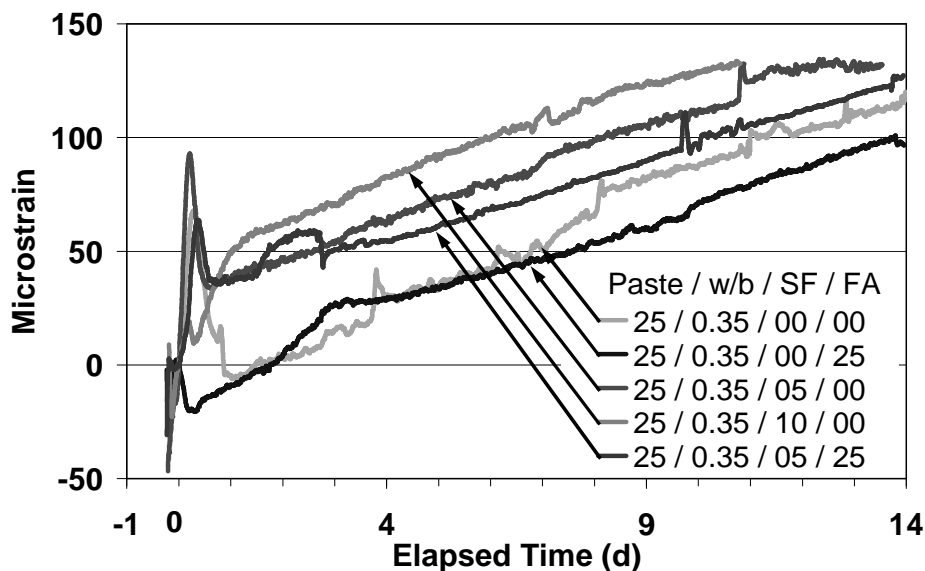
For concrete with only Portland cement binder, the autogenous shrinkage is inversely proportional to the w/b ratio (15). Fig. 6 and Fig. 7 show the same to be true for high performance concrete with silica fume and fly ash. For mixes with 5% silica fume, decreasing the w/b ratio from 0.40 to 0.35 produces 50% more autogenous shrinkage and decreasing the w/b ratio from 0.40 to 0.30 causes the autogenous shrinkage to double.

For mixes with 25% fly ash, the autogenous shrinkage follows the same trend. Decreasing the w/b ratio from 0.40 to 0.35 causes the autogenous shrinkage to double and further reducing it to 0.30 leads to a 150% increase. Further decreasing the ratio to 0.25 does not seem to lead to an increase in shrinkage. A similar trend was noted by Baroghel-Bouny, et al. (9) for concrete mixes containing only Portland cement where w/b ratios equal to and smaller than 0.30 showed similar autogenous shrinkage.

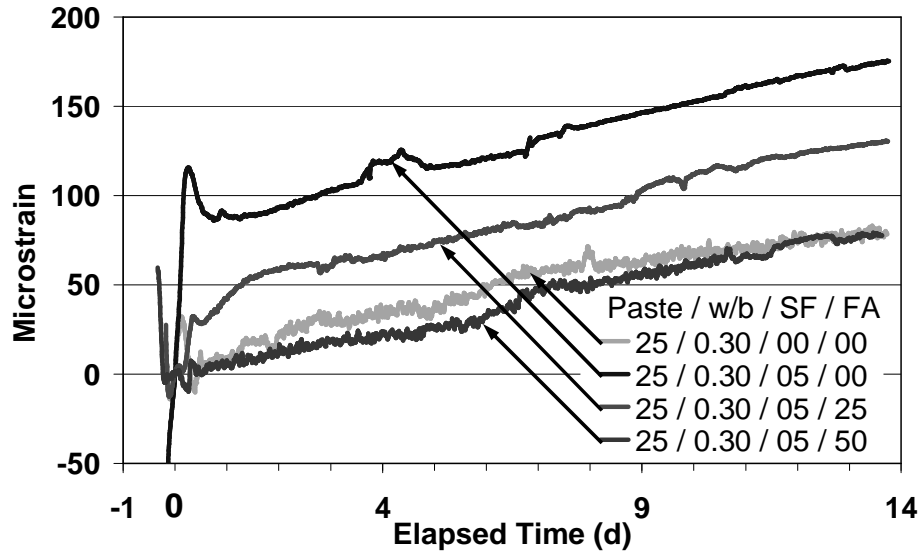


**FIGURE 8 Effect of W/B Ratio and SCMs on Chloride Permeability of Concrete**

High performance concrete is used in bridge decks for its superior durability properties, not because it has high strength. In these applications, a low w/b ratio is not required. By using a higher w/b ratio not only will autogenous shrinkage be minimized, an economy will be realized because of less total binder being required. Fig. 8 shows rapid chloride permeability results for the same mixes. Here it can be seen that a mix with a 0.40 w/b ratio and silica fume or silica fume and fly ash has similar permeability as a mix using only Portland cement with a w/b ratio of 0.25. This indicates that it is possible to use mixes with high w/b ratio that exhibit lower autogenous shrinkage without significantly compromising the durability of the concrete.



**FIGURE 9 Effect of SCM on Autogenous Shrinkage of Concrete with W/B = 0.35**



**FIGURE 10 Effect of Fly Ash on Autogenous Shrinkage of Concrete with W/B = 0.30 and 5% Silica Fume**

### Effect of Supplementary Cementitious Materials

It has been observed by others (10, 18) that adding silica fume tends to increase the autogenous shrinkage while adding fly ash will reduce the autogenous shrinkage (19). The following results show that the two SCMs can be combined and the shrinkage reducing characteristics of fly ash can be used to offset the increased autogenous shrinkage of silica fume.

Fig. 9 shows five mixes with w/b ratio = 0.35. Compared to a control mixture with 100% Portland cement, a mix with 25% fly ash exhibited 13% lower autogenous shrinkage, and the mixes with 5% and 10% silica fume replacement showed 18% and 35% more shrinkage, respectively. The addition of both fly ash and silica fume (5% and 25%) exhibited shrinkage only 9% greater than that of the control mix.

Fig. 10 shows the effect of adding successive amounts of fly ash to a mixes containing 5% silica fume. 5% silica fume causes the autogenous shrinkage to double compared to a control mix. With 25% fly ash added also, the increase is only 50%, and with 50% fly ash, the ternary mix exhibits the same shrinkage as a mix with only Portland cement.

Companion tests on the chloride permeability of the same concrete mixes (Fig. 8) have shown that ternary blends show only slightly higher permeability compared to mixes with only silica fume. Additionally, the permeability is 50% to 70% lower than mixes containing only Portland cement or cement and fly ash. This indicates that use of ternary blend concrete in a bridge deck will provide the chloride penetration resistance that is desired without compromising the integrity of the deck due to early-age shrinkage cracking.

### CONCLUSIONS

- Careful measurements of deformations at early age are necessary to capture accurately the autogenous shrinkage of high-performance concretes. It is necessary to include phase transition effects, early thermal effects due to hydration and timeliness of early-age measurements to quantify accurately autogenous shrinkage.

- An effective technique was developed to correct measured deformations for thermal movements of the concrete and mold due to heat of hydration. Measured strains are significantly different from actual autogenous shrinkage. Without correcting for thermal expansion, the autogenous shrinkage would be underestimated in most cases. In order to facilitate this temperature correction, a model was used to account for the increased thermal expansion at early age for wet concrete.
- Lowering the w/b ratio of concrete can double the amount of autogenous shrinkage. Higher w/b ratio mixes exhibit higher chloride permeability if the binder composition is held constant. Higher w/b mixes incorporating silica fume or fly ash and silica fume, however, exhibit similar permeability to control mixes with very low w/b ratios. Higher w/b ratios also yield more cost effective mixes as less binder is required, as well as less superplasticizer.
- Concrete incorporating only silica fume exhibits greater autogenous shrinkage compared to control mixtures. Conversely, mixes incorporating only fly ash show reduced autogenous shrinkage. Mixtures incorporating ternary blended binders show autogenous shrinkage that is only slightly higher than fly ash only concrete, and very similar to control mixtures.
- Chloride permeability of mixes with silica fume only is significantly improved, while fly ash causes an increase in chloride permeability. Ternary blended mixes show nearly the same improvement as silica fume only concrete.

In summary, for bridge deck applications, high performance can still be achieved without excessive autogenous shrinkage by using a higher w/b ratio, and using a ternary cement blend that will have the low permeability of a silica fume mix, and the low autogenous shrinkage of a traditional concrete mix. Such a mix will offer a savings over low w/b silica fume mixes that have traditionally been used for bridge decks by lowering the cement content and superplasticizer required, and by using less expensive fly ash in place of cement. Additionally, the use of industrial byproducts like fly ash and silica fume engineered judiciously in ternary blends provides an environmentally sound solution by reducing cement demand while at the same time providing the high performance desired.

## ACKNOWLEDGEMENTS

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