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Effect of Blended Cements on Effectiveness of Internal Curing of HPC

By Daniel Cusson

Synopsis: The effects of internal curing, type of blended cement and coarse aggregate size on early-age expansion, autogenous shrinkage and strength of high-performance concrete were investigated. To do so, twelve high-performance concrete mixtures were developed and tested under sealed and room temperature conditions. The results were statistically analyzed using the paired comparison design method. It was shown that internal curing of HPC with pre-saturated porous lightweight aggregate allowed significant autogenous expansion and resulted in considerable reduction in net autogenous shrinkage. The type of cement used in concrete, which was either ordinary Portland cement, silica fume blended cement, or slag/silica fume blended cement, had a strong effect on early-age expansion, autogenous shrinkage, and the effectiveness of internal curing. For instance, the concrete specimens made with silica fume blended cement, which yielded the largest autogenous shrinkage strains under sealed conditions, obtained the best reductions in autogenous shrinkage when tested under an internal curing condition.

Keywords: Autogenous shrinkage; cement type; early-age cracking; high-performance concrete; internal curing; lightweight aggregate; paired comparison design; restrained movement; stress development.

Biography:
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INTRODUCTION

Internal curing (IC) is a promising technique that can provide additional moisture in concrete for a more effective hydration of cement. Concrete made with saturated high-absorption aggregate carries its own internal curing water supply for a more effective and longer curing. The added IC water can reduce self-desiccation and autogenous shrinkage in high-performance concrete (HPC), especially when it has a high cement content and a low water-cementitious materials ratio (*w/cm*). Internally-cured concrete is less sensitive to poor external curing practices or unfavorable ambient conditions than conventionally-cured concrete. In low-permeability concrete, external curing alone may not be effective in preventing self-desiccation at the core of thick concrete elements. The use of internal curing, however, does not replace recommended curing practices,[1] as it is important to keep the concrete surface continuously moist during the curing process in order to prevent surface cracking due to plastic or external drying shrinkage.

There have been successful applications of internal curing in North America in recent years. In Ohio, saturated porous normal-density coarse aggregate has been used over the last 12 years in bridge decks made with air-entrained high-performance concrete.[2] A survey from the Ohio Transportation Department of their highway bridges reported consistently less concrete cracking in these bridges than in comparable bridges using lower absorption coarse aggregate in concrete. In Texas, over 400,000 m^3 (523,200 yd^3) of internally-cured concrete have been placed in many paving projects.[3] Internal curing was achieved by substituting portions of both regular fine and coarse aggregates with an intermediate size pre-soaked expanded shale lightweight aggregate (LWA). It was reported that cracking has been extremely minimal, in contrast to other projects using conventional paving concrete mixtures. Field tests indicated that the average 28-day compressive strength was improved by 20% when compared to similar mixtures without LWA.

While the technique of internal curing has been successfully applied in the aforementioned concrete structures, there is still a strong need for a better understanding of the internal curing mechanisms and the key factors determining its effectiveness. Several factors are competing together as far as internal curing is concerned[4] and some others are not completely understood. For example, it is known that the addition of some supplementary cementing materials (SCM) like silica fume in conventionally-cured high-performance concrete will increase chemical shrinkage,[4] which may increase the risk of autogenous shrinkage cracking in concrete structures. It is also known that a larger content of larger size normal-density coarse aggregate will reduce the paste volume in concrete and result in lower bulk autogenous shrinkage. It is not known, however, if these trends will apply to internally-cured HPC. It may be possible that internal curing is further activated or impeded under some specific conditions which, if not identified, may distort the estimation of the amount of IC water required to prevent autogenous shrinkage cracking in concrete structures.

To address the above concerns, the main goal of the experimental study presented in this paper was to evaluate the effects of type of curing, type of cement, and maximum size of normal-density coarse aggregate on different parameters such as early-age expansion, autogenous shrinkage and compressive strength measured on specimens made of high-performance concrete.

RESEARCH SIGNIFICANCE

Internal curing is a relatively new technique that can reduce autogenous shrinkage cracking in HPC structures. It is not known, however, how some concrete mixture parameters will influence the effectiveness of internal curing. In this study, the type of blended cement was found to strongly affect the effectiveness of internal curing at promoting early-age expansion and reducing net autogenous shrinkage. This study provides new test data to extend the current methodology used to determine the required amount of IC water in concrete. It was also shown that the risk of cracking in concrete structures can be indirectly evaluated from free shrinkage testing provided that a net shrinkage strain value is determined from the peak strain produced during expansion, if any. This is of practical importance for testing laboratories, where the risk of cracking of new HPC mixtures may be rapidly assessed without the need for sophisticated equipment.

EXPERIMENTAL INVESTIGATION

In this study, three variables were selected to investigate their effects on different performance parameters. These variables were: (i) type of curing, for which the concrete specimens were either sealed-cured or internally-cured (and sealed); (ii) type of cement, with different supplementary cementitious materials; and (iii) maximum size of normal-density coarse aggregate, which was either 10 mm (⅜ in.) or 20 mm (¾ in.). The measured performance parameters were: (i) peak autogenous expansion strain; (ii) net autogenous shrinkage strain at 7 days; and (iii) compressive strengths at 7 days and 28 days.

Materials

In order to test the 3 selected variables at 2 or 3 levels each, twelve different concrete mixtures were developed; each tested in three replicates. For comparison purposes, the water-cementitious materials ratio was maintained at 0.35, and the cement/sand/coarse aggregate mass ratio was 1:2:2 when normal-density aggregates were used. The cements used in concrete were either (Table 1):

(i) General use ASTM Type 1 ordinary Portland cement, with a Blaine surface area of 379 m^2/kg (referred to as OPC);

(ii) Portland silica fume cement containing 9% silica fume, with a Blaine surface area of 564 m^2/kg (referred to as SF cement); or

(iii) Blended Portland cement containing 20% granulated blast furnace slag and 5% silica fume, with a Blaine surface area of 575 m^2/kg (referred to as Slag/SF cement).

Of the 12 concrete mixtures, six were made without internal curing (sealed curing only), with variations in cement type and maximum size of coarse aggregate; and six additional mixtures included pre-soaked porous lightweight aggregate sand for internal curing, also with identical variations in cement type and maximum size of coarse aggregate. Table 2 presents the two main mixtures proportioned relative to a unit mass of cement. The water contained in the LWA for internal curing was not accounted for in the water-cementitious materials ratio, since internal curing water comes into play after the setting of concrete. For the internally-cured concrete mixtures, a volume fraction of the normal sand was replaced by LWA sand, resulting in a cement/sand/coarse aggregate mass ratio of 1:1.6:2. Chemical admixtures were used and adjusted for each of the twelve mixtures in order to provide similar slumps (between 120 mm and 220 mm), and air contents (between 5% and 6%) for adequate workability and freeze-thaw resistance, respectively. Table 3 provides the details on the aggregates used in these concrete mixtures.

Specimens

For each of the twelve concrete mixtures, free autogenous shrinkage tests were conducted on 3 sealed concrete prisms, which were monitored simultaneously from shortly after casting to at least 7 days of age under a controlled room temperature of 23°C (73°F). Figure 1a presents the diagram of one of the three apparatus used for free shrinkage testing, and Figure 1b illustrates a set of three shrinkage specimens during testing. The mould is made of steel plates, with inside dimensions of 75x75x295 mm (3x3x11⅝ in.). Inside the steel mould, the walls were coated with a layer of petroleum gel and a thin plastic film to reduce friction between the steel walls and the concrete specimen. The end plates of the mould were lined with 1.5-mm (1/16-in.) thick closed-cell foam rubber sheets to allow free movement of the concrete sample in the longitudinal direction in case the concrete expands at early age. The longitudinal deformation of each concrete prism was measured using a displacement transducer (LVDT) at each end of the mould. These sensors, fixed to the structural steel base of the test apparatus, were connected to 20-mm (¾-in.) diameter metal discs by stainless steel extension shafts. The discs were embedded in the ends of the prism during concrete placement. The extension shafts were guided by oil-impregnated bronze bearings mounted in small openings in the mould end plates in order to eliminate transverse displacement of the discs in fresh concrete. The concrete temperature was measured by thermocouples located at the centre and top surface of the concrete prism. Also, the compressive strength of each concrete mixture was tested on 100x200 mm (4x8 in.) cylinders at 7, 28 and 56 days, according to the ASTM C39 procedure.[5]

EXPERIMENTAL RESULTS AND DISCUSSION

Assessment of risk of cracking from shrinkage measurements

Conventional concrete starts shrinking near the time of initial setting, from which time shrinkage should be experimentally measured since, in actual concrete structures under restrained conditions, tensile stresses start to develop around that time. In this case, all of the measured shrinkage strain will be responsible for the development of tensile stresses, depending on the age-dependent visco-elastic properties of concrete. In structures made with concrete that may expand at early age, not all of the strain will produce tensile stresses under restrained conditions, as some extent of it will generate compressive stresses at early age. In that case, when testing free shrinkage of concrete specimens to assess the potential risk of cracking in concrete structures, large underestimations may occur if the extent of strain used to evaluate that risk is determined from the time of setting.

To illustrate this point, Fig. 2 presents some earlier test results[6, 7] from large concrete prisms (200x200x1000 mm (8x8x39 in.)) made of a 0.34 *w/cm* concrete and tested for free and restrained shrinkage under sealed and internal curing conditions at an ambient room temperature of 23°C. The curves represent the development of total strain (i.e. thermal + autogenous shrinkage strains) measured in a stress-free specimen and the development of the corresponding uniaxial tensile stress measured in an identical companion specimen under restrained conditions. The restrained expansion produced compressive stresses at early age, which later reversed into tensile stresses mostly due to cooling (and some autogenous shrinkage) occurring after the initial expansion. It is clearly shown that, although the measured total strain always remained positive (overall expansion), the tensile stress in the concrete specimen increased to over 2 MPa (290 psi) after only two days.

Ideally, the extent of strain that should be considered to estimate the risk of cracking of a given mixture used in concrete structures should be the amount of strain developing after the time at which compressive stresses reverse into tensile stresses (i.e. after $\varepsilon_{\sigma=0}$) during a restrained shrinkage test. From the data presented in Fig. 2, a net strain of –125 με (ε_{min}-$\varepsilon_{\sigma=0}$) is obtained at 3 days, which is much more meaningful than the plain value of +50 με measured at the same time. However, from free shrinkage testing, such zero-stress strain ($\varepsilon_{\sigma=0}$) cannot be determined. When only free shrinkage test results are available, it is therefore suggested to rely on the extent of strain measured after the peak of expansion (i.e. after ε_{max}) to obtain a conservative estimate of the strain that may produce cracking in concrete structures. From the data shown in Fig. 2 (assuming $\varepsilon_{\sigma=0}$ is not known), this net strain would be estimated at –165 με (ε_{min}-ε_{max}) at 3 days, which is actually the extent of strain contributing to the increase in the uniaxial tensile stress in the restrained concrete specimen (Fig. 2).

For the present study, in order to evaluate the effects of the selected test variables on free shrinkage reduction, the net shrinkage strain is defined as:

$$\varepsilon_{sh\ net} = \varepsilon_{sh\ min} - \varepsilon_{sh\ max} \tag{1}$$

This definition has the advantage of being independent of the onset of strain measurement, whether it is taken at casting, initial or final setting, or peak of expansion. In practice, it is suggested to use values of total strain in Eq. 1, including effects of temperature, drying and other conditions normally found in real structures, in order to obtain more representative and meaningful values of the net strain that may contribute to concrete cracking in structures.

Free autogenous shrinkage strain results

The free autogenous shrinkage strain curves measured as a function of time after setting for the twelve concrete mixtures are shown in Fig. 3 (for the specimens made with the larger size coarse aggregate) and Fig. 4 (for the specimens made with the smaller size coarse aggregate). Note that the developing thermal strain due to heat of hydration and subsequent cooling had been previously removed from the measured total strain for an accurate assessment of autogenous shrinkage. This thermal strain was estimated from the measured concrete temperature changes and the age-dependent thermal expansion coefficient of concrete, which was determined with an empirical model developed for very similar concretes.[13] The model used was: $\alpha_c(t)=8+1.3\ LN(t)$, where α_c is the coefficient of thermal expansion comprised within the limits of 8 and 11 με/°C, and t is the time (in days) after setting of concrete. The equipment and procedures used for testing the concrete CTE are described elsewhere.[13]

Visual observations of these figures can already provide clear indications on the effects of the three test variables on the overall autogenous shrinkage deformation, as follows:

(i) Internal curing allowed large autogenous expansions at very early ages and contributed to large reductions in autogenous shrinkage at 7 days;
(ii) Cement type had a significant effect on autogenous shrinkage, and on early-age expansion when internal curing was used; and
(iii) Size of coarse aggregate did not appear to have a large effect on autogenous shrinkage.

Table 4 presents selected results from Figs. 3 and 4, and from other measurements. They include the peak expansion strain, the 7-day net autogenous shrinkage strain, and the compressive strengths measured at 7 days and 28 days. These results will be used in the statistical analysis presented in the following section.

Statistical analysis of experimental data

In some simple comparative experiments, the precision can be greatly improved by making comparisons within matched pairs of experimental data.[8] The method selected to design this experiment and to conduct the analysis is called the paired comparison design,[8] which consists of comparing the results obtained within pairs of specimens by eliminating all other differences between the pairs. Figure 5 explains the method graphically, where six pairs of specimens are compared. For each matched pair of specimens considered, the difference (d_i) between the values of a given parameter (i.e. the results in Table 4) corresponding to the low and high levels of a given variable is first calculated. For example, if curing type is the variable considered, the low level is 'sealed curing' and the high level is 'internal curing'. An average difference ($\overline{d}$) is then calculated for the 6 pairs under consideration. The significance of this average difference is determined using the Student's *t* test, where the null hypothesis ($\overline{d}$ = 0) may be accepted (effect is not significant) or rejected (effect is significant). In this study, a confidence level (α) of 90%, over which an effect is considered significant, was selected.

Table 5 presents the detailed statistical analysis results for the effect of curing type on the selected performance parameters. Analyses of the type shown in Table 5 were also conducted to assess the significance of the other test variables on the selected parameters. A summary of the results from these analyses is reported in Table 6, in which the average values, standard deviation values (shown in parentheses) and confidence levels (in percent) are indicated for each test variable and performance parameter. From this statistical analysis, the following findings were drawn:

Effect of type of curing – It is clearly shown that internal curing, when compared to sealed curing, had a highly significant effect on the peak expansion strain (which increased) and the 7-day net shrinkage strain (which decreased in size), both with very high confidence levels of 99% and 100%, respectively. While the mechanisms of internal curing contributing to a reduction in autogenous shrinkage are well known,[4] the mechanisms leading to an early-age expansion are not well understood. Current shrinkage prediction models[9, 10] do not consider the possibility of early-age expansion in concrete structures. This expansion may be related to ettringite formation and/or swelling of the gel hydration products, as it has been hypothesized in previous studies.[11, 12] It appears that there may be a competition between the development of expansion and that of autogenous shrinkage. As shown in Figs. 3 and 4, expansion clearly dominated autogenous shrinkage in the internally-cured concrete specimens at very early ages (<12 hours), since early autogenous shrinkage had been significantly reduced by internal curing. After the expansion peak, however, autogenous shrinkage developed faster than autogenous expansion, regardless of the type of curing used.

Additional mechanisms responsible for the observed early-age expansion may also be considered: (i) IC water in the LWA may desorb faster than it is consumed by cement hydration at very early ages, resulting in a temporary increase in the bulk volume of concrete; (ii) LWA made of expanded shale may expand in high pH concrete; (iii) Re-absorption of bleed water (not observed in this study) may lead to an apparent increase in the bulk volume of concrete; and (iv) Apparent thermal expansion of concrete made with LWA may be higher than accounted for; however, this last hypothesis may be ruled out in some cases since previous thermal expansion test results[13] showed no difference in the coefficient of thermal expansion at early ages between two identical high-performance concretes made with and without internal curing under sealed conditions.

The statistical analysis also indicates that internal curing produced a significant increase of 2.4 MPa (348 psi) for the 7-day compressive strength (with a 97% confidence level), from an average value of 54 MPa (7830 psi). The 28-day compressive strength data, however, showed no significant strength improvement (based on the 90% threshold confidence level), with a small strength gain of 1.2 MPa (174 psi) from sealed curing to internal curing. However, Bentz demonstrated on 0.3 *w/cm* mortar specimens that the 28-day compressive strength can be increased by 10% when using internal curing.[14]

Effect of cement type – The results show that the type of cement had a significant effect on the peak expansion strain, which was further reinforced by internal curing (strong interaction). More specifically, the average peak expansion strain was the smallest with SF cement (39 µε in internally-cured concrete specimens), larger with OPC (75 µε) and the largest with Slag/SF cement (177 µε). This increased expansion does not seem to depend solely on the overall Blaine surface area of the cement but instead may rather be related to the decreasing amount of fine reactive pozzolanic cementing materials in the concrete, as it decreased from SF cement (clinker and fine SF), to OPC (clinker only), to Slag/SF cement (reduced amounts of clinker and SF). If early-age expansion were a desired characteristic of concrete in some specific applications, then Slag/SF cement combined with internal curing would be an excellent combination.

The type of cement also had a significant effect on the 7-day net autogenous shrinkage of the concrete specimens, with a clear increase from OPC to either SF cement or Slag/SF cement, which is due to the presence of SCMs in these last two cements. It is known that silica fume in cement increases the amount of chemical shrinkage, which is one of the driving forces for autogenous shrinkage.[4, 14] Also, for a given volume of chemical shrinkage, the finer pore structure in the SF cement and Slag/SF cement concrete specimens will lead to higher self-desiccation stresses in the capillaries.

Moreover, the type of cement produced a significant effect on the compressive strength of the concrete specimens (as expected), especially when SF cement was used instead of OPC, with an average increase of 9.5 MPa (1378 psi) at 7 days and 15.1 MPa (2190 psi) at 28 days. When Slag/SF cement was used instead of OPC, the compressive strength of the concrete specimens increased by a small 2.9 MPa (421 psi) at 7 days and a significant 12.6 MPa (1827 psi) at 28 days. Concrete made with slag cement is usually known for its relatively slow strength development at early age;[15] however, the Slag/SF cement used in this study allowed the 7- and 28-day compressive strengths to exceed those of OPC concrete specimens, especially at 28 days.

Effect of maximum size of coarse aggregate **–** Decreasing the maximum size of low-absorption normal-density coarse aggregate from 20 mm (¾ in.) to 10 mm (⅜ in.) was not found to significantly affect the 7-day net autogenous shrinkage of the specimens. On the other hand, decreasing the aggregate maximum size produced a large increase in the 28-day compressive strength (as expected) by a significant 6.2 MPa (899 psi) from an average strength of 63 MPa (9135 psi). This finding indicates that, with the combined use of smaller coarse aggregate and internal curing, concrete strength can be improved while keeping the risk of autogenous shrinkage cracking low.

Effectiveness of internal curing

The significance of the effects of cement type and coarse aggregate size on the effectiveness of internal curing was evaluated from the shrinkage results of Table 4. The performance indicator selected to assess the effectiveness of internal curing was the relative reduction in the 7-day net shrinkage strain, calculated as follows:

$$\Delta\varepsilon_{sh-7d} = \frac{\left(\varepsilon_{sh-7d}^{SC} - \varepsilon_{sh-7d}^{IC}\right)}{\varepsilon_{sh-7d}^{SC}} \tag{2}$$

where

$\Delta\varepsilon_{sh-7d}$ = relative reduction in the 7-day net autogenous shrinkage strain due to internal curing;

ε_{sh-7d}^{SC} = 7-day net autogenous shrinkage strain obtained under sealed curing;

ε_{sh-7d}^{IC} = 7-day net autogenous shrinkage strain obtained under internal curing.

Eq. 2 yielded shrinkage reduction values ranging from 32% to 63% for the different concrete specimens, depending on cement type and maximum size of coarse aggregate (Table 7). These particular results also indicate that reducing the coarse aggregate size significantly increased the effectiveness of internal curing (with a 97% confidence level) from 40% to 62% for the OPC specimens, 55% to 63% for SF cement concrete specimens, and from 32% to 43% for the Slag/SF cement concrete specimens. This finding also supports the use of the smaller 10-mm (⅜ in.) normal-density coarse aggregate in order to maximize the effectiveness of internal curing with pre-wetted LWA sand.

From these results, it is also clear that cement type had a significant effect on the effectiveness of internal curing. With OPC, the average shrinkage reduction was 51% due to internal curing, while SF cement obtained an average value of 59%, and Slag/SF cement obtained an average shrinkage reduction of 38%. These results lead to a very interesting finding: the concrete specimens made with SF cement, which produced the largest average autogenous shrinkage strain under sealed conditions, are the ones that benefited the most from internal curing. These results may provide some quantitative basis for extending the current IC requirement calculation method, which does not directly take into account the effect of supplementary cementing materials on the relative effectiveness of internal curing.[16]

Since chemical shrinkage is one of the driving forces for autogenous shrinkage, the mass of LWA to use in concrete in order to provide adequate internal curing can be estimated from chemical shrinkage with the following equation:[16, 17]

$$\frac{M_{LWA}}{M_c} = \frac{CS \cdot \alpha_{\max}}{S_{LWA} \cdot \phi_{LWA}} \quad \text{with} \quad \alpha_{\max} = \frac{w/cm}{0.36} \leq 1 \tag{3}$$

where

M_{LWA} = dry mass of LWA (before saturation) per unit volume of concrete;
M_c = mass of cement per unit volume of concrete;
CS = chemical shrinkage at 100% hydration (mass of consumed mixing water per unit mass of cement);
α_{max} = maximum expected degree of hydration;
S_{LWA} = saturation degree of LWA;
ϕ_{LWA} = desorption capacity of LWA (mass of IC water per unit mass of dry LWA); and
w/cm = mixing water to cementitious materials ratio of concrete.

Eq. 3 assumes that the amount of LWA (or IC water) is directly proportional to the amount of chemical shrinkage. As a result, Eq. 3 will typically require higher amounts of LWA (or IC water) for concrete mixtures containing SF cement than for equivalent OPC concrete mixtures, since silica fume increases the chemical shrinkage of the cement paste portion of concrete.[4, 14] As shown earlier in this study, internal curing seems to be more effective for SF cement concrete specimens than for OPC concrete specimens, which had identical amounts of LWA (or IC water). This indicates that chemical shrinkage alone cannot explain this particular observation. A possible explanation may come from the consideration of pore sizes in concrete relative to those in the LWA, as IC water naturally flows from larger pores to finer pores.[16, 17] In the present study, the finer pore microstructure of the SF cement concrete specimens may have produced higher internal suction forces than the OPC concrete specimens with a coarser porosity. As a result, more of the water available in the LWA may have been effectively used for internal curing at earlier ages in the SF cement concrete specimens than in the OPC concrete specimens.

Eq. 3 was used to estimate the minimum amount of LWA (or internal curing water) needed to compensate for the chemical shrinkage occurring in the concrete specimens. The following values were used: cement content of 445 kg/m^3 (750 lb/yd^3); chemical shrinkage values of 0.052, 0.054 and 0.059 (mass of water per unit mass of cement) measured on triplicate specimens of 0.40 *w/c* cement paste at 7 days for OPC, SF cement and Slag/SF cement, respectively (according to ASTM C1608);[18] maximum degree of hydration of 0.97 (for *w/cm* = 0.35); LWA saturation degree assumed at 0.95; and a measured LWA desorption capacity of 0.15**.** For the OPC control mixture, Eq. 3 yields a value of 0.354 kg of LWA per kg of cement (0.354 lb/lb), which amounts to 158 kg of dry LWA (before saturation) per cubic meter of concrete (266 lb/yd^3).

The amount of LWA (or IC water) needed to eliminate autogenous shrinkage in HPC (resulting from chemical shrinkage and self-desiccation) can be determined directly from free shrinkage testing, especially when the value of chemical shrinkage for a given blended cement is not known or when concretes with very low *w/cm* are used (self-desiccation). Assuming that the reduction of autogenous shrinkage is proportional to the content of internal curing water in concrete,[7] the amount of IC water required to eliminate the 7-day net autogenous shrinkage strain was calculated from the net shrinkage strain data of Table 4 and the following equation:

$$M_{LWA}^{required} = \frac{M_{LWA}^{used}}{\Delta\varepsilon_{sh-7d}} \qquad (4)$$

where

$M_{LWA}^{required}$ = mass of LWA required to eliminate the 7-day net autogenous shrinkage;

M_{LWA}^{used} = mass of LWA actually used in concrete;

$\Delta\varepsilon_{sh-7d}$ = relative reduction in the 7-day net autogenous shrinkage strain due to internal curing.

Eq. 4 yielded values ranging from 0.63 kg to 1.25 kg of LWA per kg of cement, depending on the concrete mixture (Table 7). It can be observed that quite large differences exist between the estimated quantities of LWA based on chemical shrinkage compensation (Eq. 3) and the corresponding quantities actually needed to eliminate the 7-day net autogenous shrinkage strain (Eq. 4). The closest estimates were obtained for the concrete specimens made with SF cement (but are still twice higher, approximately). Differences between estimated and actual quantities of LWA needed for adequate internal curing have also been reported in the literature.[4, 17]

Table 7 also includes some results obtained from earlier experiments[7] on specimens made with concrete mixtures (*w/cm*=0.34) similar to Mixture 4a (OPC and 20-mm coarse aggregate). It can be seen that the predictions based on chemical shrinkage (Eq. 3) compared very well with the IC requirements determined experimentally based on the 7-day net autogenous shrinkage strain (Eq. 4). The reasons for these apparently very good comparisons, as opposed to those obtained for the mixtures of the present study, are still unconfirmed, but may be related to the specimen size. In the previous study[7], the prismatic specimen dimensions were 200x200x1000 mm (8x8x39 in.), compared to the specimen size of 75x75x295 mm (3x3x11⅝ in.) of the present study. The specimen size may be a factor that may directly or indirectly influence the shrinkage development of concrete specimens, especially those made with 20-mm (¾ in.) coarse aggregate. The higher peak temperatures (up to 45°C (113°F)), which developed in the more massive concrete specimens due to higher heat of cement hydration, may also have an effect on shrinkage development. In comparison, the smaller concrete specimens of this study only had temperature peaks of up to 25°C (77°F). The higher concrete temperatures developing at early ages may promote different mechanisms that may reduce the apparent net autogenous shrinkage of concrete. If some of these hypotheses prove to be true, the effectiveness of internal curing in reducing autogenous shrinkage in large concrete structures may be higher than what is actually measured in smaller-scale laboratory concrete specimens.

Further research is needed for an improved understanding and estimation of the key factors influencing the effectiveness of internal curing in HPC structures, some of which are not yet taken into account in the current IC requirement calculation method (for example type and amount of SCMs,[14, 16] type and size of IC agent,[4, 17] concrete porosity,[16, 17] and type and amount of chemical admixtures).

SUMMARY AND CONCLUSIONS

The effects of type of curing, type of cement and maximum size of coarse aggregate on different performance parameters were evaluated. To study these variables, twelve high-performance concrete mixtures were developed and tested for autogenous shrinkage and other properties under sealed and room temperature conditions. The results were analyzed using the paired comparison design method. The following conclusions were drawn:

1. The risk of cracking in concrete structures can be conservatively estimated from the net shrinkage strain occurring after the peak expansion strain that may develop at early age under stress-free conditions. Neglecting to consider this expansion by using the uncorrected shrinkage strain may result in a significant underestimation of the extent of shrinkage strain contributing to the development of tensile stresses in restrained concrete structures. When only free shrinkage test results are available, it is proposed to define the net shrinkage strain as the difference between the peak expansion strain (or zero if no expansion) and the most negative shrinkage strain. This definition of net shrinkage has the advantage of being independent of the onset of strain measurement, whether it is taken at casting, initial or final setting, or peak of expansion.
2. Internal curing of concrete specimens with pre-saturated porous lightweight aggregate sand allowed significant expansion (up to 184 $\mu\varepsilon$) to occur at early ages, which may be due to mechanisms like early-age ettringite formation. After this early-age expansion, internal curing provided significant reductions (up to 63%) in the net autogenous shrinkage strain at 7 days compared to sealed curing.
3. Internal curing was also found to have a moderate contribution to early-age strength, with a 4.4% gain in the 7-day compressive strength of 54 MPa (7830 psi) concretes, even though 205 kg/m^3 (346 lb/yd^3) of saturated low-density aggregate were used in the specimens. At 28 days, the compressive strengths of the internally-cured concrete specimens were just slightly higher than those of the sealed-cured specimens (66 MPa (9570 psi)).
4. The type of cement used in the concrete specimens had a significant effect on the early-age expansion produced by internal curing. The average expansion was the largest with Slag/SF cement (177 $\mu\varepsilon$), followed by OPC (75 $\mu\varepsilon$) and SF cement (39 $\mu\varepsilon$). The extent of the peak expansion strain measured at early ages seems to be inversely proportional to amount of fine reactive pozzolanic cementing materials contained in the concrete. Under sealed curing only, the concrete specimens made with OPC displayed less net shrinkage at 7 days (-155 $\mu\varepsilon$) than the specimens made with Slag/SF (-230 $\mu\varepsilon$) and SF cements (- 260 $\mu\varepsilon$), as expected.
5. The type of cement also had a strong effect on the concrete compressive strength, as expected. For instance, when Slag/SF cement or SF cement was used instead of OPC, the 28-day compressive strength increased by 22% and 27%, respectively.
6. The maximum size of coarse aggregate, when reduced from 20 mm (¾ in.) to 10 mm (⅜ in.), produced a significant 10% increase in the 28-day compressive strength, as expected, without significantly affecting autogenous shrinkage. Combined with internal curing, the use of smaller coarse aggregate in concrete may achieve higher strengths while keeping the risk of autogenous shrinkage cracking low.
7. The effectiveness of internal curing at reducing net shrinkage was significantly affected by the type of cement used in the concrete specimens. In particular, the SF cement mixtures, which yielded the largest average net autogenous shrinkage strain at 7 days under sealed curing, benefited the most from internal curing with the highest average shrinkage reduction of 59%, compared to 51% for OPC specimens, and 38% for Slag/SF cement specimens (which all had identical quantities of LWA sand for internal curing). The improved IC effectiveness for the SF cement concrete specimens may be explained by the smaller-size concrete pores producing higher internal suction forces, which would attract more effectively a larger volume of IC water from the LWA at earlier ages. The effectiveness of internal curing was also found to improve significantly from the use of 10-mm (⅜ in.) coarse aggregate, instead of 20-mm (¾ in.) aggregate.
8. The current IC requirement calculation method was found to give low estimates compared to the quantities of LWA actually needed to eliminate the 7-day net autogenous shrinkage. Excellent estimates were found on larger-size concrete specimens, which showed superior shrinkage reductions for the same mass of saturated LWA per unit mass of cement. This may be due to a size effect on shrinkage development and/or to higher peak temperatures due to more significant heat of hydration, which may promote autogenous expansion in larger-size concrete specimens.
9. Further research is needed to identify and better understand some additional factors, which may be missing in the current IC requirement calculation method, such as type and amount of SCMs, type and size of IC agent, concrete porosity, type and amount of chemical admixtures, and curing temperatures.

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Table 1 – Cement chemical and physical data (supplied by the manufacturer)

Cement	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	SiO_2 (%)	Na_2O (%)	K_2O (%)	LOI (%)	Alkali (%)	Blaine (m^2/kg)	Fineness (% passing 45μm mesh)
OPC	4.5	2.9	62.4	2.7	3.2	-	-	-	2.0	0.68	379	96.0
SF	4.8	2.3	58.4	2.4	3.7	25.8	0.22	0.88	1.6	0.80	564	91.5
Slag/SF	5.8	2.0	54.2	4.2	4.1	27.2	0.21	0.72	1.9	0.68	575	95.5

Table 2 – Main concrete mixtures (per kg of cement)
(1 kg/m^3 = 1.6858 lb/yd^3; 1 ml = 0.034 ounce)

Constituent	**Internally-cured concretes** (including six variations)	**Sealed-cured concretes** (including six variations)
Mixing Water (kg)	0.35	0.35
Cement (kg) †	1.0	1.0
Normal Sand (kg)	1.1	2.0
Lightweight sand (kg)	0.46 ssd (0.40 dry)	0.0
Coarse aggregate (kg) ‡	2.0	2.0
Superplasticizer	varied from 6 ml to 12 ml	
Water reducer	0 ml for OPC 2 ml for SF cement and Slag/SF cement	
Air entrainer	varied from 0.12 ml to 0.17 ml	
Average density	2277 kg/m^3	2364 kg/m^3

† Cement type was either OPC, SF cement or Slag/SF cement;
‡ Coarse aggregate maximum size was either 10 mm (⅜ in.) or 20 mm (¾ in.).

Table 3 – Aggregate properties
(1 mm = 0.039 inch; 1 kg/m^3 = 1.6858 lb/yd^3)

Name	**Type**	**Max. size** (mm)	**Dry-bulk density** (kg/m^3)	**Fineness modulus**	**Water content by mass** (%)
Lightweight sand	Expanded shale	5	920	3.3	15.0
Regular sand	Silica, quartz	5	1650	2.6	0.3
Coarse aggregate	Limestone	10	1600	5.9	0.3
		20	1660	6.7	0.2

Table 4 – Shrinkage and strength test results
(1 mm = 0.039 inch; 1 MPa = 145 psi)

Mixture No.	**Curing type**	**Cement type**	**Stone Size** (mm)	**Peak expansion strain** (με)	**7-day net shrinkage strain** (με)	**7-day compressive strength †** (MPa)	**28-day compressive strength ‡** (MPa)
1a	Sealed	OPC	20	11	-140	52.6	57.1
1b	Sealed	OPC	10	24	-169	46.1	54.4
2a	Sealed	SF	20	6	-251	56.9	68.6
2b	Sealed	SF	10	8	-268	65.0	80.2
3a	Sealed	Slag/SF	20	37	-211	51.1	63.6
3b	Sealed	Slag/SF	10	21	-249	53.7	69.4
4a	Internal	OPC	20	100	-84	54.8	56.9
4b	Internal	OPC	10	49	-65	51.6	59.1
5a	Internal	SF	20	42	-114	58.0	62.7
5b	Internal	SF	10	36	-100	63.3	76.5
6a	Internal	Slag/SF	20	170	-143	55.0	69.2
6b	Internal	Slag/SF	10	184	-142	57.0	75.8

† Maximum standard deviation for 7-day compressive strength of triplicate specimens = 1.7 MPa
‡ Maximum standard deviation for 28-day compressive strength of triplicate specimens = 2.2 MPa
‡ Maximum standard deviation for 7-day net shrinkage of triplicate specimens = 26 με

Table 5 – Detailed statistical analysis of the effect of curing type on selected parameters
(1 MPa = 145 psi)

Mixture No.	**Level tested** (curing type)	**Change in peak expansion** (με)	**Change in 7d net shrinkage** (με)	**Change in 7d compressive strength** (MPa)	**Change in 28d compressive strength** (MPa)
1a vs. 4a	Sealed→Internal	89	56	2.1	-0.2
1b vs. 4b	Sealed→Internal	25	104	5.5	4.7
2a vs. 5a	Sealed→Internal	36	137	1.0	-5.9
2b vs. 5b	Sealed→Internal	28	168	-1.7	-3.7
3a vs. 6a	Sealed→Internal	133	68	3.9	5.6
3b vs. 6b	Sealed→Internal	163	107	3.3	6.4
Average:		**79**	**107**	**2.4**	**1.2**
Standard deviation:		**59**	**42**	**2.5**	**5.2**
Confidence level:		**99%**	**100%**	**97%**	**69%**

Table 6 – Summary of statistical analysis results, including average values, standard deviations and confidence levels
(1 MPa = 145 psi)

Variable tested	**Level tested**	**Change in peak expansion** (με)	**Change in 7d net shrinkage** (MPa)	**Change in 7d compressive strength** (MPa)	**Change in 28d compressive strength** (MPa)
Curing type	Sealed vs. Internal	79 (59) 99% *	107 (42) 100% *	2.4 (2.5) 97% *	1.2 (5.2) 69%
Cement type	OPC vs. SF	-23 (24) 93% *	-69 (42) 98% *	9.5 (7.3) 96% *	15.1 (8.5) 98% *
	OPC vs. Slag/SF	57 (60) 92% *	-72 (9) 100% *	2.9 (4.3) 87%	12.6 (4.5) 99% *
Stone size	20 mm vs. 10 mm	-7 (24) 75%	-8 (23) 79%	1.4 (5.4) 72%	6.2 (6.0) 97% *

* Effect considered significant when $\alpha>90\%$

Table 7–Internal curing requirements based on chemical and autogenous shrinkage values

Mix No.	**Cement type**	**Stone Size** (mm)	**LWA used in concrete specimens** (kg/kg cement)	**Measured shrinkage Reduction** (Eq. 2) (%)	**LWA estimated to compensate for chemical shrinkage** (Eq. 3) (kg/kg cement)	**LWA estimated to eliminate 7d net autogenous shrinkage** (Eq. 4) (kg/kg cement)
4a	OPC	20	0.40	40	0.35	1.00
4b	OPC	10	0.40	62	0.35	0.65
5a	SF	20	0.40	55	0.37	0.73
5b	SF	10	0.40	63	0.37	0.63
6a	Slag/SF	20	0.40	32	0.40	1.25
6b	Slag/SF	10	0.40	43	0.40	0.93
Ref	OPC	20	0.24	72	0.34	0.33
7	OPC	20	0.40	101	0.34	0.40

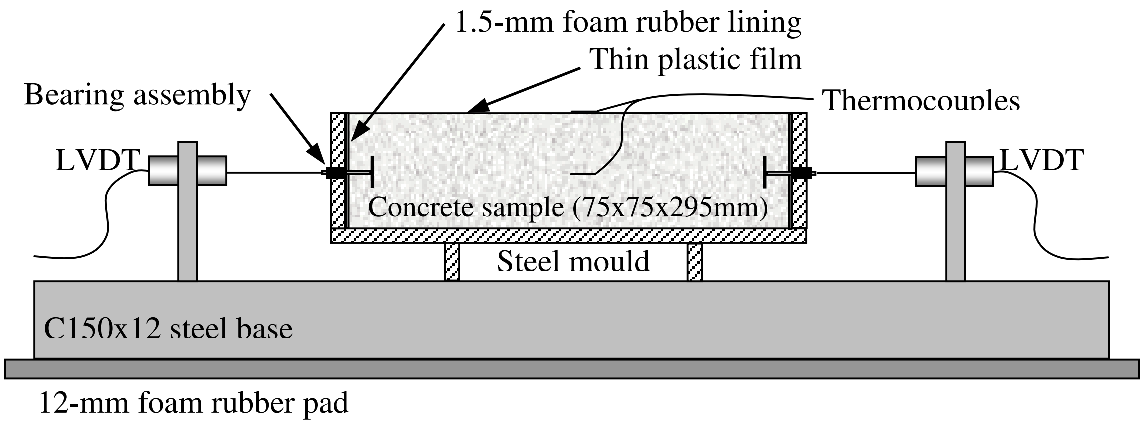

Figure 1a–Diagram of test apparatus – showing 1 of 3 identical setups.
(1 mm = 0.039 inch)

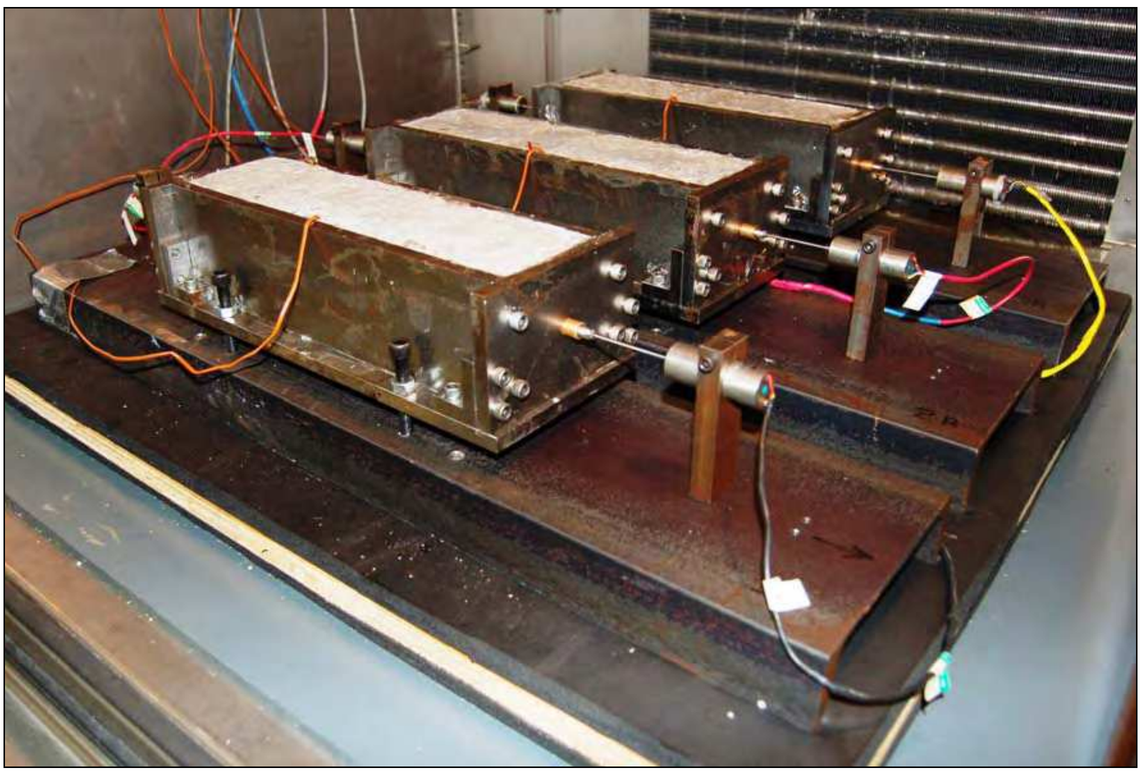

Figure 1b–Picture of test apparatus – showing 3 identical setups
(with top plastic seal removed for the picture).

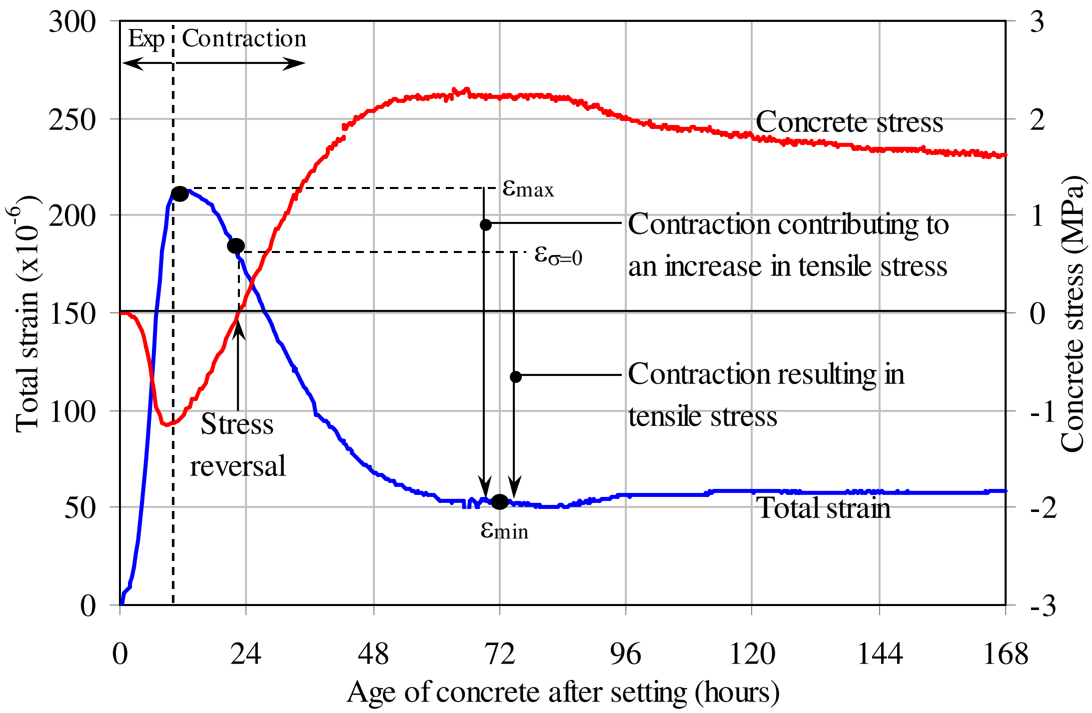

Figure 2–Total strain and resulting concrete stress under restrained conditions.
(1 MPa = 145 psi)

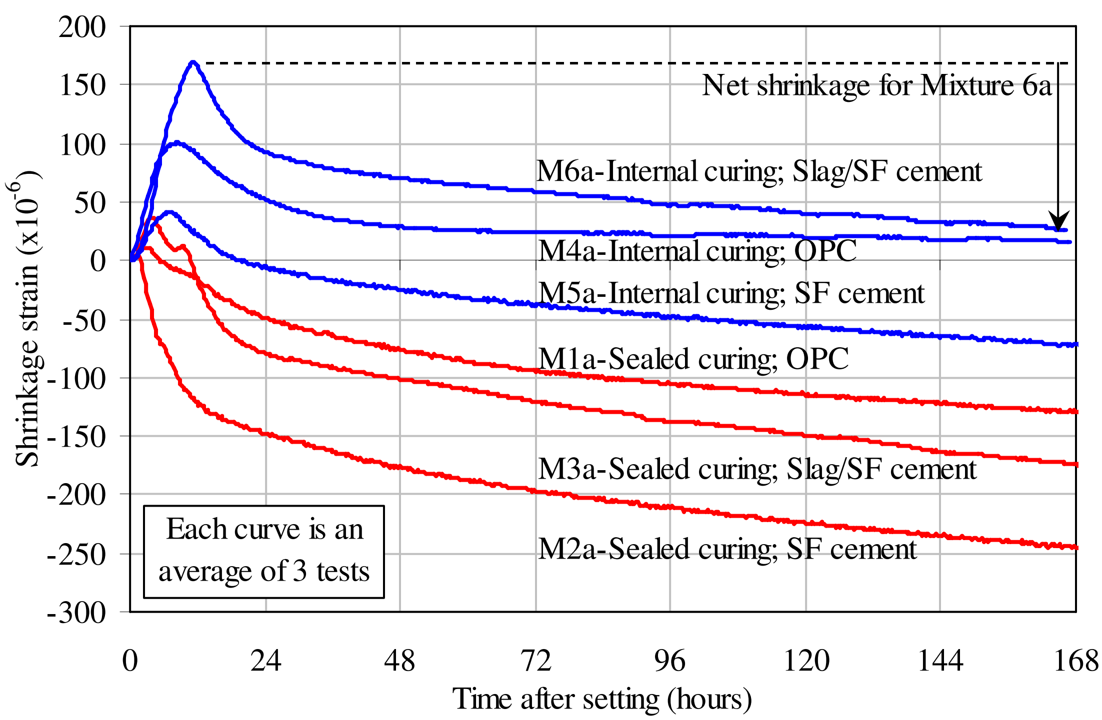

Figure 3–Autogenous shrinkage strain measured in concrete specimens made with 20mm (¾ in.) coarse aggregate.

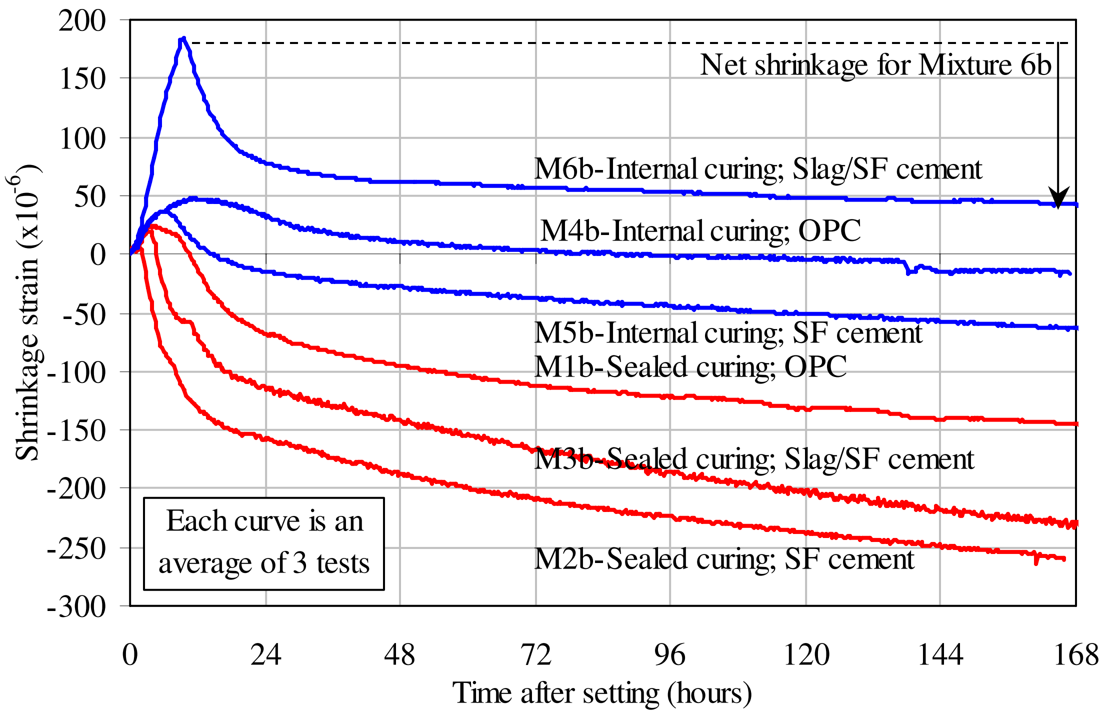

Figure 4–Autogenous shrinkage strain measured in concrete specimens made with 10mm (⅜ in.) coarse aggregate.

	Parameter value at **low level** of test variable	Parameter value at **high level** of test variable	Difference in parameter values for each pair
Pair 1:	P_{1_L}	P_{1_H}	d_1
Pair 2:	P_{2_L}	P_{2_H}	d_2
Pair 3:	P_{3_L}	P_{3_H}	d_3
Pair 4:	P_{4_L}	P_{4_H}	d_4
Pair 5:	P_{5_L}	P_{5_H}	d_5
Pair 6:	P_{6_L}	P_{6_H}	d_6

Hypothesis	Test statistic	Criteria for rejection
$H_0 : \bar{d} = 0$ $H_1 : \bar{d} < 0$	$t_0 = \dfrac{\bar{d}}{S_d / \sqrt{n}}$	$t_o < -t_{\alpha,n-1}$
$H_0 : \bar{d} = 0$ $H_1 : \bar{d} > 0$		$t_o > +t_{\alpha,n-1}$

In this study:

- Parameters are: peak expansion, net shrinkage, compressive strength
- Variables are: type of curing, type of cement, maximum size of coarse aggregate

Figure 5–Schematic representation of paired comparison design method.