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Contribution of mixture design to chemical and autogenous shrinkage of concrete at early ages

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Abstract

In this work, autogenous shrinkage at early ages (< 24 h) was accurately measured by linear displacements on slabs simulating field constructions. The best correlation of the amount of chemical to autogenous shrinkage was found at the time of 4 h after the final setting time. It was possible to account for test arrangement artifacts, such as thermal dilation, to get a measure of pure autogenous shrinkage. Many material parameters, such as superplasticizer (SP) and aggregate amount, effected the magnitude of autogenous shrinkage in secondary ways. These consequential effects, such as amount of bleed water and time of setting, were accounted for in the slab measurements. Recommendations are given for reducing the likelihood of cracking due to early age chemical and autogenous shrinkage.

Keywords: Autogenous deformation; Curing; Fresh concrete; Shrinkage

1. Introduction

1.1. Background

Concrete shrinkage is of increasing concern when focusing on maintaining durable structures. Over time, the shrinkage induces cracking, which can severely decrease concrete life expectancy. These volume changes are often attributed to drying of the concrete over a long time period, although recent observations have also focused on early age or plastic drying problems. At early ages, the concrete is still moist and there are difficulties in measuring the fluid material. These difficulties have hindered comprehensive physical testing and understanding of the factors influencing plastic shrinkage. The most common solution to reduce early age volume changes is to avoid drying by proper handling of the concrete for the first few hours after placement. It is imperative that the concrete curing begins immediately and follows correct methods [1].

A supplementary problem to drying shrinkage at early ages is the change that occurs when no moisture transfer is permitted with the environment. This volume reduction is called *autogenous shrinkage* and is attributed to chemistry and internal structural changes. Autogenous shrinkage is usually a concern in high-strength or high-performance concrete (>40 MPa or 6000 psi) where there is a low water-to-cement (w/c) ratio. Overall, early age concrete shrinkage is of increasing concern, as it can be responsible for cracking when the concrete has not gained significant strength to withstand internal stresses.

Shrinkage of concrete takes place in two distinct *stages*: early and later ages. The early stage is commonly defined as the first day, while the concrete is setting and starting to harden. Later ages, or long term, refers to the concrete at an age of 24 h and beyond. During this later stage, the concrete is demolded and standardized shrinkage measurements are conducted. The long-term shrinkage is typically the only part that is identified and addressed in literature, as well as being the portion that is accommodated in structural design.

Within each of these two stages of shrinkage, there are also various *types* of linear change which can be physically measured on a specimen, mainly drying and autogenous. Both of these types can occur during either shrinkage stage. In addition to drying and autogenous shrinkage, the concrete is also subjected to volume reductions due to thermal changes and carbonation reactions. The shrinkage types and stages are mapped in Fig. 1.

Early-age shrinkage is a concern because it is during the early hours, immediately after casting, that concrete has the

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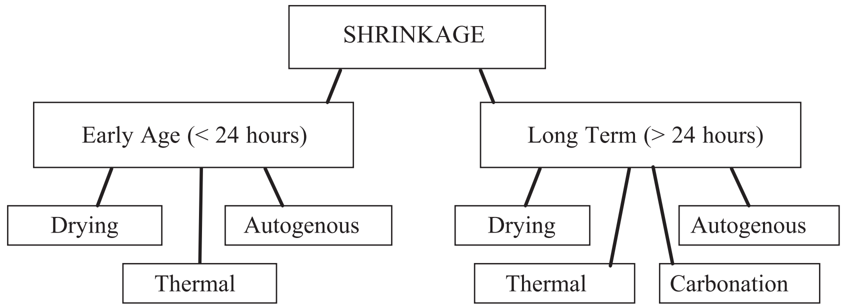

Fig. 1. Diagram of shrinkage stages and types.

lowest strain capacity and is most sensitive to internal stresses. Work by Byfors [2] in Sweden and Kasai et al. [3] in Japan has shown that concrete has the lowest tensile strain capacity in these early hours. An example from Kasai et al. [3] is given in Fig. 2, where the lowest point is reached at about 10 h and then the tensile strain capacity again increases. Some other current research is focused on developing methods to quantify these magnitudes of concrete stresses within the first hours for various shrinkage loading [4–6].

Early-age shrinkage can result in cracks that form in the same manner as at later ages. Even if the early resulting cracks are internal and microscopic, further shrinkage at later ages may merely open the existing cracks and cause problems. It is suggested by VTT and others that if the early age shrinkage magnitude exceeds 1 mm/m (1000 $\mu\varepsilon$), there is a high risk of cracking [7]. This corresponds to the American Concrete Institute guidelines [8] of an expected shrinkage of about 0.25–0.5 in. of movement in 20 ft, or 0.4–1.0 mm/m.

There is no correlation between the magnitudes of early-age and long-term shrinkage. The shrinkage occurring during these two stages should be taken together as the "total shrinkage" for a concrete. In some cases, such as poor curing conditions with rapid drying, the first day's shrinkage can easily exceed the long-term measurements. This is demonstrated in Fig. 3 for various environmental conditions during the first day [1]. The long-term shrinkage due to drying was equivalent in all cases, although the first day had a significant change to the magnitude of total shrinkage and thus affected the expected cracking. The microcracking that may occur in the first day does not modify the long-term shrinkage but subsequent long-term shrinkage may result in the cracks opening further and being more detrimental to deterioration.

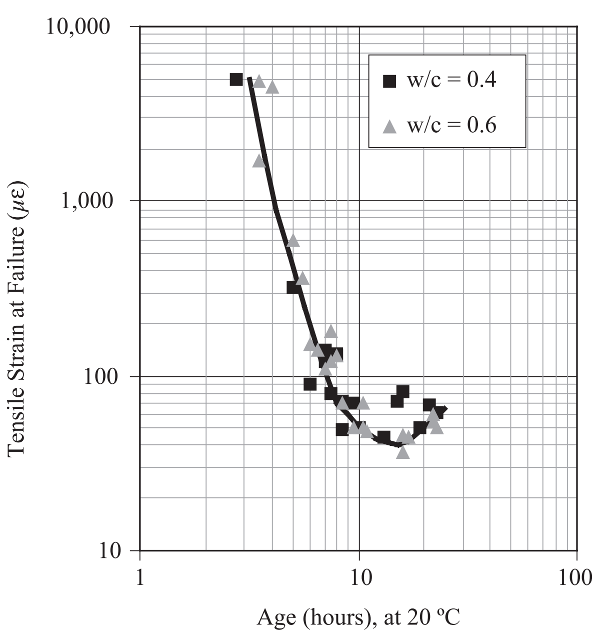

Fig. 2. Decreasing tensile capacity during early ages [1,3].

1.2. Autogenous shrinkage

Autogenous shrinkage of cement paste and concrete is defined as the macroscopic volume change occurring with no moisture transferred to the exterior surrounding environment. It is a result of chemical shrinkage affiliated with the hydration of cement particles [9]. The chemical shrinkage is an *internal* volume reduction while the autogenous shrinkage is an *external* volume change.

Autogenous shrinkage has only recently been documented and accurately measured. It was first described in

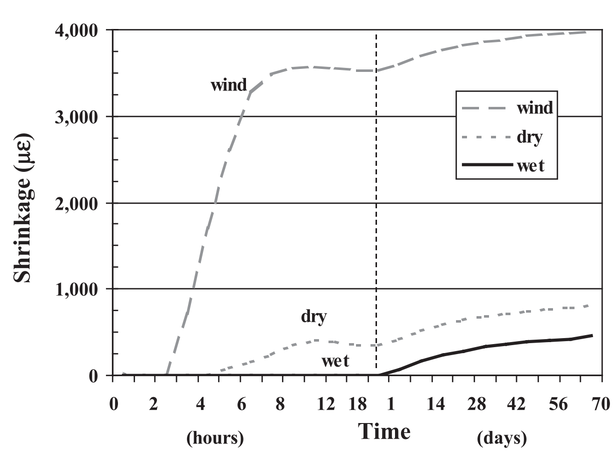

Fig. 3. Accumulation of early-age and long-term shrinkage, with various curing environments during the first day. Wind = 2 m/s (4.5 mph), dry = 40% RH, wet = 100% RH.

the 1930s [10] as a factor contributing to the total shrinkage, which was difficult to assess. In these earlier days, autogenous shrinkage was noted to occur only at very low w/c ratios that were far beyond the practical range of concretes. But with the development and frequent use of modern admixtures, such as superplasticizers (SPs) and silica fume, it is much more realistic to proportion concrete susceptible to autogenous shrinkage. Today, we often have greater structural demands for high-strength and high-performance concretes. This leads engineers and designers to specify concrete with lower w/c ratios, much beyond the limitations of the 1930s. Although many strength and durability aspects are now improved with these specifications, the risk of autogenous shrinkage is greater.

Autogenous shrinkage occurs over three different stages within the first day after concrete mixing: liquid, skeleton formation, and hardening. After the hardening stage, the concrete shrinkage can be measured using more standard long-term measuring practices. During the early phase while the concrete is still liquid, the autogenous shrinkage is equivalent to chemical shrinkage. During the skeletal formation phase, a more rigid structure is formed due to the stiffening of the paste and the concrete can resist some of the chemical shrinkage stresses. Here, the capillary pressure will also start to develop and cause shrinkage. This pressure mechanism works as the water, or meniscus, is moving between the pores. As the water is lost from subsequently smaller pores, the water meniscus will continue to be pulled into the capillary pores and will generate more stress on the capillary pore walls. This is similar to the phenomena described by Radocea [11] for drying shrinkage and it again causes a contraction in the cement paste. Once concrete has reached a hardened stage with aging (>1+ day), the autogenous shrinkage can result from self-desiccation [12,13], which is the localized drying resulting from a decreasing relative humidity in the concrete's internal pores. The lower humidity is due to the cement requiring extra water for hydration.

In a high-strength concrete with a low w/c ratio, the finer porosity causes the water meniscus to have a greater radius of curvature. These menisci cause a large compressive stress on the pore walls, thus having a greater autogenous shrinkage as the paste is pulled inwards in both early-age and long-term shrinkage.

1.3. Chemical shrinkage

As earlier described, autogenous shrinkage is fully attributed to chemical shrinkage during the very first hours after mixing. The chemical shrinkage is a result of the reactions resulting between cement and water, which lead to a volume reduction. The basic reactions of cement clinker are well understood and generally defined by four reactions of C_3S, C_2S, C_3A, and C_4AF. Each of these reactions, which requires water for reaction, is exothermic and results in a decreased volume of the reaction products.

This volume reduction, or chemical shrinkage, begins immediately after mixing of water and cement and the rate is greatest during the first hours and days. The magnitude of chemical shrinkage can be estimated using the molecular weight and densities of the compounds as they change from the basic to reaction products [1,14,15]. A generalized equation for estimating the chemical shrinkage is given in Eq. (1).

$$V_{\mathrm{CS-TOTAL}} = 0.0532[C_3S] + 0.0400[C_2S] + 0.1113[C_4AF] + 0.1785[C_3A] \quad (1)$$

The rate of chemical shrinkage is dependent on cement and concrete mixture parameters, such as the cement fineness and the efficiency of cement dispersion. Higher magnitudes of chemical shrinkage due to quicker cement reactions during the very early hours will lead to greater autogenous shrinkage.

2. Measuring methods

Early-age shrinkage measurements provide a challenge due to the difficulty in making accurate measurements of the concrete prior to demolding. The shrinkage must be measured immediately after casting in a mold which permits constant readings without disturbing the concrete. The main difference between measurements of chemical and autogenous shrinkage is that in chemical shrinkage, there is an external water source providing additional water to be absorbed by the paste. In autogenous shrinkage tests, the concrete sample is sealed and there is no moisture transfer to the surrounding environment.

Chemical shrinkage of paste and mortar is measured by placing a sample in a container and measuring the amount of water the material uptakes. The excess space generated by the smaller volume of hydration products provides pores for the exterior water source penetrate. Chemical shrinkage measurements can been done by either the dilatometry arrangement using a pipette and beaker or the reduced buoyancy arrangement with a flask underwater. Boivin et al. [16] has established a strong correlation between the two methods.

Early-age autogenous shrinkage can been measured by volumetric or linear measurements. Volumetric assessments are done by taking the weight of a paste or mortar sample sealed in a thin rubber membrane underwater. Linear measurements are done on a paste, mortar, or concrete sample that is cast in a slab mold. The linear measurements are a more realistic representation of actual field construction and the material behavior, because thermal dilation, bleeding, setting time, and other factors are accounted for in the slab test. It is possible to convert the horizontal and vertical displacements measured on the slab test to a volumetric shrinkage. It is also possible to factor out the volume change resulting from thermal changes associated with cement hydration to get a measure of pure autogenous shrinkage.

There is no standardized method of measuring early-age length change as there is for long-term shrinkage (such as ASTM C157). The most practical measures of length change are done on a concrete slab simulating field situations, such as floors or facades. These tests have been developed by work at VTT, the Technical Research Centre of Finland [17–20], as well as others in Scandinavia and Japan [5,11,21,22]. The early-age test arrangement can be used to measure drying shrinkage, autogenous shrinkage, or both.

In the slab tests, both vertical (settlement) and horizontal shrinkage are measured, along with evaporation and capillary pressure. The slab holds 7.3 l (0.25 ft^3) of concrete and the maximum aggregate size can be 32 mm. A temperature profile is also taken at two different depths, along with a simultaneous measure of setting time on a separate sample by the Italian automatic penetration test developed by Luigi Giazzi in Milan. Within the slab, a change in internal capillary pressure is the primary indicator of the start of autogenous shrinkage. The early-age measurements begin immediately after concrete placing (approximately 30 min) and continue for 24+ h. The horizontal shrinkage is measured by LVDTs over a length of 200 mm.

3. Materials and mixture designs

Tests were done using cement paste, mortar, or concrete composed of typical Finnish materials. Aggregate consisted of Finnish clean natural granite, with a density or dry rodded unit weight of 2670 kg/m^3. The fine aggregate was natural sand and the coarse aggregate had rounded particles. The maximum aggregate size was 2 mm in the mortar mixtures and 10 mm in the concrete mixtures.

All tests used Finnish rapid hardening cement containing slag, which is type CEM IIA in Europe and comparable to Type III cements in the USA. Rapid cement is commonly used for high-strength and/or high-performance products, such as in precast facade manufacturing. The Finnish rapid cement had a Blaine fineness of 440 m^2/kg, with 68% C_3S, 10% C_2S, 8% C_3A, and 8% C_4AF. The gypsum content was 3.5% with 0.5% alkalis.

Table 1
Mixture designs for autogenous shrinkage tests, all made from rapid hardening Finnish cement

Type	w/c Ratio	SP (%)	Cement (kg/m^3)	Water (kg/m^3)
Paste	**0.35**	–	1440	505
Mortar	**0.30**	–	915	275
Mortar	**0.35**	–	780	275
Mortar	**0.40**	–	685	275
Mortar	0.45	–	915	275
Mortar	**0.30**	1	915	275
Concrete	0.30	5	545	165
Concrete	0.35	2	505	165

In some cases, chemical admixtures were added to the concrete mixtures to improve the mixture characteristics. This mainly included the use of naphthalene-based SPs to aid workability of the mixtures. No air-entraining chemicals or mineral admixtures were used in any tests. In most cases, the target fresh mixture properties were a slump of 50 mm and an air content of 3%.

The mixture designs used when testing chemical and autogenous shrinkage of cement pastes, mortars, and concretes are detailed in Table 1. Mixtures in bold denote ones that are used in both the chemical and autogenous shrinkage tests.

4. Results

4.1. Autogenous data interpretation

When analyzing early-age slab test results, it was necessary to have a consistent referencing point. For uniformity when comparing the shrinkage measurements of various mixtures, it was assumed that any shrinkage occurring prior to the initial setting time was insignificant because of the fluid nature of the concrete. Any shrinkage prior to initial set is an artifact of the test arrangement. An additional concern when choosing the referencing point was the presence of bleed water on the concrete surface. In autogenous conditions, the bleed water is reabsorbed into the concrete and registers as an expansion with the displacement gauges. Therefore, if there was still bleed water on the surface of the concrete at the time of initial set, the reference point was not be taken until the bleed water was fully reabsorbed. Further discussions about the selection of the referencing point for the shrinkage data can be found in Holt's [1] work.

Another factor that was accounted for in the autogenous shrinkage slab tests was the early-age thermal dilation. Often coinciding with the time of bleed water reabsorption was the start of heat generation due to the cement hydration. The thermal volume change due to this cement hydration was removed to provide a measure of the true autogenous shrinkage without the thermal factors included.

Sample temperature profiles for paste, mortar, and concrete are shown in Fig. 4. In this figure, the paste and mortar have a w/c ratio = 0.35 and the concrete has a w/c ratio = 0.30 with 2% SP. The temperature changes result from the cement hydration, which, in turn, causes an expansion and contraction during the early ages. These initial thermal volume changes can be estimated from existing data of thermal dilation coefficients and can be factored out of the shrinkage measured in a slab test. For instance, Hedlund [6] had measured a thermal dilation value of approximately 25 $\mu\varepsilon/°C$ for a concrete at the age of 10 h. More details of this process of removing thermal dilation from slab test data can be found in other reports [1].

The early age autogenous shrinkage resulting from altering the mixture designs are presented in the next series

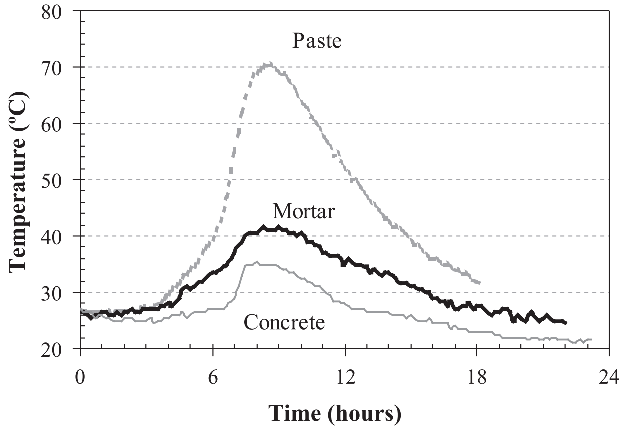

Fig. 4. Sample temperature development with time since concrete mixing.

of figures. The main tests were done on mortars, because they allow comparison to the chemical shrinkage tests. Testing mortars had the secondary effect of complicating the data interpretation due to their greater thermal change during the early ages compared to concrete. The mixture parameters that were altered included aggregate content, the use of an SP admixture, and w/c ratio. The tests are summarized in Table 2 along with their measured setting times and temperature histories. All mixtures had materials at 20 °C at the start of mixing. The time when the bleed water was reabsorbed is also listed, but these times are based on estimates from the horizontal shrinkage data. Finally, the time when the capillary pressure started to develop is noted in Table 2, based on the test data. This development point was taken when the pressure reached a level of 3 kPa, with a typical maximum of about 50 kPa.

4.2. Effect of aggregate restraint

To assess the contribution of aggregate restraint to autogenous shrinkage, tests were done on neat paste, mortar, and concrete. The measurements on cement pastes are not very representative of the true behavior of concrete because of their large thermal changes. The high heat of hydration of the cement paste results in a large thermal expansion and thus the slab shrinkage measurements will include this change that must be factored out of the results. Fig. 5 shows one of the few tests done on cement paste in the autogenous shrinkage test arrangement. The paste can be compared to a similar mortar at the same w/c ratio of 0.35 with no SP.

The data were referenced at the time when all of the bleed water was reabsorbed to the mixture and thus there was an end of expansion prior to capillary pressure development. For the mortar and neat paste mixtures of Fig. 5, this was at about 4 h. If there had been no bleeding, the reference point would have been taken at the time of initial set.

As expected, the neat paste had much greater shrinkage than the mortar due to the lack of aggregate providing restraint. This is in agreement with textbook literature regarding other forms of shrinkage, where concretes with a high paste content are expected to shrinkage more [8]. The difference in the two mixtures of this work showed the neat paste having about 1.7 times greater shrinkage compared to the mortar.

The paste mixture in Fig. 5 also showed a slight expansion beyond 12 h. This is probably not an accurate depiction and may have resulted from too great of a calculated thermal contraction as the mixture cooled. A more accurate measure of the thermal dilation coefficient would be required to improve the paste's true autogenous shrinkage estimate in the first day. Another explanation could be the possible formation of hydration products causing expansion. Further testing should be done to assess this expansion tendency.

Another two tests were done to compare the restraint provided by increasing the aggregate, both in size and volume. Both concrete and mortar mixtures were tested at a w/c ratio of 0.30 and including SP. The concrete has a paste volume of 34% compared to 57% in the mortar. The comparison of the autogenous shrinkage with the mixture types is given in Fig. 6.

In this test, it was expected, based on the mortar and paste comparisons in Fig. 5, that the concrete mixture would have less shrinkage than the mortar because the concrete has

Table 2
Summary of early-age autogenous slab test mixtures

Type	w/c Ratio	SP (%)	Initial set (h:min)	Bleeding done (h:min)	Pressure start (h:min)	Temperature	
						Peak (°C)	Time (h:min)
Paste	0.35	–	3:15	4:10	4:10	70.3	9:00
Mortar	0.30	–	1:30	–	2:15	44.0	7:50
Mortar	0.35	–	2:10	3:50	3:10	41.5	8:50
Mortar	0.40	–	2:25	4:30	4:10	37.8	11:50
Mortar	0.45	–	3:35	7:50	6:30	34.5	12:10
Mortar	0.30	1	1:30	–	2:30	47.5	8:00
Concrete	0.30	5	0:35	–	3:00	35.5	8:00
Concrete	0.35	2	2:35	–	2:25	34.0	9:00

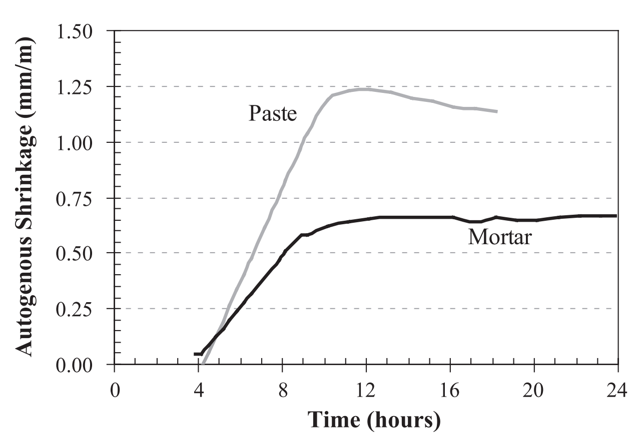

Fig. 5. Autogenous shrinkage resulting with addition of aggregate, from paste to mortar at w/c ratio = 0.35.

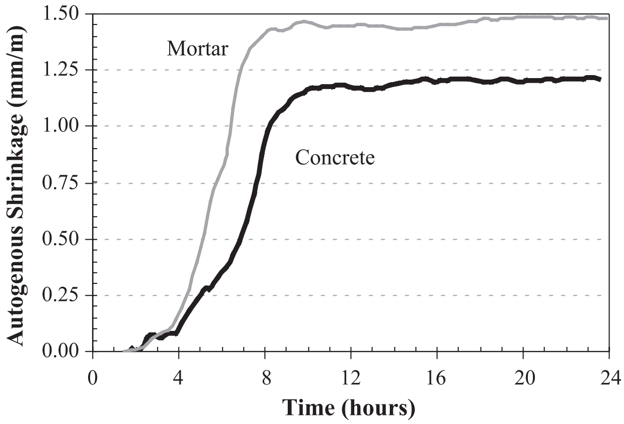

Fig. 6. Autogenous shrinkage resulting with addition of aggregate from mortar (paste volume = 57%) to concrete (paste volume = 34%) at w/c ratio = 0.30.

more aggregate restraining the shrinkable paste. The concrete mixture also had less cement (545 kg/m^3, as given in Table 1) compared to the mortar mixture (915 kg/m^3) so the amount of chemical shrinkage would be less in the concrete. Both of these theories held true, with the concrete shrinking less than the mortar.

Both the concrete and mortar mixtures in Fig. 6 had shrinkage amounts greater than the paste and mortars shown in Fig. 5. This is due to the lower w/c ratio and the presence of SP chemicals. The influence of these other two parameters is addressed in the next subsections.

4.3. Effect of SP

To test concrete mixtures having a low w/c ratio, it is often necessary to add an SP to the mixture to improve the workability and allow for adequate placement. The effect on autogenous shrinkage when an SP was added to a mortar with a w/c ratio of 0.30 is shown in Fig. 7. Both mixtures had identical proportioning except for the addition of the chemical. Therefore, their workabilities were different, but both mixtures still had little, if any bleed water. The non-superplasticized mixture is the same as the mortar with a w/c of 0.30 in Fig. 9.

In both mixtures, there was little bleeding and no signs of expansion due to bleed water reabsorption, thus the data curves start at the time of initial set (90 min). In these two mortars, the setting time was not delayed with the addition of the SP, as is often expected.

The temperature peak of the two mixtures was at about the same time of 8 h, although the superplasticized mortar had a slightly greater temperature rise. The early age autogenous shrinkage ended at about the time of maximum thermal expansion. The results showed that the superplasticized mixture had shrinkage 50% greater than the reference mixture. The greater autogenous shrinkage with SP is partially an indirect result. It may be a result of the improved cement dispersion and faster rate of hydration reactions generating shrinkage. The lower shrinkage without SP could also be attributed to increased heterogeneities, such as cluster formations between aggregates that would increase the restraint.

The same trend of greater early-age shrinkage with the use of SP also held true in the chemical shrinkage tests. The chemical shrinkage results for neat paste with the addition of 1% SP is given in Fig. 8. Similar to Fig. 7, the mixtures in Fig. 8 also were made from Finnish rapid cement and had a w/c ratio = 0.30, but no aggregate. Again, the chemical addition aided the dispersion of the cement and reaction speed during the early hours.

4.4. Effect of w/c ratio

The next set of tests investigated the changes in autogenous shrinkage magnitude due to the variation in w/c ratio of mortars. The w/c ratio was changed from 0.30 to 0.45 while the water amount was held constant at 275 kg/m^3. This corresponds to an increasing cement content and paste content while the aggregate amount remained constant. No SPs were added to the mortars so the workability varied

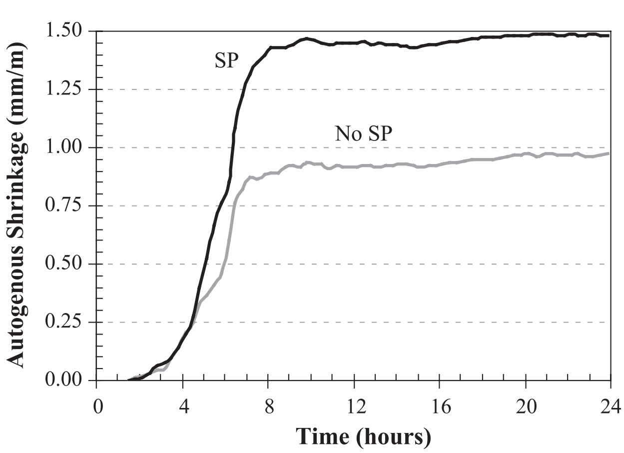

Fig. 7. Autogenous shrinkage resulting with SP addition to mortar.

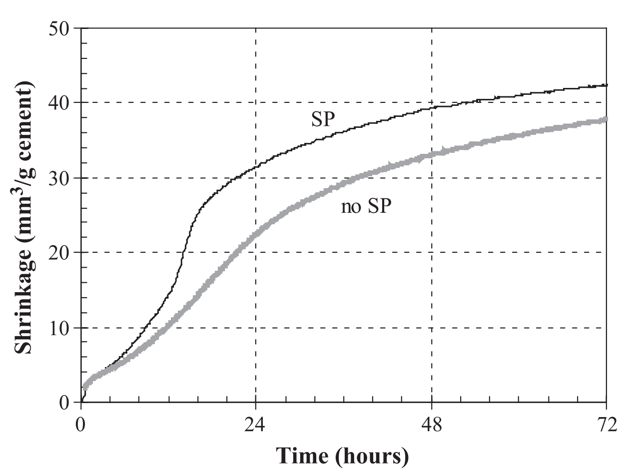

Fig. 8. Chemical shrinkage resulting with SP addition to paste.

with the four mixtures. The results of altering the w/c ratio are shown in Fig. 9.

The data were referenced at the time when the bleed water absorption was completed. For the mixture with a w/c ratio of 0.30, there was no bleeding so the referencing was done at 90 min, the time of initial set. All the mortar mixtures of this test set had increasing workability and also increasing bleeding amounts as the w/c ratio increased, and thus the referencing point was later with succeeding w/c ratios. The autogenous shrinkage ended at about the time of maximum heat generation due to cement hydration. The temperature peaks were lower and slightly later as the w/c ratio increased.

As expected, the mortar with the lowest w/c ratio had the greatest amount of autogenous shrinkage. This is because the mixtures have higher cement contents at the lower w/c ratios. The greater amount of cement results in larger autogenous shrinkage due to the contribution of chemical shrinkage. The trend is in agreement with those seen in the chemical shrinkage test shown in Fig. 10. Fig. 10 shows that with sufficient external water to aid hydration, chemical shrinkage is independent of the w/c ratio. The chemical shrinkage results are presented per gram of cement; thus, for equivalent cement contents, the shrinkage is constant.

Fig. 11 shows the pressure build-up corresponding to the shrinkages of Fig. 9. As expected, as the w/c ratio of the mortar mixtures was lowered, the capillary pressure started earlier. This is due to the finer pores in the microstructure and higher amounts of cement in the mixtures at low w/c ratios. The 0.30 w/c mixture had an initial setting time of 1 h and 30 min (Table 2), no bleeding, and the pressure began rising at about 2 h. Near the same time, the shrinkage began. The other mixtures had later setting times and a delayed onset of pressure, as well as a delayed start of horizontal shrinking. This can be explained by the observation that the mortars with higher w/c ratios (0.40 and 0.45) had excess bleed water on their surfaces. These mixtures did not have enough time for excess water to dissipate prior to setting times, and thus the capillary pressure did not induce

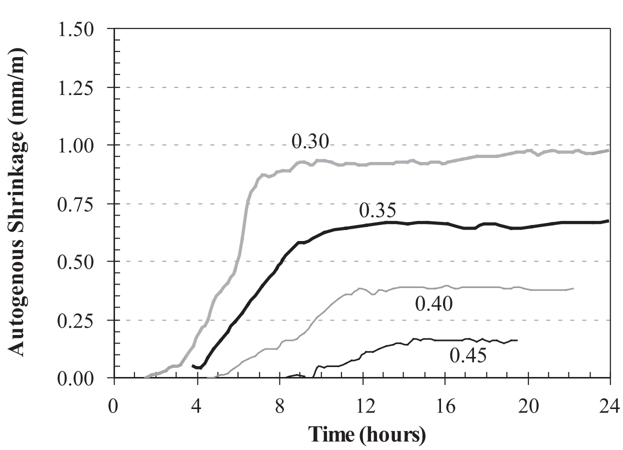

Fig. 9. Autogenous shrinkage resulting with changing w/c ratio and equivalent water amount.

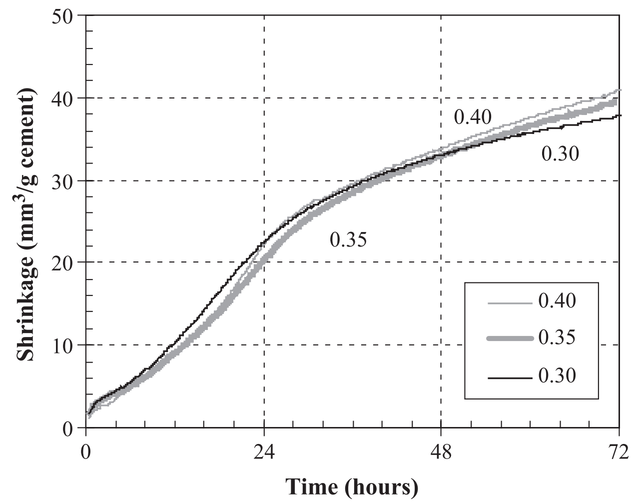

Fig. 10. Chemical shrinkage resulting with changing w/c ratio and equivalent water amount.

shrinkage. The later bleed water absorption times (4:30 and 7:50), compared to the 0.30 w/c mixture, are seen in Table 2.

Similar to the mortar tests, additional tests were done when increasing the w/c ratio of concrete mixtures. Two tests were done with concrete at w/c ratios of 0.30 and 0.35, 2% and 5% SP, and an equal amount of 165 kg/m^3 of water in each mixture. Neither mixture had any bleeding and therefore, the testing results began at the time of initial setting. The results showed higher autogenous shrinkage in the concrete with a lower w/c ratio. This mixture also had a greater temperature peak at an earlier time, as well as an earlier setting time.

4.5. Contribution of chemical to autogenous shrinkage

Chemical shrinkage tests were done for all of the pastes and mortars presented in the previous section. The volumetric measurement of chemical shrinkage was converted to a linear measurement to make a comparison to the autogenous shrinkage measured in the slab tests. [1] The amount

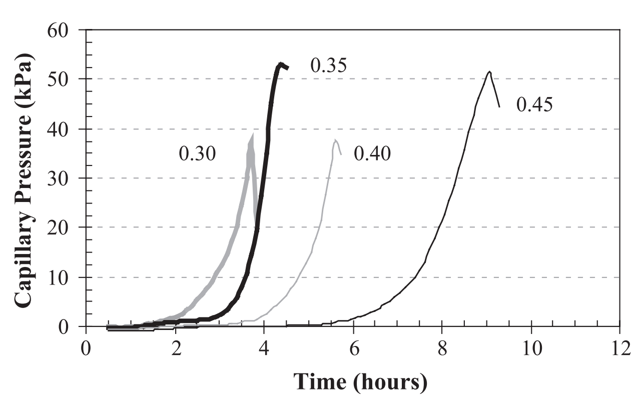

Fig. 11. Capillary pressure resulting with changing w/c ratio, corresponding to autogenous shrinkage test of Fig. 9.

of autogenous shrinkage was taken at the time of 4 h after final setting because it had the best correlation to the amount of chemical shrinkage at the same time. This point closest represents the time when the mixtures in the slab tests had enough stiffness to resist the shrinkage stresses. Fig. 12 shows the contribution of chemical to autogenous shrinkage for some of the mixture presented earlier. A similar comparison cannot be made for the concrete mixture, because the aggregate size is too large to test in the chemical shrinkage test arrangement.

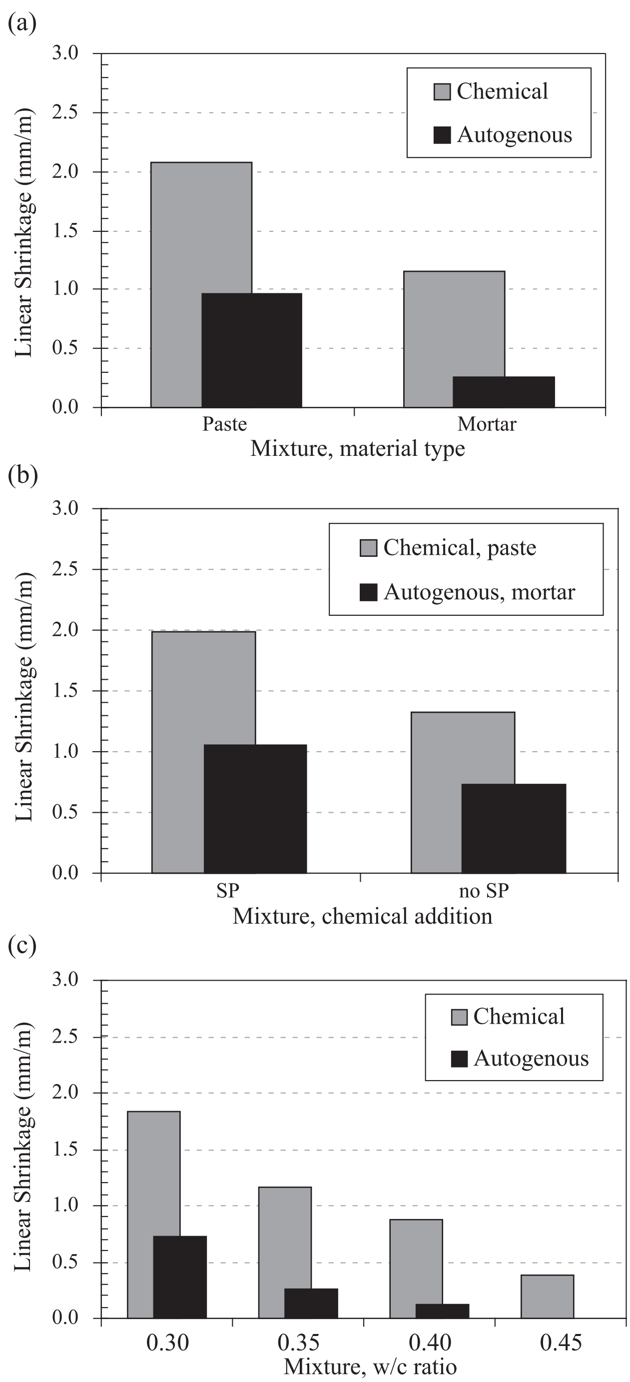

Fig. 12. Comparison of chemical to autogenous shrinkage from start of test (initial set or end of bleeding) until 4 h beyond final set time. Note that cement amounts can vary, as given in Table 1.

In Fig. 12a, the paste mixture had greater autogenous and chemical shrinkage due to the higher amount of cement and less aggregate restraint. In Fig. 12b, the addition of SP improved cement dispersion and thus shrinkage. In Fig. 12c, the lower w/c ratio mixtures had greater shrinkage due to the higher cement and paste contents, finer pore structure, and lower aggregate content. Note that in Fig. 10, the chemical shrinkage had been equivalent for all mixtures with varying w/c ratios, but this was presented with the shrinkage normalized per gram of cement. In Figs. 9 and 12c, the amount of cement was altered in each mortar mixture so the chemical shrinkage result is varying per cubic meter of mortar.

Overall, the early-age autogenous and chemical shrinkages are not equivalent during the first 24 h due to many factors. There are differences in the two types of shrinkages, such as bleed water, thermal dilation, strength development (setting), and restraint provided by aggregates. Some of the measures that can be taken to reduce the risk of early-age autogenous shrinkage are to:

- lower the chemical shrinkage by selecting cements with a low C_3A and high C_2S content,
- lower the rate of chemical shrinkage by selecting coarser ground or slow reacting cements,
- limit the chemical shrinkage by using the minimum amount (or no) SP, because these chemicals improve cement dispersion and accelerate chemical shrinkage,
- encourage a coarser pore structure (i.e., high w/c ratio, limited or no silica fume, etc.) to minimize the amount of early-age capillary pressure,
- accelerate the setting time so the concrete is stiff enough to resist shrink stresses,
- accept some bleed water, because it acts as a self-curing blanket and prevents autogenous shrinkage,
- use higher amounts of coarse aggregate to provide restraint to shrinking paste.

It must be noted that some of these recommendations may not be suitable for certain applications and the recommendations are given only with respect to how to lower autogenous shrinkage. For instance, SP may be needed to get sufficient workability for placement in congested reinforcing and a finer pore structure may be needed for highly durable concrete applications so all of these recommendations cannot be followed for all structural applications.

5. Summary

Autogenous shrinkage is a concern in high-strength and/or high-performance concrete mixtures. It occurs even when there are sufficient curing conditions, with no moisture lost to the surrounding environment. Typically, it has been addressed as a long-term durability problem that can lead to cracking if not properly designed for with the mixture proportioning. Risky autogenous shrinkage has been linked to lower w/c ratios when there is not enough water for cement hydration at later ages, thus the concrete exhibits self-desiccation. Moist curing is the best way to minimize autogenous shrinkage, but still, the shrinkage can occur within a concrete element, even when the exterior surfaces are exposed to 100% moist curing. Autogenous shrinkage cannot be fully eliminated for all cases.

This work has shown that autogenous shrinkage is also a concern during the very early ages, immediately after concrete mixing and placing. The tests described here were performed on field-simulated slab tests to assess the effects of material parameters on the magnitude of early-age autogenous shrinkage.

Autogenous shrinkage during the first hours occurs in the liquid, skeleton formation, and hardening stages. In the first stage, the autogenous deformation parallels the chemical shrinkage, until the point when there is some stiffening and a skeleton formation. With further stiffening, the concrete can resist the autogenous shrinkage stresses and the driving force changes to self-desiccation.

In this work, autogenous shrinkage at early ages was accurately measured by linear displacement of field-simulated slabs. The correlation of the amount of chemical to autogenous shrinkage was taken at 4 h after the final setting time, based on correlation studies described elsewhere [1]. It was possible to account for test arrangement artifacts, such as thermal dilation, to get a more clear measure of autogenous shrinkage alone. Many other material parameters effected the magnitude of autogenous shrinkage in secondary ways. These factors, such as amount of bleed water and time of setting, were accounted for in the slab measurements by means of the shrinkage data referencing point. Precautions were recommended to reduce the likelihood of cracking due to early-age chemical and autogenous shrinkages.

Even with any of these precautions, it is still crucial to remember that autogenous shrinkage may be insignificant if drying forces are present. The best way to ensure high-quality, crack-free concrete is to provide adequate curing immediately after mixing and placing [19]. After proper construction techniques are established, minimizing the autogenous shrinkage can be addressed by clarifying "just how strong or fast does one really need the concrete to be?"

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