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Cement & Concrete Composites 26 (2004) 521–530

Cement & Concrete Composites

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Cracking risks associated with early age shrinkage

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Abstract

When assessing the cracking potential of concrete it is critical to refer to the total shrinkage: both early age and long-term deformation, in both drying and autogenous conditions. A Finnish test arrangement has been used to measure linear and volumetric deformations of concrete immediately after mixing. The slabs are tested in either drying or autogenous conditions. Long-term shrinkage can be measured on the same slabs to give an accurate representation of the total free shrinkage. From these measurements it is possible to assess the likelihood of cracking due to early age shrinkage. Results have shown that both drying and autogenous shrinkage can be significant in certain early age scenarios. Environmental factors greatly affect drying shrinkage, while material properties affect autogenous shrinkage. This paper provides insight regarding how to interpret early age deformations, how environmental and material factors play a role, and how to minimize shrinkage and thus cracking potential in the early ages.

Keywords: Autogenous shrinkage; Capillary pressure; Drying shrinkage; Early age; Self-desiccation; Volume change

1. Introduction

Shrinkage of concrete cannot be avoided. It will occur due to at least the volume reduction resulting from the hydration of cement and water, which consumes less space than the initial products. Additional shrinkage can also be due to drying. If there is too much shrinkage the concrete will crack and the structure's durability is severely compromised. The free shrinkage is one of the major factors contributing to a structure's cracking potential, in addition to many other factors such as reinforcing, specimen size, and edge restraints. To assess the cracking risks associated with shrinkage, it is critical to view all aspects of shrinkage: in different stages and driven by different mechanisms.

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 most 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 lowest strain capacity and is most sensitive to internal stresses. Work by Byfors in Sweden [1] and Kasai in Japan [2] has shown that concrete has the lowest tensile strain capacity in these early hours. An example from Kasai [2] 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 [3–5].

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

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0958-9465/$ - see front matter
doi:10.1016/S0958-9465(03)00068-4

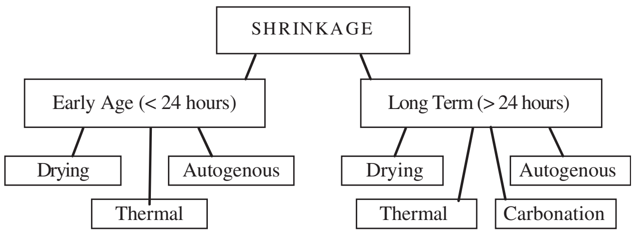

Fig. 1. Diagram of shrinkage stages and types.

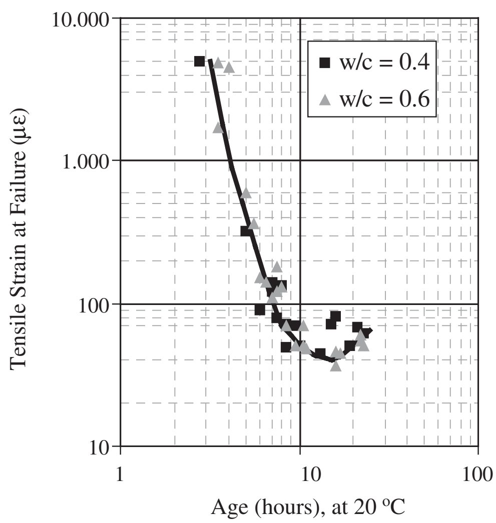

Fig. 2. Decreasing tensile capacity during early ages (1, 3).

others that if the early age free shrinkage magnitude exceeds 1 mm/m (1000 με) there is a high risk of cracking [6]. This corresponds to the American Concrete Institute guidelines [7] of an expected shrinkage of about 1/4–1/2 in. of movement in 20 feet, or 0.4–1.0 mm/m. Note that this limit of 1 mm/m is about 10 times the tensile strain capacity of concrete at the early ages (see Fig. 2).

Drying shrinkage results from a loss of water from the concrete. In the later ages (>24 h) it is well understood and has often been measured. It is typically measured as total shrinkage resulting from a length change after a prescribed period of time, such as using the test method described in ASTM C157. Most of these measurements do not factor out the shrinkage attributed to nondrying deformations. The general idea when assessing drying shrinkage is that concrete with a high w/c ratio will have a higher drying shrinkage magnitude because there is more unbound water. Recently there has also been an increase in the amount of research on early age drying shrinkage, and this will be further addressed in the next sections.

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 [8]. 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 the 1930s [9] 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 water-to-cement ratios that were far beyond the practical range of concretes. But with the development and frequent use of modern admixtures, such as superplasticizers 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. Even though many strength and durability aspects are now improved with these specifications, the risk of autogenous shrinkage is greater.

Shrinkage of concrete should always be addressed as a total amount, combining both drying and autogenous deformations. The work presented here aims at showing the variation possible in both of these types of shrinkage. Examples are given of how the environment and materials affects the shrinkage magnitudes and guidelines are given about how to reduce shrinkage and cracking potential.

2. Materials and methods

2.1. Materials for drying shrinkage tests

Various projects have been done on concrete, mortar and paste to assess their early age volume changes. In all of the drying shrinkage test results the cement was a Finnish rapid cement, type CEM II A, which corresponds to a Type III American cement.

In many of the drying shrinkage tests the w/c ratio was maintained at 0.63 and 300 kg/m^3 of cement was used. The maximum aggregate size was 10 mm and there were no chemical admixtures. These proportions are true for all of the forthcoming results regarding environmental conditions.

Some drying shrinkage results are given for adjustments to the mixture parameters. These included the additions of:

- higher dosages of melamine-based superplasticizer, where the concrete had a w/c of 0.45 and the target slump was maintained at 75 mm. The rapid cement amount was adjusted from 450 to 375 kg/m^3.
- two different shrinkage reducing admixtures (produced by Masterbuilders and Perstorp companies) to a high strength concrete, where there was 500 kg/m^3 of rapid cement and a w/c of 0.38.

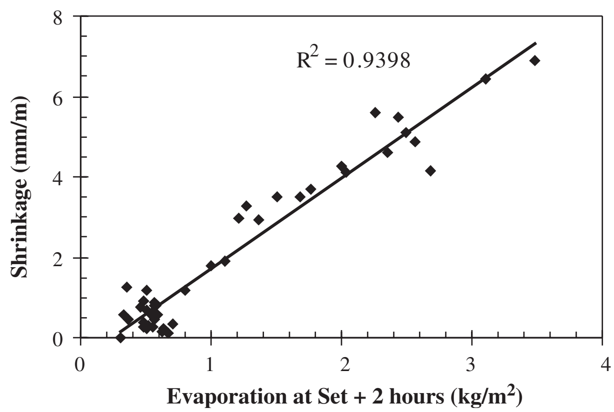

Fig. 3. Early age shrinkage dependence on evaporation (amount 2 h after setting) for VTT data with normal concrete.

When correlations are made between the environmental conditions and drying shrinkage, the above two adjusted mixtures are also included in the analysis. An additional two parameters were also included for mixture adjustments to this correlation (Fig. 3), as follows:

- maximum aggregate size changing: 5, 10 and 18 mm;
- aggregate gradation changing: sandy or rocky.

2.1.1. Materials for autogenous shrinkage tests

The results presented for autogenous shrinkage tests are taken from two different test series. The first series evaluated three mortars made from different types of cement: normal Finnish rapid cement, as described above; Finnish sulphate resistant (SR) cement; and Danish white cement. The chemical composition and fineness of these three cements is given in Table 1. All three of these mortars had a $w/c = 0.30$ and 275 kg/m^3 of water.

In the second autogenous shrinkage series the w/c ratio was adjusted from 0.30 to 0.45. The water amount was held constant at 275 kg/m^3, the same Finnish rapid cement was used, and the maximum aggregate size was 2 mm. No chemical admixtures were used.

2.2. How to measure early age shrinkage?

A test arrangement has been developed at the Technical Research Centre of Finland that allows the measurement of linear and volumetric deformations of concrete immediately after mixing. Details of the measuring equipment can be found in other Refs. [10,11]. The test is conducted on a 30 cm square slab with a thickness of 10 cm, simulating field construction with one-sided drying from the top, as in façade elements or floors. Approximately 30 min after mixing information is obtained on horizontal deformation, vertical deformation (settlement), internal capillary pressure, evaporation, setting time and temperature. The slabs can be tested in either drying or autogenous environments, with concrete, mortar or paste. Long-term shrinkage can be measured on the same slabs to give an accurate representation of the total shrinkage experienced by the concrete. From these measurements it is possible to assess the likelihood of concrete cracking due to early age shrinkage. This particular arrangement provides minimal restraint to the shrinkage, as to get a measure of free deformation. Similar testing arrangements have been created in Japan and Norway, among others [4,8,12].

When testing early age autogenous deformations and measuring the setting time, the environment is always 20 °C and 100% RH. In the case of drying shrinkage the testing environment is typically 20 °C and 40% RH. In some cases the environment has been adjusted to facilitate different evaporation rates, such as using wind speeds of 2–7 m/s, temperatures from 5 to 30 °C, and humidity from 40% to 100%.

Chemical shrinkage testing has also been done to supplement the autogenous shrinkage results from mortar mixtures. Chemical shrinkage was tested using the buoyancy method, as described by Geiker and Knudsen [13]. The test records the weight change of a fresh mortar sample that is placed underwater.

Table 1
Chemical composition and fineness of three Finnish cements used in early age autogenous testing

Compounds (%)	Rapid	White	SR
C_3S	68	67	75
C_2S	10	23	5
C_3A	8	4	1
C_4AF	8	1	14
Blaine (m^2/kg)	440	400	300

3. Results and discussion

3.1. How do environmental conditions affect shrinkage?

The magnitude of early age drying shrinkage is highly dependent on the surrounding environmental conditions. As the evaporation of free water from the fresh concrete increases, the magnitude of early age drying shrinkage also increases [14,15]. This was tested by adjusting the environment in the following ways:

- temperatures: 5, 20 and 30 °C;
- relative humidity 40%, 70% and 100%;
- wind speeds of 0, 2.5, 5 and 7.5 m/s.

The testing revealed that during the first hours after mixing the magnitude of drying shrinkage is proportional to the amount of evaporation. This is demonstrated in Fig. 3, where the amount of drying shrinkage increases with evaporation [15]. The linear trend in

Fig. 3 can be given by Eq. (1), where the total evaporation amount is taken at 2 h after initial set time:

$$\text{Early Age Drying Shrinkage (mm/m)} = [\text{Evaporation } (\text{kg/m}^2) \times 2] - 0.5. \quad (1)$$

Note that the majority of tests shown in Fig. 3 are done with no wind (20 °C and 40% RH), so many of the evaporation amounts are clustered around 1.0 kg/m^2. The data in Fig. 3 also includes only "normal" concretes. It is likely that high strength concretes would not fall on the same line since they have less bleeding and thus the water is more rapidly lost from within the concrete. For such high strength concretes it is expected that the trend line would shift towards the upper left corner and not have the "0.5" term representing bleeding at the end of Eq. (1).

As shown in the laboratory tests, the amount of evaporation from the fresh concrete is controlled by environmental factors such as wind speed, temperature and relative humidity. The rate of evaporation used to predict shrinkage can be estimated knowing these environmental factors and using various prediction tools, such as the 1954 ACI Nomograph [16]. Uno [6] has simplified the nomograph with Eq. (2), where vapour pressures are substituted by temperatures in the range of 15–35 °C:

$$E = 5\left([T_c + 18]^{2.5} - r \cdot [T_a + 18]^{2.5}\right)(V + 4) \times 10^{-6}, \quad (2)$$

where E = evaporation rate, $kg/m^2/h$; T_c = concrete (water surface) temperature, °C; T_a = air temperature, °C; r = (RH %)/100 and V = wind velocity, kph.

Knowing the evaporation rate and setting time, the "evaporation" term in Eq. (1) can be calculated and thus an estimate of early age drying shrinkage can be found.

In construction practice, it is important to stress that evaporation can be totally eliminated by proper curing techniques. Any measures that reduce evaporation will be helpful in reducing the early age drying shrinkage and thus the crack risk. Suggested measures for reducing evaporation include the use of admixtures such as evaporation retarders, covering the concrete with wet burlap and plastic, and fog spraying the environment to maintain high humidity. If the evaporation is eliminated then the early age drying shrinkage will be nonexistent and the only shrinkage stresses will be attributed to autogenous deformations.

Long-term drying shrinkage is also affected by the surrounding environment, but these phenomena are well documented in existing literature and better understood in practice.

3.2. How do material properties affect shrinkage?

The composition of concrete does affect the expected amount of total early age shrinkage. The materials selected, such as cement type and admixture dosage, have secondary roles controlling other factors within early age drying and autogenous shrinkage.

3.2.1. Drying shrinkage

Material parameters affect early age *drying shrinkage* by altering the amount and duration of bleeding and the setting time. Since the drying shrinkage is mainly attributed to environmental conditions, as described above, the problematic material factors are ones that prolong the period when shrinkage can occur. In research at VTT [6,7] it was shown that when the amount of bleeding was consistent then the concrete shrinkage amount could be predicted. The shrinkage was merely correlated to the amount of evaporation that occurred until two hours after setting. At this age the concrete had gained enough strength to withstand the stresses causing shrinkage. The trend in Fig. 3 is very general and encompasses only "normal" strength concrete with a variety of mixture proportions, but it still holds true that evaporation drives shrinkage.

Figs. 4 and 5 provide some examples of how material selection affects early age drying shrinkage. In Fig. 4 a superplasticizer has been added to the concrete, with the dosage increasing from 0% to 1.5% [11]. With increasing dosages the setting time was delayed (see Table 2) and it is also believed that the cement dispersion was improved. Both of these factors contributed to greater early age drying shrinkage, though the results still are included in the correlation given by Fig. 3 and Eq. (1).

In Fig. 5 the average results are shown for adding 1% of a shrinkage reducing admixture to high strength concrete [11]. The result is a drastic reduction in the amount of early age drying shrinkage, proving that these chemicals are effective in lowering the early age deformations by decreasing the surface tension of the water.

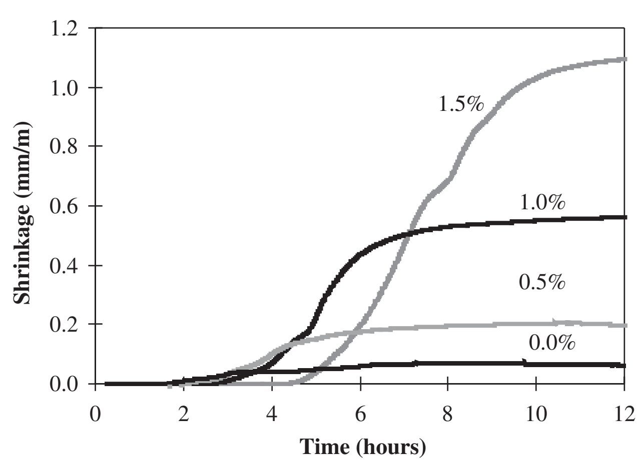

Fig. 4. Effect of increasing superplasticizer dosage on early age drying shrinkage.

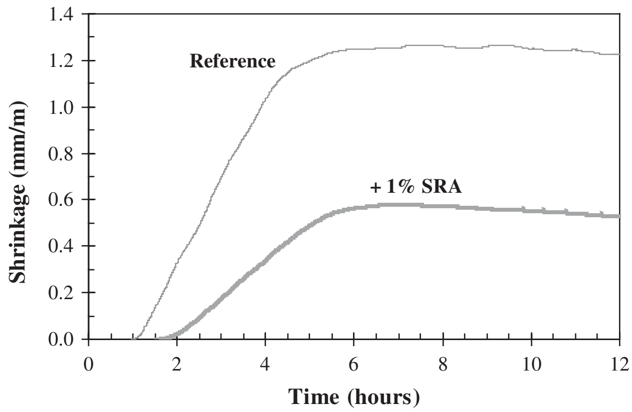

Fig. 5. Average effect of adding 1% shrinkage reducing admixture (SRA) to high strength concrete on early age drying shrinkage.

Table 2
Setting time of concretes with increasing dosage of superplasticizer, corresponding to Fig. 4

Superplasticizer dosage (%)	Set time (h:min)
0	2:50
0.5	2:50
1.0	3:20
1.5	3:50

This is in agreement with manufacturers' references to SRAs potential to reduce long-term drying shrinkage.

3.2.2. Autogenous shrinkage

Material parameters affect early age *autogenous shrinkage* over a wider range of choices. The main parameter is the amount of water and cement in the mixture, since autogenous shrinkage occurs when there is a lack of water for full cement hydration.

As a review, the *long-term* autogenous shrinkage will first be described, since it is better understood and documented in practice. Long-term autogenous shrinkage in this paper refers to the deformations occurring after one day. The main material property controlling autogenous shrinkage is the w/c ratio: as the w/c ratio is lowered the autogenous shrinkage increases. This has been explained by Powers and Brownyard [17] that autogenous shrinkage occurs due to self-desiccation when the w/c ratio is below about 0.42, since all mixing water is consumed at this ratio. This w/c limit can vary slightly, depending on the cement type and if there is an unrestricted supply of water available during curing.

Recently, these guidelines of greater long-term autogenous shrinkage occurring at lower w/c ratios have been supported by French research [18]. Baroghel-Bouny has shown that with a decreasing w/c ratio the 28-day autogenous shrinkage of cement paste increases, as shown in Fig. 6. Tazawa and Miyazawa [19] attribute this to the denser paste microstructure.

In literature the terms "self-desiccation" and "autogenous shrinkage" are often interchanged. Actually these terms should not be confused, since the internal drying or self-desiccation causes the long-term autogenous shrinkage. Even if the relative humidity is 100% there can be autogenous deformations that are not related to self-desiccation, but rather to chemical shrinkage.

Now returning to the occurrence of *early age* autogenous shrinkage (<1 day), there are newer points to address. Another main material factor contributing to early age autogenous shrinkage is the selection of cement, since autogenous deformations are fully attributed to *chemical shrinkage* during the very first hours after mixing [20]. 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 requires water for reaction, are exothermic and result in a decreased volume of the reaction products.

This volume reduction, or chemical shrinkage, begins immediately after mixing of water and cement and the

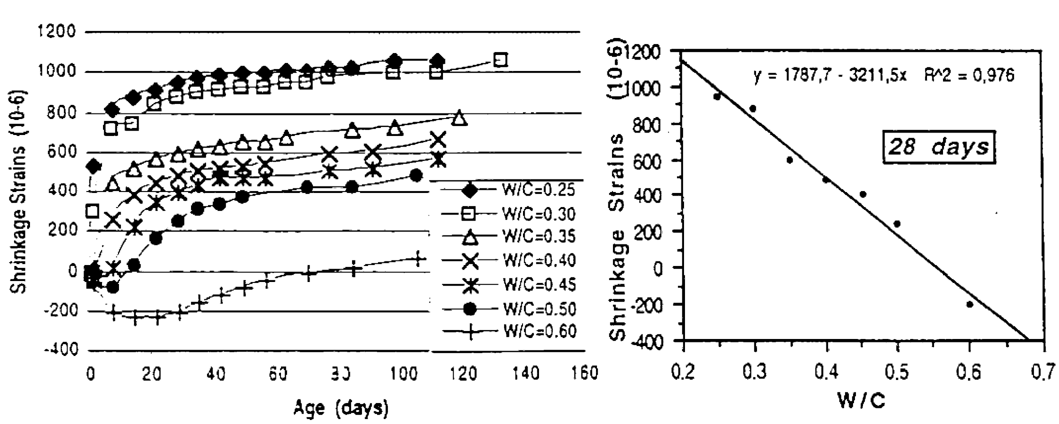

Fig. 6. Correlation between autogenous strain and w/c ratio for cement pastes aged to 28 days [18].

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 [20–22]. A generalized equation for estimating the chemical shrinkage is given in Eq. (3):

$$V_{\text{CS-TOTAL}} = 0.0532[C_3S] + 0.0400[C_2S] + 0.1113[C_4AF] + 0.1785[C_3A] \quad (3)$$

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, and thus greater total shrinkage and higher crack risk. Figs. 7 and 8 give examples of the chemical and autogenous shrinkage of mortars made with three different cement types. In Fig. 8, corrections were made to the autogenous shrinkage data to removed the volume deformations associated with thermal dilation during cement hydration, as explained elsewhere [20]. The mixture made from ‘‘rapid’’ cement had the highest C_3A content and was the fineness, thus both the chemical and autogenous shrinkages were faster and of greater magnitude.

Material proportioning or material selection that causes a finer pore structure in the concrete will lead to greater autogenous shrinkage. For instance, a lower w/c ratio or the use of silica fume will create finer pores, as typically found in high strength concrete. 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.

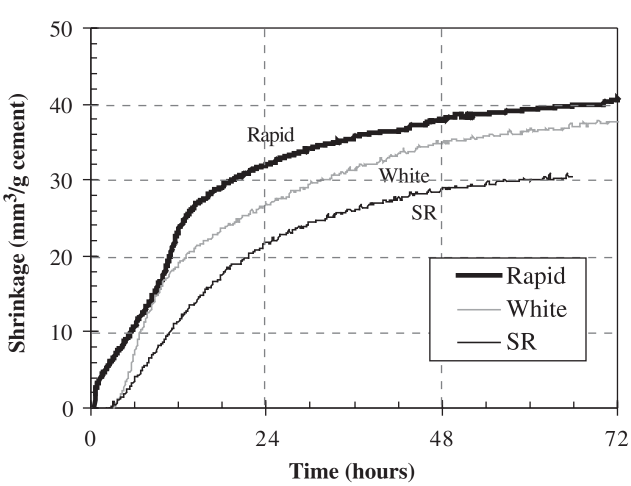

Fig. 7. Early age chemical shrinkage of mortars made from three different cements as described in Table 1.

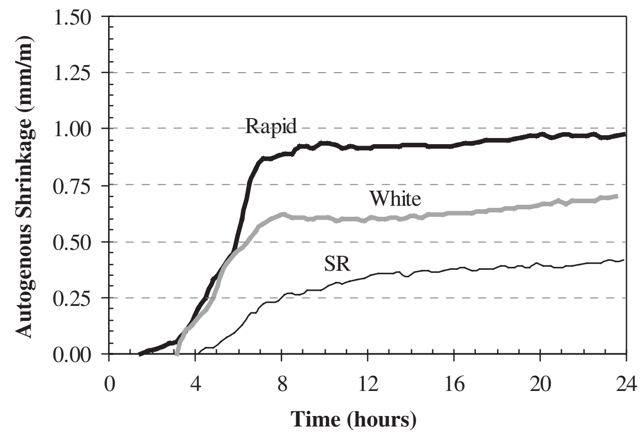

Fig. 8. Early age autogenous shrinkage of mortars made from three different cements, as described in Table 1.

An example of how the w/c ratio affects the amount of autogenous shrinkage is given in Fig. 9 for four different mortar mixtures [20]. Fig. 10 shows the corresponding developments of capillary pressure in the same four mortar mixtures. As the w/c ratio increased from 0.30 to 0.45 the time when the pressure and shrinkage began to develop was later. The times of setting and peak temperatures were also delayed for each progressive mixture, as given in Table 3. As can be seen in the figures, the denser pore structure associated with the low w/c ratio mixtures lead to the greatest amount of autogenous shrinkage. The autogenous shrinkage platformed at nearly the same time as the peak temperature, likely due to the mortar having enough stiffness to resist most of the shrinkage stresses.

Regarding a couple other material factors, aggregates work to restrain autogenous shrinkage so the amount of aggregate should be maximized to reduce cracking risk [20]. The addition of superplasticizer improves the dispersion of the cement and therefore provides a quicker chemical reaction. When a superplasticizer were added

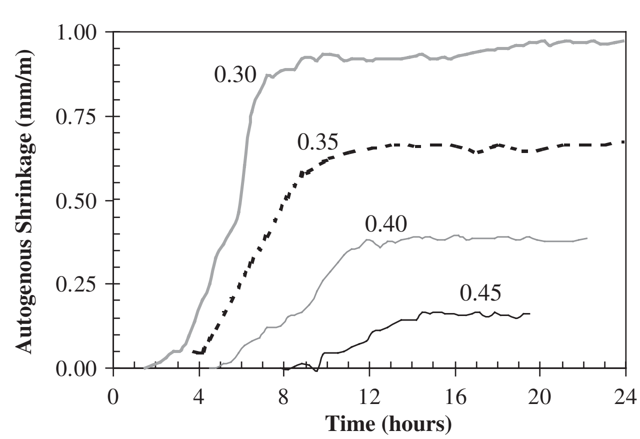

Fig. 9. Affect of changing w/c ratio on early age autogenous shrinkage or mortar.

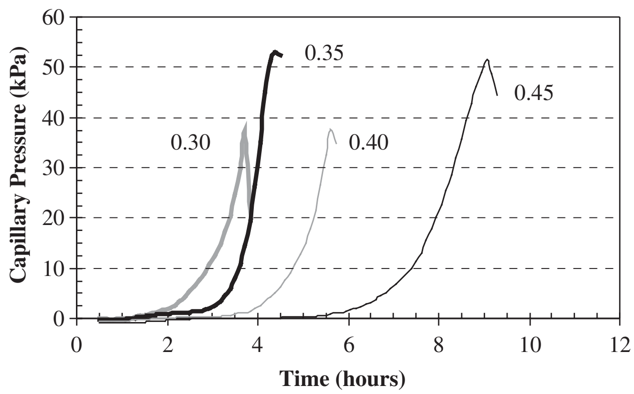

Fig. 10. Comparison of capillary pressure changing w/c ratio in autogenous shrinkage test from Fig. 11.

Table 3
Time of setting and pressure development along with peak temperatures for early age autogenous testing of mortars with varying w/c ratio

w/c ratio	Setting time (h:min)		Temperature peak		Pressure start (h:min)
	Initial	Final	(h:min)	(°C)	
0.30	1:30	2:35	7:50	44.0	2:15
0.35	2:10	2:55	8:50	41.5	3:10
0.40	2:25	3:40	11:50	37.8	4:10
0.45	3:35	5:20	12:10	34.5	6:30

to the concrete, there was a greater amount of early age autogenous shrinkage [20].

Once concrete has reached a hardened stage with aging (>1 + day), the autogenous shrinkage can result from self-desiccation [18,19], 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.

3.3. How early is shrinkage a problem?

Any amount of concrete shrinkage should be of concern, since shrinkage always means there is greater risks of cracking and deterioration. But *how early* to measure shrinkage is a tricky questions which many researchers are trying to tackle.

Research in the Nordic countries and Japan [8,12,14,20,23] has shown that concrete shrinkage starts very early, even prior to final setting. A key indicator of the onset of early age shrinkage is the development of internal capillary under-pressure [23]. In drying shrinkage, once any bleed water has evaporated or been absorbed into the concrete the pressure will start to build-up. The pressure corresponds to stresses in the cement paste that cause shrinkage [20].

The progress of early age shrinkage and its dependence on the development of capillary pressure can be clearly demonstrated with the next sequence of three graphs. This series is taken from result of concrete drying shrinkage tests with various levels of wind [20]. In this series of tests the concrete had 300 kg/m^3 of Finnish gray cement, $w/c = 0.63$, maximum aggregate size of 10 mm and no chemical admixtures. As the wind speed increased, the amount of evaporation from the concrete surface increased, thus the under-pressure (capillary suction) developed earlier. The increase of wind, evaporation and pressure ultimately led to a greater amount of early age drying shrinkage. Fig. 11 shows the evaporation rate increasing with the increase of wind speed. Fig. 12 shows the corresponding capillary pressure levels at the three different wind speeds. Notice that the pressure developed earlier at the higher wind speeds where there is greater evaporation. Finally, Fig. 13 shows the amount of horizontal drying shrinkage at these three environmental conditions, with the greatest shrinkage resulting from earlier pressure development. Note that the capillary pressure and the shrinkage began prior to the initial setting time of 4 h.

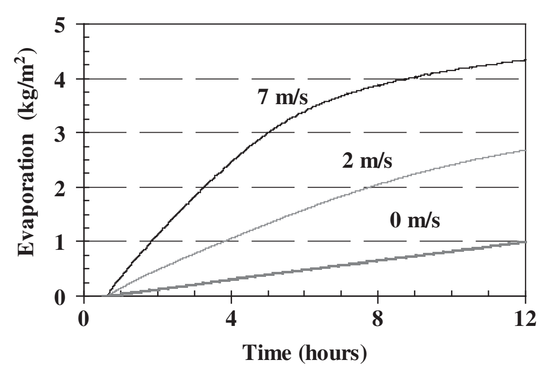

Fig. 11. Early age evaporation from a slab due to drying with three wind speeds. Concrete: $w/c = 0.63$, 300 kg/m^3 rapid cement, maximum aggregate size 10 mm.

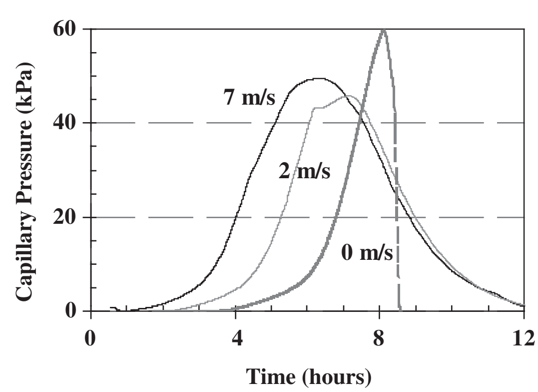

Fig. 12. Early age capillary pressure development within concrete of Fig. 11, with three wind speeds.

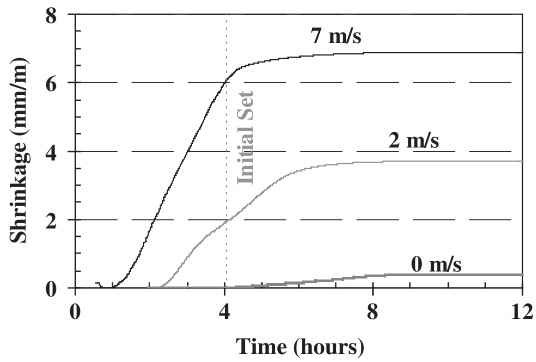

Fig. 13. Early age horizontal drying shrinkage levels for concrete of Figs. 11 and 12, with three varying wind speeds.

When evaluating the pressure the key item to interpret as a shrinkage indicator is the time when the pressure starts to develop. It is not possible to predict the amount of shrinkage based on the magnitude of the capillary pressure, since the point when the pressure stops rising is a artifact of the transducer measuring method [20,23].

In summary, shrinkage occurring in the very early ages, prior to final set of the concrete, should also be included when assessing "total shrinkage". Even this very early shrinkage can also be detrimental to the concrete's crack susceptibility and thus the durability.

3.4. How to reduce cracking potential?

In normal strength concrete or mixtures where the w/c ratio is greater than 0.45, the key ways of reducing shrinkage are to limit evaporation from the fresh concrete. This construction practices must start immediately after placement and cannot wait until the end of the day. In some environments the curing should begin even before the final finishing work.

The following items will help reduce early age drying shrinkage:

- Start curing immediately after placement.
- Cover the concrete with material (wet burlap, plastic, etc.).
- Spray chemicals on the concrete that prevent drying (curing compound, evaporation retarder, etc.).
- Reapply curing measurers after finishing.
- Keep the surrounding environment at a high humidity (i.e. use a fog spray).
- Lower the wind speed of the surround area by using wind breaks (i.e. hang plastic curtains from the upper floor on multi-story buildings to prevent wind tunnel effects).
- In warm environments, keep the concrete cool to encourage condensation.
- In cool environments, keep the concrete warm to accelerate setting.
- Do not overdose superplasticizers, which often have a side-effect of retarding setting.

In higher strength concrete where the w/c ratio is below 0.45, autogenous shrinkage can be a concern in addition to the drying shrinkage. Autogenous shrinkage cannot be prevented by construction practice but must be addressed at the time of material selection and proportioning. The following items will help reduce early age autogenous shrinkage:

- use slower hydrating cements (i.e. coarser ground) that have lower chemical shrinkage;
- use cement that has a lower C_3A and C_3S content, since these contribute the most to chemical shrinkage;
- maximize the aggregate content, since it provides the restraint to shrinkage;
- avoid delaying the setting time (i.e. superplasticizer dosage, temperature).

4. Summary: total shrinkage picture

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. 14 for various environmental conditions during the first day [20]. The long-term shrinkage due to drying was equivalent in all cases, though the first day had a significant change to

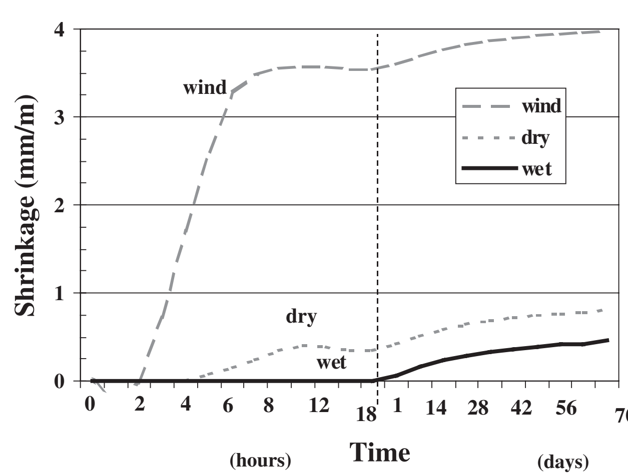

Fig. 14. Accumulation of early age and long-term shrinkage, with various curing environments during the first day. Wind = 2 m/s (4.5 mph); wind and dry = 40% RH, wet = 100% RH. Concrete: $w/c = 0.63$, 300 kg/m^3 rapid cement, maximum aggregate size 10 mm.

Table 4
Cracking risk due to total early age shrinkage, composed of drying and autogenous shrinkage when material and environmental conditions are changed

w/c	Concrete		Early age shrinkage		Cracking risk
	Curing	Additions/notes	Autogenous	Drying	
>0.45	Good, early	–	–	–	None
>0.45	OK	Delay of setting time	–	+	Low
>0.45	OK	High bleeding	–	–	None
>0.45	Poor, high evaporation	–	–	+++	High
<0.40	Good, early	–	+	–	Low
<0.40	Poor, high evaporation	–	+	+++	High
<0.40	Good, early	Silica fume	++	–	Medium
<0.40	Good, early	High SP dosage	++	–	Medium
<0.35	Good, early	–	++		Medium
<0.35	Poor, high evaporation	–	++	+++	High
<0.35	Poor, high evaporation	Silica fume, SP	+++	+++	Very high

"+" represents anticipated amount, from low (+) to high (+++).

the magnitude of "total shrinkage" and thus affected the expected cracking.

To get a picture of the *total early age shrinkage* it is necessary to compare both the drying and autogenous shrinkage. There is no direct correlation between these two types of shrinkage, in the same manner that there is no correlation between early age and long-term shrinkage magnitudes [6]. If ideal curing procedures are used, all shrinkage will result from autogenous deformations. In the cases of high strength and/or high performance concrete, the magnitude of autogenous shrinkage can exceed that of drying shrinkage in the early stages [5]. It is critical to assess both types of shrinkage when assessing the likelihood of cracking.

Various scenarios for early age drying and autogenous shrinkage are given in Table 4. Here the w/c ratio, curing compound and additions to the concrete are evaluated with their respect to both types of shrinkage. From these values it is possible to see the variation in possible cracking risks. For instance, if the w/c ratio is lowered, along with curing becoming worse and using more additions, the risk of cracking due to total early age shrinkage becomes greatest. It should also be noted that other factors besides shrinkage affect the cracking potential, such as reinforcing, edge restraint, specimen size, etc.

With regard to the total shrinkage picture, in the first day environmental factors (such as wind and humidity) greatly affect the magnitude of drying shrinkage, while material properties (such as w/c ratio and cement type) affect the magnitude of autogenous shrinkage. Therefore, early age drying shrinkage can be avoided by proper construction practice while autogenous shrinkage is only a factor of concrete mixture design. Each concrete structure, both from the material and structural design points, has to be evaluated independently in order to estimate the magnitude of total shrinkage and the cracking risk.

Even though long-term shrinkage is not within the scope of this paper, it should be pointed out that the long-term deformations are better understood and guidelines are already existing. It is the early age deformations that need to be further studied and addressed in current practice.

Acknowledgements

Portions of this work have been supported by the Valle Scandinavian Exchange program, the Fulbright organization and the National Science Foundation under grant no. 9978607.

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