Mitigation strategies for autogenous shrinkage cracking

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Abstract

As the use of high-performance concrete has increased, problems with early-age cracking have become prominent. The reduction in water-to-cement ratio, the incorporation of silica fume, and the increase in binder content of high-performance concretes all contribute to this problem. In this paper, the fundamental parameters contributing to the autogenous shrinkage and resultant early-age cracking of concrete are presented. Basic characteristics of the cement paste that contribute to or control the autogenous shrinkage response include the surface tension of the pore solution, the geometry of the pore network, the visco-elastic response of the developing solid framework, and the kinetics of the cementitious reactions. While the complexity of this phenomenon may hinder a quantitative interpretation of a specific cement-based system, it also offers a wide variety of possible solutions to the problem of early-age cracking due to autogenous shrinkage. Mitigation strategies discussed in this paper include: the addition of shrinkage-reducing admixtures more commonly used to control drying shrinkage, control of the cement particle size distribution, modification of the mineralogical composition of the cement, the addition of saturated lightweight fine aggregates, the use of controlled permeability formwork, and the new concept of ''water-entrained'' concrete. As with any remedy, new problems may be created by the application of each of these strategies. But, with careful attention to detail in the field, it should be possible to minimize cracking due to autogenous shrinkage via some combination of the presented approaches.
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1. Introduction

While concrete can undergo dimensional changes for a variety of reasons, one of the most common is due to the loss of water during environmental exposure. Commonly referred to as drying shrinkage, this phenomena can lead to cracking of concrete members if not properly accounted for during the design and construction process. Typically, early-age moisture loss is minimized by specification of a curing regimen for the concrete [1]. In addition to preventing evaporation and the accompanying drying-type shrinkage, good curing practices also maximize the degree of hydration achieved by the cement within the concrete, potentially leading to stronger and more durable concrete.

Additional complications with respect to curing, shrinkage, and cracking appear when one considers so-called high-performance concretes (HPCs). While many definitions exist for HPC, typical HPC mixtures are characterized by a low (<0.4) water-to-cement ratio (w/c), an increased cement content, and the incorporation of silica fume (or other pozzolans) and a superplasticizer. In these concretes, a dense microstructure can form within a few days or less, preventing the introduction of external curing water to complete the hydration. For w/c below about 0.40, there is insufficient water in the initial mixture to complete the ''potential'' hydration. Because, as observed by Le Chatelier [2], the reaction products formed during the hydration of cement occupy less space than the corresponding reactants (i.e., chemical shrinkage occurs), a cement paste hydrating under sealed conditions will self-desiccate (creating empty pores within the hydrating paste structure). If external water is not available to fill these ''empty'' pores, considerable shrinkage can result. In 1934, Lynam [3] was perhaps the first to define such shrinkage as *autogenous* shrinkage, that is, shrinkage that is not due to thermal causes, to stresses caused by external loads or restraints, or to the loss of moisture to the environment.

As use of HPC has increased, so has research on self-desiccation and autogenous shrinkage [4], as evidenced

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by the now yearly conferences devoted to this subject [5–8]. Autogenous shrinkage, however, is not only a negative attribute of a cement-based material. For example, it may provide a beneficial clamping pressure on fibers incorporated into concrete mixtures [9] or on aggregates (leading to interfacial strength increases), and it may offset thermal expansion due to temperature increases during hardening. But, generally, autogenous shrinkage is unwanted because it may cause cracking, as the deformations produced during autogenous shrinkage may easily exceed 1000 microstrains. Cracking is a complex phenomenon dependent on several factors including shrinkage rate, restraint, and stress relaxation [10]. Compared with long term drying shrinkage that generally occurs from the outside surface of the concrete inward, autogenous shrinkage develops uniformly through the concrete member, but can be more likely to cause cracking, because it develops more rapidly and occurs when the cement paste is young and has poorly developed mechanical properties (modulus of elasticity, fracture energy, etc.) [11]. Cracking due to autogenous shrinkage may lead to reduced strength, decreased durability, loss of prestress in prestressing applications, and problems with aesthetics and cleanliness. Therefore, the focus of this paper is to provide a structured overview of strategies for eliminating or minimizing autogenous shrinkage cracking. Also apparently impracticable ideas for mitigating autogenous shrinkage cracking are presented in the paper, since this may be the basis of useful further development in this area.

2. Terminology

In this paper, the different strategies to mitigate autogenous shrinkage are classified relative to the terminology in current use. For this reason, the terminology is described briefly here (see Fig. 1).

The *autogenous deformation* of concrete is defined as the unrestrained, bulk deformation that occurs when concrete is kept sealed and at a constant temperature. When the autogenous deformation is a contraction, it may be referred to as *autogenous shrinkage*. Autogenous deformation may be caused by different mechanisms. As an example, the growth of certain salt crystals, such as ettringite, may cause expansion during hydration. As was mentioned, the more common example originates in the fact that the hydration products formed by portland cement hydration occupy less space than the reacting water and cement. This phenomenon, *chemical shrinkage*, causes a successive emptying of the pore structure and leads to tensile stresses in the pore water through the formation of menisci. Menisci formation causes the relative humidity to drop, and self-desiccation occurs in the cement paste. The build-up of tensile stresses in the pore solution, furthermore, results in a bulk shrinkage of the hardening concrete, so-called self-desiccation shrinkage. The concrete may crack globally (macro-cracking, if restrained) or locally at the surface of non-shrinking aggregates (microcracking). Experimental evidence suggests that self-desiccation shrinkage is an important type of autogenous deformation [12,13].

Strategies to mitigate autogenous shrinkage cracking may be of either an autogenous or a non-autogenous nature. Basically, autogenous strategies concern the concrete mixture proportions, whereas all other strategies are non-autogenous in nature. In the following sections, examples of these strategies are discussed.

3. Autogenous strategies

At a given temperature, autogenous shrinkage is determined by the concrete mixture composition. Changes in mixture composition (cement type, silica fume fine-
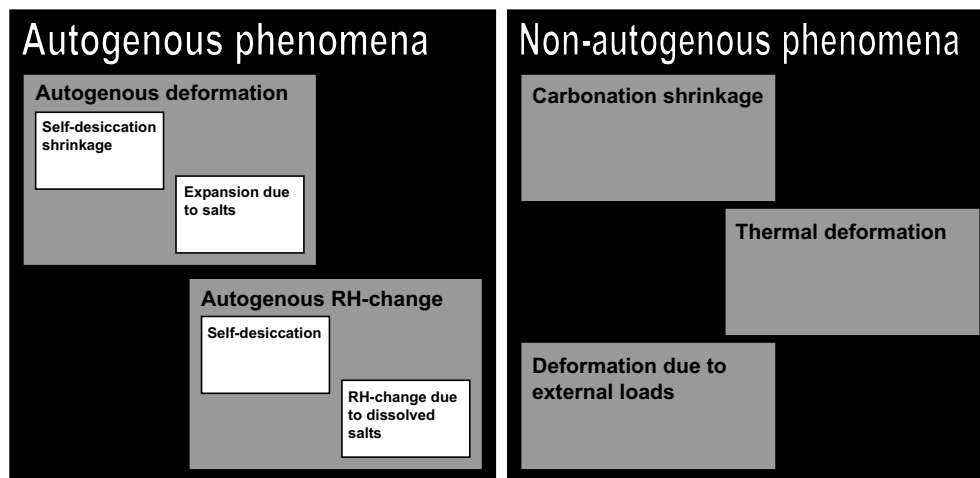

Fig. 1. Graphical representation of applied terminology; self-desiccation shrinkage and salt expansion are proper subsets of autogenous deformation [20]. Autogenous relative humidity change is a phenomenon closely related to autogenous deformation.

ness, aggregate content, slag [14], etc.) will therefore change autogenous shrinkage [15]. Shrinkage cracking can be mitigated either by reducing shrinkage or by increasing the strain capacity of the concrete. When a mitigation strategy relies on the use of chemical admixtures, compatibility with other chemical admixtures is required [16].

The influence of isothermal curing temperature on autogenous shrinkage is quite complex. While hydration reactions are accelerated by increasing temperature, Geiker has noted that the measured ultimate chemical shrinkage is significantly less for samples cured at elevated temperatures [17]. Also, creep and stress relaxation are functions of temperature [18]. In concrete specimens, it has been observed that early-age shrinkage is maximized at an intermediate curing temperature (such as 30 °C) [14].

3.1. Self-desiccation

Much can be learned about self-desiccation shrinkage by examining a few basic equations critical to the phenomenon. One should begin with the Kelvin equation which provides the vapor pressure (relative humidity) above a meniscus in a cylindrical pore of radius r as [19]:

$$\ln(\text{RH}) = \frac{-2\gamma V_m}{rRT} \tag{1}$$

where RH is the relative humidity, γ is the surface tension of the pore solution (N/m), V_m is its molar volume (m^3/mol), r is the radius of the largest water-filled cylindrical pore (m), R is the universal gas constant (8.314 J/(mol K)), and T is absolute temperature (K). In addition, a contact angle of 0° (complete wetting) is assumed in Eq. (1). This equation indicates that as vapor-filled pores are created within the concrete, the internal relative humidity will decrease [20,21]. The capillary tension, σ_{cap} (Pa), in the pore liquid is given by

$$\sigma_{cap} = \frac{2\gamma}{r} \tag{2}$$

Based on a slight modification of an equation originally provided by MacKenzie [22] and Bentz et al. [23], the shrinkage of a partially saturated porous medium due to the capillary stresses in the water-filled pores can be estimated as

$$\varepsilon = \frac{S\sigma_{cap}}{3}\left(\frac{1}{K} - \frac{1}{K_s}\right) \tag{3}$$

where ε is the linear strain or shrinkage, S is the saturation fraction or fraction of water-filled pores, K is the bulk modulus of the porous material (Pa), and K_s is the bulk modulus of the solid framework within the porous material (Pa). This equation is strictly valid for a fully saturated linear elastic material; it is only approximate for partial saturation. Also, hydrating cement paste is a

visco-elastic material and it is well known that creep and stress relaxation have a significant influence on self-desiccation strains and stresses [11,12]. In Eq. (3), it is interesting to note that in terms of shrinkage, there are two counteracting effects of removing water from a porous material. First, as water is removed and smaller and smaller pores are emptied (and r decreases), the values of σ_{cap} will increase as shown in Eq. (2). But, as water is removed, the saturation value, S, decreases. Depending on the specific system being examined and the relationship between S and r (determined by the pore size distribution), it is thus possible for the shrinkage to first increase to a local maximum as water is removed from the microstructure and then decrease (and perhaps increase again). This has been observed in the drying of porous Vycor glass [24] and in one set of drying shrinkage experimental results for cement-based materials [25], where a local maximum was observed at a relative humidity of about 50% (but is perhaps not relevant for autogenous shrinkage, which usually occurs in the high [>80%] relative humidity range). Based on these and similar equations, models for predicting the shrinkage of cement-based materials [12,26] and porous materials such as Vycor [23] have been developed, with generally good agreement with experimental results. From these equations, one can clearly observe that two parameters critical to self-desiccation shrinkage are the surface tension of the pore solution and the meniscus radius of the largest water-filled pore within the microstructure.

3.1.1. Surface tension

As shown above, a direct method for influencing autogenous shrinkage is by changing the surface tension of the pore solution. The history and use of shrinkage-reducing admixtures (SRAs) that decrease surface tension has been reviewed recently by Nmai et al. [27]. Such materials were first patented as SRAs in Japan in 1982 [28]. Generally based on polyalkyl ethers, these organic admixtures can reduce the surface tension of distilled water by a factor of 2 or more [29]. Tazawa and Miyazawa [30] have noted that the observed percentage decrease in autogenous shrinkage basically corresponds to the percentage decrease in the solution surface tension. This would be expected based on Eqs. (2) and (3), where the shrinkage strain ε is directly proportional to the capillary stresses, which in turn are directly proportional to the surface tension of the solution that is filling the pores (neglecting creep and stress relaxation).

Of course, if the surface tension reducing molecules are absorbed by cement hydration products, the effectiveness of these SRAs may decrease over time [29]. Other possible disadvantages of these materials include that they may destabilize the air void system, that they may retard the hydration reactions (increase in setting time), and that they may possibly reduce strength

[31,32]. The ultimate effects on strength will depend strongly on the mixture proportions and curing conditions, as a small strength enhancement has actually been observed for mortars with a water-to-solids ratio (w/s) of 0.35 and an 8% silica fume addition, cured under sealed conditions at 30 °C for 28 d [29]. As shown in Eq. (1), for the same partially saturated microstructure (e.g., for the same value of r), the relative humidity will be higher in systems where the surface tension is reduced. Since both cementitious and pozzolanic reaction rates are reduced as relative humidity decreases [33,34], the maintenance of an elevated relative humidity could enhance longer term reaction rates, leading to higher degrees of hydration and strengths. This is clearly an area where more research is needed to clarify under which conditions the SRAs can enhance long term strength. While SRAs are simple to use and generally effective, their effects on longer term properties such as durability have yet to be clarified [35].

When considering SRAs, it should be kept in mind that surface tension is also mildly influenced by temperature. For pure water, the surface tension increases by a factor of about 1.09 as the temperature decreases from 40 to 0 °C. In addition to mitigating autogenous shrinkage, SRAs also slow the kinetics of drying shrinkage, their first and most conventional usage.

3.1.2. Meniscus radius

It is the combination of chemical shrinkage and pore structure that determines the meniscus radius r [12], as shown in Fig. 2. The chemical shrinkage determines the volume of empty porosity created, while the pore size distribution determines the size of the largest water-filled pore for a given value of empty porosity volume. Based on measurements of internal relative humidity within hydrating cement paste, indications are that as chemical

Fig. 2. Hypothetical pore size distribution for cement-based materials indicating that as more empty porosity is created due to self-desiccation, smaller and smaller pores are being emptied, in analogy to the filling of pores by mercury during an intrusion experiment.

shrinkage occurs, the largest pores within the microstructure empty first. This is consistent both with thermodynamic considerations and microstructural observations [36] and has major implications for developing successful mitigation strategies as outlined below.

The developed chemical shrinkage depends on the cementitious reactions, and consequently on the cement composition and the presence of supplementary cementitious materials. For example, measurements indicate that the pozzolanic reaction of silica fume with calcium hydroxide involves a chemical shrinkage of about 22 cm^3/100 g silica fume [37], whereas the chemical shrinkage produced by the four clinker minerals may amount to C$_3$S: 5 cm^3/100 g, C$_2$S: 1 cm^3/100 g, C$_3$A: 16 cm^3/100 g, and C$_4$AF: 11 cm^3/100 g [38]. For a Type I ordinary portland cement, the measured chemical shrinkage is typically on the order of 6 cm^3/100 g cement. A simple comparison of total chemical shrinkage values, however, is inadequate to assess the resulting self-desiccation shrinkage. A number of other factors have to be taken into consideration, including the sensitivity of the cementitious reactions to relative humidity. As shown by Eq. (1), emptying of the pore structure due to chemical shrinkage causes a lowering of the internal relative humidity, and this reduces the reaction rates of the cementitious reactions. For example, the pozzolanic reaction of silica fume may be much less sensitive to a lowering of the relative humidity than the cement clinker mineral reactions. In a low w/c self-desiccating cement paste, the ultimate degree of hydration of the cement under sealed curing conditions may be on the order of 50%, whereas the silica fume may react to near completion [39]. As a result, a significant contribution to the total chemical shrinkage in a high-performance cement paste may come from the silica fume.

Based on considerations like those just presented, it should be possible to evaluate the influence of cement composition on self-desiccation shrinkage. Experiments show that cement composition has a significant influence on self-desiccation shrinkage. This is an area, however, where more research is needed since apparently contradictory results can be found in the literature [33,40].

Another important factor is the pore structure of the cementitious material. Other things being equal, a coarser pore structure (from a coarser cement for instance) will lead to reduced self-desiccation shrinkage, as has been demonstrated experimentally [26,30,41] as shown in Fig. 3 [41], and based on computer modelling [42]. It has also long been noted that coarser cements produce less autogenous shrinkage [43] and more durable concretes [44]. Because silica fume particles (<1 μm in diameter) are much finer than cement, they create a much finer pore structure within the hydrating cement paste. While an increase in the w/c or a decrease in the silica fume content would also lead to a coarser pore structure and reduce self-desiccation shrinkage, these
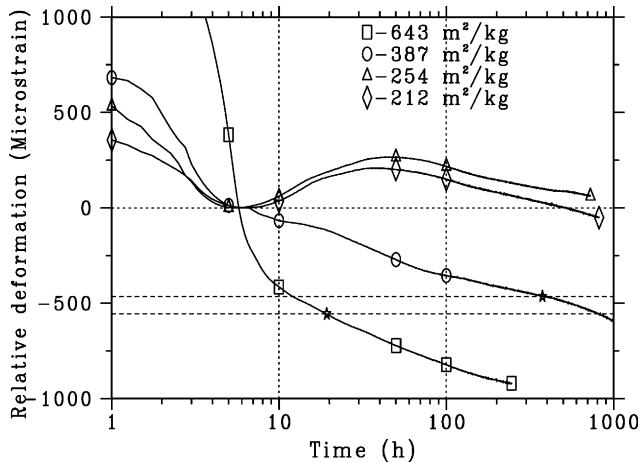
Fig. 3. Autogenous deformation vs. time as a function of cement fineness for four cements ground to different finenesses from the same clinker [41]. Setting time for each w/c = 0.35 paste corresponds to the point where each curve first reaches a relative deformation value of zero (5–8 h). After setting, the two finest cements are observed to exhibit considerable autogenous shrinkage, while the two coarser ones actually expand before later shrinking. After Fig. 8 in Ref. [41].

may be less attractive options, since a low w/c and the addition of silica fume are often two of the general defining characteristics of a HPC mixture. Still, there may be some room for improvement by simply avoiding the extremes; using a w/c of 0.35–0.40 and a 5% silica fume replacement may offer a large improvement with respect to autogenous shrinkage relative to a w/c = 0.30, 10% silica fume cement paste.

The pore structure of aggregate particles may have a strong effect on self-desiccation shrinkage. Aggregate particles may contain water in coarse pores and provide so-called internal curing for the hydrating cement paste. In this case, the formation of empty pores due to chemical shrinkage takes place first in the coarser aggregate pores and does not involve the fine pores in the cement paste. Active use of this principle has been carried out with saturated lightweight aggregate particles [45–47]. Furthermore, it has been demonstrated by both computer simulation [48] and experiments [49] that self-desiccation shrinkage is best minimized by the use of fine saturated lightweight aggregates as opposed to coarser ones, as the former results in a more uniform distribution of the needed curing water throughout the microstructure. With this technique, it appears that self-desiccation shrinkage can be completely eliminated. A number of possible problems, however, are connected with this technique, including possible difficulties in controlling rheological consistency and potential reductions in the strength and the elastic modulus of the concrete.

Recently, a new technique of internal curing has been proposed, so-called water entrainment [50,51]. The concept consists of using fine (expanded diameter of hundreds of micrometers), superabsorbent polymer particles

as a concrete admixture. This leads to the formation of water-filled macro pore inclusions in the cement paste. Water-entrainment mitigates self-desiccation shrinkage based on the same principle as addition of saturated lightweight aggregate particles, but the technique is more straightforward and produces a highly controlled microstructure. Furthermore, it is possible that the spherical voids left behind as the water is drawn from the water-filled inclusions to the hydrating cement paste could function as part of an effective air void system to protect the concrete from freezing and thawing damage.

3.2. Internal restraint

In a typical concrete, while the cement paste is undergoing self-desiccation shrinkage, many of the other components are providing a passive internal restraint system that resists this deformation and reduces the measured physical shrinkage. Chief amongst these are the aggregate particles that typically occupy 55–75% of the overall concrete volume. For ordinary concretes (where the elastic modulus of the paste is much less than that of the aggregates), Hobbs [52] showed that the key characteristics of the aggregate that influence concrete shrinkage are its volume fraction and its drying shrinkage. A similar conclusion was reached by Hansen and Nielsen [53]. Since most aggregates are non-shrinking, ordinary concrete shrinkage should depend only on the shrinkage properties of the paste and the volume fraction of the aggregates. Naturally, an increased aggregate volume fraction will result in reduced shrinkage. In HPCs, however, the elastic modulus of the paste can approach that of the aggregates, and concrete shrinkage will thus also be influenced by the stiffness of the aggregates. Other characteristics being equivalent, stiffer, higher elastic modulus, aggregates will reduce the overall shrinkage of a concrete [11,54], but may increase local stresses leading to cracking within the interfacial transition zones surrounding the aggregates. The overall effects of the aggregates in reducing shrinkage are quite substantial, as the shrinkage of a neat cement paste may be almost 10 times larger than the shrinkage of a concrete [54,55].

At the micrometer level, passive restraint may be provided by several components including unhydrated cement particles and calcium hydroxide (CH) crystals [21]. The hypothesis that restraint is provided by the CH crystals is supported by the results of Carde and Francois [56] that indicate a significant loss of mechanical properties as CH crystals are leached out of cement paste and by Power's theory [57] for carbonation shrinkage being due to the dissolution of CH crystals that are under compressive stresses.

The addition of fibers (polymeric, cellulose, metallic, or carbon) may also have a significant influence on the early-age cracking of concrete. While these fibers

typically do not significantly reduce the shrinkage of concrete, they can substantially increase the resistance to crack propagation and decrease the crack width and frequency [10].

3.3. Expansive reactions

For the two coarsest cements in Fig. 3, rather than undergoing self-desiccation shrinkage after initial setting, they instead exhibit an initial expansion (up to about 40 h), as the effects of self-desiccation are initially overwhelmed by those of ettringite formation [41]. From this figure, it is obvious that self-desiccation shrinkage can be at least partially offset by the use of compensating expansive reactions. While the techniques outlined in the previous section basically deal with passive restraint, expansive reactions may be viewed as a type of active restraint.

Taylor [58] provides an excellent summary of the different commonly used expansive cements. Expansive cements may be either shrinkage-compensating or self-stressing. In the former case, the goal is to use the expansion to balance the drying shrinkage in order to prevent cracking. In the latter, larger expansions are generated to actually stress the concrete internally provided that there is restraint to the expansion. As indicated by Nagataki and Gomi [59], several thousands microstrain of expansion in concrete can be produced by using expansive cements.

The most common method of producing an expansive cement is via the formation of ettringite. There are several additions that can be used to increase ettringite formation in a portland cement, including calcium aluminate cements or $C_4A_3\overline{S}$. It is generally accepted that in these cements, expansion is due to forces generated during the growth of preferentially oriented ettringite crystals. Other possibilities for producing expansive cements are via the hydration of free lime (CaO) or periclase (MgO) [58].

In practice, expansive cements are often difficult to regulate and control as the expansion produced will depend on the reactivity of the expansive components and their spatial distribution within the cement powder. Thus, while self-desiccation is generally uniform throughout a concrete (due to the continuity of the water phase), expansion due to ettringite crystal formation, for example, can be a highly localized phenomena, due to the discrete nature of the growing crystals [41].

4. Non-autogenous strategies

4.1. Exchange of water with the surroundings

If concrete is allowed to freely imbibe water from the surroundings during curing, self-desiccation shrinkage will be delayed and cracking may be avoided. The water may be supplied to the concrete, for example, through membrane or fleece-lined forms [60], which may be considered as a reverse type of a controlled permeability formwork [61,62]. Also, fog misting or water ponding of the concrete surface may be used. Wet curing should be started as soon as hydration begins [63]. In HPCs, however, it must be recognized that during the hydration, a point will be reached where the capillary porosity becomes depercolated [64], basically eliminating the ingress of curing water from the external environment. The degree of hydration necessary to achieve this depercolation decreases as the w/c decreases [64,65]. Over 50 years ago, Powers [66] suggested maintaining saturated curing conditions only until this depercolation occurs. It is for this reason that the use of the internal curing strategies discussed above is especially important for HPCs. Still, the ingress of water from the external environment during just the first few days of hydration/curing can result in substantial improvements in the mechanical and transport properties of the hardened concrete.

Of course, the effectiveness of water exchange between the environment and a concrete element will depend to some extent on its thickness. For young concrete, water rearrangement due to capillary forces can evidently move water large distances (tens of millimeters) [67], so that at early ages, water may be drawn from the exposed surface deep into the concrete. As the cement paste hydrates, however, and the permeability of the concrete is reduced by many orders of magnitude, after a few days, water movement will become effectively limited to within the top few millimeters of the exposed concrete surface. Still, since the surface layer of the concrete is particularly critical for durability performance, it is normally worthwhile to moist cure even this top few millimeters for as long as feasible.

Certain substances which ingress from the surroundings may react with aggregate particles and lead to expansion of the concrete. Examples of these include sulfates and alkalis. This may potentially counteract autogenous shrinkage of the concrete, but in reality, it may be difficult, if not impossible, to utilize this mitigation strategy in practice.

4.2. Counteracting temperature changes

Swayze has shown that autogenous shrinkage can be used to offset thermal expansion of concrete [68]. Conversely, thermal expansion can be used to mitigate autogenous shrinkage. Of course, the concrete will eventually cool down, but this approach gives the mechanical properties of the concrete a chance to fully develop before the concrete is subjected to significant thermal stresses. For field concrete, the viability of this approach may be compromised due to the simple fact that the

weather cannot be predicted precisely. Thus, unless the field concrete is cured in a controlled environment, its thermal history and thermal expansion cannot be predicted a priori. In any case, this mitigation strategy will be very difficult to utilize in practice.

4.3. External restraint

The autogenous shrinkage cracking that develops in a structure depends not only on the autogenous shrinkage of the concrete, but also on the external restraint on the concrete. Such restraint may be due to adjacent members, formwork or reinforcement. Whereas internal restraint, e.g., from aggregate particles, may result in diffuse microcracking, external restraint may lead to macrocracking across the section. Uncontrolled cracking due to restraint from adjacent members may be avoided by the use of contraction joints or control joints in the shrinking concrete or alternatively in the adjacent member. In either case, this can be considered a type of controlled cracking. Flexible formwork can be useful [69,70], especially if the deformation of the concrete is restrained only due to its geometry. The restraining effect from the reinforcement may also lead to cracking. For certain restraining conditions, however, reinforcement may facilitate the formation of more evenly spaced and narrower cracks as opposed to a few wide cracks. This means that reinforcement may be required to provide crack control and to ensure the integrity of the structure [71,72].

5. Conclusions

To produce long lasting durable concrete, early-age cracking must be minimized. Unfortunately, many of the recent trends toward higher early-age strengths also result in an increased propensity for early-age cracking. As demonstrated in this paper, the concrete materials engineer has numerous options available as mitigation strategies. In each case, a basic understanding of the underlying physical phenomena will aid the engineer in either selecting appropriate materials or adapting the structural design to control cracking due to autogenous shrinkage. Many of the proposed mitigation strategies are still in their infancy and must yet be evaluated in terms of effectiveness, robustness, ease of implementation, and effects on durability. The tremendous need to produce crack-free concrete, however, will surely greatly expedite this evaluation process.

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