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Effects of variable curing temperatures on autogenous deformation of blended cement concretes

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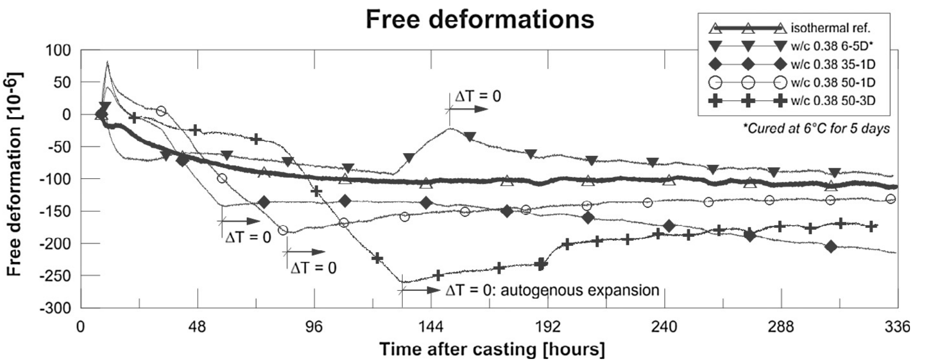
HIGHLIGHTS

- Autogenous shrinkage under variable temperature curing investigated.
- Concretes with blended cement (fly ash) tested.
- Prominent expansive behavior found in high temperature curing.
- Expansion could not be linked to fly ash content.
- Different curing paths likely result in different thermal coefficient developments.

GRAPHICAL ABSTRACT



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ABSTRACT

Shrinkage tests have been performed on blended Portland cement based early-age concrete with different w/c ratios, undergoing variable temperature curing. Results showed presence of induced non-negligible autogenous swelling which could mitigate part of the stresses related to shrinkage at very young concrete age. Recorded swelling was higher at higher curing temperatures and longer duration, especially pronounced for the low w/c mix. The swelling continued for several days after the temperature stabilized. Although not investigated directly, evidence to the nonlinear nature of the thermal expansion coefficient in young concrete has also been provided.

1. Introduction

1.1. Autogenous deformation and cracking risk

The young concrete is at an increased risk of cracking due to the combination of differential shrinkage and internal restraints. In mass concrete, differential shrinkage results from inability of the structure to dissipate quickly the heat generated, resulting in larger temperature gradients and corresponding larger autogenous shrinkage (AS) in the center, while the aggregates act as restraint [1]. In thin structures with large surfaces drying out, combined autogenous and drying shrinkage can generate high enough stresses that lead to early-age cracking.

Autogenous, or self-desiccation shrinkage is an inherent part of the total deformation that is unavoidable [2–4], because it is a

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direct consequence of chemical shrinkage that happens after the final set of concrete [4–8]. With the recent increased use of high early strength-, high performance-, and/or blended binder concretes, with low water/cement ratio the AS makes up for a substantially larger part of the total shrinkage [9–12]. It is significant enough to induce micro- or macro cracking due to the increased paste volume and higher binder content per unit volume. In a high performance concrete sample, AS reached 240×10^{-6} by 24 h of age [9] this presents a significant cracking risk if movements are restrained.

1.2. Autogenous expansion

Typically, autogenous deformation (AD) manifests as shrinkage. Recent research, however, has reported on cases where a substantial autogenous expansion or "AD swelling", as commonly referred to, has occurred; e.g., [10,13–18]. This expansion may be beneficial since it has the potential to partially mitigate tensile stresses when the young concrete has a very low modulus of elasticity. For estimating cracking risk in young concrete undergoing early expansion, however, it has been recommended that the conservative estimation of using the net shrinkage (occurring after early-age expansion) be used, instead of the total deformation after first setting [9], thereby ignoring the possible shrinkage-mitigating effects of the early-age expansion.

Autogenous expansion in early age concrete/mortar typically takes place after the cooling down stage. Earlier studies showed that the natural cooling down phase from temperatures exceeding 50 °C was characterized by a reduced rate of AS and was followed by autogenous expansion. The expansion started at about 4 days of age and was attributed to thermally induced swelling, [10]. Heating-cooling curing regime has been observed to cause AD swelling during the cooling off phase, lasting until the temperature levels off [19]. The AD swelling is likely to appear in concrete having w/c ratios over 0.40.

Recently, slow expansion of over 10 days in fly ash concretes was observed, [13]. The onset of swelling about coincides with the maximum temperature and continues throughout the cooling down phase. Swelling is prominent when $\Delta T \leq 20\,^{\circ}C$, regardless of fly ash content (17–45%). The Type I OPC reference sample, however, exhibits swelling despite that it has undergone a 30 °C temperature change. AD swelling was also observed in both OPC cement paste and OPC with 30% and 45% blast furnace slag (w/c 0.40) [16]. In that case, the curing temperature of 60 °C was applied 50 h after casting. The AD swelling was observed for the entire duration of the cooling down phase [16]. A smaller but steady swelling was also observed in the OPC sample cured at 40 °C. AD swelling in OPC concrete with 50% fly ash, w/c 0.30, under 20 °C isothermal conditions has been reported by others, [15]. The expansion occurred well after the concrete has cooled down; the temperature in the sample did not reach 25 °C at any point. The swelling was prominent at around day five and lasted for another 7–8 days. The authors attributed the swelling to possible ettringite formation. No swelling was observed in mixes with only 25% fly ash. Finally, AD swelling has been also linked to possible ettringite formation in mixes made with coarser cements by [17].

1.3. Thermal dilation

During hydration, fully coupled autogenous deformation (AD) and thermal deformation (TD) are recorded as free deformations. For a generalized model capable to describe any conceivable temperature history and to calculate shrinkage-induced stresses, it is fundamental to have a robust, generalized model for both AD and TD [10]. Assuming that the development of CTE over time is known for the young concrete, the total deformation could be split into AD and TD to determine the relative importance of each mechanism separately. However, for young concrete, the thermal dilation coefficient CTE(t) is highly nonlinear, depending heavily on the moisture content [20,21], since water has a CTE about 7 times that of hardened concrete. The development of CTE appears to be less affected by the curing regime history than the AD and may also be influenced be the pore structure in the concrete body [21]. After casting, the CTE decreases sharply during the first hours due to large amounts of unbound water (above $20 \times 10^{-6}/^{\circ}C$) [22–24], to a minimum value around setting time ($\sim$6–$7 \times 10^{-6}/^{\circ}C$), and thereafter it slowly increases with time due to self-desiccation [20], converging to the value characteristic of hardened concrete ($9\ldots12 \times 10^{-6}/^{\circ}C$). The reduction around setting time is due to the fact that before setting, the free water is continuous while as a solid skeleton is being built up, this continuity gets disrupted. Ranges of CTE (typically for hardened concrete) are available in literature, but data for early-age concrete are rather limited and inconsistent.

It was beyond the scope of this study to determine the development of CTE for the specific concrete mixes. However, if splitting of the total (free) deformations is attempted to characterize the autogenous deformation separately, it is crucial to use proper CTE values.

1.4. Variable temperature curing

It has been well known and implemented in early models [25,26] that the magnitude of AS depends on the maximum temperature reached throughout the curing process. Variable temperature curing where the length of the curing certain temperature level varies, has not been taken into account when modeling AS.

Recent data reveals that different imposed temperature paths result in substantially different AD developments, even despite the same degree of hydration; and that the AD can manifest as expansion in certain circumstances. Measuring AD directly, at *constant* temperature levels, and deducing AD from these for other temperature levels does not appear to be possible due to both the magnitude and the development rate of AD showing strong temperature history dependence [5,10,13,14,27,27]. Others also emphasized that higher temperature does not necessarily lead to higher AS. As a result, AD in a real structure cannot be predicted from isothermal test results because the fundamental behavior (contraction or expansion) depends on the specific imposed temperature history [28].

This study has been focusing on providing experimental data for the modeling of AD under variable temperature curing, for later incorporation into existing AD models, in order to address the knowledge gap regarding variable temperature curing.

2. Experimental procedure

2.1. Materials

Tests have been performed on ordinary concrete with w/c ratios of 0.38 and 0.55. The mix designs are tabulated in Table 1.

As binder, two different kinds of Portland cement, both produced by Cementa, Sweden were used. The BAS cement, type II/A-V 52.5N, according to EN 197-1, contains 16% fly ash and 4% limestone. The coarser ANL cement type CEM I 42.5N - SR 3 MH/LA, according to EN 197-1, has low C_3A content. The physical and chemical properties of both cements are shown in Table 2.

Mix ANLFA 0.38 was made by replacing 30 wt% of the cement of a proven Cementa mix ("ANL 0.38"; not used here) with fly ash. In addition, the 16/27 aggregate was replaced by 8/16 in order to ensure a better d_{max} : sample diameter ratio. This mix was not optimized further. ANL is a much coarser cement, therefore, in the ANLFA mix, more prominent swelling could be expected for the same curing conditions than in any other tests since both the cement coarseness and the high fly ash content have been linked to expansion or delayed ettringite formation; [17] and [15], respectively.