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Aggregate and slag cement effects on autogenous shrinkage in cementitious materials

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HIGHLIGHTS

- Autogenous shrinkage is calculated by removing the thermal effects associated with cement hydration.
- Aggregate content effect is studied by an improved Pickett's model.
- Slag cement effect is characterized by a scaling method.
- Partial replacement with LWA is used to effectively mitigate autogenous shrinkage.

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ABSTRACT

This study investigates the susceptibility of cementitious materials to internal moisture condition by the autogenous deformation measurement in the 0.35 water-binder (w/b) ratio systems (paste, mortar and concrete). Autogenous shrinkage is obtained by separating the thermal effects from the measured total deformation using the maturity concept and the coefficient of thermal deformation (CTD). Three factors affecting the autogenous shrinkage are presented, that is the aggregate content, the partial replacement of portland cement with slag cement and of normal weight fine aggregate with lightweight aggregate (LWA). Autogenous shrinkage is clearly reduced by an increasing aggregate content and this effect is predicted by an improved Pickett's model using a time-dependent aggregate restraining factor. A binary cementitious system of portland cement and slag cement increases the autogenous shrinkage in the long term. Contribution of slag cement can be characterized by the difference in autogenous shrinkage between the binary system and the control system scaled down by the replacement ratio. The negative effect of slag cement can be neutralized by the incorporation of LWA as a partial sand replacement.

1. Introduction

Concrete is intrinsically susceptible to moisture from different aspects. Moisture is the carrier of deleterious species into concrete, such as chloride ions accelerating the corrosion of embedded reinforcements and sulfate ions causing internal cracking and disintegration of the cementitious matrix [1]. Sub-freezing phase transformation of the internal moisture is also the culprit for frost damage in concrete [2]. This susceptibility can be minimized by the advent of high performance concrete (HPC) which features a low water-binder (w/b) ratio and the addition of supplementary cementitious materials (or SCM, such as slag cement) [3]. These characteristics reduce the porosity and re-configure the pore structure towards a more refined pore size [4,5], which results in a denser matrix (thus limiting the penetration of the detrimental chemicals) and a lower amount of freezable moisture (thus reducing the risk of frost damage).

At the same time, HPC experiences exacerbated internal pore drying due to the secondary chemical reaction of SCM with the moisture [6]. This self-desiccation effect [7], when coupled with a finer pore size, generates an enhanced net compressive stress on capillary pores on a micro-scale and more significant autogenous volume contraction on a macro-scale [8,9]. This is exemplified by the increased autogenous shrinkage in concrete with partial replacement by slag cement in the long term [10–14]. As a result, there is an increasing concern in the autogenous shrinkage-induced cracking in HPC nowadays [15–17]. This creates the need for accurate characterization of the autogenous shrinkage, which has resulted in a number of prediction models for concrete shrinkage based on the elastic properties of concrete and its components

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[18–22]. In addition, several mitigation strategies have been developed [23,24], including the use of chemical admixtures (such as shrinkage reducing admixture, expansive additives) [25], the entrainment of internal curing agents (such as lightweight aggregate and super absorbent polymer) [26] or the application of a lean mix [27].

Autogenous shrinkage is a result of an exothermic chemical reaction between cementitious materials and water, which can lead to a temperature rise and thermal dilation in the specimen in the early age. However, the typical measurement techniques for monitoring the deformation of a sealed homogenous specimen indiscriminately include both the autogenous and thermal deformations. As a result, there have been many efforts in separating the two components [28–31].

In this paper, autogenous shrinkage was calculated from the measured total deformation on cementitious systems of different compositions by accounting for the thermal effects. Factors affecting the autogenous shrinkage were studied such as the aggregate content, the addition of slag cement and/or lightweight aggregate (LWA). This work will hopefully result in improved understanding of autogenous shrinkage characteristics and the mitigation strategies.

2. Experimental

2.1. Materials and mix characteristics

Type I portland cement was used as the cementitious material. Fine aggregate was silica sand with a fineness modulus of 2.43 and an absorption capacity of 1.6%. Coarse aggregate was crushed lime stone with a 19 mm nominal maximum size and an absorption capacity of 1.2%. A commercially available LWA was used as a partial replacement for fine aggregate. LWA was in saturated surface dry (SSD) with a SSD specific gravity of 1.77 and an absorption capacity of 10%. The gradation curves are shown in Fig. 1 for each aggregate.

Mixes consisted of one w/b ratio (0.35), five different aggregate fractions (0%, 20%, 40%, 60% and 78% by volume). In the case of the mixes with 40% and 78% aggregate contents, two replacement ratios (25% and 50%) were used for portland cement with slag cement by weight; in addition, two replacement ratios (25% and 50%) for normal sand with LWA by volume were used for the mix with 40% aggregate content. Mix design is listed in Table 1. The mix nomenclature is as follows: the first part is the w/b ratio, the middle part is the mass replacement ratio with slag cement and the last part specifies the volume fraction of aggregate (either normal weight aggregate denoted as NA or lightweight aggregate denoted as LWA, if included). Compressive strength at different ages was tested on the sealed-cured concrete specimens (0.35-0S-78NA, 0.35-25S-78NA and 0.35-05S-78NA) according to ASTM C 39 [32].

2.2. Autogenous deformation measurement

Autogenous shrinkage and temperature were measured simultaneously on duplicate cementitious systems of 60 × 100 × 1000 mm, as shown in Fig. 2. Immediately after mixing, the concrete mixes at 60% and 78% aggregate volumes were cast while the fresh paste and mortar mixes were stored in a sealed bucket. Bleeding is a common unwanted feature and is especially severe at a low aggregate content, which may interfere the displacement measurement [33]. Regular stirring was accordingly carried out to create a homogenous mix prior to casting. When no clear sign of bleeding water was observed, the mix was thoroughly agitated before casting. The standing period ranged from 3 to 9 h, depending on the aggregate content. Double polystyrene films were used to seal the specimen to prevent external drying. Two layers of the 2-mm thick foam rubber were used to separate the sealed specimen and the rig to minimize the friction. While there was a short period of temperature fluctuation in the early age due to cement hydration, an isothermal condition at 20 ± 1 °C was achieved in the long run by circulating water through chambers embedded into the lateral sides and bottom of the rigs. Specimen temperature was monitored by a thermocouple inserted into the mid-depth of the specimen. The specimen was positioned with one end fixed to the rig and the other end connected to a movable plate in contact with a LVDT of a 0.1 μm resolution. The specimen displacement and temperature were both measured every 5 min and the displacement was automatically converted to strain.

Table 1
Mix design (kg/m^3).

Mix	Portland cement	Slag cement	Gravel	Normal sand	LWA	Water
035-0S-0NA	1497	0	0	0	0	524
035-0S-20NA	1198	0	0	530	0	419
035-0S-40NA	899	0	0	1059	0	314
035-25S-40NA	667	222	0	1059	0	311
035-50S-40NA	440	440	0	1059	0	308
035-0S-60NA	599	0	941	649	0	210
035-0S-78NA	329	0	1223	843	0	115
035-25S-78NA	245	82	1223	843	0	114
035-50S-78NA	161	161	1223	843	0	113
035-0S-30NA-10LWA	899	0	0	795	177	314
035-0S-20NA-20LWA	899	0	0	530	353	314
035-50S-30NA-10LWA	440	440	0	794	177	308
035-50S-20NA-20LWA	440	440	0	530	353	308

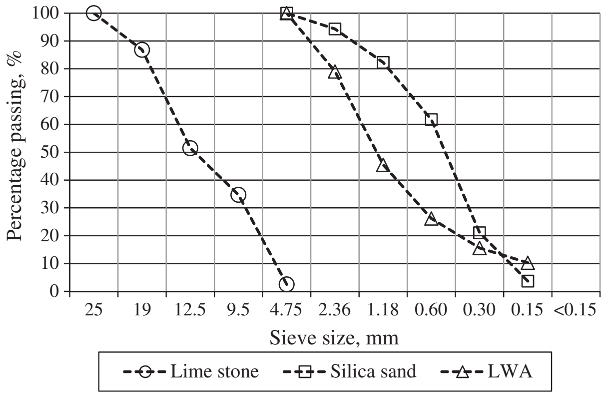

Fig. 1. Gradation curves for the aggregates.

2.3. Coefficient of thermal deformation (CTD) measurement

One 100 × 200 mm cylinder was prepared for each system the same way as the shrinkage test. The mixing date was one day apart between each mix, such that the test age was the same. The cylinders were sealed cured in the mold at 20 °C for 28 days. Then a concrete saw was used to cut two small-scale prisms (10 × 10 × 90 mm) out of each cylinder. Extra moisture was removed from the specimen by a damp cloth and the plastic wrap was used to seal the four lateral sides of the specimen to minimize moisture loss during the test.

CTD of the cementitious systems was measured by a high-precision dilatometer capable of simultaneous displacement and temperature measurements (Fig. 3(a)). The dilatometer has a length-change resolution of 1.25 nm/digit and a temperature precision of 0.1 K. The sample holder was customized to accommodate specimens up to 12 mm × 12 mm in cross section and 100 mm in length (Fig. 1(b)) and a liquid nitrogen dewar was equipped for low temperature control. The specimen was placed in the sample holder with the thermocouple touching the lateral side for temperature measurement. The pushrod connecting the LVDT system was in contact with one specimen end for displacement recording (Fig. 3(b)). The specimen was exposed to a specific temperature profile fluctuating between 10 °C and 40 °C, as shown in Fig. 3(c). Both the cooling and heating rates were 10 °C/h.

3. Results and discussion

The total deformation and corresponding temperature profile were measured continuously on the 0.35 w/b ratio cementitious systems (paste, mortar and concrete) with different aggregate contents (0%, 20%, 40%, 60% and 78%), as shown in Fig. 4. In this study, positive strain denotes shrinkage and negative strain denotes expansion on the y-axis. The zero time on the x-axis represents the mixing time.

It can be seen there is good reproducibility between the two specimens in the measured total strain. Specimen temperature is well maintained at around 20 °C during the test, except for the presence of a small short-lived bump in the very early stage. This is a result of the latent heat liberated during cement hydration