



Plastic shrinkage of mortars with shrinkage reducing admixture and lightweight aggregates studied by neutron tomography



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ABSTRACT

Water transport in fresh, highly permeable concrete and rapid water evaporation from the concrete surface during the first few hours after placement are the key parameters influencing plastic shrinkage cracking. In this work, neutron tomography was used to determine both the water loss from the concrete surface due to evaporation and the redistribution of fluid that occurs in fresh mortars exposed to external drying. In addition to the reference mortar with a water to cement ratio (w/c) of 0.30, a mortar with the addition of pre-wetted lightweight aggregates (LWA) and a mortar with a shrinkage reducing admixture (SRA) were tested. The addition of SRA reduced the evaporation rate from the mortar at the initial stages of drying and reduced the total water loss. The pre-wetted LWA released a large part of the absorbed water as a consequence of capillary pressure developing in the fresh mortar due to evaporation.

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1. Introduction

Drying of concrete surfaces during the initial hours after casting may lead to a very pronounced water loss due to the high permeability of fresh concrete. The fast water loss in the stage when concrete is still plastic causes deformations referred to as plastic shrinkage [1]. Plastic shrinkage may lead to cracking that propagates easily due to the very low concrete strength and ultimately impair concrete performance and require expensive repairs. The risk of plastic shrinkage cracking increases with increased evaporation rates, i.e. for exposed surfaces at high wind speed, high temperature and low relative humidity conditions [2]. Established strategies against plastic shrinkage cracking can be generally divided into active and passive solutions. The active solutions aim at limiting the early water loss by wetting the surface with water, applying curing compounds that limit evaporation, covering the surface with plastic sheets or shading the elements from sun and/or wind [3]. A passive solution consists of designing concrete mixtures with lower risk of plastic shrinkage cracking, which often includes (polypropylene) fibers [4,5], shrinkage reducing admixtures (SRAs) [6–8] and recently also internal curing by means of lightweight aggregates (LWA) [9]. The performance of these different methods and the

sensitivity of a given mixture composition to plastic shrinkage cracking is usually assessed in a test where a fresh concrete sample is exposed to rapid evaporative conditions and the formation of cracks on the surface, often provoked by highly restraining molds, is quantified, e.g. Refs. [4,5,7,9,10]. During the test, the water loss from the surface can be followed by weighing the drying sample. Further quantities that allow addressing the cracking risk are the amount of bleeding water, the development of capillary pressures measured with pressure sensors, and the displacements of the concrete surface in the vertical and horizontal directions [10,11].

The main mechanism leading to plastic shrinkage cracking is the development of capillary suction in the pore fluid [2,8]. At the initial stages after casting, the water, or more precisely, pore solution, migrates through the very permeable, fresh concrete and accumulates at the upper surface (a phenomenon called bleeding) due to settlement of the cement and aggregates driven by gravity. The evaporation rate from the concrete surface in this phase (constant rate period) is close to the free evaporation of water [8]. At high evaporation rates, starting from several minutes to 1–2 h after placement, and due to decrease of the permeability of fresh concrete, bleeding water cannot accumulate at the surface fast enough and the concrete surface becomes dry. Once water–air menisci form between the solid particles, a capillary pressure gradient forms between the surface and the bulk [12]. The capillary pressure drives the water to the drying surface and at the same time it compresses the solid skeleton. The compression of the solid skeleton

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finally leads to its consolidation, after which point any restraint to horizontal or vertical deformation may lead to cracking while the concrete is still plastic [7].

In view of the aforementioned mechanisms, transport of water in fresh concrete and its evaporation from the surface is of key importance in understanding and reducing plastic shrinkage and the risk of cracking. In-vivo imaging of migration of water absorbed in porous materials based on X-ray absorption, e.g. Refs. [13,14], meets serious accuracy limitations due to a low signal-to-noise ratio. Better contrast for water can be obtained with nuclear magnetic resonance (NMR) relaxometry [15], X-ray small angle scattering [16] or neutron imaging [17]. In this work, water loss from mortars exposed to drying during the initial 14 h after casting was investigated by means of neutron tomography. Thanks to the large neutron cross-section of hydrogen, a neutron beam is highly attenuated (mainly due to neutron scattering) by substances containing hydrogen [17–19]. The high attenuation due to water present in cementitious materials, compared to relatively low attenuation due to the solids makes neutron imaging a very useful non-destructive technique for following water transport [20–25]. However, due to a low neutron flux, neutron imaging requires relatively long exposure times compared to X-rays. In the case of computed tomography (CT), the time required to acquire a series of projections necessary for reconstructing the 3-D dataset [26] has long been a limiting factor for studying dynamic processes. Instead, radiography was commonly applied to enable sufficiently fast temporal resolution of the imaging, e.g. Refs. [24,25,27,28]. However, investigations based only on radiography require samples with 2-D geometry, which are often artificial. Recently, thanks to applying non-sequential decomposition of projection angles and algebraic reconstruction methods [29], tomographic scans of dynamic water transport in early-age cementitious materials became possible [20,21,30]. This approach has been also followed here, enabling CT scans at temporal resolution of 15 min at the initial stages of drying and 1.5 h at later stages.

We studied small cylindrical probes (22 mm diameter, 23 mm height) of different mortars: a reference mortar with w/c of 0.3 and 50% by volume of aggregates, a mortar with addition of prewetted LWA particles and a mortar with 5% water replacement by SRA. The samples were exposed to harsh drying conditions leading to fast evaporation. In addition to the neutron CT measurements on mortars, the free evaporation from a water container was followed during the tomographic scans and the mass loss of the mortars was measured.

2. Materials and methods

2.1. Sample preparation

Mortars were prepared with a water to cement ratio (w/c) of 0.30 and 50% aggregate by volume. Three mortars were tested: a reference mortar (denoted as REF), a mortar with six LWA particles embedded in the sample during casting (denoted as LWA) and a mortar where 5% of the mix water was replaced with a Shrinkage Reducing Admixture (SRA) (denoted as SRA). Ordinary Portland cement CEM I 42.5 N was used with the following oxide composition (by mass): CaO 63%, SiO₂ 20%, Al₂O₃ 4.5%, Fe₂O₃ 2.9%, MgO 1.9%, SO₃ 2.8%, K₂O 0.95%, Na₂O 1%, and Cl 0.03% and Blaine fineness of 2770 cm²/g. Deionized water was used as mixing water. A liquid polycarboxylate-based superplasticizer replaced part of the mixing water in an amount corresponding to 0.6% by cement weight. The normal weight aggregate (NWA) was alluvial sand composed of (by mass): sandstone 37%, limestone 37%, dolomite 18% and metamorphic rocks 8%, with well-rounded particles of sizes 0–4 mm, density of 2620 kg/m³ and water absorption of 1.03% according to EN 1097-6. Approximately 200 ml of mortar was mixed at 450 rpm for 2 min in a vacuum mixer (Twister Evolution).

Immediately after mixing, about 30 g of each of the mortars were cast into cylindrical holders made of glass-reinforced Teflon and compacted by delicate tapping of the holder on the table. Teflon has

low neutron attenuation and does not react with cementitious systems. The dimensions of the holders were: internal diameter 22.0 ± 0.1 mm, height 23 ± 0.1 mm, wall thickness 1.5 ± 0.1 mm. SRA mortar was mixed first, followed by the REF mortar. For the sample with LWA, exactly the same reference mortar was used as for the REF sample, but additionally six pre-wetted LWA particles were placed in two layers during casting of the sample. The LWA were expanded shale particles that passed the #8 sieve (approximately 4 mm), with an oven-dry specific gravity of 1.56 and a 24 h absorption of 15.6% [40]. The LWA were pre-wetted by submerging in deionized water for 24 h prior to mixing. After preparing the samples, the containers were weighed on a 0.01 g-resolution balance. The sample holders were then mounted one above another on a vertical aluminum rod using aluminum adhesive tape, Fig. 1. Approximately 20 mm of free space was provided between the sample holders. In addition to the three sample holders filled with mortars, a container filled with deionized water was placed at the bottom of the sample stack, Fig. 1, to allow assessing free evaporation conditions in the vicinity of the samples.

2.2. Test procedure

The stack of samples (the four holders shown in Fig. 1), was placed on a rotation stage in a neutron beamline hutch. At times of 40 min (for the REF and LWA mortars) and 55 min (for the SRA mortar) from

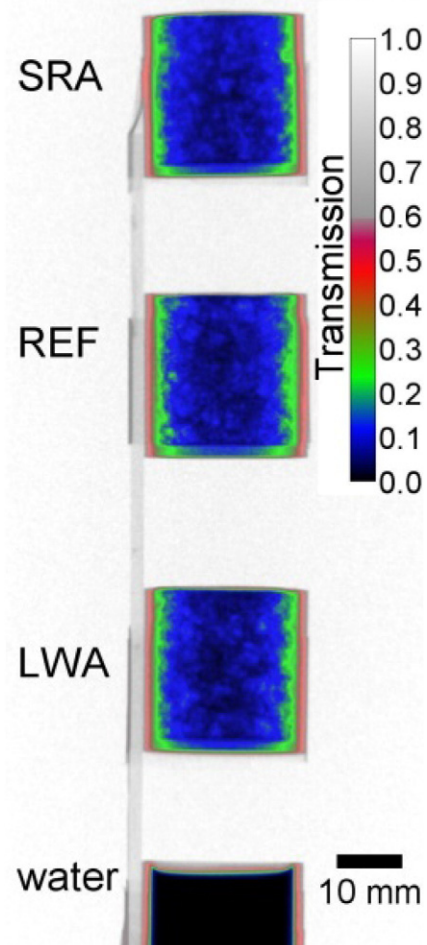


Fig. 1. Neutron radiograph showing the Teflon holders filled with fresh mortar (upper three containers) or deionized water (the lowest container) mounted on a vertical aluminum rod. Beam transmission in the range 0.0–0.6 is displayed in RGB color scale for better visualizing transmission in the sample area, and in the cropped grayscale scale for higher transmission. The whole setup was rotating along the vertical axis at angles following the golden ratio decomposition [29] to enable tomographic scans.

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