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Consequences of longer sealed curing on drying shrinkage, cracking and carbonation of concrete

Hamza Samouh, Emmanuel Rozière, Vincent Wisniewski, Ahmed Loukili *

Institut de Recherche en Génie Civil et Mécanique (GeM), UMR-CNRS 6183, Centrale Nantes, France

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ABSTRACT

The influence of sealed curing on long-term drying behaviour and durability of concrete is investigated in this experimental study. Two concretes were cured for 16 h, 24 h, 48 h, and 1 month then exposed to drying at 20 °C and 50% RH. Mass-loss, total and autogenous shrinkage were monitored. Hydration and microstructural development were studied by isothermal calorimetry and mercury intrusion porosimetry. The drying depth was assessed to quantify the heterogeneity of concrete specimens exposed to drying. The carbonated depth was measured after 6 months, 1 year and 4 years.

Longer sealed curing allowed better hydration of cement and reduced long-term water loss. The curing duration significantly influenced the total and drying shrinkage magnitudes. Maximum values were found experimentally and numerically between 24-hour and 48-hour curing. The shrinkage-induced cracking sensitivity was also affected; the shortest sealed curing duration resulted in the lowest cracking index.

Linear correlations were found between five properties: compressive strength and degree of hydration at exposure, carbonated depth, median pore diameter, and drying depth. These indicators can be used to optimize the durability of concrete. Sealed curing should be as long as possible to allow hydration of cementitious materials, to minimize drying depth, and to maximize the resistance to carbonation. However, drying shrinkage shows a pessimum; this should be taken into account in the design of durable concrete cover.

1. Introduction

The study of the influence of the initial conditions on the behaviour of cement-based materials helps understanding the effect of the actual construction site conditions on the long-term behaviour of concrete. After a longer curing period, concrete shows higher strength and stiffness due to better hydration of cement-based materials [1–3]. A longer curing is also recommended to improve durability [4]. Long formwork duration allows a good hydration of cement, and thus reduces the free water content. At the same time, the capillary pores become finer and the water loss due to drying decreases [5–9]. Alhozaimy studied two moist-curing periods (7 and 14 days), and concluded that the extended period led to a reduced concrete permeability especially in the presence of fly ash and at higher replacement levels [10]. The influence of curing time on these concrete properties involved in concrete durability is well known, but the published studies related to the influence of curing time on shrinkage are much scarcer.

Designing durable concrete cover actually requires taking into account shrinkage and cracking sensitivity, which was observed to increase with curing time in some published studies. As far as drying shrinkage is concerned, conflicting results have been reported in the literature. Miyazawa actually suggested that delayed sealed curing does not have a significant effect on drying shrinkage for concretes with three water-cement ratios 0.4, 0.5, and 0.6 [11]. However, Aly and Sanjayan compared 1 day and 7 days curing, and confirmed that concretes cured for longer periods showed higher shrinkage [12]. Monge worked on a mortar exposed to drying after four curing durations 1 day, 2 days, 3 days and 7 days. He observed that shrinkage increased with curing time [6–7]. Mauroux confirmed this result on a mortar with and without cellulose for three periods: 1 day, 3 days and 7 days [8]. Hajibabaee monitored the curling of paste beams and simulated the development of effective pore pressure for three durations: no curing, 3 days, and 14 days to conclude that the developed internal pressure increased with the time of wet curing [13–15]. In order to assess shrinkage-induced cracking, Monge conducted an experimental study and showed that cracks appear more rapidly with the long curing duration [6–7]. Most of these authors concentrated on capillary tension and the influence of pore sizes. As the pore radii decrease with curing time due to hydration, drying results in higher stresses thus higher shrinkage strain. These studies deal with specific conditions in terms of materials [6–8] or relatively short curing times, as the 28-day curing was not included. Only one published paper reported a pessimum initial curing time with respect to drying shrinkage [16]. In 1963, Perenchio

* Corresponding author.
E-mail address: ahmed.loukili@ec-nantes.fr (A. Loukili).

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conducted a study published in 1997 where he stated that concrete produces the highest ultimate shrinkage between 3 and 7 days of curing, and lower shrinkage for 28 and 90-day curing. However the mechanisms were not discussed in his paper.

This paper presents a comprehensive experimental study on the influence of sealed curing provided by formworks on shrinkage, microstructure, and durability of cement-based materials. A new approach is described. It aims at understanding the effects of sealed curing duration on shrinkage and shrinkage-induced cracking as well as other concrete properties involved in durability issues. The monitored properties are related to the hydration degree. The new notion of drying depth is used to analyse the drying shrinkage vs. mass loss curves and to investigate the impact of early drying on hydration and microstructure development [17]. A simple model is used to confirm assumptions on the mechanisms involved in the observed pessimum curing time.

The RILEM Technical Committee 196-ICC classified the curing methods in two categories: external and internal curing as shown in Fig. 1. In this paper, demoulding is delayed to prevent the exchange of moisture with surrounding media. This method is within the scope of the external curing and, more specifically, the sealed curing definition given by Kovler and Jensen [17].

This paper aims to study the effect of the sealed curing duration on the long term-behaviour of two types of concrete: vibrated concrete and self-consolidating concrete. The experimental investigation includes the coupling between hydration and drying, long-term shrinkage, microstructure, and cracking sensitivity. Thus, hydration, drying and free shrinkage are monitored for the different curing durations. The microstructure is studied by mercury intrusion porosimetry (MIP). The carbonated depth is measured at different drying times and compared with drying depth, hydration degree at exposure and MIP results. The relation between drying depth which represents the skin effect (high porosity, high permeability, microcracking) and traditional concrete durability indicators (carbonated depth, median pore diameter, degree of hydration and strength at exposure) are investigated. Finally, the risk of shrinkage-induced cracking is estimated by the ring test.

2. Experimental procedures

2.1. Materials, mixtures, and curing

Ordinary Portland cement CEM I 52.5 N was used for both concrete mixes. Its chemical and physical properties are detailed in Table 1. Limestone filler was used for self-consolidating concrete mixture. Its calcium carbonate proportion was 97%, its density was 2.7 kg/m^3 and its Blaine surface 4350 cm^2/g. The coarse aggregates of sizes 10/14 and 6/10 mm were crushed amphibolite rocks with low water absorption (0.3%). The fine aggregate used in concrete was sea sand of granular class 0/4 mm. Its water absorption coefficient was 0.6%. A polycarboxylate based superplasticizer was used for SCC mixture.

As mentioned earlier, two concrete compositions were studied: self-consolidating concrete (SCC) and vibrated concrete (VC) (Table 2). The

Table 1
Cement oxide analysis, phase concentrations and Blaine fineness.

Oxide mass fractions (%)						
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
19.6	4.5	2.3	63.7	3.9	2.6	0.7
Phase mass concentrations (%)					Physical properties	
Clinker	C_3S	C_2S	C_3A	C_4AF	Density (Kg/m^3)	Blaine (cm^2/g)
98	69	9	9	7	3.13	3900

water content W corresponds to the effective water content, i.e. the difference between total water content and water absorbed by aggregates.

Cylindrical specimens (7.8 cm in diameter and 28 cm in height) were made to study shrinkage, drying, and microstructure of SCC and VC. Both series of specimens were demoulded after different sealed curing periods at 20 °C constant temperature. Then they were stored in an air-conditioned room at controlled temperature (20 ± 1 °C) and relative humidity (50 ± 5%). Three sets of SCC cylindrical specimens (Ø11 × 22 cm^2) of the same batch were demoulded after 16 h, 24 h, 48 h of sealed curing. Compressive strength and Young's modulus tests were performed on each set of specimens at ages of 16 h, 24 h, 48 h, 7 days, and 1 month (Table 3 and Table 4). The Young's modulus was determined by using LVDT sensors during compressive tests.

A second series of compressive tests were conducted on SCC and VC samples, immediately after demoulding. All specimens were kept in their moulds and stored in the climatic room at 20 °C constant temperature until compressive testing time. According to these data (Table 3 and Table 4), the compressive strength and elastic modulus of SCC was not systematically higher than that of VC. SCC contains limestone filler which provides nucleation sites for the hydration products and induces an acceleration of the hydration [18]. Consequently, the increase of strength and elastic modulus for SCC is higher at early age. However, the higher paste volume of SCC results in lower ultimate strength and Young's modulus [19]. The 28-day strength and elastic modulus of SCC were actually lower than VC.

The lowest sealed curing duration (16 h) lead to lower compressive strength during the first week. However, after one month the strength was not found to depend on the sealed curing duration, drying actually make menisci appear in the specimens exposed to drying before testing time. The effects of capillary tension were more significant for earlier demoulding because they had a longer time to develop and menisci finally reached finer pores. This provided concrete with higher apparent strength [20]. The observed tendency could also be partly due to the high water-to-cement ratio. In this studied case the earlier mould removal slowed down the strength evolution without much affecting its long-term value (Table 3). This slowdown can be explained by the coupling between hydration and drying which mainly affects the external part of the specimen during the first days, but the relatively high available water content allowed hydration to go on slowly.

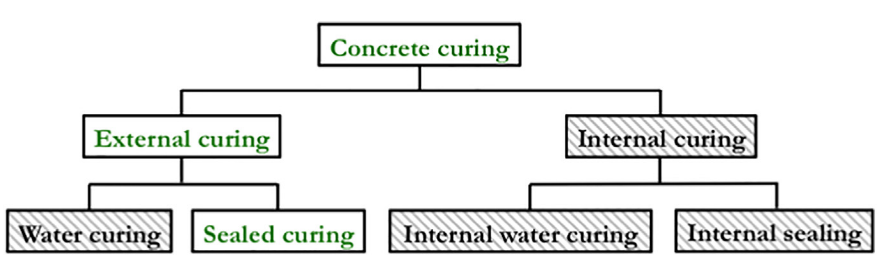

Fig. 1. Sealed curing and other curing means, adapted from [17].