Construction and Building Materials 113 (2016) 134–143

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Early age carbonation curing for precast reinforced concretes

Duo Zhang, Yixin Shao *

Department of Civil Engineering, McGill University, 817 Sherbrooke Street West, Montreal, Quebec H3A 2K6, Canada

HIGHLIGHTS

- Early age carbonation curing is developed for precast reinforced concrete.
- Carbonation curing forms carbonate-rich surface with higher electric resistivity.
- Carbonated concrete (pH > 12) is not more vulnerable to weathering carbonation.
- The process has shown environmental, technical and economical benefits.

ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form 22 February 2016
Accepted 11 March 2016
Available online 16 March 2016

Keywords:
Carbonation curing
Precast reinforced concrete
pH values
Weathering carbonation
Carbon dioxide storage

ABSTRACT

Carbonation is considered detrimental to reinforced concrete. However if carbonation is performed at early age through curing, the process could be beneficial. This paper is to present a study on a unique process that is developed for early age carbonation curing of precast reinforced concrete to maximize the performance improvement and the carbon storage capacity. The process includes vibration casting, in-mold curing, off-mold preconditioning, carbonation curing and subsequent hydration. It was found that a carbon uptake of 16% based on the cement content could reduce concrete pH to 9.2 on the surface and maintain pH of 13.0 at core immediately after 12 h carbonation. The subsequent hydration was able to increase the pH on surface over 12.3 which was comparable to hydration reference. The carbonated concrete had shown more resistance to permeation by having a higher electrical resistivity on surface and was not more vulnerable to weathering carbonation. The off-mold preconditioning in open air caused no shrinkage cracking because of the controlled evaporation rate. The process makes concrete a sandwich structure with carbonate-rich surface which is responsible for strength gain, carbon storage and durability enhancement and is suitable for precast reinforced concrete production.

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1. Introduction

Precast concrete accounts for 20–30% of total concrete market including both dry-mix and wet-mix products [1]. The dry-mix concretes, such as concrete blocks, pavers and hollow core slabs, are typical zero-slump concrete with low cement content. They are consolidated by special vibration compaction and can be demolded immediately after casting. Wet-mix concretes constitute the majority of precast products which are formed using superplasticizer and internal vibrator. The wet-mix concretes require 24 h curing before the mold can be removed.

Recent research has shown that dry-mix concrete can be treated with carbonation curing at early age for accelerated strength gain and improved durability [2]. Carbonation curing has been applied successfully to production of concrete masonry unit [3] and hollow core slab [4]. However early age carbonation curing of wet-mix concrete is not investigated. The challenge is the wet-mix concrete contains higher liquid content including water and superplasticizer which may impede penetration of carbon dioxide. In addition, the wet-mix concretes are usually reinforced by steel bars. There is concern on the reduction of alkalinity in concrete due to the early carbonation which could generate corrosion of reinforcing steel.

Carbonation corrosion of concrete subject to weathering carbonation is well studied. The progressive weathering carbonation takes place when matured concrete reacts with atmospheric carbon dioxide. The progressive reaction reduces pH value of concrete and is detrimental to long term performance of concrete. It is believed that steel remains in passive state in alkaline environment provided by concrete pore solution. Reduction of pH to 11.0 by weathering carbonation could destroy passivation film on steel surface and thus initiate corrosion [5]. It was found that pH transition from passive to active corrosion of mild steel bars happened between 9.4 and 10 [6]. It was also reported by X-ray photoelectron

* Corresponding author.
E-mail address: yixin.shao@mcgill.ca (Y. Shao).

http://dx.doi.org/10.1016/j.conbuildmat.2016.03.048
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spectroscopy (XPS) that passivation of mild steel could be achieved if pH value of the concrete was ranged from 10 to 13 [6]. The pH value of concrete becomes a critical indicator for carbonation corrosion.

Carbonation curing at early age is different from weathering carbonation. It is introduced to fresh concrete within 24 h after casting. Therefore the subsequent hydration will take place after early carbonation. There are two approaches for early age carbonation. If carbonation is performed immediately after casting, the reaction occurs between C_3S or C_2S and carbon dioxide. The governing equations are given by Eqs. (1) and (2) [7]. If carbonation is applied after a short period of initial hydration, carbonation happens to both anhydrous (C_3S and C_2S) and hydrous ($Ca(OH)_2$, C—S—H) phases. The corresponding reactions are governed by Eqs. (1)–(4). In either case, the reaction products are the hybrid of hydrates and carbonates. The reaction kinetics was studied through a mathematical modelling [8].

$$C_3S + (3 - x)CO_2 + yH_2O \rightarrow C_xSH_y + (3 - x)CaCO_3 \quad (1)$$

$$C_2S + (2 - x)CO_2 + yH_2O \rightarrow C_xSH_y + (2 - x)CaCO_3 \quad (2)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

$$C{-}S{-}H + 2CO_2 \rightarrow SiO_2 + 2CaCO_3 + H_2O \quad (4)$$

Eqs. (1)–(4) also indicate that carbonation curing at early age is a carbon uptake process. Gaseous carbon dioxide is converted to solid carbonates and can be permanently stored in concrete for emission reduction [9]. To maximize the benefits of the process and promote its application in wet-mix precast concrete with reinforcing steel, the effect of early carbonation curing on pH value of concrete shall be examined. In addition, a special process is needed for carbonation of wet-mix concrete with high slump.

The purpose of this study is to develop an early carbonation curing process for wet-mix precast concrete with high slump. It includes in-mold hydration curing, off-mold preconditioning after demolding, carbonation curing and subsequent hydration. To maximize the reaction degree and its related carbon dioxide storage capacity, process parameters such as water content and carbonation duration are studied. The concrete performance is evaluated by carbon dioxide uptake, strength gain, permeability, pH distribution, weathering carbonation depth and preconditioning shrinkage.

2. Experimental program

2.1. Materials and mixture proportions

Precast concrete was proportioned for general use. Ordinary Portland Cement (OPC) and granite aggregates were chosen. The use of granite is to eliminate the effect of carbon content in aggregate on thermal analysis of concrete. The water absorption of fine and coarse aggregate is about 4.3% and 1.6%, respectively. Fineness modulus of fine granite is 3.0 and the maximum aggregate size is 12 mm. Sieve analysis was performed and presented in Fig. 1. The gradation was selected following Fuller equation for a maximum packing density.

Two mixture proportions were examined. They are presented in Table 1. Mix A was developed for carbonation with water to cement ratio (w/c) of 0.4 while Mix B was for w/c of 0.3. Mix B concrete is commonly used in high performance precast concrete [10] such as railway crosstie production. Superplasticizer was used to achieve a slump of about 150 mm. It is intended to examine if carbonation could produce a concrete with less cement for equivalent strength. To maintain the same slump value, Mix B employed three times higher superplasticizer than Mix A. Superplasticizer was provided by W. R. Grace (AVDA Cast 575). Concrete was cast in 100 mm cubes and consolidated by 30-s vibration on a vibration table.

2.2. Carbonation curing procedure

A carbonation procedure was established for wet-mix concrete. It was involved with four steps as shown in Fig. 2: (1) in-mold curing, (2) off-mold preconditioning, (3) carbonation curing and (4) subsequent hydration.

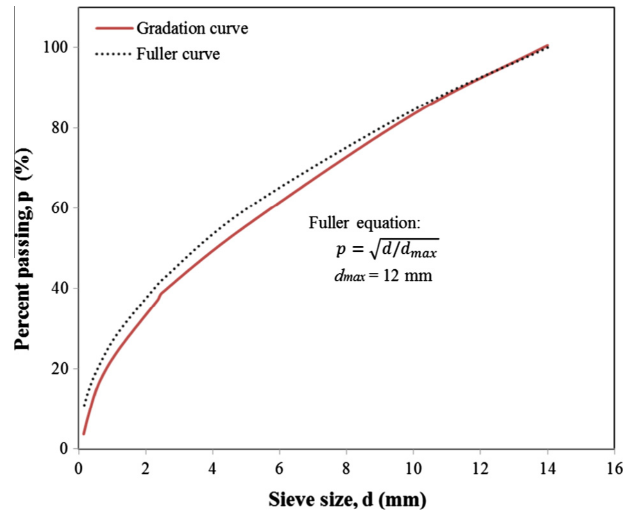

Fig. 1. Aggregate sieve analysis.

Table 1
Mixture proportions of concrete.

	Mix A	Mix B
Cement (c), kg/m^3	452	526
Water (w), kg/m^3	181	158
Coarse granite, kg/m^3	1060	1060
Fine granite, kg/m^3	680	680
Concrete, kg/m^3	2375	2431
Superplasticizer (sp), mL/m^3	2055	7173
w/c	0.4	0.3
SP/c, %	0.5	1.5
Slump, mm	158	151

Step 1 is in-mold curing. Since wet-mix concrete has a higher slump, it is not possible to demold right after casting. Therefore initial hydration curing in mold is necessary. The time required for this step is dependent on the mixture proportion. For Mix A and B, it took about 5 h to reach initial set at ambient condition (25 °C and 60% relative humidity) in an open air. This was also intended to naturally evaporate part of the mixing water. After initial set, the four side plates were removed and concrete cubes were left on bottom plates. Off-mold preconditioning by fan drying was then performed. It was accomplished at a wind speed of 1 m/s in a room of 25 °C and 50 ± 5% relative humidity. Step 2 is critically important. The preconditioning further removes part of the free water and makes more space for carbon dioxide to penetrate. To remove 40% free water, it takes about 5 h. In step 3, the conditioned concrete was carbonated in a pressure chamber with a CO_2 gas of 99.8% purity and at varied duration and pressure. After carbonation, the concrete cubes were placed in moisture room (25 °C, 95% RH) for another 27 days subsequent hydration. The hydration references were also prepared. They were cured in sealed mold within the first 24 h and then demolded and further cured in the same moisture room for 27 days.

The setup for carbonation curing is shown in Fig. 3. Carbon dioxide gas was injected into the chamber to a constant pressure. The chamber was placed on a digital balance to obtain the CO_2 uptake by concrete through a mass curve measurement. To enhance the degree of early carbonation for strength gain and carbon storage, the effect of processing parameters are studied. They include percent water removal by preconditioning, gas pressure and carbonation duration. Degree of carbonation is assessed by CO_2 uptake of the concrete.

2.3. CO_2 uptake estimation

CO_2 uptake is estimated by two methods: mass gain method and mass curve method. Mass gain method calculates CO_2 uptake in concrete by comparing mass of samples before and after carbonation (Eq. (5)), in which m_1 and m_2 represents sample mass before and after carbonation reaction. Carbonation-induced water loss (m_{water}) was collected by absorbent paper and added to final mass (m_2). By treating the system as a closed system, it was imperative to include the evaporated water, which was initially inside the samples prior to carbonation. Percent CO_2 uptake is expressed with reference to the dry cement mass (m_{cement}).

$$CO_2 \text{ uptake } (\%) = \frac{m_2 + m_{water} - m_1}{m_{cement}} \times 100\% \quad (5)$$

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