Construction and Building Materials 136 (2017) 565–573

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing

Shamsad Ahmad *, Rida Alwi Assaggaf, Mohammed Maslehuddin, Omar S. Baghabra Al-Amoudi, Saheed Kolawole Adekunle, Syed Imran Ali

King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

HIGHLIGHTS

- Effects carbonation pressure and duration on effectiveness of accelerated carbonation curing (ACC) of concrete studied.
- ACC of concrete at a pressure of 60 psi over a period of 10 h found to be most effective.
- Duration of ACC had major effect, increase in pressure from 10 to 60 psi had no significant effect.

ARTICLE INFO

Article history:
Received 23 July 2016
Received in revised form 20 January 2017
Accepted 21 January 2017
Available online 29 January 2017

Keywords:
Concrete
Accelerated carbonation curing
Carbon sequestration
Physico-mechanical properties
Compressive strength
Durability

ABSTRACT

Accelerated carbonation curing (ACC) is a new technique for curing of concrete that entails sequestering carbon dioxide (CO_2) gas into freshly cast concrete, resulting in the improvement of physico-mechanical properties and durability characteristics of concrete. This paper presents the results of an experimental study conducted to evaluate the effects of carbonation pressure and duration on the CO_2 uptake and evolution of strength of a concrete mixture. Concrete specimens were cured under six ACC pressures varying from 10 to 60 psi, applied for a duration of 1–10 h in a closed chamber. The effectiveness of varying ACC pressure and duration on the properties of concrete was assessed by measuring compressive strength gain, CO_2 uptake, morphology and mineralogy of concrete. It was noted that ACC at 60 psi (414 kPa) for 10 h resulted in the maximum strength gain and CO_2 uptake, leading to a post-ACC compressive strength of more than 200% of the pre-ACC strength, and a CO_2 uptake of about 11% by mass of cement. Finally, the analysis of variance of the experimental data indicated that the duration of ACC controls the concrete properties more than the pressure used for ACC.

1. Introduction

Carbonation is a diffusion process in which the CO_2 gas present in the atmosphere penetrates into concrete and forms carbonic acid in the presence of moisture. The carbonic acid reacts with $Ca(OH)_2$ in concrete forming $CaCO_3$ [1,2]. The $CaCO_3$ produced due to carbonation of concrete makes it dense, improving the properties of concrete. However, if carbonation of hardened concrete is allowed to take place over a long period it will cause significant reduction in the alkalinity of the concrete that can result in the initiation of reinforcement corrosion. Therefore, to exploit the positive effect of carbonation of concrete and to sequester CO_2 inside concrete, an accelerated carbonation for a short duration could be useful.

The exposure of young concrete to high concentrations of CO_2 at a high pressure for a limited time, termed accelerated carbonation curing (ACC), has been recently reported to offer an improvement in the physico-mechanical properties and durability characteristics of concrete [3]. Various concrete properties, which can be improved by ACC include strength, modulus of elasticity, sulfate resistance, freeze-thaw resistance, water absorption and chloride ion penetration [1,4–7]. As a reassurance of safety from the negative impacts of long-term natural carbonation, relating to carbonation-induced reinforcement corrosion, it was reported by Rostami et al. [6] that the reduction in pH due to ACC of concrete does not usually occur beyond a few millimeters below the exposed surface.

Some of the reported studies on ACC of concrete dealt with full penetration of carbonation front into the concrete. The idea of full depth carbonation is only applicable to the concrete elements without steel reinforcement, such as masonry blocks, where

* Corresponding author.
E-mail address: shamsad@kfupm.edu.sa (S. Ahmad).

http://dx.doi.org/10.1016/j.conbuildmat.2017.01.069

carbonation-induced de-alkalization is not a concern. However, for reinforced concrete elements the accelerated carbonation up to a few millimeters from the surface of concrete is allowed. Some explanations for the ACC-induced strength gain in concrete have been proposed in the literature. For example, Monkman and Shao [5] have associated the ACC-induced strength gain in concrete to the accelerating effect on hydration offered by the temperature rise accompanying the carbonation process, since it is an exothermic reaction.

The most important benefit of ACC besides its ability to improve the quality of concrete is to facilitate an avenue for the consumption of CO_2, reducing the environmental pollution. Concrete has been repeatedly claimed to be the most consumed single substance on earth, after water. As of 2003, the global annual concrete production was about 7 billion tons [8] while the current annual production of concrete has become more than double of the 2003 figure [9]. The concrete production process itself accounts for 5–7% of the global CO_2 emissions. Therefore, while research and development efforts are ongoing for the reduction in the quantity of CO_2 emission from the production of concrete, it is highly desirable that these efforts are extended to sequester some captured CO_2 into concrete, via ACC, thus contributing to a reduction in the global greenhouse gas emissions. Along this direction, Monkman and Shao [10] have reported that an estimated 1.5 million tons of recovered CO_2 or 1.0 million tons of flue gas could be sequestered into precast concrete products in USA and Canada annually. A similar estimate was also reported by Kashef-Haghighi and Ghoshal [11].

Considering the technical and environmental benefits of ACC, it is needed to intensify research efforts towards exploring the possibility of adopting ACC as a partial or full replacement of conventional curing of precast concrete products globally. Possible issues with ACC, for example carbonation shrinkage can be reduced by incorporating mineral admixtures, such as slag [5]. Zhan et al. [2] have reported a lower drying shrinkage for ACC-cured concrete blocks, compared to moist-cured blocks.

The current research was aimed at contributing to further insights on the effects of ACC on the properties of concrete. The effect of CO_2 pressure and duration on the compressive strength of Portland cement concrete was investigated to optimize these parameters for further detailed study. Thereafter, the effect of ACC on the compressive strength gain, CO_2 uptake, morphology, and phase composition of concrete was evaluated.

2. Experimental program

2.1. Materials

Type I cement, complying with ASTM C 150, was used in the preparation of the concrete specimens. Table 1 shows the chemical composition of the cement used in the study. Crushed limestone with a maximum size of 12 mm, specific gravity of 2.60 and water absorption of 1.4% was used as coarse aggregate. Fine quartz sand (dune sand) with a specific gravity of 2.56 and water absorption of 0.4% was used as fine aggregate. Fig. 1 shows the grading of coarse and fine aggregates. A polycarboxylic-based superplasticizer (SP) was used to achieve a desirable workability. CO_2 gas of 99.9% purity, contained in a gas cylinder that was equipped with pressure regulating devices, was used for carrying out ACC of the concrete specimens.

Table 1
Chemical composition of the cement used in the study.

Oxide	Composition, %
CaO	64.35
SiO_2	22.00
Al_2O_3	5.64
Fe_2O_3	3.80
K_2O	0.36
Na_2O	0.19
MgO	2.11

2.2. Concrete mixture

A typical normal concrete mixture was prepared with a cement content of 375 kg/m^3 and a water to cement ratio of 0.45 (by mass). The superplasticizer (SP) was used at a dosage of 0.4% by weight of cement to maintain a slump of 100 mm (±20 mm). Table 2 shows the weights of the constituent materials for preparing one cubic meter of concrete mixture.

2.3. Standardization of the initial strength of the concrete mixture

Since the preparation of concrete specimens for the accelerated carbonation curing (ACC) was done in batches, standardization of the initial strength of the concrete mixture was undertaken to ensure that the measured strength of the carbonation-cured concrete specimens at various pressures and durations would be compared to approximately the same initial strength grade concrete. In other words, the standardization process aimed at making sure that each batch of concrete mixture had almost the same initial compressive strength after demolding and before applying ACC, within a narrow range of deviation. The gross material properties of a highly heterogeneous material like concrete are significantly affected by variations in mixing and casting methods, even if the mixture proportions are same. This idea of standardization of initial strength of mixture eliminates the effect of significant differences in the initial strengths, which may be difficult to account for, from the overall response of the carbonation-cured concrete specimens. Consequently, the measured responses can be attributed only to variations in the two experimental parameters: carbonation pressures and exposure duration.

For standardization of the initial strength of the reference concrete mixture, three batches of the mixture were prepared, each with the same mixture proportions and aggregate type and gradation. In each batch, the exact mixing and casting procedures were adopted. Immediately after the mixing process, the mixture was cast in 50 mm cube molds. The exposed concrete top surfaces in molds were protected from evaporation with the aid of plastic sheets. After 18 h of post-casting curing in the mold in the laboratory condition at 23 ± 2 °C, the concrete specimens were demolded and tested immediately for initial compressive strength. A loading rate of 1 kN/s, corresponding to 0.4 MPa/s, was maintained for all

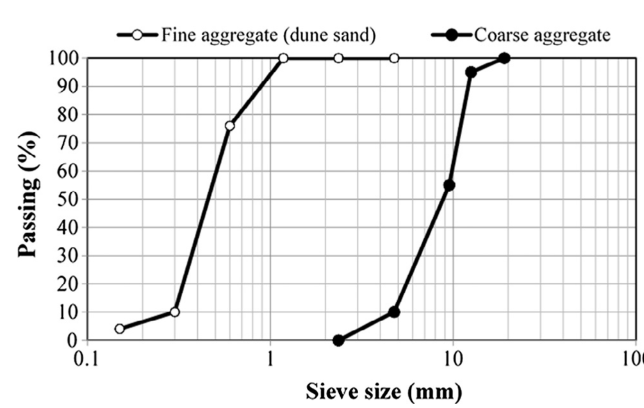

Fig. 1. Grading of fine and coarse aggregates.