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Durability of concrete pipes subjected to combined steam and carbonation curing

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ABSTRACT

A beneficial use of carbonation as an auxiliary curing regime for concrete pipes was studied in an attempt to reduce steam curing time, improve durability performance and explore the possibility of using concrete pipe to sequester carbon dioxide. Durability performance of the carbonated concretes was characterized by carbon uptake, strength gain, pH, calcium hydroxide content, permeability, sorptivity and sulfate and acid resistance. It was found that initial curing using steam is necessary to facilitate carbonation. Although the contribution of early carbonation to strength gain is not noticeable after initial steam curing, the process is unique in promoting enhanced durability performance of concrete. The early carbonation leads to a reduction in calcium hydroxide near the surface while maintaining a pH above the corrosion threshold value at the core. Carbonated concretes also exhibit improved resistance to sulfate attack, water absorption, and chloride ion penetration. A carbon uptake of 9% by cement mass makes concrete pipe an ideal candidate for carbon dioxide capture and storage.

1. Introduction

Concrete pipes have been widely utilized for managing storm water, sewage and drainage for more than a century. Deterioration of concrete pipes constitutes a serious problem to society. It has been reported that annual maintenance and repair costs of deteriorated concrete pipes in Canada in the early 1990s was approximately $2.5 billion dollars [1].

Concrete pipes are susceptible to chemical and biogenic attacks, as well as freeze–thaw, corrosion, and abrasion damage. The ingress of water-borne sulfate ions into concrete pipes from the surrounding environment can result in chemical degradation of the calcium hydroxide and alumina phases, which leads to deteriorative formation of ettringite and gypsum [2]. The source of acid attack in concrete pipes is usually biogenic sulfuric acid which can form in sewers and attack hydration products [3].

The primary methods for increasing durability of concrete pipes against such threats include: using low alumina cement, using only sulfate-free aggregates and additives, incorporating pozzolanic materials, decreasing water-to-cement (w/c) ratio and ensuring proper mixing and workmanship [4]. Low alumina cement and sulfate-free aggregates are two approaches to limiting the presence of reactants in the pore solution, thus enhancing sulfate resistance. Adding pozzolanic material such as fly ash helps sulfate resistance of concrete pipes by lowering the concentration of calcium hydroxide, which is vulnerable to sulfate attack, and improving transport properties. A lower w/c ratio in concrete mix design, coupled with proper compaction, also leads to improved transport properties, thus enhancing resistance to sulfate attack and freeze–thaw damage.

In addition, the durability performance of concrete pipes can be improved through controlled carbonation curing. The CO_2 captured at industrial point sources can be used as a carbonating agent. Since carbonation is basically a lime consuming process, carbonated concrete pipes so produced are expected to have enhanced durability due to an overall reduction in reactive lime.

Studies to date on the effect of carbonation on concrete can be categorized into two groups: carbonation of mature concrete and carbonation of fresh concrete. The former is a phenomenon in which well-developed hydration products react with atmospheric CO_2 through prolonged exposure, while in the latter case carbonation is intentionally applied to freshly cast concrete wherein CO_2 reacts with the anhydrous phases to form strength contributing hydrates and carbonates.

Carbonation of mature concrete, also referred to as weathering carbonation, and primarily resulting from long term exposure to atmospheric CO_2, has been extensively studied. It is generally accepted that carbonation of hardened concrete is detrimental to long term performance of concrete because of the associated reduction in pH of the pore solution, which can lead to the initiation of reinforcement corrosion, and paste shrinkage leading to cracking. The corresponding carbonation reactions are believed to occur according to Eqs. (1) and (2). Prolonged carbonation is considered to be responsible for neutralizing the pore solution and reducing its pH below the threshold value of about 10.5 in the vicinity of reinforcement, leading to the loss of the protective film on reinforcing steel and accelerated steel corrosion [5]. Long term

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carbonation of hydrated concrete is also found to cause shrinkage [6] and reduce the Ca/Si ratio in calcium silicate hydrates, manifesting in decalcification of the phase [7]. However, it has been observed that long term carbonation of hardened concrete at atmospheric pressure, from 1 week to 1 year, leads to a gain in compressive strength [8–12]. Carbonation of mature concrete can also result in improved performance by producing a more refined pore structure. The prolonged atmospheric carbonation of hydrated concrete has been observed to decrease sorptivity due to a reduction in surface capillary porosity through deposition of carbonates [13]. Water permeability of hydrated mortars subjected to long term exposure to CO_2 can also be decreased due to reduced porosity [14].

$$\mathrm{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O} \tag{1}$$

$$\mathrm{C{-}S{-}H + 2CO_2 \rightarrow SiO_2 + 2CaCO_3 + H_2O} \tag{2}$$

Carbonation of fresh concrete has also been studied [15–17]. Accelerated setting of cement paste and rapid strength gain are the primary advantages in employing carbonation curing at early age. The main anhydrous cement phases which can be carbonated are tricalcium silicate (C_3S) and dicalcium silicate (C_2S). These reactions take place according to Eqs. (3) and (4), where calcium silicate phases react with carbon dioxide in the presence of water, and produce calcium silicate hydrates (C_xSH_y) and chemically stable calcium carbonate instead of calcium hydroxide [17]:

$$\mathrm{C_3S} + (3-x)\mathrm{CO_2} + y\mathrm{H_2O} \rightarrow \mathrm{C}_x\mathrm{SH}_y + (3-x)\mathrm{CaCO_3} \tag{3}$$

$$\mathrm{C_2S} + (2-x)\mathrm{CO_2} + y\mathrm{H_2O} \rightarrow \mathrm{C}_x\mathrm{SH}_y + (2-x)\mathrm{CaCO_3} \tag{4}$$

According to Reactions (3) and (4), the carbonation of calcium silicate phases generates calcium silicate hydrates while producing no calcium hydroxide.

From Eqs. (1)–(4) it can be seen that carbonation of concrete at any age is a CO_2 uptake process. Carbon dioxide sequestration and material performance enhancement have been recently studied in an attempt to integrate an early carbonation process into precast concrete production to gain environmental, technical and economic benefits [18].

This paper describes an investigation into the durability of concrete pipes subject to combined steam and carbonation curing. The proposed carbonation treatment occurs within 24 h after the concrete is cast and is thus considered to be early age carbonation. In this treatment, steam is utilized to accelerate the initial curing and carbonation to improve the durability of the concrete. It was reported that a 4-h steam curing period produced a hydration degree of C_3S of only 30% [19]. Therefore, the phases available for carbonation, after the initial steam curing, can be both anhydrous calcium silicates and hydration products. Since the treatment is applied at early age, the subsequent hydration still plays a critical role in the overall performance of the concrete. Intentional carbonation of hardened concrete has also been investigated on concrete blocks after steam curing to improve the block resistance to atmospheric carbonation shrinkage [20]. This research examines the effect of early carbonation on long term performance of concrete through calcium hydroxide formation, pH value, sorptivity, permeability, sulfate resistance and acid resistance.

2. Experimental procedure

2.1. Casting and curing

In the laboratory investigation, concrete pipes were simulated by slab samples with dimensions of 40 mm thick, 76 mm height and 127 mm wide. The mixtures were proportioned using ordinary Portland cement (CSA Type GU) at 286 kg/m^3, coarse aggregates 730 kg/m^3, fine aggregates 1050 kg/m^3 and water 100 kg/m^3. Both coarse and fine aggregates were crushed granite with a coarse to fine ratio of 0.7. The coarse aggregates had a maximum aggregate size of 12 mm and the fine aggregates had a fineness modulus of 4.1. The water to cement ratio was 0.35. No admixtures were used. The concretes were dry mix concrete with zero slump. Slab samples were formed by vibration casting following the procedure for commercial production of 40-mm thick concrete pipes.

Table 1
Curing scheme of concrete samples.

Batch	Initial curing		Subsequent curing	No. of samples	Test age
1	4S	4 h steam	Sealed air curing	9	4 h/28d/90d
2	4S	4 h steam	Water curing	3	90d
3	2S + 2C	2 h steam + 2 h carbonation	Sealed air curing	9	4 h/28d/90d
4	2S + 2C	2 h steam + 2 h carbonation	Water curing	3	90d
5	2S + 2A	2 h steam + 2 h sealed air	–	3	4 h
6	4C	4 h carbonation	–	3	4 h
7	2S	2 h steam	–	3	2 h

Table 1 shows the curing schemes that were applied to the concrete after vibration compact forming and upon removal of forms. Batches 1 and 2 were subject to the same initial 4-h steam curing, which was followed by either air or water subsequent curing. They acted as reference specimens for Batches 3 and 4, in which 2-h steam curing was followed by 2-h carbonation. Batch 5 was again a reference for Batches 3 and 4 to compare the 2-h carbonation period with 2-h air curing. 4-h carbonation without steam was also performed immediately after demoulding (Batch 6). This was to examine whether steam could be totally replaced by carbonation at early age. Batch 7 underwent 2-h steam curing representing the starting material for the carbonation process. In steam curing, the temperature was raised at a rate of 40 °C/h up to 63 °C. After steam at designated time, the temperature was dropped by slow cooling in steam chamber. For combined steam and carbonation (Batches 3 and 4), the 2-h steamed samples were transferred to the carbonation chamber immediately after steam for 2-h carbonation curing. The carbonation setup is shown in Fig. 1, wherein CO_2 of 99.5% purity, simulating the recovered CO_2 from industrial point sources, was injected into a sealed chamber and the interior pressure was regulated at a constant of 1.5 bar so that the consumed CO_2 could be replenished. Using a digital balance, the mass gain due to CO_2 uptake was recorded throughout the carbonation process. Subsequent curing took place either in a sealed bag or in water until 28 days and 90 days to investigate the effect of early carbonation on later strength.

2.2. CO_2 uptake

The degree of CO_2 uptake was measured using two different methods, the mass curve method and the mass gain method, and reported as the ratio of the bound CO_2 to cement content. In the mass curve method, the mass the of entire chamber containing the samples was recorded as a function of time and was corrected by a calibrated CO_2 mass at 1.5 bar with nonreactive dummy samples of the same volume. The generated mass curve represents reaction kinetics. The mass gain method calculates CO_2 uptake using Eq. (5) by measuring the mass of the samples before and after carbonation. Evaporated water from the exothermic carbonation reaction was collected by absorbent paper and added to the final mass. These two methods are totally independent and can be used to verify consistency.

$$Mass\ gain(\%) = \frac{(Mass_{aftercarbonation} + Water_{lost}) - Mass_{beforecarbonation}}{Mass_{cement}} \tag{5}$$

2.3. Compressive strength testing

To investigate the contribution of the carbonation treatment on strength gain, compression tests were conducted on samples with a cross-section of 127 mm × 40 mm and compressive strengths were calculated at 4-h, 28-day and 90-day ages.

2.4. pH measurement

In the carbonated samples, pH of the pore solution was measured in successive layers 5 mm thick to examine the effect of carbonation treatment on pH value distribution with respect to depth from surface. Since calcium hydroxide is the major hydroxyl ion supplier in the pore solution, a pH drop in the carbonated zone of the concrete is likely to occur. Meanwhile, the pH measurement could make it possible to correlate between the carbonation induced consumption of the CH and the pH of pore solution in different ages and at various depths. The pH measurements were carried out on 5 mm thick slices which were also used in XRD phase analysis.