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Influence of loading and cracks on carbonation of RC elements made of different concrete types

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HIGHLIGHTS

- Carbonation of loaded and unloaded PC, FA and GGBS concretes was experimentally studied.
- Both compressive and tensile stresses had major influence on concrete carbonation.
- Loading had much larger effect on carbonation of FA and GGBS concretes.
- Casting position, cracking and stirrups affected carbonation.

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ABSTRACT

Accurate prediction of concrete carbonation is important for the correct assessment of both durability and environmental impact of reinforced concrete (RC) structures. Loading applied to a RC structure and concrete cracking caused by this loading may significantly affect the concrete carbonation process. However, so far these factors have received little attention of researchers, especially this concerns 'green' concretes, i.e. concretes in which Portland cement (PC) is partially replaced by supplementary cementitious materials such as fly ash (FA) and ground granulated blast-furnace slag (GGBS). Thus, the aim of the study presented in the paper was to experimentally investigate the influence of static loading and associated concrete cracking on carbonation of RC elements made of PC concretes and 'green' concretes containing significant amounts FA and GGBS. For this purpose, six concrete mixes with two water/binder (w/b) ratios (0.40 and 0.55) and different proportions of PC, FA and GGBS were prepared. The mixes were used to cast twelve RC beams (100 × 120 × 900-mm) and a larger number of 100-mm concrete cubes. The beam specimens were loaded in four-point bending to produce flexural cracks of maximum width of either 0.1 mm or 0.3 mm. The loaded beam specimens along with unloaded cube specimens were then placed into a carbonation chamber and subject to accelerated carbonation for 120 days. After that the carbonation depths in the beams and cubes were measured. Results of the tests show a significant effect of load induced stresses (both tensile and compressive) on the carbonation resistance of the concretes, especially of 'green' concretes. The influence of cracking on concrete carbonation was also observed and discussed in the paper.

1. Introduction

Climate change is one of the key challenges facing the human race in the 21st century. This phenomenon is primarily attributed to anthropogenic emissions of greenhouse gases, most notably carbon dioxide (CO_2). One of major global contributors to the anthropogenic CO_2 emissions is the concrete industry, which contributes 5% to those, mainly from a calcination reaction involved in the Portland cement production [1]. CO_2 emissions associated with the concrete industry can be reduced by decreasing the amount of Portland cement used in concrete. This is usually achieved by replacing Portland cement (PC) with supplementary cementitious materials (SCM), mostly industrial by-products such as fly ash (FA), ground granulated blast-furnace slag (GGBS) and silica fume (e.g. [2]) or fillers such as limestone. Concretes containing such materials are often referred to as 'green' concretes [3]. A number

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of studies comparing the environmental impact of traditional and 'green' concretes have been published (e.g. [4,5]).

After a concrete structure has been constructed, the cement paste in the structure becomes exposed to carbon dioxide present in the atmosphere and a carbonation process takes place. During this process, CO_2 diffuses through air-filled pores in the concrete and reacts with the alkaline cement hydration products, in particular with calcium hydroxide, $Ca(OH)_2$. On one hand, carbonation has a positive environmental effect because CO_2 reabsorbed in this process partially offsets its emission during calcination [6]. On the other hand, the reaction between CO_2 and $Ca(OH)_2$ reduces the alkalinity of the concrete pore solution and can lead to corrosion of reinforcing steel when the carbonation front reaches the steel (e.g. [7]). This effect of carbonation on the durability of RC structures instigated research of this phenomenon, including experimental studies (e.g. [8–11]), field measurements (e.g. [12–15]) and modelling (e.g. [16–20]). In particular, it has been observed that 'green' concretes, in which PC is partially replaced by SCM, can have lower resistance to carbonation than traditional ones (e.g. [10,21–23]). More recently, the positive effect of carbonation on the CO_2 balance of the concrete industry has also attracted attention of researchers (e.g. [24–26]).

Since natural carbonation (i.e. carbonation under actual atmospheric conditions at which the CO_2 concentration is about 0.04%) is a very slow process, in order to obtain meaningful experimental results within a reasonable time accelerated carbonation tests with increased CO_2 concentrations are usually performed. The range of the CO_2 concentration used in such tests has varied between 1% and 100%, while in most of the tests it has been between 3% and 10% [26]. Since an increase in the CO_2 concentration can affect chemical reactions and transport mechanisms involved in carbonation there has been an extensive discussion about the validity of the accelerated tests (e.g. [9,11,27,28]). Although full consensus has not been reached, it has been recommended to keep the partial pressure of CO_2 between 3% and 5%, in order to obtain results similar to natural conditions; in particular, this has been shown for 'green' concretes containing fly ash and blast furnace slag [22,23]. Among the factors that affect the rate of carbonation, loading and associated cracking have received limited attention and the research has been mainly restricted to PC concretes and effects of tensile stresses caused by static and cyclic loading [29–31]. These studies have demonstrated that tensile stresses/strains have a major effect on carbonation of the elements, i.e. the carbonation rate noticeably increased depending on the stress/strain level [29,31]. It has also been shown that CO_2 can freely diffuse through cracks with width $\geq 60\ \mu m$ so that the carbonation depth perpendicular to the crack wall was similar to that at the concrete surface; the diffusion slowed down for smaller crack widths and there was no carbonation penetration perpendicular to the crack wall for crack widths $\leq 9\ \mu m$ [30]. It is worth to note that the CO_2 concentration used in this study was 50%.

Thus, the aim of the study described in this paper was to experimentally investigate the influence of static loading and associated cracking on the carbonation performance of RC elements made of PC concretes and 'green' concretes containing FA and GGBS. For this purpose, six concrete mixes with two water/binder (w/b) ratios (0.40 and 0.55) and different proportions of PC, FA and GGBS were prepared. The mixes were used to cast twelve RC beams (100 × 120 × 900-mm) and 100-mm concrete cubes. The beam specimens were then loaded in four-point bending to produce flexural cracks of different widths. After that both RC beam specimens (loaded) and concrete cubes (unloaded) were transferred to a carbonation chamber. The specimens were subject to accelerated carbonation for 120 days and then the carbonation depths were measured. In the following, the experiments will be described in more detail and their results presented and discussed. Special attention will be paid to effects on carbonation of both tensile and compressive stresses, concrete cracking and casting position.

2. Experimental programme

2.1. Materials

Six concrete mixes were used in this experimental study. All mixes included PC (CEM I 52.5 N), in two of them this cement was partially replaced by FA (30%) and in other two by GGBS (50%). The replacement values are typical for 'green' concretes. The aggregates in all mixes were Cambusmore sand and 10-mm gravel. Half of the mixes had the w/b ratio of 0.55 and the other half of 0.40; a plasticizer was added to the mixes with the lower w/b ratio. Table 1 shows the mix constituent proportions per cubic metre of concrete and was provided by the precaster, who produced the test specimens prior to transferring them to the laboratory. 8 mm and 10 mm reinforcing bars used in the specimens had yield strength of 500 MPa.

2.2. Test specimens

Twelve RC beams with a rectangular cross section of 100 × 120 mm and length 900 mm were cast. The beams were reinforced in the longitudinal direction with two 10-mm diameter deformed bars at the bottom (tensile reinforcement) and two 8-mm diameter bars at the top (compression reinforcement), and in the transverse direction with stirrups made of 8-mm diameter bars. The concrete cover of the longitudinal tensile bars was to be 25 mm. The spacing between the stirrups was 46 mm near the beam ends and 105 mm closer to the midspan, while the central 200-mm long part of the beams was without shear reinforcement. Two vertical (i.e. along the beam depth) 18-mm diameter holes at 100 mm from the beam ends (so that the distance between the holes was 700 mm) were made in each beam in order to create later a four-point bending system. Fig. 1 shows the beam dimensions and reinforcement details. The beams were cast horizontally in wood moulds. In addition to the beams, seven 100-mm cubes were cast from each mix to determine the compressive strength and porosity of concretes made of the mixes and also the carbonation rate of unloaded specimens. All specimens were standard cured for 28 days.

As noted previously, the specimens were fabricated by a precaster. Thus, compared to the fabrication of specimens in a laboratory, the composition and quality of the specimens were not fully controlled by the researchers. However, the tests were probably more realistic since the specimens were more representative of typical RC elements produced by the industry.

2.3. Preconditioning of the specimens

All specimens (i.e. both beams and cubes) intended for accelerated carbonation were kept for 3 months under ambient conditions (i.e. temperature and RH) similar to those in the carbonation chamber. The beam specimens were then quasi-statically loaded in four-point bending using a universal testing machine, as shown in Fig. 2. In accordance to the beam dimensions (Fig. 1), the distance between two supporting pins was 700 mm (i.e. they were placed at the location of the holes) and the distance between two loading pins 200 mm. The level of the applied load was controlled to ensure that the maximum width of cracks in the tensile zone of the beams due to bending was either 0.1 mm or 0.3 mm. The load required to induce 0.1-mm wide cracks was about two-thirds of that used to induce 0.3-mm wide cracks. At the same time, three concrete cubes from each mix were tested to determine the compressive strength of the concretes. After the