Carbonation of concrete with mineral additions

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ABSTRACT
This study investigated how mineral addition, fly ash and slag (GGBS), influences carbonation, and how carbonation affects chloride migration and transport properties in mortar. Accelerated carbonation, Rapid Chloride Migration (RCM), capillary absorption tests (NT Build 368) and compressive strength tests (SS-EN 196-1) were conducted in a comparative study of mortar mixtures with different levels of mineral addition and *w*/*b* ratios. Carbonation rate increased and compressive strength was reduced with increased amount of mineral addition. The results also showed an interdependence between different deteriorating processes. Carbonation reduced the porosity, rate of reaching saturation and connectivity of the pore structure.

Key words: Carbonation, Supplementary Cementitious Materials (SCM), Testing.

1. INTRODUCTION

Porosity affects the rate of deterioration, by influencing the diffusion of CO_2 during carbonation and the ingress of chlorides. Generally, reduced total porosity leads to less connectivity between the capillary pores, which decrease permeability and penetration of chlorides and the rate of CO_2-diffusion. From a durability point of view, there is a critical value of capillary porosity around 25%, above which the permeability increases significantly. The increase in permeability consequently increases capillary absorption, through which water containing chlorides and CO_2 can penetrate. Both the capillary porosity and the pore size decrease by decreased *w*/*b* ratio and increased degree of hydration. According to Nagala & Page [1] carbonation reduces the total porosity, in both PC concrete and concrete with mineral additions, but with a redistribution of the pore size, showing a slight increase of the proportion of large capillary pores (diameters above 30 nm) in PC concretes and a significant increase in blended concretes. This effect is caused by the reduction of hydration products, e.g. calcium hydroxide, as a result of the larger volume in the formation of $CaCO_3$ (Dyer 2014). A study carried out by Wu & Ye [2] did however show that cement pastes containing high levels of mineral additions increases porosity. This is explained by an increase in porosity when C-S-H is carbonated, while carbonation of $Ca(OH)_2$ decreases porosity. As mineral additions contain less $Ca(OH)_2$ compared to Portland cement, which explains differences in porosity-change after carbonation between concretes with high and low amount of mineral addition. This paper presents the result from a master thesis [3] where the relative carbonation resistance of different binders (CEM I, fly ash and GGBS) was investigated and how carbonation effect transport properties, capillary absorption and chloride migration. The results for chloride migration is presented in [3].

2. EXPERIMENTAL PROGRAMME

The test program is based on the test matrix presented in Table 1 showing the *w/b* ratios, type of cement and amount of mineral addition. All tests were carried out on mortar specimens mixed with sea sand from Denmark, sieved to sieve-size < 2 mm.

Table 1. Investigated binder mixes (GGBS and Fly ash amount of total binder content).

Cement	GGBS / Fly ash	*w/b*
CEM I 42.5 N SR 3 MH/LA	0 %	0.40, 0.50, 0.60
CEM I 52.5 N	0 %	0.40, 0.50, 0.60
CEM I 52.5 N	20 % & 35 % FA	0.40, 0.50, 0.60
CEM I 52.5 N	35 %, 50 % & 65 % GGBS	0.40, 0.50, 0.60

For all the investigated binder mixes in Table 1, the compressive strength and the carbonation depth and rate were determined. For the carbonation tests the specimens were water cured for 7 days and then stored at 65 % RH (20°C) until 28 days age, where after they were placed in a CO_2-chamber with 2.0 % CO_2 and 65 % RH (20°C) and exposed for 7 weeks. Prior to CO_2 exposure, two side faces of the prisms (top and bottom) were coated to prevent carbonation. For the mixes with *w/b* 0.50 capillary absorption tests (NT Build 368) [4] and Rapid Chloride Migration tests (NT Build 492) [5] were conducted on un-carbonated and partially carbonated specimens (due to time limitations). Hence, the carbonated specimens were not homogenous in this respect which needs to be considered when comparing the results.

3. RESULTS AND DISCUSSION

In Figure 1 the carbonation rate (calculated from 2.0% to 0.04% CO_2) has been plotted against the compressive strength for all binder mixes. What can be seen from Figure 1 is that at lower amounts (20 % FA and 35 % GGBS) the effect on compressive strength and carbonation rate is not that large, but at higher dosage rates the effect is more substantial and that the effect of 35 % fly ash corresponds to 50 % GGBS.

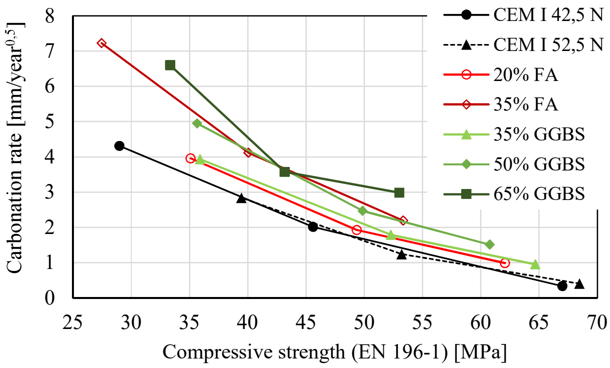


Figure 1. Carbonation rate (calculated to a CO_2 concentration of 0.04 %) versus compressive strength.

In Table 2 the calculated k-values based on compressive strength and on carbonation rate is presented, the calculation is based on the principle introduced by Smith [6]. The calculated *k*-values for strength is higher than for those based on carbonation. With respect to carbonation, all mixes except the one with 35 % fly ash have a *k*-value higher than the prescribed value in EN 206 [7]. It should be noted that the accelerated testing on the mixes with higher amounts of fly ash and slag are more negatively affected by an accelerated carbonation test due to the slower and lower degree of hydration when starting the test compared to a natural exposure.

Table 2. Calculated k-values based on strength and carbonation resistance.

Mix	*k*-value strength	*k*-value carbonation	Prescribed *k*-value (EN 206)
20 % Fly ash	0.73	0.58	0.4
35 % Fly ash i)	0.55	0.25	(0.4)
35 % GGBS	0.96	0.81	0.6
50 % GGBS	0.92	0.75	0.6
65 % GGBS ii)	0.81	0.65	(0.6)

i) In EN 206 the maximum amount of fly ash to be taken into account is 25 % (fly ash/cement ≤ 0.33).
ii) In EN 206 the maximum amount of GGBS to be taken into account is 50 % (GGBS/cement ≤ 1.0)

In Figure 3 the results from the capillary absorption tests are presented, please not that these tests were conducted on un-carbonated and partially carbonated specimens (due to time limitations). The capillary absorption coefficient k_{cap} (or inverse of this, $1/k$) is shown in Figure 3(a) and in Figure 3(b) the capillary absorption resistance m_{cap} is presented. The coefficients are determined as:

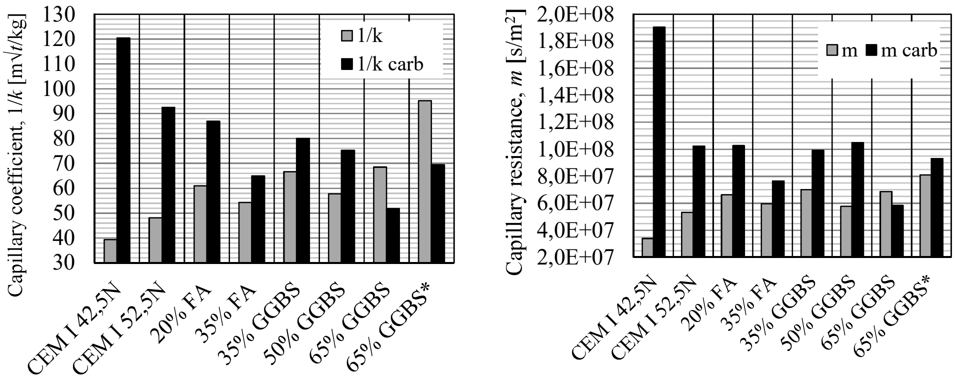
$$k_{cap} = \frac{Q_{cap}}{\sqrt{t_{cap}}} \quad [\mathrm{kg/(m^2\sqrt{s})}] \tag{1}$$

where Q_{cap} is the absorbed water (kg/m^2) and t_{cap} is the time to completion of capillary absorption (s).

$$m_{cap} = \frac{t_{cap}}{h^2} \quad [\mathrm{s/m^2}] \tag{2}$$

where h is the thickness of the specimen (m).

As can be seen in Figure 2, carbonation leads to a decreased capillary absorption coefficient ($1/k_{cap}$ increases) and increased capillary absorption resistance (m_{cap} increases), the only exception is the mix with 65 % GGBS. The effect is more significant for the specimens with CEM I, and in particular the CEM I 42.5 N SR3 MH/LA). These changes, decreased k_{cap} and increased m_{cap}, indicate that the porosity is reduced as a result of carbonation. It was also found that all the carbonated mortars showed a reduction in total open porosity, see [3]. Fly ash mortars showed the greatest decrease in total open porosity, with increasing porosity-reduction by increasing amount of mineral addition. GGBS mortars, on the other hand, showed a peak in porosity-reduction at 50% GGBS.



(a) *(b)*

Figure 2. Effect of carbonation on (a) the inverse capillary coefficient (1/k) and (b) the capillary resistance. For 65% GGBS the fineness was increased from Blaine 420 m^2/kg to 520 m^2/kg.*

4. CONCLUSIONS

Based on the result of this study, the following conclusions can be made:

- In the accelerated carbonation tests (2.0 % CO_2) the carbonation rate increased with mineral additions. But at moderate amounts (up to 20 % fly ash and 50 % GGBS) the effect was moderate and when comparing with the mixes made of CEM I 42.5 N SR MH/LA the carbonation rate was only slightly higher.
- The calculated *k*-values based on compressive strength was higher when based on carbonation. The calculated *k*-values were however higher than the ones prescribed in EN 206 [7], the only exception being the *k*-value for carbonation for the mix with 35 % fly ash.
- The capillary absorption tests on carbonated and un-carbonated specimens showed that the porosity was reduced by carbonation, with the exception of the mix with 65 % GGBS.

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