THE EFFECTS OF CARBONATION ON BLENDED CEMENT CONCRETES

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ABSTRACT
This paper reports on the results of a study undertaken to assess the carbonation of blended concretes exposed to a range of micro-climate variations in inland environments, particularly with variations in carbon dioxide content, temperature and relative humidity conditions. Concretes samples were prepared using five binder types representing variations of blends with GGBS, FA and CSF and four w/b ratios ranging from 0.4 to 0.75 and subjected to different degrees of initial water curing. These samples were placed in three exposure conditions: indoors in laboratory air, outdoors sheltered from rain and sun and outdoors fully exposed to the elements. The depths of carbonation of these samples were monitored over a period of 24 months in order to determine the rates of carbonation. Findings suggest that the rate of concrete carbonation may be usefully applied as performance specifications where durability of reinforced concrete structures must be guaranteed.
Keywords: Durability, Supplementary cementing materials (SCM), Blended Concretes, Reinforced concrete structures.

INTRODUCTION
The combined use of concrete and steel reinforcement became common practice from the beginning of the twentieth century and led to a widespread use of reinforced concrete in the construction of structures throughout the world [1]. As concrete in itself, from the time of the Romans, had shown a good performance even under aggressive environmental conditions, it was initially assumed that reinforced concrete could also be considered as an intrinsically durable construction material [1, 11]. However, especially from the second half of the twentieth century, deterioration of reinforced concrete structures became a major problem and structural engineers, asset managers as well as material scientists had to focus on the durability performance and service life of reinforced concrete structures. It appeared that very often durability performance of reinforced concrete structures was limited by the corrosion of the steel reinforcement [1, 2, 3, 4].

Background
Durability performance and service life of reinforced concrete structures situated in the inland environment is often principally affected by the ingress of carbon dioxide. When atmospheric air penetrates reinforced or unreinforced concrete, carbon dioxide in the air dissolves in the pore water of the concrete to form carbonic acid which then chemically reacts with alkalis (hydroxide) in the cement paste that are produced from the hydration reaction of cement to form carbonate with the release of water. This reaction is commonly referred to as "carbonation" and it moves as a "front" into the concrete [5, 6]. The carbonation front advances beyond a particular point when all the carbonatable materials at that point have been converted to carbonates. Thus, the rate of movement of the carbonation front depends on the concrete characteristics as well as the environmental exposure condition and this follows a square-root of time law [3]. The water released during the carbonation reaction makes the carbonation process self-sustaining but it is limited by

the increasing difficulty of the carbon dioxide to penetrate the depth of the concrete [7]. This is because the carbonates produced are deposited in the concrete pores, reducing the permeability by decreasing the pore size and the degree of interconnection between the pores. In addition, carbon dioxide can only move beyond a particular point after all the carbonatable materials at that point have been consumed in the carbonation reaction.

In unreinforced concrete, carbonation has beneficial implications for both strength and durability by the reduction of concrete pore volume and permeability [6]. However, in reinforced concrete, carbonation has an important effect in initiating the corrosion of reinforcing steel, therefore reducing the durability performance and service life of reinforced concrete structures. The carbonation reaction process reduces the pH of the concrete pore water from above 14 to below 8.5 upon complete carbonation. When this process reaches the reinforcing steel level, the reduced pH causes the passive gamma-ferric oxide layer on the steel to become unstable and the steel is depassivated. Gamma ferric oxide is a thin film of γFe_2O_3 that forms on the surface of steel under an alkaline environment [8]. If sufficient oxygen and moisture is available, the steel will start corroding with subsequent loss in cross sectional area and bonding with the concrete. Hence, serviceability and load bearing capacity of the reinforced concrete member/element or structure will decrease.

Experimental Procedure
The cements used conform to SABS EN 197-1, type CEM I class 52.5 and CEM V class 32.5 [9]. The GGBS, FA and SF conform to SABS 1491 Parts 1, 2 and 3 [10], respectively. The oxide contents of the binder materials can be found in associated articles [11, 12]. The range of replacement levels by each of the three supplementary materials used, together with the concrete mixture proportions are also given in these articles. The carbonation test was carried out on concrete samples at three different curing ages (3, 7 and 28). The test was initiated at 6, 12, 18 and 24months of age after exposure to the natural exposure conditions. The samples taken from the curing chamber after 2, 6 and 27 days of moist curing were preconditioned in the laboratory room at 20 ± 5°C temperature and 60 ± 5% RH for 14 days. Within this period, four of the faces of the concrete cubes were coated with a water based epoxy on four surfaces including the top and the bottom faces of the concrete as cast, thus allowing carbonation to occur from two opposite faces. After 6, 12, 18 and 24 months on the exposure sites, two cubes each from the different concrete mixture and curing regime were tested for carbonation depth. About 33 mm thick slices were broken-off from the concrete cubes, perpendicular to the exposed faces. The freshly broken face was cleaned by brushing and sprayed with a phenolphthalein pH indicator. The average carbonation depth was measured normal to the exposed surface in accordance with RILEM specification [13]. In the non-carbonated part of the sample where the concrete is still highly alkaline, purple-red coloration is obtained, while in the carbonated part of the sample where the alkalinity is reduced no coloration occurs. The measured carbonation depth results from the carbonation tests on concrete samples exposed to the natural environments are given in associated articles [11, 12]. Each value shown represents the averages of six individual carbonation depth measurements on the two opposite side faces of the concrete cube samples.

RESULTS AND DISCUSSION

The carbonation depth results of the concrete samples exhibit a fairly wide scatter, not only because concrete itself is a variable material, but also due to the variable processing factors and randomness of the micro-climatic conditions. From the carbonation depth results of the concretes observed in these studies and for any given exposure condition investigated, the factors that influence the variability of the depth of carbonation of the concretes are the w/b ratio, binder types and contents, as well as the initial extent of moist curing of the concrete. Variability in the carbonation depth of the concretes across exposure conditions (sites) seems to be influenced also by the environmental conditions surrounding the concretes. The results of the carbonation depths of the concrete presented on these articles [11, 12] are plotted against their respective square root of exposure period. From the plots of carbonation coefficients versus w/b ratios presented in Figures 1 - 3 for the indoor, outdoor sheltered, and outdoor exposed exposures respectively, it is evident that the carbonation rate of the concretes followed similar pattern for the different exposure conditions investigated. Hence, a general explanation will be given for the trends observed in the concrete carbonation resistance results. The trends observed were distinctly influenced by the w/b ratio, SCM used and initial moist curing conditions of the concrete. Similarly, the rate of carbonation of the concretes also varies across the different exposure conditions, influenced by the micro-climates of the exposure conditions (see Figure 4). Thus, variations of the carbonation rates for the concretes will be explained in relation to each of these influencing factors.
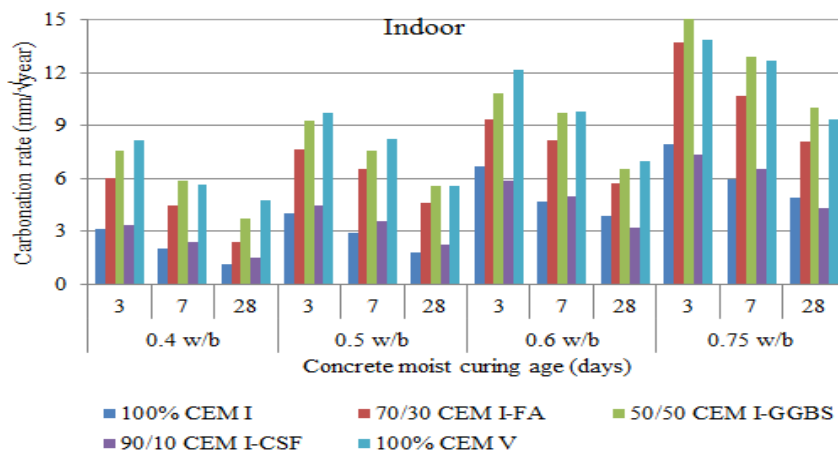

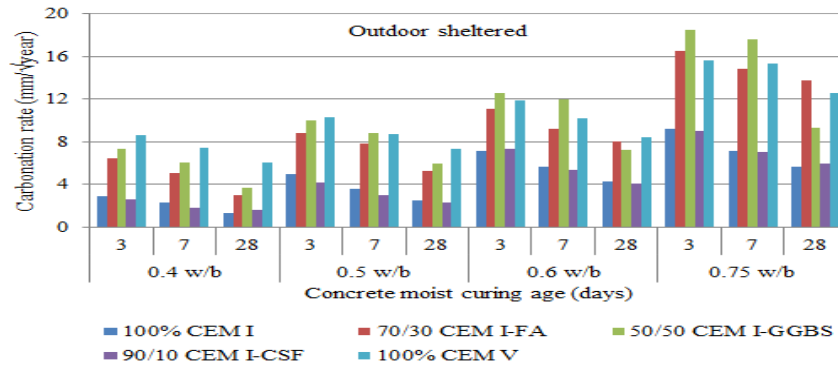Figure 1: Carbonation rate vs. Concrete age for all the concrete types exposed indoors

Figure 2: Carbonation rate vs. Concrete age for all the concrete types exposed outdoor sheltered
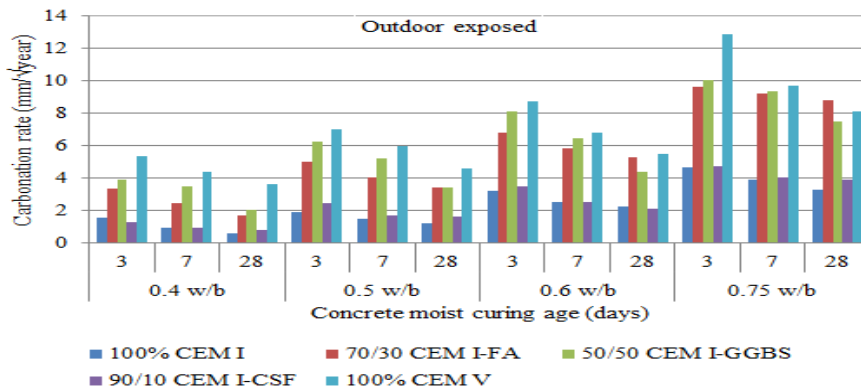

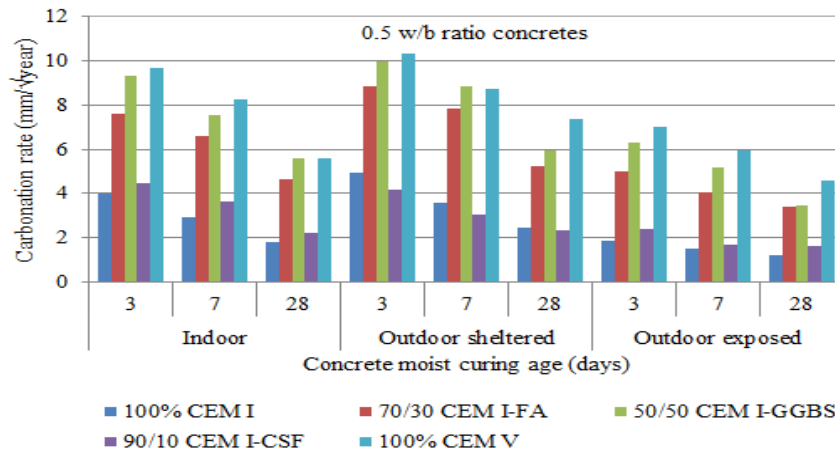Figure 3: Carbonation rate vs. Concrete age for all the concrete types exposed outdoors

Figure 4: Carbonation rate vs. Exposure conditions for all the 0.5 w/b ratio concretes exposed to natural conditions

Effect of w/b ratio on Carbonation Rate of Concrete

From the carbonation rate plots for all the concrete types (see Figures 1-3), it can be noted that the carbonation rate increases with an increase in w/b ratio irrespective of the concretes' initial moist curing periods and binder types [11, 12]. It is also evident that the effect of w/b ratio is more significant than the moist curing duration effect as the carbonation rates increases significantly as w/b ratio varies. This is attributed to increased pore connectivity of the concrete since w/b ratio primarily determines the gel/space ratio, the capillary porosity and thus the permeability of the concrete. Concretes of lower w/b ratio had better resistance against the diffusion of CO_2, possibly due to the denser pore structure and higher $Ca(OH)_2$ content. Similar findings in relation to the effect of w/b ratio on carbonation have also been reported in the literature [14, 15]. The decrease in the carbonation rates of the concretes at lower w/b ratio can be attributed to the fact that the cumulative pore volume and the amount of pores are lower compared to a higher w/b ratio concrete. This fact was also evident from the permeation test results of the concretes [11]. Hence, the lower w/b ratio concretes, either blended or unblended showed superior resistance against carbonation.

Effect of SCM on Carbonation Rate of Concrete

The effects of SCM on the carbonation rate of concretes can be found in the associated articles[11, 12] for the different exposure conditions investigated (see also Figures 1 - 3). At all w/b ratios for the different exposure conditions, SCM blended concretes presented higher carbonation rates irrespective of the initial moist curing period and w/b ratio. However, the CSF blended concretes are an exception. This observation is consistent with the trend noted by other researchers [16, 17, 18]. Although the pore structure of blended concretes is denser as a result of the finer particle size and filler effects of SCM[11], the carbonation rates of blended concretes are higher. This suggests that pore structure is not the only parameter that controls the rate of carbonation in concretes, but also the amount of $Ca(OH)_2$ present within the hydrated cement paste of the concretes [11]. The presence of $Ca(OH)_2$ in concrete results from the hydration reaction of C_2S and C_3S, which are the main components of cement. In the presence of SCM, the amount of $Ca(OH)_2$ available to react with CO_2 is lower, for two reasons; firstly, less CaO is added to the concretes and secondly, some of the $Ca(OH)_2$ produced reacts with the SCM present.

Effect of initial water curing period of the concrete on its carbonation rate

The effects of the initial water curing duration of the concrete on its carbonation rates can also be observed [11, 12], (see also Figures 1 – 4). It can be noted from the figures that a longer initial moist curing duration generally resulted in a lower carbonation rate. This is attributed to the fact that as curing increases hydration in concrete, the pore spaces in concrete reduces, particularly in the near surface zone. Additionally, curing influences the chemical properties of the concrete, for instance in unblended concrete it increase the $Ca(OH)_2$ content of the concrete thereby improving its buffering effect against CO_2. Curing, however reduces the $Ca(OH)_2$ content in blended concretes but improves the concrete microstructure. For example, in plain concretes, the carbonation rate decreased significantly with curing age within the first seven days [11]. In the case of concrete

containing SCM, the carbonation rate continued to decrease even after 7 days of curing again pointing to the later hydration effect of these SCM.

Effect of Natural Exposure condition on Carbonation Rate of Concrete

The influence of the different natural exposure conditions investigated on the rate of concrete carbonation is also shown on the associated articles [11, 12](see Figure 4). From the figure, concrete cube samples exposed to the outdoor sheltered conditions presented the highest carbonation rate while the lowest carbonation rates were observed in the concrete cube samples at the outdoor exposed site. The wetting and drying period experienced by samples on the exposed site is probably the reason for the reduced carbonation rate, since both the outdoor sheltered and unsheltered exposure conditions have similar micro-climates in terms of CO_2 content, RH and temperature as noted in the article [11]. In addition, concrete cube samples exposed outdoor to rain and sun have higher internal humidity during the summer months from precipitation effects, thus reducing CO_2 ingress during this period. Furthermore, these concretes had improved pore structures from rapid hydration effects as a result of its high internal moisture content during the summer months. The micro-climate factors known to influence the carbonation rate of concretes are the CO_2 concentration, RH and temperature with the most important being RH. The RH surrounding the concrete influences the concretes internal humidity which then affects the ingress of CO_2. For instance, Ananmaley [16] noted an insignificant effect on concrete carbonation rate for specimen with compressive strength less than or equal to 40 MPa when the CO_2 concentrations were varied between 7% and 18%. While for concretes with strength higher than 40 MPa, variation of a greater order of magnitude in CO_2 concentration may be required to show any significant effect on the carbonation rate. The rate of carbonation in concrete is also weakly sensitive to temperature within the range 20-40 °C[19, 20]. A similar observation regarding the insensitivity of temperature to the rate of carbonation in concrete was also noted by Loo et al.in the work [20].

OBSERVATIONS AND CONCLUSIONS

1. For concrete prepared at the same workability and compressive strength there is no significant difference between the rate of carbonation between plain and blended cement concrete because the increased tendency to carbonate by blended concrete because of the low carbonatable material is offset by it increased permeability.

2. Increasing the duration of moist curing and reducing the amount of addition of supplementary cementing materials has a significant effect on decreasing the rate of carbonation in concrete.

3. Concrete samples in the outdoor exposed sites presented lower rate of carbonation compared to the sheltered sites but higher than for the indoor sites. Although samples in this exposure site presented moderate carbonation, the risk of reinforcement corrosion is likely to be high compared to the other two sites. This is as a result of the higher relative humidity and the cyclic wetting during rain period.

Acknowledgement

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