CARBONATION OF FLY ASH AND GGBS CONCRETE

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ABSTRACT. This study presents the carbonation resistance of concrete made with fly ash (FA) and ground granulated blast furnace slag (GGBS), based on global data-matrix with 65000 entries, built from 440 studies, originating from 41 countries published since 1968, using analytical systemisation method. The carbonation of concrete increases at an increasing rate as FA and GGBS content increases. The effect is greater for concrete designed on an equal water/cement ratio to Portland cement concrete than that on an equal strength basis. Other influencing factors such as fineness of the materials and curing are discussed. The carbonation depth of concrete made with FA and GGBS is likely to exceed the specified cover in the Eurocode 2 specification. Measures to minimise the carbonation effect of these materials are also discussed.

Keywords: Fly ash, Ground granulated blast furnace slag, Carbonation, Structural concrete

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INTRODUCTION

With an increase awareness of sustainability in the construction industry, the use of pozolanic materials such as fly ash (FA) and ground granulated blast furnace slag (GGBS) as a replacement for Portland cement (PC) to reduce the carbon footprint of cement used in concrete construction has become an attractive engineering solution. The use of such materials are now covered by all major standards such as BS EN 197-1 [1], in which the FA and GGBS content can be as high as 35% and 95%, respectively.

Whilst the use of pozzolanic materials is preferable in terms of sustainability, it is also necessary to ensure that the durability of the concrete has not been compensated. This is particularly true for the carbonation resistance of concrete made with pozzolanic materials as both the pozzolanic reaction and carbonation process involve the consumption of calcium hydroxide, which can result in corrosion in reinforced concrete due to depassivation of the steel reinforcement.

This study presents the carbonation resistance of concrete made with FA and GGBS, based on global data-matrix with 65000 entries, built from 440 studies, published since 1968, and undertaken by 721 researchers from 332 institutions in 41 countries, using *analytical systemisation* method as described in [2 – 6]. Although not included, similar study has been taken for concrete made with limestone powder [7].

OVERVIEW OF LITERATURE

In this section, the overview of literature based on technical reports from established organisations and experimental studies, as consolidated by [8, 9], are provided.

Technical Reports from Established Organisations

The main observations from the technical reports for the carbonation effect of concrete made with FA and GGBS, produced from established organisations mainly in Europe and North America, are given in Table 1, based on [8, 9]. In general, the following three factors have been suggested to affect the carbonation of concrete:

- **FA and GGBS content:** the carbonation increases as FA and GGBS content increases, although the effect is significant for concrete with less than 30% FA or 50% GGBS.

- **Curing:** Improper curing can lead to high carbonation.

- **Compressive strength:** The carbonation of FA and GGBS concrete is similar to that of PC concrete at equal strength.

The information provided in the technical reports is useful, however, the numbers of references cited are very small, being no more than ten in general, and at worst not even one in most cases. Without substantial visible background information, it is difficult to inspire engineers to specify FA and GGBS as a replacement for PC for use in structural concrete.

Table 1 Main observations of the carbonation of concrete made with FA and GGBS from various organisations

REFERENCE	CARBONATION EFFECT OF FLY ASH/ GGBS	
	w.r.t PC	CONDITIONS
(a) Fly ASH		
CANMET, Canada	Similar	Good quality concrete
COIN, Norway	Similar	High volume FA and well-cured
Concrete Society, UK	Similar	For 25% FA, high strength and normal exposure
BRE, UK	Similar	For 25 – 30% at equal 28 days strength to PC
	Higher	Lower grade FA concrete
RILEM Committee 67 FAB	Similar	For < 40% and strength > 30 MPa
PCA, USA	Similar	At equal 28 days strength to PC
	Higher	High FA content, poorly cured low strength concrete
(b) GGBS		
JSCE, Japan	Similar	For up to 50% GGBS
CANMET, Canada	-	Carbonation increases with GGBS content
MTL, Canada	-	Controlled by curing, and low w/c design
Stichting Betonprisma, the Netherlands	Similar	No threat to marine structures
German Groups, German	Higher	High GGBS content, affected by curing and environmental conditions
NPRA and TNO, the Netherlands	Similar	57% GGBS
	Higher	66 – 80% GGBS

Experimental Studies

Apart from the technical reports, an initial appraisal of the experimental results of the effect of FA and GGBS on the carbonation in based on 440 studies has been consolidated by [8, 9], as summarised below:

- The vast majority of the studies (65 – 70%) suggested that the use of FA and GGBS could result in higher carbonation.
- Only 3-4% of the studies suggested that the carbonation of FA and GGBS concrete is lower than that of PC concrete.
- Less than 5% of the studies recorded no change in carbonation when either FA and GGBS is used.

- About 10% of the studies reported both increase and decrease in carbonation when PC is replaced by FA and GGBS, and the carbonation resistance is affected by the strength design, curing and other factors.

- About 15% of the studies did not compare the carbonation of FA and GGBS concrete with PC concrete.

CARBONATION OF FLY ASH AND GGBS CONCRETE

Consolidating from 583 studies [8, 9], the relative change of carbonation of FA and GGBS concrete relative to reference PC concrete under both accelerated and natural carbonation exposures are shown in Figure 1, together with the range of FA and GGBS contents in the range of CEM II and CEM III as specified in BS EN 197-1. The results are separated based on equal strength design and equal water/cement ratio design to PC concrete.

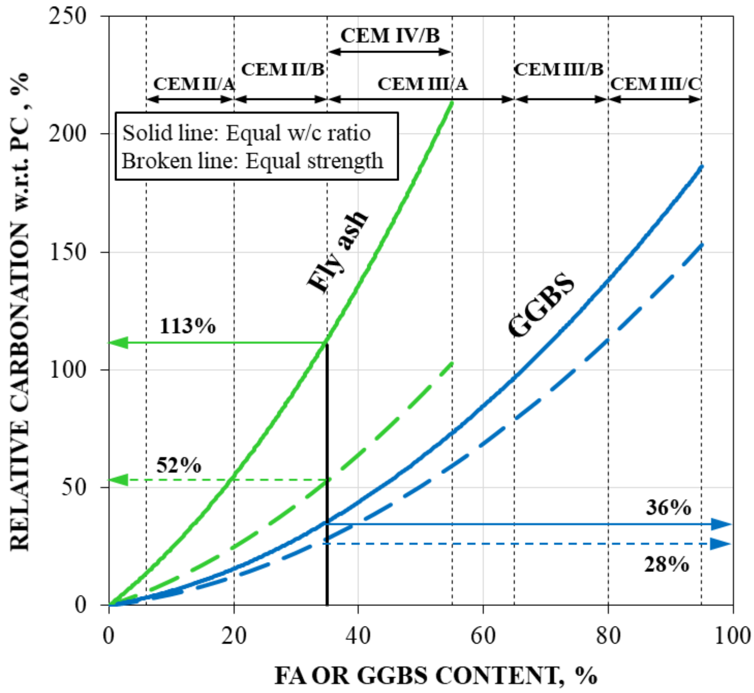

Figure 1 Effect of FA and GGBS on the carbonation of concrete for accelerated and natural exposures (adapted from [8, 9])

Typically, the concrete specimens were cured for 28 days and exposed to 3-5% CO_2 concentration under accelerated carbonation test or exposed to indoor environment with 20 - 25 °C and 50 -70% RH under natural carbonation test. The carbonation depth was commonly measured using phenolphthalein test method. The following main points can be observed from Figure 1:

- The relative increase in carbonation of FA and GGBS concrete increases, at an increasing rate, as FA and GGBS content increases.

- For both FA and GGBS concrete, the relative increase in carbonation of concrete on the basis of equal water/cement ratio is consistently higher than that of equal strength basis.

- At a given PC replacement, the use of FA can lead to higher increase carbonation compared with GGBS. For example, with an equal water cement ratio and 35% FA and GGBS addition, the concrete exhibited a 113% and 36% increase, respectively, in carbonation compared to PC concrete. For an equal strength design, the corresponding values are 52% for FA and 28% for GGBS.

OTHER INFLUENCING FACTORS

In addition to the effect of the FA and GGBS content on carbonation, other influencing factors have been identified, these include:

- The carbonation of air-cured concrete is higher than that of moist-cured concrete, in which FA and GGBS concrete is more sensitive than PC concrete.

- The carbonation of concrete decreases as the total cement content increases.

- An increase in FA and GGBS fineness is likely to improve the carbonation resistance of concrete.

CARBONATION DEPTH WITH STRENGTH OF CONCRETE

Taking 50 years as the design working life (category 4 for building structures as per Eurocode 0 [10]), the relationship between the estimated carbonation depth of concrete and the corresponding characteristic cube strength has been established [8, 9]. Figure 2 shows that relationship for concrete subjected to indoor condition. For comparison purposes, the minimum characteristic strength of 37 MPa and minimum cover of 25 mm, both corresponding to XC3 exposure recommended in Eurocode 2 [11], are also shown in Figure 2. For all the concrete with 37 MPa made with either CEM I, CEM II/A (6-20% FA) or CEM III (36 -65 % GGBS), the 50-year estimated carbonation depth exceeds the minimum cover of 25 mm.

The results suggest that concrete made with FA and GGBS requires an increase in strength or cover in order to prevent the corrosion of reinforcement. Another option but less beneficial from the environmental point of view is to limit the FA and GGBS content in concrete.

CONCLUSIONS

- The use of FA and GGBS as a replacement for PC, similar to the range adopted in BS EN 197-1 gives rise to an increase in carbonation.

- The extent of this increase of carbonation depends on the pozzolanic cement content, fineness of the material and the curing of the concrete.

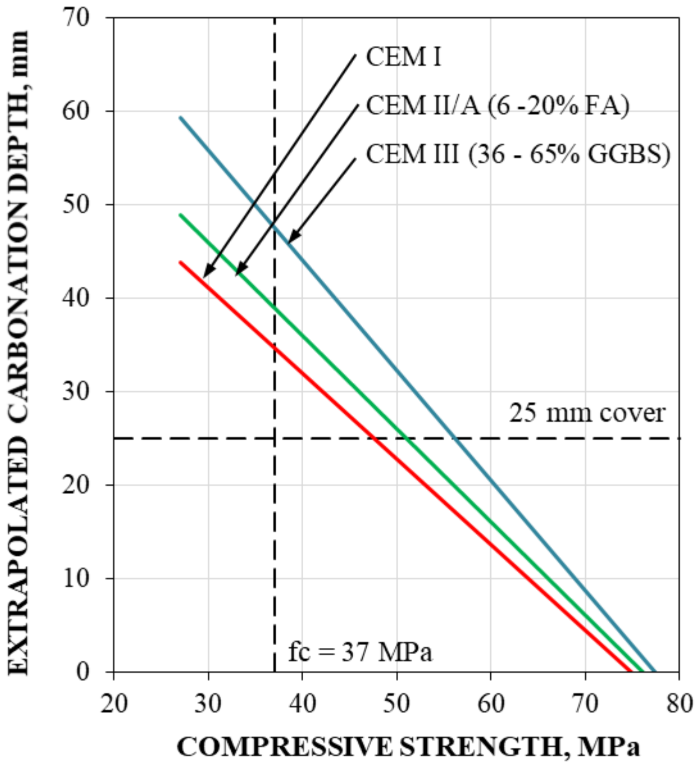

Figure 2 Extrapolated carbonation depth at 50 years of FA and GGBS concrete exposed to indoor carbonation at different characteristic strength (based on [8, 9]).

- For a give FA and GGBS content, the increase in carbonation of concrete designed on equal water/cement ratio to PC concrete s higher than that based on an equal strength basis.

- The minimum cover of 25 mm for concrete with characteristic strength of 37 MPa exposed to XC3 condition may need to be reconsidered for concrete containing FA and GGBS, as well as PC.

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