Carbonation resistance of GGBS concrete

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This study presents an analysis of a 30 000 strong data matrix derived from 227 studies originating from 35 countries since 1968. Similar to the fly ash effect, the carbonation of concrete increases with the incorporation of ground granulated blast-furnace slag (GGBS), but the rate increases as GGBS content is increased. This effect is greater for concrete designed on an equal water/cement (w/c) basis to the corresponding Portland cement (PC) concrete than on an equal strength basis. The Eurocode 2 specification for XC3 carbonation exposure in terms of the characteristic cube strength of concrete (or its w/c ratio) may need to be increased (or decreased) with the addition of GGBS. Other influencing factors, including GGBS fineness, total cement content and curing, were also investigated. In some cases, the carbonation of in-service GGBS concrete has been estimated to exceed the specified cover before 50 years of service life. Measures to minimise the carbonation of GGBS concrete are proposed. Fully carbonated reinforced GGBS concrete is assessed to show a higher corrosion rate. In relation to PC concrete, the carbonation of GGBS concrete is essentially similar when exposed to 3–5% carbon dioxide accelerated or indoor natural exposure, and the conversion factor of 1 week accelerated carbonation equal to 0.6 year is established.

Introduction

Background

Ground granulated blast-furnace slag (GGBS), a by-product of iron manufacture, because of its latent hydraulic nature requires alkali activation, from Portland cement (PC) for example. Indeed, the use of GGBS in combination with PC in concrete (GGBS concrete) has long been acknowledged. The first blast-furnace slag cement works was opened in Germany in 1865 and specifications for GGBS use with PC began to appear in Germany towards the end of the nineteenth century and in the UK during the early part of the twentieth century (BSI, 1923). The allowable proportion of GGBS as a cement component increased from about 30% in the 1910s to 90% in the 1970s (BSI, 1968).

With sustainability increasingly an issue, and sustainable construction materials seen as central to the sustainability agenda, the use of increasingly high proportions of GGBS in attempts to reduce the carbon dioxide footprint of cement used in construction has become attractive. Its use is now covered by all the major standards, such as BS EN 197-1 (BSI, 2011), and permissible GGBS content can be as high as 95% (known as CEM III/C cement).

Notwithstanding the above, as durability forms a major element of concrete specification and is directly connected with

sustainable construction, issues related to durability need to be carefully examined. In terms of chemical composition, GGBS can be assumed to improve the resistance of concrete to chloride ingress (and thereby reduce the risk of reinforcement corrosion), sulfate attack and alkali–silica reaction. However, despite the great deal of research undertaken, with 227 published papers in the English medium from 35 countries mainly since 1985, consensus on the effect of GGBS on the carbonation resistance and carbonation-induced corrosion of reinforced concrete remains to be assessed.

Aims and objectives

The primary aim of this study was to assess the carbonation resistance of GGBS concrete relative to PC concrete using exhaustively sourced published literature in the English medium. To achieve this, the following objectives were established.

- To undertake a narrative review of the effect of GGBS on the carbonation resistance of concrete.
- To systematically analyse and evaluate the published data, taking account of the variables involved to ascertain the effect of GGBS on the carbonation resistance of concrete as well as its consequences.
- In relation to the carbonation resistance of concrete, to propose method(s) for making effective and sustainable use of GGBS in concrete.

- To compare the carbonation resistance of GGBS concrete with that of fly ash (FA) concrete, as recently reported by the authors (Lye *et al.*, 2015).

Outline of the approach adopted

A near-exhaustive global literature search, limited to the English medium, was conducted using combinations of keywords defining and elaborating the subject area considered in this study. Many sources were used, such as the American Concrete Institute, the American Society of Civil Engineers and Institution of Civil Engineers libraries and Engineering Village, Google, Google Scholar, Science Direct, Scopus, Springer Link, Taylor & Francis Online and Wiley Online.

In total, 227 publications were sourced, covering 48 years since 1968 (Figure 1) and originating from 35 countries (Figure 2). It can be seen from Figure 1 that the subject began to attract more research attention during the mid-1980s and thereafter showed a general increasing trend over the years.

Based on their content, the publications were categorised into the following three groups, as shown in Figure 3.

- (a) Narrative review papers presenting previous research on the carbonation of GGBS concrete.
- (b) Papers with experimental results in which test data were obtained from dedicated cast specimens, analysed,

Figure 1. Distribution of year of publication

Figure 2. Distribution of country of publications based on the first author

^a Numbers in parentheses are the number of publications
^b Some publications may appear in more than one category

Figure 3. Distribution of literature data

evaluated and discussed by the researchers of the studies themselves. These studies covered the carbonation resistance of GGBS concrete in which the results were expressed as either carbonation depth/rate or the carbonation-induced corrosion of steel reinforcement.

For the papers concerning carbonation depth/rate of GGBS concrete, a further breakdown was made where

- the data available for the carbonation of GGBS concrete and that of the corresponding reference PC concrete were original
- the data of carbonation of GGBS concrete were original but the corresponding information for reference PC concrete were not available
- the same data were reported in more than one publication in the identified literature.

The data were further divided into various groups based on the following two basic factors, in which the carbonation behaviour within the same group was assumed to be comparable.

- Exposure conditions. Carbonation exposure was separated into accelerated carbonation exposure (with carbon dioxide concentration the main influencing factor), natural carbonation exposure (with a split into indoor, outdoor-sheltered and

outdoor-unsheltered conditions) and multiple exposures (carbonation depth of specimens measured after being subjected to alternate drying and wetting cycles in water or chloride solutions, freeze–thaw cycles or a marine environment).

- Mix types. Two categories were considered – paste and concrete/mortar (hereafter referred to as concrete).
- In-situ measurement papers in which the data were obtained from specimens cored from actual concrete structures.

In the main, the study investigated the carbonation resistance of concrete containing 6–95% GGBS. This covers the recommended GGBS content, from the lowest (6–35%) of Portland–slag cement (CEM II/A-S and B-S) to the highest (36–95%) of blast-furnace cement (CEM III/A, B and C) adopted in BS EN 197-1(BSI, 2011).

The notation ‘c’ adopted in this paper is for both PC and its combinations with various proportions of GGBS; as such, water/cement (w/c) ratio implies water/(PC + GGBS) ratio.

In addition, to facilitate easy comparison between the two commonly used materials of GGBS and FA in combination with PC, the structure of the paper and the data analysis and

Reference	Number of papers cited	Main observations
ACI (2003), ACI Committee 233, USA	3	Permeability of 'good-quality concrete' containing GGBS is low, thus resulting in low carbonation depth
Bamforth (2004), Concrete Society, UK	5	Carbonation resistance of GGBS concrete is affected by GGBS content (especially > 70%), total cement content, concrete strength (especially low strength) and curing duration
Bijen (1996a, 1996b), Association of the Netherlands Cement Industry, The Netherlands	2	In practice, the carbonation resistance of GGBS concrete is similar to that of PC concrete, albeit it is reported higher in laboratory data; no threat to marine structures
Bouzoubaa and Foo (2005), MTL, Canada	0	Carbonation resistance of GGBS concrete decreases with increasing GGBS content and may be controlled with prolonged curing and low w/c design
CSWP (2011), Concrete Society, UK	7	Strength and environment are primary factors affecting the carbonation of concrete while GGBS content is a secondary factor, even at higher content
Douglas (1987) CANMET, Canada	6	Carbonation depth of GGBS concrete increases with increasing GGBS content
JSCE (1996), JSCE, Japan	0	Carbonation of concrete with up to 50% GGBS can be considered practically similar to that of PC concrete
Muller (2007), German Groups ^a , Germany	10	Carbonation rate of concrete with high GGBS content is higher than that of PC concrete; it is also significantly affected by curing and environmental conditions
Osborne (1992), BRE, UK	1	Carbonation resistance of GGBS concrete is affected by GGBS content (significant at 70% but not 50%) and environments (especially for sheltered exposure)
Polder <i>et al.</i> (2014) NPRA and TNO, The Netherlands	12	Carbonation of concrete with 57% and 66–80% GGBS content is comparable to and higher than that of PC concrete, respectively; however, it is not significant under marine conditions in practice

^aThe Federal Association of the German Ready-Mixed Concrete Industry, Institute for Building Materials Research and Association of German Cement Works

Table 1. Compilation of main observations of carbonation of GGBS concrete from various organisations

evaluation approach adopted have deliberately been kept similar to that adopted previously by the authors in the study of carbonation of FA concrete (Lye *et al.*, 2015).

Overview of the literature

Technical reports and review papers

The publications identified under this category were sorted into two groups based on their origins – firstly, technical reports produced from established organisations mainly in Europe and North America and one in Asia and, secondly, review papers originating from individual researchers (Ayub *et al.*, 2013; Bertolini *et al.*, 2013; Hamada, 1968; Jain *et al.*, 2007; Nagataki *et al.*, 1989; Pacheco Torgal *et al.*, 2012; Richardson *et al.*, 2012; Sakai *et al.*, 2012; Sanjuan *et al.*, 2011; Siddique, 2008; Siddique and Khan, 2011; Song and Saraswathy, 2006). The main observations from the former group are summarised in Table 1. These observations were found to be very similar to those of the second group.

Table 1 indicates that the technical reports tend to correlate the carbonation resistance of GGBS concrete with the following four factors.

- **GGBS content.** In general, the carbonation resistance of GGBS concrete is noted to decrease with increasing GGBS content, although three reports suggested no significant change at 50% GGBS content (JSCE, 1996; Osborne, 1992; Polder *et al.*, 2014). One report suggested that the effect of GGBS content is only secondary after strength and environmental factors (CSWP, 2011) and another report suggested GGBS concrete has similar carbonation to PC concrete in practice (Bijen, 1996a, 1996b).
- **Curing practice.** Curing practice has been considered important in controlling the carbonation resistance of GGBS concrete (Bamforth, 2004; Bouzoubaa and Foo, 2005; Muller, 2007).

Observation of carbonation depth ^a	Main suggested causes	Number of studies		
		Accelerated	Natural	Total
Higher (140)	Cement, design			
Accelerated (76)	Reduction of Portland clinker	8	3	11
Natural (64)	Low calcium oxide content in cement	2	2	4
	Chemical difference in cement	1	0	1
	Insufficient curing	4	3	7
	Hardened properties			
	Slow reaction/pozzolanic reaction	3	1	4
	Reduction in strength	0	2	2
	Reduction of calcium hydroxide	32	27	59
	Carbonation of C-S-H	9	3	12
	Reduction of pH	6	5	11
	Higher permeability	4	4	8
	Higher porosity/coarser pore	15	10	25
	Not given	30	30	60
Lower (6)	Design			
Accelerated (6)	Low w/c ratio	2	0	2
Natural (0)	Hardened properties			
	Pozzolanic effect	1	0	1
	Denser packing/lower porosity	4	0	4
	Uniform interfacial transition zone	1	0	1
	Not given	1	0	1
No change (2)	Not given	1	1	2
Accelerated (1)				
Natural (1)				
Variable (16)	Cement			
Accelerated (7)	GGBS fineness	3	0	3
Natural (9)	Total cement content	0	1	1
	Design			
	Water/cement ratio design	0	1	1
	Strength design	1	4	7
	Curing duration	2	3	5
	Not given	1	2	3
No reference mix (39)	Not applicable	23	16	39
Accelerated (23)				
Natural (16)				

^aHigher/lower/no change/variable carbonation depth of GGBS concrete with respect to corresponding reference PC concrete

Table 2. Suggested causes of carbonation phenomenon of GGBS concrete from the literature

- Strength. Two reports suggested that carbonation resistance is unchanged for GGBS concrete with low w/c ratio design (thus higher strength) or a similar strength grade (higher than 30 MPa) to PC concrete at 50% GGBS content (Bamforth, 2004; Bouzoubaa and Foo, 2005).
- Exposure conditions. Under dry or sheltered exposure, GGBS concrete tends to carbonate faster than PC concrete, while under wet or marine conditions, the

carbonation of GGBS concrete is essentially not significantly different to that of PC concrete (Bijen, 1996a, 1996b; CSWP, 2011; Muller, 2007; Osborne, 1992; Polder *et al.*, 2014).

Although these four influencing factors for the carbonation of GGBS concrete have been identified, the technical reports have not clearly addressed how to take these factors into account in

Parameter	Variable	Number of studies	Parameter	Variable	Number of studies	
<i>Carbonation</i>			<i>Accelerated exposure conditions</i>			
Accelerated	—	113	Carbon dioxide	< 3%	14	
	Total ^a	113		3–5%	42	
Natural	Indoor	66		6–10%	28	
	Outdoor, sheltered	13		15–100%	18	
	Outdoor, unsheltered	16		Not given	17	
	Outdoor, not given	8		Total ^a	119	
	Not given	7	Duration	≤ 30 d	30	
	Total ^a	110		31–90 d	28	
		91–180 d		32		
<i>Specimen</i>				> 180 d	16	
Specimen type	Cylinder	35		Not given	10	
	Prism	64		Total ^a	116	
	Cube	25	Temperature	20–30°C	75	
	Block	6		> 30°C	9	
	Column/slab/wall	4		Not given	26	
	Not given	46		Total ^a	110	
	Total ^a	180	Humidity	40–60%	56	
Preparation	Sealed	45		61–90%	37	
	Unsealed	17		Not given	22	
	Unspecified	118		Total ^a	115	
	Total ^a	180				
<i>Curing</i>			<i>Natural exposure conditions</i>			
Exposure	Moist	159	(a) Indoor			
	Air	26	Duration	≤1 year	38	
	Not given	21		1–5 years	27	
	Total ^a	206		6–20 years	7	
Duration	1–14 d	142		Not given	2	
	15–28 d	83	Total ^a	74		
	56–91 d	18	Temperature	18–35°C	46	
	> 91 d	9		Not given	22	
	Not given	35		Total ^a	68	
	Total ^a	287	Humidity	50–95%	49	
	Temperature	< 20°C		1	Not given	19
		20–30°C		66	Total ^a	68
> 30°C		9				
Not given		125	(b) Outdoor-sheltered			
Total ^a	201	Duration	≤1 year	3		
Humidity	80–100%		140	1–5 years	7	
	50–80%		12	5–16 years	8	
	Not given	49	Not given	1		
	Total ^a	201	Total ^a	19		
<i>Pre-conditioning</i>			(c) Outdoor-unsheltered			
Preparation	Omitted	63	Duration	≤1 year	4	
	Applied	65		1–5 years	8	
	Not given	70		6–16 years	4	
	Total ^a	198		Not given	1	
Duration ^b	1–7 d	19	Total ^a	17		
	10–32 d	35	(d) Outdoor-unspecified			
	50–180 d	12	Duration	≤1 year	1	
	Not given	6		1–5 years	6	
	Total ^a	72		6–16 years	1	
		Total ^a		8		

Table 3. Compilation of test parameters of carbonation measurements in the literature (continued on next page)

Parameter	Variable	Number of studies	Parameter	Variable	Number of studies
Temperature ^b	20–30°C	31	(e) Not given		
	40–60°C	15	Duration	≤1 year	4
	Not given	20		1–5 years	3
	Total ^a	66		Total ^a	7
Humidity ^b	50–75%	40	<i>Measurement</i>		
	Not given	27			
	Total ^a	67	Method	Phenolphthalein	126
				Other	3
				Not given	58
				Total ^a	187
			Concentration ^c	1%	45
				Other (0.1–3%)	7
				Not given	74
				Total ^a	126

^aTotal number of publications for each individual parameter

^bData compiled from studies where preconditioning was applied

^cData compiled from studies where phenolphthalein was used

Table 3. Continued

designing concrete made with GGBS to ensure its carbonation resistance is not compromised.

Experimental studies

In order to obtain a general impression, an initial appraisal of the literature is produced in Table 2, along with the suggested main causes. The main aspects of Table 2 can be summarised as follows.

(a) Higher carbonation depth

- The vast majority of the studies (69%) showed that the use of GGBS as PC replacement results in higher carbonation.
- A commonly suggested cause for the increase in carbonation depth of GGBS concrete is the reduction of calcium hydroxide (Ca(OH)₂) normally associated with the reduction of Portland clinker or low calcium oxide (CaO) in total cement, leading to a reduction in the alkalinity of the concrete.
- Another commonly claimed cause is the increase in porosity or coarser pore structure of hardened GGBS concrete, as a consequence of carbonation of calcium silicate hydrate (C-S-H), insufficient curing or slow reaction of GGBS, facilitating the ingress of carbon dioxide (CO₂).

(b) Lower carbonation depth

- In contrast to the above, only six studies (3%) reported the carbonation of GGBS concrete being lower than the corresponding PC concrete. Coincidentally, all these studies were done under accelerated carbonation exposure.

- The denser cement paste structure in concrete, due to the pozzolanic activity of GGBS, is suggested as the cause of lower carbonation.

(c) No change in carbonation depth

- The smallest number of studies (1%) recorded no change in carbonation depth of GGBS concrete compared to PC concrete, but no explanation was offered.

(d) Varying carbonation depth

- About 8% of the studies showed that the carbonation resistance of GGBS concrete could vary from being lower to comparable with, or even higher than that of the PC concrete, depending on GGBS fineness, w/c ratio, strength or curing of the concrete.

(e) No reference

- A significant number of studies (19%) tested only GGBS concrete for carbonation resistance and therefore these data could not be compared.

Systematic analysis and evaluation of published data

Variation in the test procedures used

The details of the procedures used for conducting carbonation tests on GGBS concrete were separated into seven groups, with a further breakdown of the main parameters and the corresponding variables. This information is given in Table 3 and can be summarised as follows.

- Carbonation. The numbers of studies undertaken using accelerated or natural exposures were very similar. Within

the natural exposure groups, indoor exposure was more common than outdoor.

- Specimen. The test specimens were usually cast in prisms, followed by cylinders and cubes, but some test specimens were cored from elements cast in the laboratory in the form of concrete blocks, columns, slabs or walls. Information on sealed/unsealed test specimens is lacking, with only 45 studies specifying that the surfaces of the specimens were sealed for uniaxial directional carbonation to take place.
- Curing. In general, moist curing of test specimens for up to 2 weeks was commonly adopted. The temperature of curing was usually not stated, but it is most likely to be in the region of 20–30°C with a few studies at higher temperature for heat curing.
- Pre-conditioning. For the studies in which this information is available, test specimens were commonly conditioned for up to a month in an environment of 20–30°C and 50–75% relative humidity (RH).
- Accelerated exposure. The most commonly adopted conditions were carbon dioxide concentration of 3–5%, temperature of 20–30°C and humidity of 40–60%, for durations of up to 180 d.
- Natural exposure. For indoor exposure, the temperature and humidity ranges reported usually tended to fluctuate, but were mostly in the region of 20–25°C and 50–70% RH. The most commonly reported exposure period was up to 5 years for all natural exposure conditions.
- Measurement of carbonation depth. This was commonly measured using the phenolphthalein test method.

GGBS effect

General impression of overall published data

Consolidating the overall published data, the relative change of carbonation of GGBS concrete relative to reference PC concrete under both accelerated and natural carbonation exposures are plotted in Figure 4, together with the range of GGBS contents in Portland-slag cement (CEM II) and blast-furnace cement (CEM III) as adopted in BS EN 197-1 (BSI, 2011) for ease of reference.

In preparing the figure, the data points were dispersed slightly to avoid overlapping in order to provide a clearer view. At each GGBS replacement level, box-and-whisker plots were created in order to visualise the data distribution and determine the outliers. Additionally, some of the results were not used. These results were where

- the carbonation of a reference PC concrete was not available
- the carbonation data were for paste specimens.
- specimens were subjected to multiple exposures (to avoid confusion)
- the same data were reported in more than one publication.

Additionally, the results of GGBS concrete specimens that were fully carbonated were also excluded. These results had one or more of the following factors in common: GGBS content over 50%, w/c ratio over 0.70, insufficient moist curing, unconventional accelerated carbonation conditions (i.e. 50% carbon dioxide, under high pressure) or 4–10 years of natural carbonation.

In establishing the relative mean carbonation value at each GGBS content and the trendline for the relationship between the carbonation of concrete and its GGBS content, the following data were not considered.

- (a) Data giving carbonation higher than 300%. These amounted to 19.0% of the total data population. This figure is greater than the combined figure of 7.8% and 5.4% GGBS concrete data showing carbonation lower than and equal to PC concrete respectively, which were considered in developing the relationship shown in Figure 4.
- (b) Outliers determined using the box-and-whisker plots; these accounted for 3.5% (i.e. 34 out of 960) of the data population.

Generally, it can be seen from Figure 4 that the increase in carbonation of GGBS concrete relative to PC concrete up to 20% GGBS content is not significant, but beyond this value the relative carbonation increases at an increasing rate with increasing GGBS content. Overall, a polynomial regression was obtained, giving a correlation of 0.8055. It is noted that the mean data at 80% and 85% GGBS deviate significantly from the trendline, but their effects may be regarded as cancelling out each other.

To summarise, Figure 4 shows that the use of GGBS as a component of cement in concrete results in higher carbonation with an average increase of carbonation at 30%, 50% and 70% GGBS likely to be of the order of 25%, 60% and 115%, respectively.

Further analysis

The data used in plotting Figure 4 were separated in terms of equal w/c ratio and equal 28 d concrete cube strength for both accelerated and natural carbonation exposures, as shown in Figures 5(a) and 5(b) and Figures 6(a) and 6(b), respectively.

In establishing Figures 5 and 6, about 15% of the data were not considered for the following reasons.

- The mixes did not meet the limiting values for carbonation-induced corrosion recommended in BS EN 206 (BSI, 2013) (i.e. having w/c ratio higher than 0.65, strength less than 25 MPa and/or cement content below 260 kg/m³).

Figure 4. Influence of GGBS on carbonation resistance of concrete for accelerated and natural carbonation exposures. Data taken from Ahmed *et al.* (1999); Akcaozoglu and Atis (2011); Alavi *et al.* (2013); Alexander and Beushausen (2010); Al-Otaibi (2004); Ali and Dunster (1998); Al-Otaibi (2008); Andrade and Buják (2013); Audenaert and de Schutter (2007); Audenaert *et al.* (2007); Ba *et al.* (2010); Bahador and Arezoo (2009); Bahador and Cahyadi (2009); Bahador *et al.* (2014); Balayssac *et al.* (1995); Ballim (1993); Barker and Matthews (1994); Backus *et al.* (2012);

Batis *et al.* (2002); Battaglia *et al.* (2010); Bier (1986); Bier *et al.* (1989); Bijen and Van Selsti (1991); Bijen *et al.* (1989); Borges *et al.* (2010; 2012); Borsoi *et al.* (2007); Boubitsas (2001); Bouikni *et al.* (2009); Bouquet (2002); Bucher *et al.* (2015); Buttler and Ashby (1986); Cahyadi and Uomoto (1994); Clear and Chapman-Andrew (1991); Collepardi (1994); Collepardi *et al.* (2004); Collins (1987); Copuroglu *et al.* (2006a; 2006b); Courard and Michel (2014); Cui *et al.* (2010); de Castro *et al.* (2004); De Ceukelaire and Van Nieuwenburg (1993); (continued on next page)

Figure 4. Continued

De Schutter and Audenaert (2004); de Vries *et al.* (1998); Dhir *et al.* (1994a; 1994b; 1996; 2004); Dinakar *et al.* (2007); Dinku and Reinhardt (1996); Duan *et al.* (2013); Dunster (2000); Eguchi *et al.* (2013); Eguez *et al.* (2015); Espion *et al.* (2013); Fukudome *et al.* (2012); Gallias *et al.* (2010); Gao *et al.* (2013); Georgescu *et al.* (2009); Gruyaert and De Belie (2012); Gruyaert *et al.* (2010; 2013a; 2013b); Gunter *et al.* (1987); Haibier and Wu (2012); Hakkinen (1992); Harrison *et al.* (2012a; 2012b); Higashiyama *et al.* (2014); Holt and Leivo (2011); Holt *et al.* (2010); Hooton and Vassilev (2012); Horiguchi *et al.* (1994); Hyvert *et al.* (2010); Iyoda and Komiyama (2013); Imamoto and Tanaka (2012); Iyoda and Toyomura (2012); Iyoda *et al.* (2008; 2015); Jariyathitipong *et al.* (2013); Jones and Abbas (2002); Jones *et al.* (1999; 2001); Jortzick and Schubert (1986); Kandasami *et al.* (2012); Kasai *et al.* (1983); Kinoshita *et al.* (2014); Knaack and Stark (1997); Kurz (1984); Koo *et al.* (2014); LaBarca *et al.* (2007); Lang (2002; 2005; 2006); Lang and Geiseler (1996); Leeman *et al.* (2015); Leivo *et al.* (2011); Li *et al.* (2012); Liu *et al.* (2014); Ludwig (1980); Maage (1985); Mackechnie and Alexander (2002); Maeda *et al.* (1998); Malami *et al.* (1994); Malhotra *et al.* (2000); Mangat and Khatib (1993); Maslehuddin *et al.* (1996); Matsumoto *et al.* (2010); McNally and Seymour (2010); McNally and Sheils (2012); McPolin

et al. (2007; 2009); Medagoda (2008); Meyer (1968); Misaka and Iyoda (2013); Miyazawa *et al.* (2003; 2014); Mohammed *et al.* (2002; 2003; 2004); Morioka *et al.* (2002); Muller *et al.* (2010); Mun *et al.* (2007); Nagataki *et al.* (1987); Nagao *et al.* (2003); Nakamoto and Togawa (1995); Naruse and Nakayama (2002); Ngala and Page (1997); Ohga *et al.* (1998); Osborne (1986; 1989; 1999); Oslen and Summers (1997); Otsuki *et al.* (2014); Owsiak and Grzmil (2015); Paillere *et al.* (1986); Pal *et al.* (2002); Parrott (1990; 1992a; 1992b; 1996); Ramezaniapour *et al.* (1998); Sagawa *et al.* (2004); Sagoe-Crentsil *et al.* (2001); Sakai and Watanabe (1993); Sakai *et al.* (1992); Sasatani *et al.* (1995); Schmidt *et al.* (1993); Shi *et al.* (2009); Shiraiwa *et al.* (2015); Sisomphon and Franke (2007); Sisomphon *et al.* (2010; 2011); Smolczyk (1972); Sonebi *et al.* (2008); Stark *et al.* (1997); Sugi *et al.* (2013); Sulapha *et al.* (2003); Taniguchi *et al.* (2013); Thiel *et al.* (2014); Tian *et al.* (2014); Tomisawa *et al.* (1992); Toyomura *et al.* (2012); Turcry *et al.* (2012); Uji *et al.* (2004); Utgenannt (2008); Visser (2011; 2012); Vollpracht *et al.* (2010); Watanabe and Miyazato (2011); Wee *et al.* (1999); Wei *et al.* (2015); Wierig (1984); Woyciechowski (2012); Yatagai *et al.* (2013); Yonezawa *et al.* (2013); You *et al.* (2015); Younsi *et al.* (2012; 2013); Yunusa (2014); Zhang *et al.* (2004; 2013); Zhao *et al.* (2015).

Figure 5. Influence of GGBS on carbonation of concrete at equal w/c ratio for (a) accelerated and (b) natural carbonation exposure

Figure 6. Influence of GGBS on carbonation of concrete at equal strength for (a) accelerated and (b) natural carbonation exposure

- Mixes designed in an impractical manner or data showing inconsistency in the carbonation measurements with GGBS content, curing, development of hardened concrete properties with time.

Figures 5 and 6 show that, while the shape of the trendlines obtained is similar to that of Figure 4

- regardless of equal w/c ratio or strength basis, the increasing rate of relative carbonation of GGBS concrete with respect to PC concrete is essentially similar under both accelerated and natural carbonation exposures
- for given exposure conditions, the carbonation rate of GGBS concrete on the basis of equal w/c ratio is consistently higher than that of the equal strength basis, with differences being 5–10%, 10–15% and 15–20% at 30%, 50% and 70% GGBS content, respectively.

Influence of GGBS fineness

The effect of GGBS fineness on the carbonation of cement paste and concrete was investigated over a range of fineness 300–2900 m²/kg and content up to 85%, with PC fineness generally in the range of 300–345 m²/kg. The test specimens were subjected to 1–28 d moist curing and exposed to both

accelerated and natural exposures. Collectively, the following main points emerged from analysis of the data.

- With the exception of the work of Sakai and Watanabe (1994), for a given GGBS content, the carbonation of cement paste and concrete decreased with increasing fineness. This effect was more pronounced with increasing GGBS content, as illustrated in Figure 7 as an example.
- On average, at up to 30% GGBS content and with fineness double that of the PC, the carbonation resistance of GGBS concrete was essentially the same as that of the PC concrete.

Figure 8 shows the carbonation reduction per 100 m²/kg fineness of GGBS. Although a weak correlation, the trendline suggests that, for a given difference in fineness of GGBS, its effectiveness in reducing concrete carbonation increases with increasing GGBS content.

Data from the only study on natural carbonation (Frignione and Sersale, 1994) show that the carbonation depth of concrete made with 70% GGBS after 3-year exposure reduces from 1.5 mm to 5.0 mm for every increase of 100 m²/kg GGBS fineness, with an increase of 1–3% in its sulfur trioxide (SO₃) content.

Figure 7. Influence of GGBS fineness on carbonation of paste under accelerated exposure (adapted from Li *et al.* (1998))

Figure 8. Influence of GGBS fineness on carbonation of paste/concrete under accelerated carbonation

Effect of cement content

Carbonation studies of concrete made with 40–70% GGBS as a component of cement (and thereby, for example, covering BS EN 197-1 (BSI, 2011) cements in the form of CEM II/B-S, CEM III/A and CEM III/B) have been reported using cement contents of 270–450 kg/m³ at a constant w/c ratio range of 0.45–0.60 and using 28 d moist-cured test specimens subjected to both accelerated and natural exposure conditions.

The data obtained were analysed and are shown plotted separately in terms of accelerated exposure (Figures 9(a) and 9(b)) and natural exposure (Figures 9(c) and 9(d)). It should be mentioned that only the results of Dhir *et al.* (2004) for accelerated carbonation and Ramezaniapour *et al.* (1998) for natural carbonation show consistent trends. Figure 9 shows four different trends.

- Trend 1 – carbonation of concrete decreases with increasing cement content under accelerated exposure (Dhir *et al.*, 2004; Kandasami *et al.*, 2012) and natural exposure (Harrison *et al.*, 2012a; Ramezaniapour *et al.*, 1998) (Figures 9(a) and 9(c)). The average carbonation depth reduction rate in accelerated and natural carbonation is essentially similar, being 0.5 mm and 0.6 mm per 10 kg cement content increase, respectively.
- Trend 2 – another equally dominant trend, and again present in both accelerated (Kandasami *et al.*, 2012) and natural (Harrison *et al.*, 2012a; Leeman *et al.*, 2015) exposures, shows inconsistent carbonation change, which first decreases and then increases as cement content is increased (Figures 9(b) and 9(d)).
- Trend 3 – a number of test specimens made, all from Harrison *et al.* (2012a), show no sign of carbonation at any of the cement contents used (Figure 9(d)).
- Trend 4 – although not a dominant trend, some data show that carbonation increases with increasing cement content for both accelerated (Kandasami *et al.*, 2012) and natural exposures (Leeman *et al.*, 2015), as shown in Figures 9(b) and 9(d), respectively.

Given that PC provides the source of calcium hydroxide for carbon dioxide to react with, provided that the overall mix proportion is well considered, an increase in cement content should increase the carbonation resistance of concrete. Such an increase in resistance should be more marked with PC than with a combination of PC and GGBS. However, the available data do not show this level of sensitivity.

Effect of curing

Curing conditions

To avoid unnecessary confusion, the reported data were grouped into three types – moist curing, air curing and heat curing. The trends for both accelerated and natural

Figure 9. Influence of cement content on carbonation of GGBS concrete exposed to accelerated carbonation ((a) and (b)) and natural carbonation ((c) and (d))

carbonation exposures were found to be essentially similar. The data reported for the accelerated exposure conditions were generally a carbon dioxide concentration of $5 \pm 2\%$, temperature of $25 \pm 5^\circ\text{C}$, relative humidity of $65 \pm 5\%$ and test duration of up to 25 weeks, and these are plotted in Figure 10.

As expected, the carbonation of air-cured concrete is higher than moist-cured concrete, with the rate of increase increasing with GGBS content. The limited data for heat-cured concrete suggest that even though this results in higher strength, it gives little improvement in resistance to carbonation. Contrary to Figures 5 and 6, the carbonation rate of concrete does not

Figure 10. Influence of curing condition on carbonation of GGBS concrete exposed to accelerated carbonation

differ significantly with a change in curing conditions when compared on an equal strength or w/c ratio basis, though this is most likely due to the limited data available on curing conditions. Overall, it is evident that moist curing of GGBS concrete is necessary to control an unduly higher increase in its carbonation rate.

Curing duration

The data regarding the influence of the duration of moist curing, covering a range of important parameters, are plotted in Figure 11. Acknowledging that the coefficients of correlation are generally very poor and therefore the trendlines observed can at best only be considered as

Figure 11. Influence of moist curing duration on carbonation of GGBS concrete of equal w/c ratio and strength design to PC concrete

qualitative, the following points of practical relevance can be noted.

- Notwithstanding that the resistance to carbonation decreases with GGBS content, and the results in

Figure 11 support this, GGBS concrete is more sensitive to curing and therefore it benefits more than PC concrete from moist curing, particularly during the initial stages (up to 1 month duration). This could be expected to be more significant for higher GGBS

contents, but the available results are inconclusive on this point.

- Concrete with GGBS content up to 30% and designed for a given strength can, with approximately 1 month of moist curing, develop resistance to carbonation similar to the corresponding PC concrete. However, on an equal w/c ratio basis, the comparable carbonation resistance is likely to be achieved with approximately 2 months of moist curing. This highlights the importance of moist curing when GGBS-based CEM II cement is used, and more so with CEM III cements.
- Once again, the trends observed concerning the duration of moist curing for the carbonation resistance of concrete with and without GGBS are generally similar for both accelerated and natural exposures.

Carbonation depth with strength grade of concrete

Taking 50 years as the design working life (category 4 for building structures as per Eurocode 0), the estimated carbonation depth data of concrete are shown plotted against 28 d characteristic cube strength in Figure 12. In developing Figure 12

- the data used were taken from Figures 5 and 6 and also studies without PC reference concrete
- the estimated carbonation depth at 50 years (D_{50}) was calculated as $D_{50} = Kt^{0.5}$, K being the coefficient of carbonation and $t = 50$ years; the value of K used in

each case was either as given in the respective publication or calculated from the carbonation depth data

- where the final carbonation depth was reported as zero, the data were not considered further
- characteristic cube strength was calculated using a coefficient of variance of 6% as given in ACI 301: 2005 for fair laboratory control
- for convenience of use, a linear regression was applied in analysis of the data.

Figure 12 shows that concrete subjected to indoor exposure resulted in the highest carbonation, followed by outdoor-sheltered and outdoor-unsheltered exposures. Within each natural exposure condition, concrete carbonation increased with decreasing strength and increasing GGBS content.

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 (BSI, 2004), are shown by the dotted lines in Figure 12. Comparison of the data reveals the following.

- For indoor exposure, the 50-year estimated carbonation depth of both PC and GGBS concretes of 37 MPa characteristic strength exceeds the minimum cover of 25 mm.
- For outdoor-sheltered exposure, the 50-year estimated carbonation depth of PC concrete is below 25 mm, whilst

Figure 12. Extrapolated carbonation depth at 50 years of GGBS concrete exposed to natural carbonation ((a) indoor, (b) outdoor-sheltered and (c) outdoor-unsheltered) at different characteristic strengths

Cement	(a) At 37 MPa		(b) At 25 mm cover		(c) At 0.55 w/c		(d) At 25 mm cover	
	Carbonation depth: mm		Characteristic strength: MPa		Carbonation depth: mm		w/c ratio	
	Indoor	Outdoor-sheltered	Indoor	Outdoor-sheltered	Indoor	Outdoor-sheltered	Indoor	Outdoor-sheltered
CEM I	35	21	47	31	28	21	0.52	0.61
CEM II/A-S (5–20% GGBS)	36	n/a ^a	49	n/a	36	n/a	0.45	n/a
CEM II/B-S (21–35% GGBS)	40	26	52	38	40	28	0.41	0.53
CEM III/A (36–65% GGBS)	48	29	56	42	55	39	0.35	0.42
CEM III/B (66–80% GGBS)	54	33	59	45	61	44	0.32	0.39
CEM III/C (81–95% GGBS)	57	n/a	60	n/a	67	n/a	0.30	n/a

^an/a = not available

Table 4. 50-year extrapolated carbonation depth, characteristic strength and w/c ratio of PC and GGBS concrete for different design parameters

that of concrete with 21–35% GGBS (CEM II/B-S) is fairly close to 25 mm when the characteristic strength is 37 MPa. Concrete containing more than 36% GGBS (CEM III) has a carbonation depth greater than the minimum cover.

- For outdoor-unsheltered exposure, although the data population is relatively small, the 50-year carbonation depth of both PC and GGBS concretes are below 25 mm, with the latter concrete tending to be close to the minimum cover.

Table 4 summarises, for indoor and outdoor-sheltered exposures, (a) the estimated 50-year carbonation value corresponding to 37 MPa and (b) characteristic cube strength corresponding to 25 mm cover of concrete made with PC and GGBS contents as covered by BS EN 197-1 (BSI, 2011).

Figure 12 also suggests how to make the carbonation of GGBS concrete similar to that of PC concrete. Taking the carbonation of PC concrete at 37 MPa exposed to indoor and outdoor-sheltered conditions as an example, to match the carbonation of PC concrete, the strength of GGBS concrete needs to be increased on average by about 5.5 MPa, 9.5 MPa and 13 MPa for CEM II/B-S (21–35% GGBS), CEM III/A (36–65% GGBS) and CEM III/B (66–80% GGBS), respectively.

In order to compare the data between accelerated and natural carbonation, a similar analysis method was adopted for concrete exposed to 3–5% carbon dioxide concentration. This showed that 1 week of accelerated carbonation exposure for concrete made with PC, CEM II/B-S (21–35% GGBS), CEM III/A (36–65% GGBS) and CEM III/B (66–80% GGBS) is equivalent to about 0.55, 0.50, 0.60 and 0.65 year of natural indoor exposure, respectively. These values are very different to that proposed by Ho and Lewis (1987), who suggested that

Figure 13. Extrapolated carbonation depth at 50 years of GGBS concrete based on accelerated carbonation (3–5% carbon dioxide concentration) at different characteristic strengths

1 week of accelerated carbonation is equivalent to 1 year of indoor exposure. These conversion factors were used in developing Figure 13, so that the trendlines are almost similar to that of natural indoor carbonation.

Figure 14. Extrapolated carbonation depth at 50 years of GGBS concrete exposed to natural carbonation ((a) indoor, (b) outdoor-sheltered and (c) outdoor-unsheltered) at different w/c ratios

Carbonation depth of concrete at specified w/c ratio

Using another design parameter (w/c ratio) for the 50-year estimated carbonation depth of concrete, the analysis of the data is shown plotted in Figure 14, together with the recommended maximum w/c ratio of 0.55 for XC3 exposure given in BS EN 206 (BSI, 2013) and the corresponding minimum cover of 25 mm given in Eurocode 2 (BSI, 2004).

- As expected, the carbonation behaviour of concrete shown in Figure 14 is similar to that in Figure 12, except that there is greater sensitivity to carbonation rate.
- For similar carbonation to PC concrete at 0.55 w/c ratio under indoor and outdoor-sheltered exposures, Figure 14 suggests that the w/c ratio of GGBS concrete made with CEM II/B-S (21–35% GGBS), CEM III/A (36–65% GGBS) and CEM III/B (66–80% GGBS) needs to be reduced by these amounts, in the region of 0.10, 0.20 and 0.22, respectively.

Limiting to 3–5% carbon dioxide accelerated carbonation exposure, the estimated 50-year carbonation depth of concrete made with PC, CEM II/B-S (21–35% GGBS), CEM III/A (36–65% GGBS) and CEM III/B (66–80% GGBS), using conversion factors of 1 week approximately equal to 0.60, 0.60, 0.60 and 0.65 year of indoor exposure, respectively, is shown plotted against the corresponding w/c ratio in Figure 15. Comparing the conversion factors found in the previous section (Carbonation

Figure 15. Extrapolated carbonation depth at 50 years of GGBS concrete based on accelerated carbonation (3–5% carbon dioxide concentration) at different w/c ratios

Reference	Main points emerging
Accelerated carbonation	
Andrade and Buják (2013)	Corrosion rate of GGBS concrete higher than that of PC concrete Prism specimen, 20 × 55 × 80 mm; cover, n/a ^a ; GGBS, 0 and 70%; w/c ratio, 0.50; moist curing, 28 d; carbon dioxide, 100%; temperature, n/a; RH, 65%; duration, 2 weeks
Medagoda (2008)	Use of GGBS resulted in higher corrosion rate than that of PC concrete Cube specimen, 100 × 100 × 100 mm; cover, 25 mm; GGBS, 0 and 30%; w/c ratio, 0.55; moist curing, 28 d; carbon dioxide, 4%; temperature, 20°C; RH, 55%; duration, 24 weeks
Natural carbonation	
Oslen and Summers (1997)	Concrete made with GGBS showed greater corrosion rate than PC concrete Prism specimen, 100 × 100 × 300 mm; cover, 10 and 20 mm; GGBS, 0 and 70%; w/c ratio, 0.49–0.89; moist curing, 28 d (series 1), uncured (series 2); exposure, outdoor unspecified; duration, 10 years
Parrott (1990, 1994)	Corrosion rate of GGBS concrete higher than that of PC concrete and was not significantly affected by curing and w/c ratio Cube specimen, 100 × 100 × 100 mm; cover, 4, 8, 12 and 20 mm; GGBS, 0 and 50%; w/c ratio, 0.35–0.83; moist curing, 3, 28 and 545 d; exposure, indoor, outdoor-unsheltered and outdoor-unsheltered; duration, 4 years
Parrott (1996)	Corrosion rate of GGBS concrete higher than that of PC concrete and was not significantly affected by curing Cube specimen, 100 × 100 × 100 mm; cover, 4, 8, 12 and 20 mm; GGBS, 0 and 50%; w/c ratio, 0.59; moist curing, 1–28 d; exposure, indoor; duration, 1.5 years

^an/a = not available

Table 5. Summary of influence of GGBS on carbonation-induced corrosion

depth with strength grade of concrete), although the conversion factor increases with increasing GGBS content, for practical purposes, on average a conversion factor of 1 week accelerated carbonation equals 0.60 year of indoor exposure can be assumed.

Influence of GGBS in carbonation-induced corrosion of reinforcement

Given that the use of GGBS as a cement component makes concrete more prone to carbonation, it is important to know if this affects the corrosion of steel reinforcement. Only the data where carbonation was reported to have reached the reinforcement is summarised in Table 5. The data where carbonation has not reached the reinforcement have not been considered further (Alonso *et al.*, 1988; Chi *et al.*, 2002; Redaelli and Bertolini, 2011; Sanchaoren and Uomoto, 2004; Sanchaoren and Uomoto, 2005). In general, the test specimens were made with up to 70% GGBS with w/c ratios of 0.35–0.83 and subjected to accelerated carbonation for up to 24 weeks or natural carbonation for up to 10 years. The corrosion of reinforcement was measured in terms of corrosion potential, corrosion current and weight loss of reinforcement. The overall results suggest that when carbonation reaches the reinforcement and its passivating layer is lost, the rate of corrosion of concrete made with GGBS is higher than

that of the corresponding PC concrete. Interestingly, it has also been reported that the rate of corrosion is not significantly influenced by w/c ratio or the duration of moist curing (Parrott, 1990, 1994, 1996).

In situ carbonation measurements

The measurements taken in Europe, Japan and the USA on in-service concrete structural members containing GGBS up to 85% and built since 1910 and tested at the age up to 60 years are given in Table 6 for GGBS concrete with corresponding PC concrete and in Table 7 for GGBS concrete alone (corresponding PC concrete data not available).

Table 6 shows that the addition of GGBS to PC at a similar w/c ratio reduces the carbonation resistance of concrete, even though the GGBS concrete benefits from higher long-term strength gain and exceeding the strength of the corresponding PC concrete. In one case, over a period of 20 years, the reported strength of GGBS concrete was 30% higher than the corresponding PC concrete (Litvan and Meyer, 1986), while the carbonation depths for PC and GGBS concrete were respectively 6 mm and 22 mm for indoor exposure and 3 mm and 13 mm for outdoor-unsheltered exposure.

Region	Structure				Concrete		In situ strength: MPa ^c	Cover: mm	Carbonation	
	Member/type	Year ^a	Age: years ^b	Exposure/ service condition	GGBS: %	w/c			Depth: mm	Rate: mm/year ^{0.5d}
Litvan and Meyer (1986)										
Beckum, Germany	Wall	1963–1964	20	Indoor	0	0.61	40.4 (co)	n/a ^e	6	1.34
					40	0.58	52.8 (co)	n/a	22	4.92
				Outdoor-unsheltered	0	0.61	40.4 (co)	n/a	3	0.67
					40	0.58	52.8 (co)	n/a	13	2.91
Meyer (1968)										
Germany	Building components	1910	53	Outdoor-sheltered	0	0.50	n/a	n/a	10–15	1.41–2.12
					45–75	0.50	n/a	n/a	> 15	> 2.12
Osborne (1989)										
North England	Roof slab	n/a	5	Outdoor-unsheltered	0	0.50	n/a	n/a	0	0
					70	0.50	37.2 (cu)	n/a	6	2.68
	Side wall	n/a	5	Outdoor-unsheltered	0	0.50	n/a	n/a	0	0
					70	0.45	47.8 (cu)	n/a	5.5	2.46
Thomas <i>et al.</i> (1990)										
England	Water tank wall	1986	2.5	n/a	0	0.55	58.5 (cu)	50	2.0	1.26
					50	0.55	64.0 (cu)	50	3.9	2.47

^aConstruction year

^bAge at field measurement

^cEstimated in-situ cube strength (cu), in-situ core strength (co)

^dApproximate estimated carbonation rate based on available data

^en/a = not available

Table 6. Compilation of field measurement data of concrete made with PC and GGBS

Region	Structure				Concrete		In situ strength: MPa ^c	Cover: mm	Carbonation	
	Member/type	Year ^a	Age: years ^b	Exposure/service condition	GGBS: %	w/c			Depth: mm	Rate: mm/year ^{0.5d}
Bertolini <i>et al.</i> (2004, 2011) Northern Italy	Wall	Early 1970s	30	Industrial (nuclear power plant)	n/a ^e	0.35–0.53	65.9 (cu)	28–40	16	2.92
					n/a	0.39–0.50	57.2 (cu)	18–38	14	2.55
					n/a	0.45–0.59	56.5 (cu)	28–44	23	4.20
					n/a	0.45–0.50	n/a	19–37	17	3.10
Lion <i>et al.</i> (2011) Northern France	Girder	1970s	30	Industrial, outdoor-unsheltered, marine salts	40	0.50	49.3 (n/a) ^f	n/a	15–20	2.74–3.65
Osborne (1989) North England	Column	n/a	5	Outdoor-sheltered	70	0.50	36.7 (cu)	n/a	15	6.71
	Floor/slab		4.5	Outdoor-unsheltered	50	0.50	38.5 (cu)	n/a	2	0.94
	Manhole cover		5		70	0.50	n/a	n/a	7	3.13
	Side wall		4	Indoor, dry, airy	50	0.62	n/a	n/a	19	9.5
	Base/floor		11		50	0.54	n/a	n/a	6.0–8.5	1.81–2.56
	Floor		4	Indoor, draughty	50	0.54	n/a	n/a	18.5	9.25
	Floor		11	Indoor, moist, humid to wet	50	0.54	n/a	n/a	5	1.51
	Wall		4	Indoor, dry and warm	70	0.45	n/a	n/a	17	8.5
Osborne (1994, 1999) Midlands, UK	Column	n/a	9.5	Outdoor-sheltered	70	n/a	65.0 (cu)	35	11–26	3.57–8.44
	Column			Outdoor-unsheltered	70	n/a	n/a	35	5.5	1.78
	Floor slab				70	n/a	51.0 (cu)	35	0.5–4.5	0.16–1.60
Schlörholtz and Hooton (2008) USA	Pavements, bridge decks	1992–2005	n/a	Outdoor-unsheltered	30–50	0.36–0.45	n/a	n/a	0–12	n/a
Soers and Meyskens (1991) Belgium	Building high floor	n/a	10	Outdoor	65	0.30–0.40	n/a	n/a	30	9.49
	Building low floor				65	0.30–0.40	n/a	n/a	10	3.16
Ozaki and Sugata (1988) Hokkaido, Japan	Caissons	1984	60	Marine – below sea level	70–85	n/a	n/a	n/a	0–4	0–0.52
Polder and de Rooij (2005) Scheveningen, Netherlands	Deck	1960	> 18	Marine	> 65	< 0.45	50–75 (n/a) ^f	35	2	< 0.47

Table 7. Compilation of field measurement data of concrete made with GGBS only (continued on next page)

Region	Structure			Concrete		In situ strength: MPa ^c	Cover: mm	Carbonation	
	Member/type	Year ^a	Age: years ^b	Exposure/service condition	GGBS: %	w/c		Depth: mm	Rate: mm/year ^{0.5d}
Polder <i>et al.</i> (2014) and Wiebenga (1980) North Sea Coast, Netherlands	Pier, quay wall, marine works	n/a	40–50	Marine	66–80	0.40	n/a	0–10	< 1.58
			30–40		66–80	0.40–0.45	n/a	1–8	< 1.46
			20–30		66–80	0.45–0.70	n/a	0–6	< 1.34
			10–20		66–80	0.38–0.55	n/a	0–5	< 1.58
			0–10		66–80	0.45–0.50	n/a	0–6	< 1.89

^aConstruction year
^bAge at field measurement
^cEstimated in-situ cube strength (cu)
^dApproximate estimated carbonation rate based on available data
^en/a = not available
^fAuthors did not specify whether the strength was cube or cored strength

Table 7. Continued

The data presented in Table 7 are for GGBS concrete alone and cover numerous parameters, making data analysis very difficult. However, based on the figures given in Table 6 and using the typical rate of 2.2 mm/year^{0.5} for PC concrete given by the Building Research Establishment (BRE, 1995), Table 7 shows that the estimated rate of carbonation of the GGBS concrete can be significantly higher than that of the PC concrete. The results of Osborne (1989) and Bertolini *et al.* (2004, 2011) in the table suggest that this can be so, particularly where exposure conditions are sensitive to carbonation. The results reported for the marine environment by Ozaki and Sugata (1988), Polder and de Rooij (2005), Polder *et al.* (2014) and Wiebenga (1980) are not helpful as the test concrete was likely to have been constantly in a saturated condition. Although information on concrete cover has been reported only in a few studies (Bertolini *et al.*, 2004, 2011; Osborne, 1994, 1999) and the data showed that carbonation had not reached the reinforcement at the time of reporting, it is estimated that some of the concrete members might have carbonation progressing beyond the cover depth before 50 years of service life. No follow-up reports on the relevant data could be sourced.

Measures to minimise the carbonation effect of GGBS concrete

While increased moist curing will definitely help to improve the resistance of GGBS concrete to carbonation, additional measures that may be taken into consideration when weighing up the ultimate balance between durability, sustainability, practicality and cost benefits are as follows.

- (a) Limit the GGBS content to a maximum of 35% as per Figure 4. This suggests that Portland–slag cement of type CEM II/A-S (6–20% GGBS) and CEM II/B-S (21–35% GGBS) as per BS EN 197 (BSI, 2011) may be used in concrete without significantly reducing its carbonation resistance. However, this option is less beneficial for reducing the carbon dioxide footprint.
- (b) Increase the strength of the concrete by significantly reducing the mix water content with the use of a high-range superplasticising admixture. This method can be applied instead of increasing the cement content of the concrete mix, which will enhance sustainability aspects.
- (c) Increase the cover when GGBS concrete is specified as per Figures 12 and 13. However, this option will directly affect the structural design and sustainability and cost implications, and is unlikely to be favoured by design engineers.

Comparing the carbonation resistance of GGBS and FA concretes

As mentioned previously, this study was deliberately structured to be similar to one on FA previously conducted by the authors (Lye *et al.*, 2015) so that a comparison of the effect of the GGBS and FA used as a component of cement on the

Cement replacement: %	Increase in carbonation with respect to PC: %		Cement	Mix adjustment for similar carbonation	
	FA	GGBS		Additional strength: MPa ^a	w/c reduction ^b
20	30	12	CEM I	0	0
30	45	25	CEM II/A (5–20% FA)	5.0	0.05
40	60	40	CEM II/A-S (5–20% GGBS)	n/a	n/a
50	75	60	CEM II/B (21–35% FA)	7.5	0.15
60	90	80	CEM II/B-S (21–35% GGBS)	5.5	0.10
70	n/a	110	CEM IV/B (36–55% FA)	10	0.25
80	n/a	140	CEM III/A (36–65% GGBS)	9.5	0.20
			CEM III/B (66–80% GGBS)	13	0.22

Table 8. Comparison of FA concrete and GGBS concrete: effect of replacement

^aPC at 37 MPa
^bPC at 0.55 w/c

Table 10. Comparison of FA and GGBS concretes: mix adjustment for similar carbonation

Cement	50-year estimated carbonation depth: mm ^a			
	At 37 MPa		At 0.55 w/c	
	Indoor	Outdoor-sheltered	Indoor	Outdoor-sheltered
CEM I	35	21	35	21
CEM II/A (5–20% FA)	40	25	43	27
CEM II/A-S (5–20% GGBS)	36	n/a	41	n/a
CEM II/B (21–35% FA)	45	28	56	42
CEM II/B-S (21–35% GGBS)	40	26	46	27
CEM IV/B (36–55% FA)	50	32	66	54
CEM III/A (36–65% GGBS)	48	29	59	34
CEM III/B (66–80% GGBS)	54	33	65	38
CEM III/C (81–95% GGBS)	57	n/a	75	n/a

^aData normalised so that the 50-year estimated carbonation of PC reference in FA and GGBS studies is similar under the same carbonation exposure

Table 9. Comparison of 50-year estimated carbonation depth for FA and GGBS concretes

carbonation resistance of concrete can be established with realism and confidence and in a manner that can be of practical value. Tables 8–11 summarise the salient points, which are as follows.

Cement type	Duration equivalent to 1 week accelerated exposure: year
FA	0.38–0.54
GGBS	0.60–0.65

Table 11. Relationship between accelerated and indoor carbonation relationship for FA and GGBS concretes

Addition effect

At the same addition level, the use of FA results in a higher increase in the carbonation of concrete than the use of GGBS (Table 8). At FA addition 10% below than that of GGBS, carbonation of the two concretes is essentially similar. As the GGBS contents used in practice are normally higher (commonly 40–60% GGBS compared with 20–30% FA), the carbonation of GGBS concrete is likely to be higher than that of FA concrete in practice.

50-year estimated carbonation depth

In relation to PC concrete, the carbonation rate of both FA and GGBS concretes designed on equal w/c ratio basis is higher than that of concretes based on equal strength basis (Table 9). Taking 25 mm minimum cover for concrete with a w/c ratio of 0.55 or characteristic cube strength of 37 MPa as specified in BS EN 206 (BSI, 2013), in indoor conditions, all three concretes (GGBS, FA and reference PC) are estimated to exceed the cover at 50 years. However, for outdoor-sheltered exposure, this minimum cover is sufficient for concrete made with CEM I, CEM II/A (5–20% FA), CEM II/A-S (5–20%

GGBS) and CEM II/B-S (21–35% GGBS) but not for CEM II/B (21–25% FA), CEM IV/B (36–55% FA), CEM III/A (36–65% GGBS), CEM III/B (66–80% GGBS) and CEM III/C (81–95% GGBS).

Mix adjustment for similar carbonation

In order to achieve similar carbonation to PC concrete, it is expected that the mix adjustment made in terms of additional strength or w/c ratio reduction for FA concrete would be more than for GGBS concrete at a similar addition level. However, with the current specifications for GGBS and FA additions, use of the former will call for greater mix adjustment than the latter (Table 10).

Accelerated and indoor carbonation relationship

Although the relationships between accelerated and natural carbonation established in the two studies (this work and Lye *et al.* (2015)) are different for FA and GGBS (as shown in Table 11), for practical purposes, a conversion factor of 1 week of accelerated carbonation (at 3–5% carbon dioxide concentration) equal to about 0.5 year indoor carbonation can be assumed.

Conclusions

- (a) In general terms, the combination of ground granulated blast-furnace slag (GGBS) with PC (Portland cement), similar to the range adopted in BS EN 197–1 (BSI, 2011), gives rise to increased carbonation. The extent of this increase depends in the main on parameters relating to the fineness of the GGBS and PC, the mix design and the maturity of the concrete at the time of exposure to carbonation.
- (b) Systematic analysis and evaluation of experimental data published over the last 50 years on the effect of GGBS in combination with PC on the carbonation of concrete brought out the following main points.
 - (i) In general, the carbonation of GGBS concrete remains similar to PC concrete up to 20% GGBS content (CEM II/A-S in BS EN 197-1 (BSI, 2011)); beyond this, the increasing rate of carbonation with GGBS content is of the order of 25%, 60% and 115% with 30% GGBS (CEM II/B-S), 50% GGBS (CEM III/A) and 75% GGBS (CEM III/B) content, respectively.
 - (ii) For a given GGBS replacement level, the increase in carbonation rate of GGBS concrete designed on an equal w/c ratio basis is higher than that based on an equal strength basis, with the difference between the two increasing with GGBS content. This was observed to be essentially similar for concrete exposed to accelerated and natural carbonation exposures. This should give more

credence to the accelerated carbonation testing of concrete, which was hitherto lacking.

- (iii) Although less extensively studied, there are indications that an increase in GGBS fineness or an increase in cement content with GGBS at a given w/c ratio improves the carbonation resistance of concrete.
- (iv) Provision for increased moist curing is the key to controlling the carbonation of GGBS concrete. Using increased moist curing coupled with equal strength design and lowering the GGBS content, the carbonation resistance of GGBS concrete can be engineered to be similar to that of PC concrete.
- (v) Plotting estimated 50-year carbonation data against the corresponding characteristic cube strength and w/c ratio suggests that indoor exposure results in the highest carbonation, followed by outdoor-sheltered and outdoor-unsheltered. The minimum cover of 25 mm for concrete with a minimum characteristic cube strength of 37 MPa or maximum 0.55 w/c ratio specified for the XC3 condition (for indoor and outdoor-sheltered exposures) in Eurocode 2 (BSI, 2004) may need to be reconsidered for concrete containing GGBS.
- (vi) One week of accelerated carbonation at 3–5% carbon dioxide concentration was found to be approximately equivalent to 0.6 years of indoor carbonation.
- (vii) The limited carbonation-induced corrosion data show that the rate of corrosion of GGBS concrete is higher than that of PC concrete when carbonation has reached the reinforcement.
- (viii) Field measurement data for in-service structural GGBS concrete members in Europe, Japan and the USA suggest that the carbonation rate of GGBS concrete could be higher than that of PC concrete, especially when exposed to carbonation-prone conditions. Some of the structures were estimated to have carbonation reaching beyond the cover depth before 50 years of service life.
- (c) In order to minimise the carbonation effect of GGBS concrete on the design of structural members, considerations may be given to limiting the addition of GGBS, increasing the characteristic strength and/or the cover depth of concrete. However, these options would have to be weighed against the various aspects that need to be considered when designing structural concrete, such as durability, sustainability, practicality and cost benefits.
- (d) Comparing GGBS concrete carbonation data with FA concrete carbonation data reported previously by the authors (Lye *et al.*, 2015), the main similarities and dissimilarities are as follows.
 - (i) Similarities. The increase in carbonation rate of both GGBS and FA concrete with respect to PC concrete

designed on an equal w/c ratio basis is higher than that based on an equal strength basis. The minimum cover recommended for a w/c ratio of 0.55 or characteristic cube strength of 37 MPa as specified in Eurocode 2 for XC3 exposure may need to be reconsidered for concrete containing GGBS and FA.

- (ii) Dissimilarities. Although the carbonation resistance of concrete with a given FA content is higher than that of concrete containing GGBS at the same level, as the latter is commonly used at a much higher level than the former in practice, GGBS concrete is likely to be at a higher risk than FA concrete. As such, the requirements for GGBS concrete in achieving a similar carbonation to PC concrete may have to be more stringent. Although the accelerated to indoor carbonation relationship varies for the two materials, this difference is within the associated variability of the data analysed and, for simplicity, it is possible to assume that 1 week of accelerated exposure equals 0.5 year of indoor carbonation.

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