DURABILITY ASPECTS OF MIXER ADDITION BLENDS OF GGBS WITH CEM I AND CEM II/A CEMENTS

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Abstract
This paper presents an overview of results of research into the durability characteristics of blends of GGBS with CEM I and CEM II/A cements. Ireland has led the way in Europe in permitting the mixer addition of GGBS to CEM II/A cements in the concrete mixer, in I.S. EN206-1. The development of this Irish standard has been contingent on the demonstration of the durability characteristics of these blends. To demonstrate this durability, specific research has been carried out in Ireland. These results are complemented by the results of similar research in Holland. The results of these studies are presented. Comparisons are made between the durability characteristics of these blends to concretes made with CEM III/A and CEM III/B cements.

Keywords: Carbonation, chloride ingress concrete durability, GGBS

1. Introduction

Concrete is the most-used man-made material on earth. However its main constituent, clinker-based cement, has a relatively high carbon footprint. The construction industry worldwide has embarked on a programme to reduce this carbon footprint, through many measures, in particular the substitution of clinker with supplementary cementitious materials, such as GGBS and fly-ash, and by using inert limestone filler.

As the cement industry in Ireland responded to the imperative to reduce its carbon intensity, new cement types came on to the market. CEM II/A cements replaced the more carbon-intensive CEM I cements, and GGBS became commercially available to Irish concrete manufacturers. With these new cement types, and combinations thereof, it was necessary to demonstrate the performance, in particular durability, of blends of these cements made at the concrete mixer.

In the 2006 revision to the Irish national Annex to EN 206-1, specific suitability had been established for the use of up to 50% GGBS with CEM II/A cements. However there was a growing demand from industry to move the upper limit up to 70% GGBS with CEM II/A cements for technical and environmental reasons.

2. Durability Testing

To determine the durability of combinations of CEM II/A cements with relatively high quantities of GGBS, a series of performance tests were conducted. Specific suitability for the use of up to 50% GGBS with CEM II/A, and up to 70% GGBS with CEM I had previously been established in earlier versions of the National Annex to EN 206-1. Before specific suitability could be established for the use of up to 70% GGBS with CEM II/A cements, supporting research data was required.

A number of key concrete durability aspects were considered: resistance to chloride ingress, resistance to carbonation and strength development. Freeze-thaw testing was not included due to the unavailability of suitable testing equipment at the time. Resistance to sulfate attack is not easily measured using concrete samples and as such is not included in this paper. The results of a separate research programme into the sulfate resistance of GGBS and CEM II/A cements is the subject of a separate paper at this conference.

2.1 Testing Methodology

Based on these concrete durability criteria, a series of tests were required to determine the performance of the concrete mixes. The tests were selected to be conducted in a reasonable time frame to allow direct comparison of the performance of the various concrete mixes.

Resistance to Chloride Ingress

Traditional test methods to quantify this resistance involve the long-term immersion of concrete samples within chloride-rich environments. While these experiments have been shown to produce reliable diffusion coefficients (McNally et al, 2005), they have the disadvantage of being very slow. Tang and Nilsson (1993) developed an accelerated test-method whereby the chloride diffusivity of a concrete sample may be determined by the application of an electric field. The depth of chloride penetration is visually determined by staining with silver nitrate and is used to determine a non-steady state migration coefficient. Tang and Nilsson have also shown how this can be converted to produce the more familiar effective diffusion coefficient, D_{eff}. This easy-to-use method is more commonly known as the Rapid Migration Test (RMT) and was formalised in Nordtest NT Build 492 (1999).

The RMT is typically measured on cylindrical test specimens A series of concrete slabs were cast that were 300 mm square and 100 mm deep. The slabs were cured for 3 weeks in water at 20°C, after which they were moved to a constant temperature room with a relative humidity of approximately 65%. When the samples were 3 months old test specimens were cored from this slab and subsequently cut to produce a test sample that was 100 mm in diameter and 50 mm thick. This was then subjected to the preconditioning and testing procedures as specified in NT Build 492.

Resistance to Carbonation

Resistance to the diffusion of CO_2 into the concrete matrix was determined using an accelerated carbonation testing unit that was built in house at UCD. The test chamber allows the user to set the desired temperature and CO_2 content. Relative humidity is not controlled but experience has shown that the system is constant in this respect. The carbonation chamber is instrumented with sensors to measure CO_2 content, temperature and relative humidity. A LabView programme was written to control the test environment and is connected to a CO_2 supply and an internal heater. A circulation fan is also fitted inside the chamber to ensure a consistent test environment and typical target test conditions are a CO_2 content of 5% and a temperature of 20°C.

The tests were conducted on 100 mm cube samples stored in the test chamber for preset time periods. The cubes were cured for 3 weeks in water at 20°C, after which they were moved to a constant temperature room with a relative humidity of approximately 65% for a further 7 days before testing. Samples were removed from the chamber after 7, 28 and 56 days and split in indirect tension. These were then treated using a phenolphthalein indicator and the carbonation depth measured by callipers on a set of 3 samples.

Compressive Strength
The compressive strength of the various mixes was determined using the standard method of casting concrete cubes and crushing them at preset time intervals up to 90 days.

Materials
For these tests, a series of concrete mixes were designed to reflect the mix designs featured in the National Annex to EN206. These comprised binder contents of 320 and 400 kg/m^3 and water/binder ratios of 0.55 and 0.45 respectively. The full list of combinations tested is shown below in Table 1.

Table 1 - Binder combinations chosen for testing

Mix No	Cement Type	GGBS Replacement Level (%)	Binder Content	Water/Binder Ratio
A1	CEM II/A-L	0	320 kg/m^3	0.55
A2		50		
A3		70		
A4	CEM II/A-V	0		
A5		50		
A6		70		
A7	CEM III/B	0		
B1	CEM II/A-L	0	400 kg/m^3	0.45
B2		50		
B3		70		
B4	CEM II/A-V	0		
B5		50		
B6		70		
B7	CEM III/B	0		

The coarse and fine aggregates used were sourced from a commercial quarry and are commonly used in concrete production. The cementitious binders used in the testing programme were a combination of the following:

- CEM II/A-L: class 42.5 Portland limestone cement
- CEM II/A-V: class 42.5 Portland fly-ash cement
- CEM III/B: class 32.5 Blastfurnace cement
- Ground granulated blast furnace slag (GGBS)

Note: CEM III/A cement has a GGBS content between 36% and 65%; CEM III/B cement has a GGBS content between 66% and 80%.

3. Results

The tests were carried out according to the methodologies previously described and the results are discussed below.

3.1 Resistance to Chloride Ingress

The RMT was conducted on 2 samples per binder combination and the results were processed following the procedures developed by Tang & Nilsson (1993) to produce an effective diffusion coefficient. Average values were calculated and these are presented in Figure 1. It can be seen that the highest diffusion coefficients all correspond to the binder combinations that contained 100% CEM II/A-L or A-V; this is observed for both sets of samples (i.e. 320 and 400 kg/m^3 of binder). In all cases the addition of 50% and 70% GGBS lead to significant reduction in the effective diffusion coefficient. It was observed that the addition of 50% or 70% GGBS produced binder combinations that were approximately equivalent with respect to their resistance to chloride ingress.

3.2 Resistance to Carbonation

Papadakis and Tsimas (2002) studied carbonation testing of concrete and found that the carbonation depth can be calculated from:

$$x_c = \sqrt{\frac{2\,D_{e,CO_2}\left(CO_2/100\right)t}{0.218\left(C+kP\right)}} \qquad (1)$$

where:

x_c is the carbonation depth;
t is time;
C is cement content (kg/m^3);
P is the SCM content (kg/m^3);
$D_{e,CO2}$ is the effective CO_2 diffusivity of concrete;
CO_2 is the CO_2 content of air at the concrete surface (%);
k is the efficiency factor of the SCM with respect to CO_2 diffusion

Furthermore Papadakis has shown that the CO2 effective diffusion coefficient is heavily influenced by the relative humidity, (2)

$$D_{e,CO_2} = 6.1x10^{-6}\ f(C,P,k,W)\left(1-\frac{RH}{100}\right)^{2.2} \qquad (2)$$

Samples were taken from the carbonation chamber at 7, 28 and 56 days and the depth of carbonation was determined. This was plotted against the square root of time and the slope of the trend line determined. The relative humidity was observed to be approximately 60% for the test duration. By assuming the $D_{e,CO2}$ to be constant with time, the slope of the trend line can be used with Equations (1) and (2) to predict the carbonation depth of concrete at CO_2 = 0.03%, RH = 80% after 50 years. These values are typical of the environment a structure such as a standard urban bridge can expect to encounter in service. The results of this analysis are presented below in Figure 2.

The results are in agreement with previous work done by Papadakis (2000) who found that Supplementary Cementitious Materials (SCM) when used as a cement replacement, lead to increased carbonation depths. This is confirmed in this experimental programme where it is observed that the higher carbonation depths for each cement type corresponds to the use of 70% GGBS.

It should also be noted that the relative humidity of the ambient air plays a significant role on the observed carbonation depths, with increases in RH leading to reductions in carbonation (Papadakis & Tsimas, 2002). The carbonation chamber used for this study does not control humidity, but instead monitors the RH levels; for the duration of these tests the RH level was observed to be consistently around 60%. If these tests were conducted with a variable RH corresponding to field conditions, it is expected that the relative performance of the concrete binder combinations would remain, but the values of the carbonation depths would change.

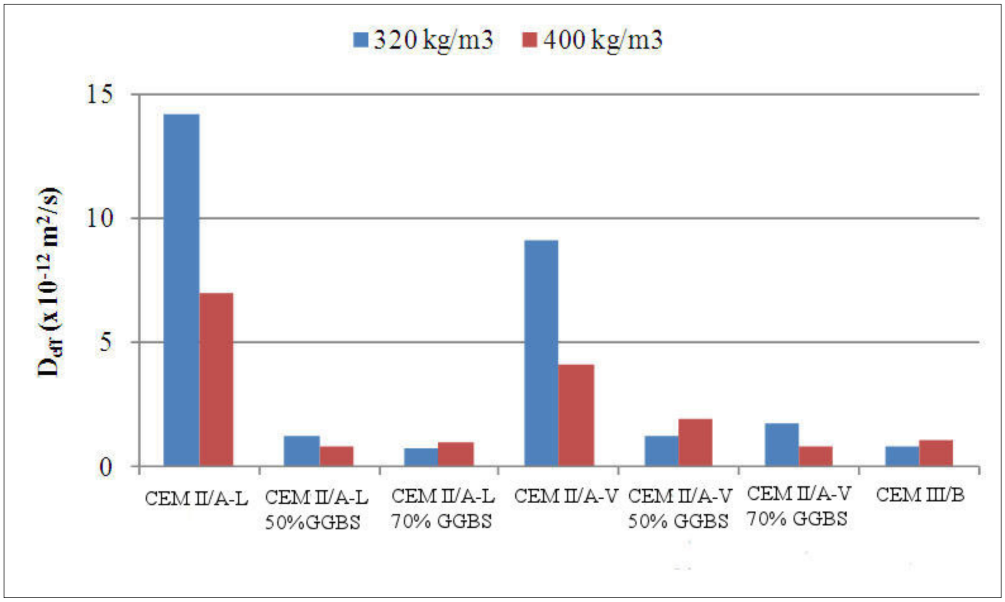

Figure 1 – Effective diffusion coefficients for the various binder combinations tested

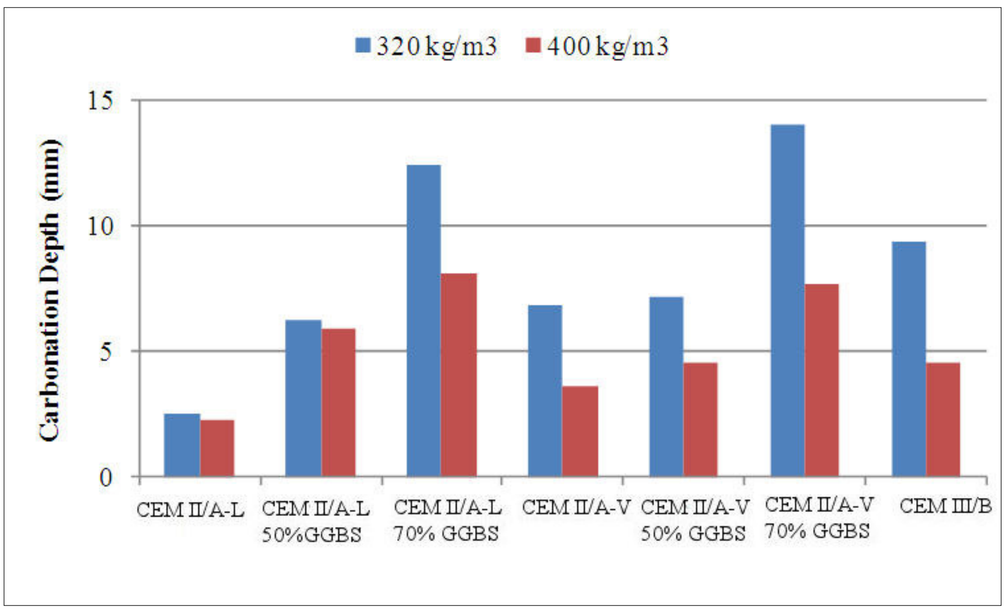

Figure 2 – Predicted 50 yr carbonation depth for the various binder combinations tested, based on Papadakis & Tsimas (2002)

3.3 Compressive Strength

The compressive strength of the various binder combinations was determined and these are presented in Figures 3 and 4. It can be seen that higher strengths were associated with the CEM II/A-L cement and not the CEM II/A-V cement. The use of a 50% GGBS replacement level resulted in almost unchanged strength levels at 28 days for both CEM II/A cement types. The lowest strength for each binder content corresponded to the combination of CEM II/A-V with 70% GGBS.

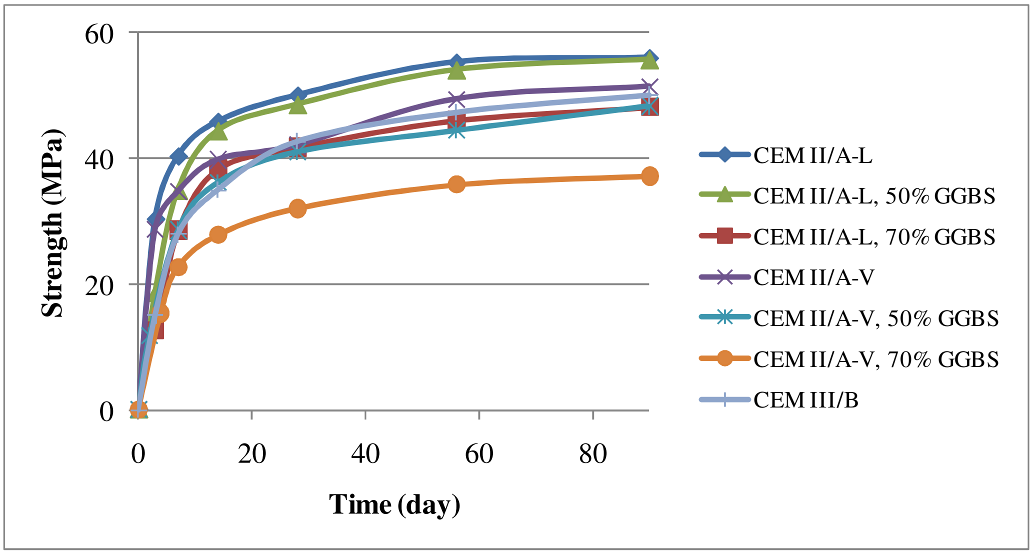

Figure 3 – Compressive strengths for binder contents 320 kg/m^3, w/b ratio 0.55

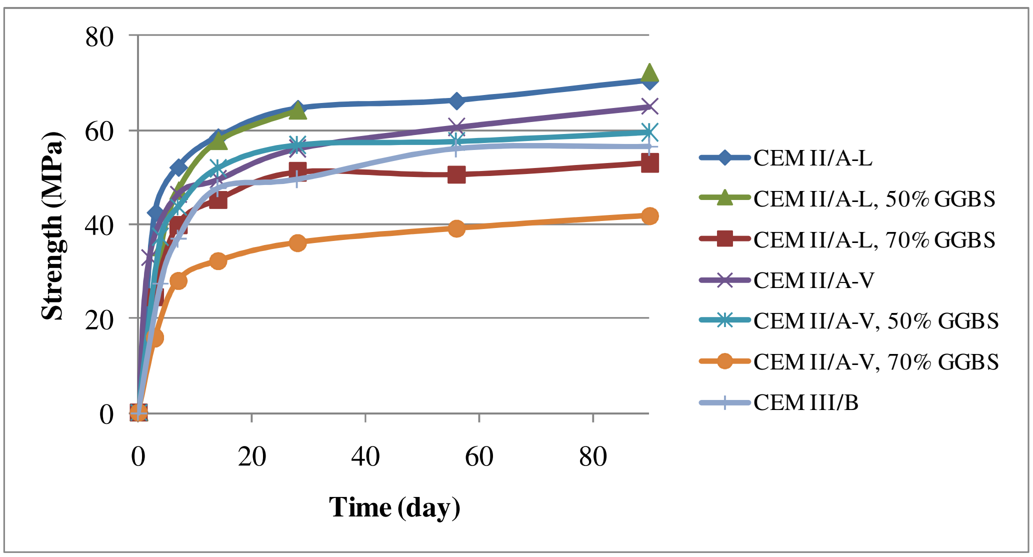

Figure 4 – Compressive strengths for binder contents 400 kg/m^3, w/b ratio 0.45

4. Comparison with International Studies

Mixer addition of GGBS with CEM I cements has been in use in the Netherlands since 2002. Comparative studies have been carried out (Creemers, 2008) to demonstrate the equivalent performance with CEM III cements, for which suitability is generally established in the Dutch market. Studies were carried out on GGBS:CEM I mixer blends at 50:50 and 70:30, to compare to CEM III/A and CEM III/B cements respectively. The results of these tests are summarised below.

4.1 Resistance to Chloride Ingress

The results in Table 2 demonstrate that the performance of mixer addition of GGBS and CEM I cements are comparable to, or even slightly better than the CEM III cements. These tests were carried out on concretes with a binder content of 340 kg/m^3, and a w/c ratio of 0.45. The tests were carried out according to the Nordtest NT-Build 443 testing methodology.

Table 2 – Resistance of binder combinations to chloride ingress

Sample Type	**Effective Diffusion Coefficient (x 10^{-12} m^2/s)**			
	a	**b**	**c**	**Mean**
CEM III/A (42.5 N)	2.7	4.5	3.6	3.6
50:50 GGBS:CEM I (42.5 R)	1.7	2.8	3.2	2.6
50:50 GGBS:CEM I (52.5 R)	1.9	2.0	2.0	2.0
CEM III/B (42.5 N)	2.8	3.4	1.8	2.7
CEM III/B (42.5 N)	3.2	3.6	3.0	3.3
CEM III/B (32.5 N)	2.6	2.7	2.1	2.5
70:30 GGBS:CEM I (52.5 R)	2.1	1.7	1.5	1.8
70:30 GGBS:CEM I (42.5 R)	1.5	2.1	2.0	1.9
70:30 GGBS:CEM I (52.5 R)	2.0	1.5	2.4	2.0
70:30 GGBS:CEM I (42.5 R)	2.6	2.5	1.7	2.3

Table 3 – Resistance of binder combinations to carbonation

Sample type	**Binder content (kg/m^3)**	**w/c ratio**	**Average carbonation depth (3 samples, mm)**
CEM III/A (42.5 N)	300	0.55	3.0
50:50 GGBS:CEM I (42.5 R)	300	0.55	3.0
50:50 GGBS:CEM I (52.5 R)	300	0.55	2.0
CEM III/B (42.5 N)	300	0.55	5.0
70:30 GGBS:CEM I (52.5 R)	300	0.55	5.0
CEM III/B (42.5 N)	340	0.45	5.0
70:30 GGBS:CEM I (42.5 R)*	340	0.45	4.5
70:30 GGBS:CEM I (52.5 R)	340	0.45	2.3
CEM III/B (32.5 N)	340	0.45	2.5
70:30 GGBS:CEM I (42.5 R)*	340	0.45	2.0

*Note: Results are for two different CEM I (42.5 R) cements

4.2 Resistance to Carbonation

Carbonation tests were carried out on samples made with CEM III cements and with mixer addition of GGBS and CEM I. The tests were carried out according to the CUR 48 methodology, with CO_2 concentrations were 0.04% at a temperature of 20°C and RH of 65%. Concretes with binder contents of 300 kg/m^3 and 340 kg/m^3 were tested. The tests results indicate that there are no adverse effects on resistance to carbonation when concretes are made with mixer additions of GGBS and CEM I, compared to the CEM III cements.

5. Discussion

The test results show that the substitution of up to 50% to 70% GGBS for CEM II/A significantly reduces the chloride diffusion coefficient in concrete compared to the

CEM II/A cements alone. The diffusion coefficient with the blends of GGBS and CEM II/A are similar to those measured in concretes made with CEM III/B cements.

The presence of GGBS in concrete does increase the depth of carbonation as measured under laboratory conditions. However the test data demonstrates that this is still low relative to the concrete cover required by I.S. EN 206-1 to protect against carbonation induced corrosion. This is in agreement with long-term carbonation studies in Germany (Wierig, 1984) that have shown carbonation depths of concretes with up to 75% GGBS to be low in relation to concrete cover. This experience is reflected in the German concrete standard (DIN 1045-2:2008) where the limiting values in the carbonation exposure classes are the same for both CEM I and CEM III/B cements, as is the case for UK, Dutch and French concrete standards.

Data from comparative durability testing conducted in the Netherlands supports the practice of mixer addition of high levels of GGBS with CEM I cements. For a series of binder combinations, it was shown that these mixes produced approximately equivalent durability performance in terms of chloride and carbonation induced corrosion as concretes manufactured using either CEM III/A or CEM III/B factory blended cements.

6. Conclusions

The use of GGBS in concrete, whether added at the concrete mixer or as a factory-blended CEM III cement, improves the resistance of concrete to chloride attack; it will also result in an increase in the carbonation depth in concrete.

The data presented above has been used to support a change in the Irish National Annex to EN 206, which now permits the mixer addition of 70% GGBS with either a CEM II/A-L or CEM II/A-V across all exposure classes. This change now offers more flexibility to concrete manufacturers seeking to produce a product with a reduced carbon footprint.

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