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Durability of Portland blast-furnace slag cement concrete

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Abstract

This paper summarizes the results of studies carried out at the Building Research Establishment in the UK, on the performance and long-term durability of concrete where ground glassy blast-furnace slag (granulated and pelletized) has been used as a cementitious material. Using data from tests on site structures and laboratory and exposure site studies, comparisons are made of the properties and performances of the slag cement concretes with normal Portland cement concretes of similar mixture proportions. A number of recommendations are given for the effective use of ground glassy blast-furnace slag in concrete. The many technical benefits available to the concrete user, such as reduced heat evolution, lower permeability and higher strength at later ages, decreased chloride ion penetration, increased resistance to sulfate attack and alkali silica reaction were affirmed. However, a cautionary warning of the importance of good early curing is made to ensure that the adverse effects of higher rates of carbonation, surface scaling and frost attack are minimized. The paper is intended to provide guidance for those concerned with the design, specification, application and performance of concrete in practice where slag can also help to reduce costs and energy demands in the production of cement compared with normal Portland cement. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Blast-furnace slag cement; Concrete durability; Performance in marine environment; Portland cement; Site structures

1. Introduction

The Building Research Establishment has carried out laboratory and field studies for many years to assess the performance and durability of concretes containing Portland cements and blends of the same with ground granulated and pelletized blast-furnace slags [1]. The influence of ground glassy blast-furnace slag to BS 6699:1986, "Ground granulated blast-furnace slag for use with Portland cement" on selected concrete properties and the contributions to the improvement of these properties, particularly on long-term durability of laboratory-prepared concrete, have been determined in recent studies at the Building Research Establishment [1–7]. The main properties covered were carbonation, permeability, sulfate resistance, acid resistance, performance in marine environments and the effect on alkali–silica reaction. The penetration of ionic species, protection of steel reinforcement and frost resistance are dealt with in the section on marine studies. These studies, which also cover heat-release data, examined mainly materials available in the UK but have included some from abroad.

Among early examples of the use of ground granulated blast-furnace slag (GGBS) in structural concrete in the UK is the Humber Bridge and a more recent structure containing GGBS is the Tees Barrage [5,6]. The long-term durability of concrete is dependent upon a number of physical and chemical parameters. It is generally recognized that the foremost prerequisite for durable concrete is that it be dense and impermeable to liquids and gases with a high resistance to the penetration of ionic species such as sulfates and chlorides. For the best performance the mixture proportions must be appropriate to the particular application and the preparation, placing, compaction and curing should be carried out under proper supervision. In the UK, British Standard BS 8110:Part 1:1985 "The structural use of concrete" is the code of practice for design and construction.

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BS 5328:Part 1:1990, "Guide to specifying concrete", advises on the selection of material and the specification of mixes for the production of concrete with the required properties in the fresh and hardened state, and places a considerable emphasis on durability. Distinction is made in BS 5328 between structural and non-structural concrete and between unreinforced, reinforced and prestressed concretes. Account is taken of standard specifications relating to GGBS used in composite cements or in equivalent combinations. Other specifications relevant to these studies are BS 6349:Part 1:1984, "Code of practice for maritime structures, Part 1. General criteria", and the Draft European Standard, EN206, Concrete, document N249, "Concrete-performance, production, placing and compliance criteria".

Most of the data reported relate to studies carried out by the Building Research Establishment in the UK and this paper is essentially an expanded update of Building Research Establishment Information Paper 1P6/92 [1]. However, the results of an important case study on the performance of high-quality slag concrete exposed to a severe Arabian Gulf environment are also highlighted [8]. Particular attention is drawn to the adverse effects of poor early curing of slag cement concretes with respect to surface scaling of concrete.

2. Studies of site structures

The quality and performance of concrete in large, site-stored blocks and in actual structures have been determined by testing drilled cores taken from a number of locations in the UK [1–6]. The concrete cores contained different levels of ground granulated blast-furnace slag (0, 30, 50 and 70%) by weight as cement replacement material and were assessed in terms of their depth of carbonation and gas or water permeability, and compressive strength. The field structures had been designed to comply with BS 5337:1976, "Code of practice for the structural use of concrete for retaining aqueous liquids" (now BS 8007:1990). Data are given from three case studies.

1. For cores taken from two identical reinforced concrete structures where 70% GGBS was used with 30% Portland cement [4].
2. From a series of large concrete blocks, stored at an industrial site, where 0, 30, 50 and 70% of GGBS was used as replacement.
3. From metre cubes of concrete made with 70% GGBS/30% PC, placed upstream and downstream of the Tees Barrage [5,6].

2.1. The structures studied

2.1.1. Two identical reinforced concrete structures

Slender reinforced concrete columns which formed sheltered walkways on either side of a plant house building in the Midlands, UK, and made from the same concrete as the floors adjacent to them, contained 70% GGBS as cementitious material and had a total cementitious content of 370 kg/m^3. The main findings of this study have been reported previously [4] and relate to the variable effects that the external microclimate surrounding the columns had on important concrete properties such as carbonation, permeability, strength and on the longer term durability. Some of the results are given in Table 1 and Table 2.

2.1.2. Series of large concrete blocks (750 mm)

A series of nine large concrete blocks, (750 mm cube), initially cured in their moulds for 7 days, while stored outside on an industrial site at Scunthorpe in NE England were assessed at 7–8 months, 30 months and at 7.5 years of age. The side faces, partly protected from driving rain, were cored at each age, and carbonation depths, oxygen permeability and compressive strengths determined. The results are given in Table 3 and Table 4 and comparisons made between the different concretes of 390 kg/m^3 cement content which contained a range of GGBS levels in the cement and had gravel or limestone as aggregates.

Table 1
Carbonation data from Midland site cores [4]

Concrete Element (370 kg/m^3)	External Environment	Mean depth of carbonation (mm)			
		East side		West side	
		5 years	9.5 years	5 years	9.5 years
Vertical columns	Open/sheltered	ND	11–13.5	14–15	16.5–26$\neq$
	Exposed to the elements	ND	5.5	ND	ND
Floor slab	Fully exposed	ND	4.5	0.5	1.0

ND, Not Determined, $\neq$, maxima of 35 mm at some rebar locations.

Table 2
Permeability and strength data from cores [4]

Concrete	Oxygen permeability (mean)				Estimated *in situ* mean compressive strength (MPa)
	Core section depth from surface (mm)	Conditioning prior to test (days)	Permeability coefficient ($ko \times 10^{-17}$ m^2)		
			5 years	9.5 years	9.5 years
East-side					
Vertical column	0–100	28		2.06	63.5
	100–200	28		0.56	66.0
	200–300	28		5.69	ND
Floor slab	0–50	28		3.15	ND
	50–150	28		ND	51.0
West-side					5 years
Vertical column	0–100	27–38	6.40	22.2	36.5
	100–200	27–38	4.33	3.16	40.5
	200–270	38	3.07	ND	ND
Floor slab	0–100	41	11.40	ND	ND
	100–200	27–41	2.38	0.40	35.0

2.1.3. *Metre cubes of concrete at Tees Barrage*

To help meet the durability requirements of a 120-year design life for the prestigious concrete barrage across the River Tees in NE England, a blend of GGBS and Portland cement was used. Sacrificial concrete blocks (m^3) were made using the same concrete mixture proportions as the concrete barrage. The blocks were cured outside in their moulds for 4 days, then demoulded and left for about a year before being placed downstream in the tidal seawater and in a semi-submerged situation upstream in freshwater. The Building Research Establishment was commissioned to monitor the concrete performance of the Tees Barrage itself and used cores from the metre cubes in this assessment [5,6]. The results of tests to determine changes in permeability to oxygen and chloride ions are given in Figs 1 and 2.

2.2. *Discussion of results from site studies*

2.2.1. *Carbonation*

The depth of carbonation of these site-stored concretes, as measured by spraying the cores with phenolphthalein indicator, showed a wide range of values. The two main factors influencing the carbonation were the environmental conditions in which the concretes were situated and the level of slag as replacement for Portland cement. Evidence from earlier studies on field structures [2,3] showed that concretes with 50% slag as replacement achieved resistance to carbonation similar to that of normal Portland cement concretes of equivalent mixture proportions, in most indoor and outdoor environments. However, carbonation was greater in the high-slag-content (70%) cements, especially if associated with a sheltered or

Table 3
Carbonation of large concrete blocks (750 mm)

Block no	Total cement kg/m^3	Slag %	Aggregate		Mean depth of carbonation (mm)	
			Gravel	LST	2.5 years	7.5 years
1	390	50			<0.5	0
2	390	50			1	1
3	393	50			1	0
4	397	0			0	0
5	390	30			0.5	0.5
6	390	70			4.5	5.5
7	390	50			1	1
8	391	70			8	5
9	390	50			1.5	1.5

Table 4
Permeability and strength data (750 mm block) at 7.5 years

Core	Oxygen permeability (ko × 10^{-18} m^2)			Core strength	Estimated cube strength (MPa)
	Section 1	Section 2	Section 4	Section 3	
1	6.12	3.45	3.51	84.0	87.0
2	3.56	0.68	0.50	86.5	91.0
3	2.97	1.09	0.65	101.5	105.0
4	6.15	4.29	1.03	65.5	67.5
5	18.32	3.96	1.50	79.0	82.5
6	4.87	4.61	2.95	87.0	88.5
7	4.12	1.09	3.81	86.0	89.0
8	6.01	3.75	1.84	83.5	86.0
9	2.01	0.96	2.25	ND	ND

$$\text{Estimated Cube Strength} = \frac{\text{D} \times \text{measured core strength}}{1.5 + \frac{1}{\lambda}}.$$

D = 2.5 (for horizontally drilled cores). λ = length of core diameter.

drying microclimate. This confirmed the findings of earlier laboratory-based studies at Building Research Establishment [7]. These studies had shown that slag cement concretes, particularly at high levels of replacement, such as 70 and 80%, carbonated significantly more than Portland cement concretes of similar mixture proportions when specimens were not moist-cured and were subsequently stored in dry internal environments. Carbonation was greater in the high-slag-content concretes in these situations and they developed lower compressive strengths. However, the concretes stored in water or those from the exposure sites that had been subjected to moist conditions, attained their design strengths and showed little or no carbonation. For this series of concretes there was a good correlation between depth of carbonation and compressive strength at 28 days and later ages, with the carbonation depth varying proportionally to the square root of the age of the concrete [7]. The data from the three more recent studies [4–6] are discussed below.

2.2.1.1. Slender reinforced columns (300 mm)

The predominant factor to affect the rate of carbonation of these and other concretes was the microclimate around the vertical columns and floor slabs of the structure (Table 1). The level of GGBS as replacement for normal Portland cement and total cementitious content was also important, as the concretes with 70%

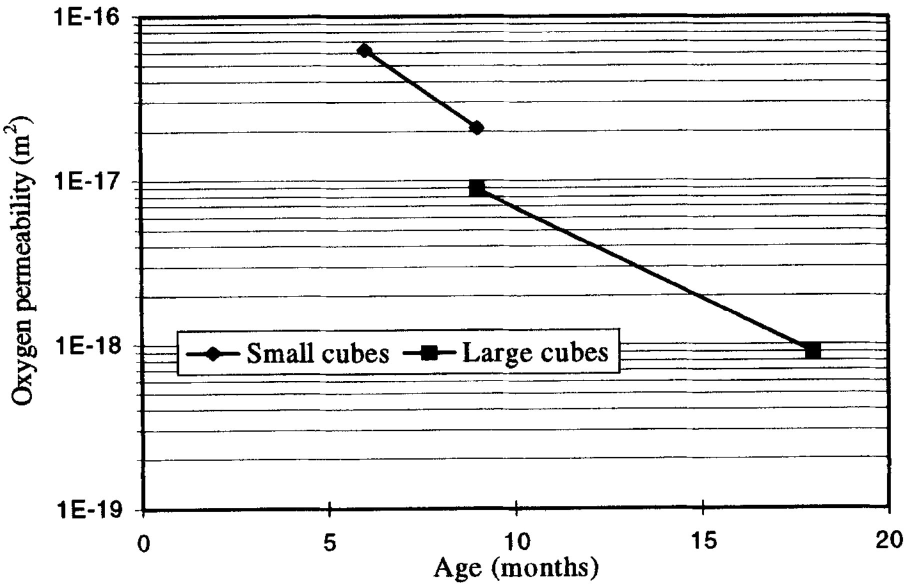

Fig. 1. Change in oxygen permeability with time.

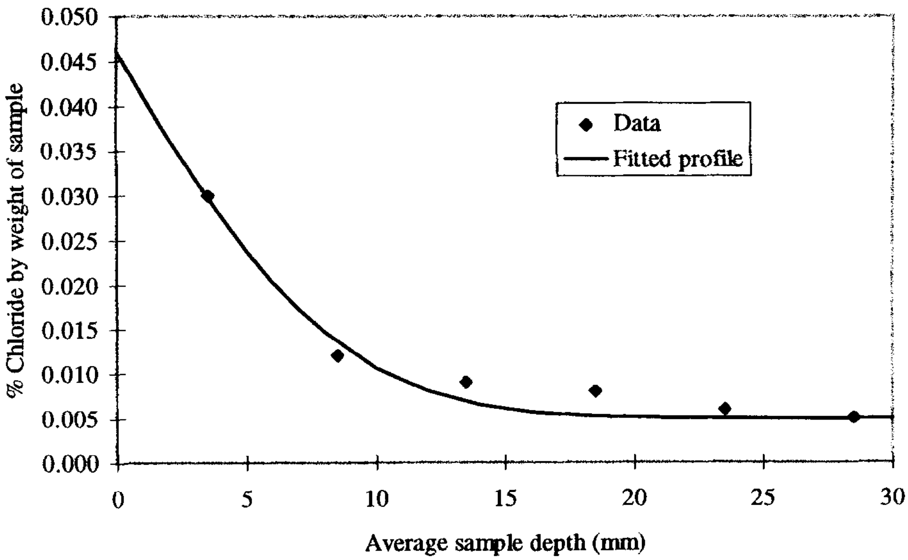

Fig. 2. Chloride ion penetration into metre blocks.

GGBS produced high rates of carbonation in certain situations, such as in a sheltered windy environment. In places carbonation had extended beyond the steel reinforcement to depths of 35 mm in 9.5 years, yet there were no signs of corrosion [4] (Fig. 3).

2.2.1.2. Large concrete blocks on an industrial site

Carbonation was slow to commence but had developed to a near constant depth at 2.5 years in what was essentially a mass concrete in the fairly exposed industrial environment. There was little change after a further 5 years of exposure (Table 3). The 70% GGBS, gravel and limestone aggregate, concretes had carbonated to ≈5 mm, compared with ≈1–1.5 mm for the 50% slag concretes. There were only small differences between the plain PC concretes and those with 30 and 50% of slag, irrespective of aggregate type.

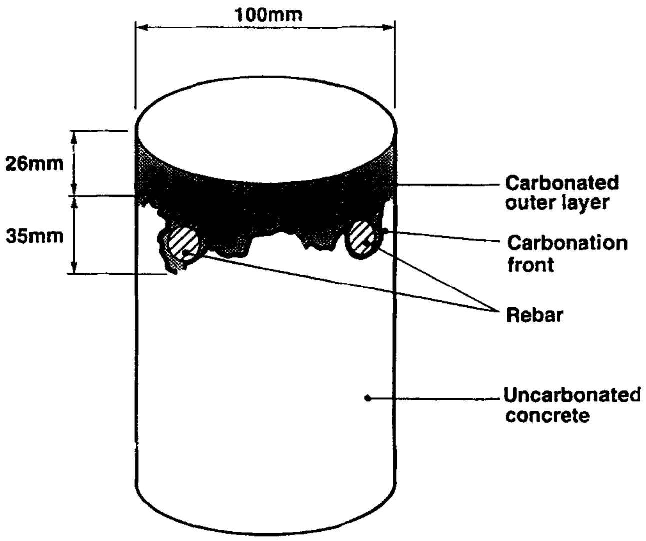

Fig. 3. Concrete core showing carbonation beyond rebar after 9.5 years' exposure.

2.2.1.3. Metre concrete blocks at Tees Barrage

Limited carbonation measurements, taken when the slag cement concrete was aged, ≈3 years, indicated that depths of 5–6 mm were present.

2.2.2. Oxygen permeability and compressive strength

Parallel-sided 50-mm sections, and some 105-mm-long sections, cut from 100-mm-diameter cores, were used for oxygen permeability and compressive-strength measurements respectively. Sections 50-mm deep taken from 150-mm cores were also used to determine the concrete permeability using the method developed by Lawrence [9], following periods of at least 27 days of conditioning in a special nitrogen-purge cabinet to maintain a carbon-dioxide-free atmosphere. The outer sections sometimes contained a carbonated layer, while the inner sections (100–200 mm) were representative of totally uncarbonated concrete. The technique utilizes a combination of Darcy's law and the Poiseuille equation for the determination of the permeability coefficient *ko*.

2.2.2.1. Slender reinforced columns (300 mm)

The oxygen permeability and compressive-strength data presented in Table 2 provide a comparison of 5 and 9.5-year data from the eastside and the westside structures. (There were no 5-year permeability data from the eastside structure).

2.2.2.2. Floor slabs

Concrete from the floor slabs where carbonation was minimal has become less permeable with time. The permeability coefficient *ko* values of the order of 0.4×10^{-17} m^2 are considered to be typical of good, low-permeability concrete [10].

2.2.2.3. Columns

Cores cut from the columns showed that sections from the inner concrete had similar *ko* values at both ages, in the range 3–4.5 $\times 10^{-17}$ m^2, also considered to be of fairly low permeability. Outer sections cut to depths of up to 100 mm tended to be more permeable and in the range $ko = 6.4\text{–}\approx 20 \times 10^{-17}$ m^2. These data indicate that, in certain microclimates within external, sheltered, but windy environments, higher rates of carbonation in slender columns may be associated with increased gas permeability. Problems could arise later if intermittent wetting occurred, as the reinforcing steel may become vulnerable to the effects of moisture and oxygen and lead to corrosion. However, although the slender concrete columns had carbonated beyond the rebar in places, no corrosion had taken place as the relative humidity inside the concrete at these sites was not sufficiently high [4,11]. Compressive strength data were encouraging as, in general for both the slabs and columns, these high-slag-cement concretes had continued to gain in strength with time in all situations [4].

2.2.2.4. Large concrete blocks on an industrial site

In general, gas permeability decreased slightly and as slag replacement levels were reduced from 70% to 50%, although *ko* values were in the range 0.5–18.3 $\times 10^{-18}$ m^2 which indicated that the concretes were of low permeability [10]. Compressive strength gains were realized with time for all concretes, irrespective of cementitious content or aggregate type (Table 4). With the exception of the plain Portland cement concrete which had the lowest, but reasonable, strength of 67.5 MPa at 7.5 years the slag cement concretes were very high strength and in the range of 82.5–105 MPa at the same age, clearly demonstrating the benefical longer term effect of slag.

2.2.2.5. Metre blocks at Tees Barrage

Figure 1 shows the decrease in oxygen permeability with time over the first 18 months of the site-monitoring programme. The intrinsic permeability *ko*, ranged from 6.2×10^{-17} m^2 (in small cubes at an age of 6 months) to 8.9×10^{-19} m^2 in the metre blocks aged 18 months. Compressive strength data have been obtained at various ages from both small test cubes (150 mm) and cores from large test blocks. The mean compressive strength at ages of 5, 9 and 18 months were 58, 63 and 72 MPa respectively, showing improved long-term strength and associated reduced permeability.

3. Laboratory and exposure-site studies

The resistance of Portland and slag cement concretes to sulfate, acid and marine environments was assessed in a series of durability studies using laboratory storage and external exposure sites. Concretes were prepared at the Building Research Establishment with mixture proportions that satisfied the minimum requirements of the relevant British Standard specifications for severe sulfate and marine exposure conditions. BRE Digest 363 (Table 1 Classes 3–5) [12] covered the sulfate-resistance studies and all concretes were designed to equal cementitious (slag + PC) content and workability and not to the same 28-day strength. A series of concretes were prepared using three Portland cements of low, medium and high tricalcium aluminate (C_3A) content and five blast-furnace slags (two pelletized and three granulated) with low, medium and high alumina (Al_2O_3) levels. Thames Valley coarse and fine aggregates were used. Specimens cast were plain concrete cubes (100 mm) and prisms (305 × 100 × 100 mm) containing reinforcing bars (rebars) at nominal cover depths of 10 and 20 mm. All concretes had a nominal cementitious content (i.e. Portland cement plus slag) of 380 kg/m^3. Details of the concrete mixture proportions, fresh concrete properties and curing regimes have been reported previously [13], although the basic information on the mixture design and the chemical analyses are given in Tables 5 and 6.

3.1. Sulfate resistance

Studies [13,14] have shown that the sulfate resistance of Portland and blast-furnace slag cement concretes is dependent upon the following criteria: curing regime, cement type (C_3A content of Portland cement and alumina content of slag) and the storage solution.

3.1.1. Curing regime

The early curing of concrete (in the first few weeks after manufacture) was the most significant factor influencing sulfate resistance, as it was with other

Table 5
Selective analytical data for Portland cements and blast-furnace slags

Cementitious materials			
Portland cement	C_3A (%)	Blast-furnace slag	Al_2O_3 (%)
SRPC 853	0.6	M302 (Pelletized)	7.5
PC 850	8.8	M347 (Pelletized)	11.1
PC 814	14.1	M357 (Granulated)	9.3
		M364 (Granulated)	11.5
		M286 (Granulated)	14.7

Table 6
Concrete mixture proportions and wet concrete properties

Concrete mix proportions					Fresh concrete properties (mean values)		
Thames Valley aggregates			Cement	Water			
20–10 mm (67%)	10–5 mm	<5 mm	(Slag + PC)	Total W/C (free W/C)	Cement content (kg/m³)	Wet density (kg/m³)	Slump (mm)
	2.91 (33%)	1.75	1.0	0.5 (0.45)	380	2340	75

cement properties. However, contrary to requirements for other durability properties, it was found that a period of air storage before immersion in sulfate solutions is beneficial to sulfate resistance. Irrespective of cement type, concretes cured in air for 27 days at 20°C and 65% relative humidity, before immersion in high-strength sulfate solution, were extremely resistant to sulfate attack. Even concretes demoulded after 1 day and placed in sulfate solution within the next few hours, showed better resistance to attack than specimens water-cured for up to 28 days to attain their design strength before immersion. This is at variance with the normal requirements and recommendations for the proper curing of concrete for most other applications, where there is a need to minimize the effects of carbonation and to attain optimum strength development as discussed earlier. However, the effectiveness of 27 days of air storage was clearly demonstrated by the excellent physical appearance, strength retention and low degree of sulfate attack observed in Portland and blast-furnace slag cement concretes alike (See Fig. 4). This beneficial effect is thought to be primarily due to the formation of a carbonated outer layer leading to blocking of the pores and refinement of the pore structure [14]. The practical significance of this finding is discussed in a Building Research Establishment report of long-term studies of sulfate resistance of buried concrete [15].

3.1.2. Cement type

The main chemical factors that influenced the sulfate resistance of Portland and blast-furnace slag cements were the C_3A content of the Portland cement and the alumina level of the slag [14,16]. Low C_3A, sulfate-resisting Portland cement (SRPC) concretes were highly resistant to attack, as were combinations of the medium and high C_3A normal Portland cements with low alumina slags. Sulfate attack was greatest when both the C_3A content of the Portland cement and the alumina level of the slag were high (Fig. 4). The level of replacement of normal Portland cement by slag was also important with 70 and 80% proving most beneficial, particularly for high C_3A normal Portland cements, when substantial reductions in sulfate-ion ingress were realized.

3.1.3. Storage solution

Magnesium sulfate was generally a more aggressive agent than the equivalent strength sodium sulfate solution. There appears to be an increased sensitivity of slag cements (and cements containing fly ash) to strong magnesium sulfate solution. Consequently the additional precaution of limiting water-soluble magnesium has been introduced when these cements are used in sulfate classes 4 and 5 in BRE Digest 363 [12].

3.1.4. Building Research Establishment Digest 363

The beneficial effect of GGBS on the sulfate resistance of concrete has been clearly demonstrated in Building Research Establishment work [12–16]. This is recognized in BRE Digest 363 [12], which advocates the use of a minimum of 70% slag as replacement of normal Portland cement in severe sulfate conditions (classes 4 and 5), with caveats on the alumina content of the slag and C_3A level of normal Portland cement. The digest recommends that: "for sulfate resistance purposes, slags with an alumina content of over 14% should be used only with Portland cements with low to moderate C_3A content (typically less than 10%)." Recommendations made in the digest were based upon the studies of immersion of concrete cubes in sulfate solutions described above, together with the results from a study of concretes buried in London's highly sulfated clayey soils at Northwick Park [15].

3.2. Acid resistance

The performance of slag cement concrete specimens stored in moorland water of ≈pH 4.0., but with little dissolved carbon dioxide, is being studied by Building Research Establishment at an exposure site in South Yorkshire in the UK. In general the quality of the concrete has been found to be of greater importance than the type of cement used in such aggressive solutions [1]. However, the reduced calcium hydroxide content and lower porosity resulting from well-cured PC/slag and PC/fly ash concretes is generally regarded as being beneficial in reducing the rate of attack [12]. Marginal benefits have been achieved by using higher levels of slag as replacement for PC and these need to be substantiated at greater ages.

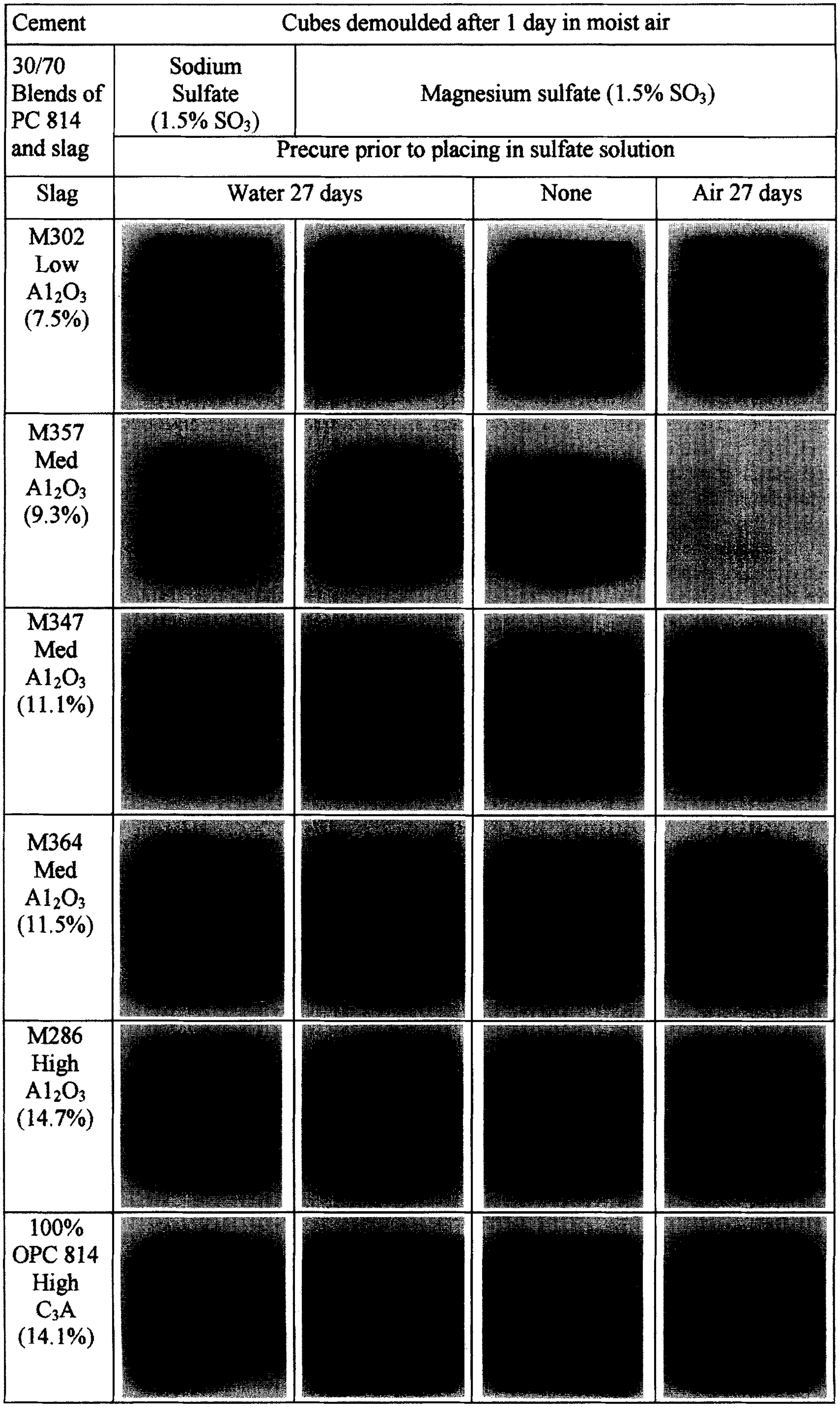

Fig. 4. Sulfate resistance of Portland blast-furnace slag cement (70% GGBS) concretes at 2 years.

3.3. Resistance to marine environments

Generally, most Portland and blast-furnace slag cement concretes showed good resistance to sea-water attack after 5 years of exposure in tidal and full-immersion zones at the Building Research Establishment's marine exposure site at Shoeburyness [17]. All but the SRPC and high C_3A PC concretes in the full-immersion zone, and concrete with 80% high-alumina slag and 20% high C_3A cement in the tidal zone, were rated as having good sea-water resistance and had retained at least 70% of their control strength (water-stored) at 5 years. The following trends in performance and behaviour were observed.

3.3.1. Sea-water resistance, chloride ingress and protection of rebar

Concretes with 70% slag as replacement for Portland cement showed good strength development and suffered the least attack in the full-immersion zone, irrespective of the type of Portland cement or slag. These concretes, like the medium C_3A PC concretes, had very good resistance to sea-water, but importantly also showed significantly reduced ingress of chloride compared with the PC concretes. Those with 60% slag tended to suffer some sea-water attack and had slightly higher chloride concentrations than those with 70% slag. Concretes with 80% slag had reduced strength development, but also had the lowest degree of chloride penetration, particularly when in combination with the medium C_3A PC. At depths of 21 mm these 5-year-old concretes had less than 0.5% chloride by weight of cement, compared with more than 2% for the SRPC concrete (low C_3A cement) which showed the highest levels of chloride ingress in both sea-water environments, and in which the rebar would therefore be far more vulnerable to corrosion. These findings are consistent with the BS 6349 recommendations for a minimum C_3A level of 4% for marine structures, and BS 8110 which advocates the use of higher cover (an extra 10 mm) for SRPC concrete in very severe or extreme exposure conditions. Pelletized slag cement concretes, while attaining slightly lower strengths than their granulated slag cement counterparts, showed marginally lower chloride ingress [17].

These results suggest that, in practice, corrosion of reinforcing steel in slag cement concretes would be minimal provided that the guidance on mixture proportions and cover to reinforcement given in BS 8110 and BS 6349 is followed. BS 6349:Part 1:1984, Clause 58.10 "Prevention of reinforcement corrosion", recommends that the cover in maritime structures should be preferably 75 mm but not less than 50 mm.

The concrete barrage across the River Tees was designed and constructed with all the current specifications and recommendations for good concrete practice included [5,6]. Some of the benefits of using 70% GGBS in the concrete of low permeability to oxygen and increased long-term strength were discussed earlier. Chloride ion penetration data at 6 months were typical of the type of profile obtained for slag cement concrete, with a significantly higher concentration of chloride at the surface and very much lower concentrations at greater depth [6,17]. However, even at the surface the chloride concentration was low and rapidly fell to background levels (Fig. 2).

3.3.2. Freezing and thawing under marine conditions

All blast-furnace slag cement concretes in the tidal zone had suffered surface frost damage to some degree in the form of "pop-outs" and spalling that are characteristic of freezing and thawing attack. It was observed that this form of attack tended to occur during the first winter of exposure, when the concrete was relatively new and not fully cured. There were few, if any, signs of this progressing further at later ages [17]. The use of air entrainment should prevent this freezing and thawing attack. There was no such damage with any of the fully immersed specimens or with the tidal Portland cement concretes. These observations are covered in both BS 8110 and BS 5328 which recommend air entrainment if concrete is likely to be subjected to freezing while wet.

3.3.3. Surface scaling of concrete

There have also been instances of scaling and surface softening of slag cement concretes in other climatic situations. Scaling or salt weathering is a phenomenon often observed at concrete structures along the Gulf coast, especially at the soil–air interface, and as Al-Rabiah reports is a factor taken into account for the design of concrete structures [8,18]. He also observed [8] that the scaling was associated with early drying out of the surface layers and the resulting coarser pore structure. Concrete specimens taken from the King Fahd Causeway which contained a Dutch 72/28 blended blast-furnace slag cement (400 kg/m^3) were therefore, not surprisingly, vulnerable to dry curing. However, he reported that the porous–permeable zone did not extend more than $\approx$10–15 mm into the concrete after 10 years of exposure, and is likely to be restricted to that. Generally the concrete was found to be sound, dense and with no sign of deterioration or cracks in the super or substructure. Carbonation depths of cores taken from the concrete piles were only 8 mm at 10 years and chloride ion penetration was very low, apart from the high level in the surface layers due to weak scaling [8].

High-slag-cement concretes are more susceptible to drying out and reduced hydration during the early stages of curing, than normal Portland cement concretes. The surface concrete, in very exposed environments with changeable microclimates, is affected by and subject to increased carbonation. This highlights the importance of maintaining sufficiently long curing and formwork cover times for concretes containing high levels of slag as replacement for normal Portland cement.

3.4. Alkali–silica reaction

Recommendations for minimizing the risk of alkali-silica reaction in concrete have been given in the BRE Digest 330 [19], and include the use of GGBS. Where GGBS and fly ash are used to minimize the risk of damaging ASR, minimum proportions are recommended in Part 2 of the 1997 edition of Digest 330 which covers detailed guidance for new construction. Different minimum proportions of these two materials are recommended depending on the reactivity class of the aggregate. No account needs to be taken of alkali in these materials when they are used at or above the minimum proportions recommended for a particular classification [19].

4. Heat release properties

Modern UK Portland cements have higher heats of hydration with more heat evolved at early ages [20]. Concrete develops a greater proportion of strength up to 28 days with lower increases at later ages. The benefits which can be gained from the use of GGBS or fly ash as cementitious materials in concrete, through reductions in heat output, improved long-term strength development and enhanced durability have been recognized more clearly in recent years. The significance of maintaining low temperature rises is that temperature differentials and associated thermal cracking of concrete are kept to a minimum. A metre cube of slag cement concrete containing 75% GGBS and a cementitious content of 380 kg/m^3, was cast using the same concrete as was being laid in a large mass concrete floor slab at BRE's Cardington Hanger in the UK. Thermocouples were used to measure the temperature profile of both concrete units. The maximum temperatures recorded were 54.0°C and 53.6°C for the metre cube and floor slab respectively. These temperatures are known to be substantially lower than normal Portland cement concrete of equivalent mixture proportions. Neither the metre cube or the massive continuous concrete pour of nearly 3500 m^3 showed signs of thermal cracking, although there were some minor plastic shrinkage cracks in places on the slab laid during summer 1992.

In a more recent study Matthews established the maximum temperature which might be achieved in mass concrete by using an "oven technique" which simulates a large concrete pour [21]. He showed that when fly ash and slag were used as replacement for normal Portland cement, on the basis of equal or similar binder content, temperature rises in slag and, especially, fly ash concretes were substantially lower than in the corresponding Portland cement concrete.

5. Conclusions and recommendations

1. Structural concretes containing up to 50% of slag as cementitious material are considered suitable for the same uses, in ordinary and mild exposure applications, as conventional Portland cement concretes of the same design strength. Rates of carbonation and permeability to gaseous species are likely to be similar.
2. For slender, reinforced concrete columns containing GGBS, careful consideration should be made as to the prudency of using very high levels of slag as replacement for Portland cement in certain outdoor situations. Reinforcing steel may be rendered vulnerable to the agents of corrosion (oxygen, water and chloride ions), owing to the concrete's susceptibility to increased carbonation in drying, exterior microclimates.
3. Where the carbonation front has extended beyond the reinforcing steel, sites for potential corrosion of steel are made available and decisions on whether to apply a sealer coat as a remedial or protective measure may need to be made to help prevent further carbonation [4].
4. Considerations could be made as to whether concrete structures should be monitored for carbonation, permeability and strength changes in order to validate the specifications for achieving the predicted life-time of that structure.
5. The vulnerability of slag cement concretes, with slag contents of more than 50%, to the adverse effects of poor curing merit special attention. There is a need to address more closely the requirements and specifications for good concrete practice, particularly in terms of curing times and depth of cover for reinforcing steel in BS 8110 and ENV 206, and other concrete standards. In special cases the use of controlled permeability formwork may be beneficially employed, although initially expensive [22].
6. Combinations of Portland cement with ground granulated or pelletized blast-furnace slags can be classed, like SRPC, as providing good sulfate-resisting properties in most of the sulfate conditions described by the BRE Digest 363 [12], provided that the alumina level in the slag is less than 14%. Alternatively, if the alumina content of the slag exceeds 14%, the C_3A content of the Portland cement should not exceed 10%.

7. Blast-furnace slag cement concretes with a 380 kg/m^3 cement content, a total water:cement ratio of 0.5, and with 70% slag as replacement for PC, performed well when immersed in sea-water but suffered surface damage from severe frost action in the tidal zone. In unreinforced concrete their performance and durability were equivalent to that of Portland cement concretes containing medium C_3A PC, as specified in BS 6349:Part 1 (Clause 58.2 "Chemical attack"), which advocates a maximum C_3A content of 10% and minimum of 4% for use in reinforced concrete maritime structures. It was demonstrated that use of high levels of slag gave the added benefit of reducing chloride ingress, which provided enhanced protection to steel reinforcement. In situations where superficial spalling in the tidal zone is aesthetically unacceptable, air entrainment may be used as a means of preventing such frost attack. Surface scaling can also be minimized by attention to proper curing or the use of a surface coating.
8. Higher levels of slag (70%) can be usefully employed in accordance with BS 8110:Part 1:1985 or BS 5328:Part 1:1990, where chemical resistance to sulfates, chlorides and sea-water is required. However, in more general construction, it is recommended that for thin sections particular attention should be given to both curing and cover of reinforcement, and in environmental situations where there is a risk of excessive carbonation, slag levels should be restricted to 50%.
9. In mass concrete pours, with high cementitious contents, substantial reductions in the rate of temperature rise, overall heat release and peak temperatures in concretes can be achieved by using GGBS at higher levels of replacements, thereby minimizing the risk of thermal cracking and providing economic benefits.

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