australasian (iron & steel) slag association

REFERENCE DATA SHEET 3 - 2011

Blast Furnace Slag Cements

Properties, Characteristics and Applications

1. INTRODUCTION

This data sheet reviews in some detail the properties of ground granulated iron blast furnace slag (GGBFS) used as a supplementary cementitious material in concrete. Granulated iron blast furnace slag (GBFS) is produced by directing the stream of molten slag leaving the furnace into a large volume of cold water in a granulator. The rapid "quenching" or chilling prevents crystallization and converts the molten slag into sand-sized particles of predominantly amorphous or non-crystalline glass, referred to as granulated slag.

It is generally recognized that the cementitious action of a slag is dependent on the glass content, although its only one of many factors which will have influence. Slowly cooled slags, e.g. air cooled blast furnace slag, are predominantly crystalline and do not possess significant cementitious properties.

In Australia, GGBFS has been in use since the mid-sixties[1,2,3]. Currently, the use of granulated slag that is then ground for use as a supplementary cementitious material is in high demand. Approximately XXX,XXX current data tonnes of GBFS is further processed into various valued added products, including blended cements manufactured by the major cement producers in Australia as well as being used as a direct addition into concrete4.

Historically slag was utilised in the production of high slag blends for marine and sulfate resistance in major civil works for it is in these applications that the long-term properties of slag cements are ideal.

In recent years, slag use as a supplementary cementitious material in concrete has significantly increased in Australia for general concrete production. This has been both as blended cements in concrete (following AS3972)[5] and as a direct addition into a concrete mix as a supplementary cementitious material (following AS3582.2)[6]. In addition, sustainability requirements for concrete have also driven the use of GGBFS.

The durability, performance and economics advantages for the use of GGBFS are well developed in the literature for the built environment. Heidrich, Hinczak and Ryan argue that the most significant opportunity for built environment participants is from the significant reductions in greenhouse gas emissions that can be achieved. The average weighted direct emission reduction for Portland cement replaced by GGBFS is 710 kgs CO_2-e[7].

These reductions can be achieved without the need for significant additional capital resources and associated emissions from traditional cement manufacturing technologies.

2. PROPERTIES OF SLAG CEMENTS

2.1 HYDRATION OF SLAG CEMENTS

There is general agreement among researchers that the hydrated materials formed when GGBFS is mixed individually or in combinations with cement and water are similar to the principal products formed when Portland cement hydrates, although differences are noted in the rate of hydration[1,8,9,10].

The hydration of GGBFS depends upon breakdown and dissolution of the glassy structure by hydroxyl ions derived from portlandite which is released during the hydration of the Portland cement. The hydration of the GGBFS proceeds and continues to consume calcium hydroxide and uses it for additional CSH formation. X-ray diffraction indicates that ettringite is the predominant hydration product at early ages [7,11].

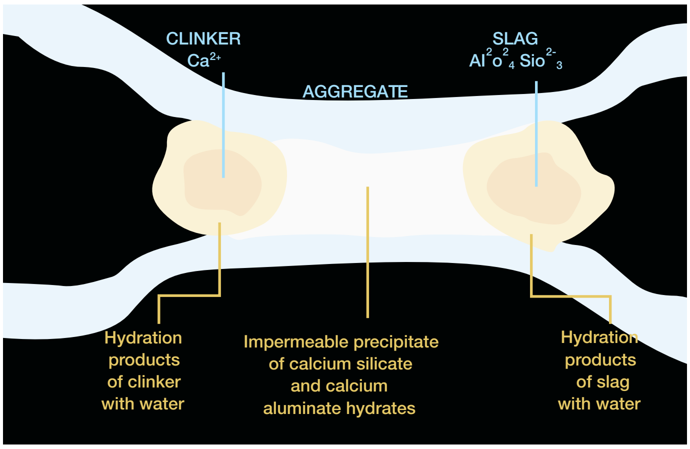

Figure 1 – Schematic of hydration of GGBFS

The morphology of the GGBFS hydrates is found to be more gel-like than the products of hydration of Portland cement and add denseness to the cement paste[12].

2.2 PROPORTIONING OF GGBFS BINDERS IN CONCRETE APPLICATIONS

Commonly, GGBFS is used in proportions of 20% to 80% of the total binder in concrete[13]. The proportions of GGBFS should be dictated by the purposes for which the concrete is to be used. Recommendations are given in Table 1.

Table 1 – Suggested Binder Inclusion of GGBFS in Concrete Application	
Application	**Slag Proportion (%)**
General construction (Note 1)	20-40
Reduction of heat hydration (Note 2)	50-80
Structures exposed to chloride attack (Notes 3, 4)	50-80
Structures exposed to sulfate attack (Notes 3, 4)	50-80
Marine structures	60- 80

Note 1: Higher GGBFS contents may be considered for certain applications.
Note 2: Depends on degree of heat reduction required.
Note 3: Degree of severity requires consideration.
Note 4: Concrete required to have particular durability or material behaviour will need additional specified requirements (e.g. minimum concrete grade).

For each grade of concrete, there is an optimum proportion of GGBFS to achieve the most efficient mix cost. This optimum will depend on many factors including other binder systems within the concrete and to a lesser extent other component materials included within the mix. GGBFS from different sources may also differ in reactivity and thus influence strength development[14].

Other considerations that will determine the proportions of GGBFS to be used will depend on the requirements for temperature rise control, time of setting and finishing, sulfate and chloride resistance, and the control of expansion due to alkali-aggregate reaction[15,16].

GGBFS used to manufacture slag cements need to comply with the provisions of AS 3582.2[5] which sets out the requirements for slag as a supplementary cementitious material for use with General Purpose and Blended Cement. Where GGBFS is blended with Portland cement, the combination will result in physical properties which are characteristics of the predominant material. If high contents of GGBFS are used, a slower rate of strength gain should be expected particularly at early ages unless the water content is substantially reduced or accelerated curing is provided. Where low GGBFS percentages are used, the properties of the Portland cement will dominate[1,7].

3. EFFECTS OF GGBFS ON PROPERTIES OF CONCRETE

In Australia, concrete structures are designed to Australian Standard AS3600[17] and bridge structures to AS5100[18]. The specification and supply of concrete is carried out in accordance with AS1379[19]. In relation to GGBFS, AS1379 references two commonly used standards, AS3582.2[5], and AS3972[4].

The most commonly specified tests for concrete in projects are detailed in the various parts of AS1012[20]. Tests for concrete can be generally classified into three areas:

- Early age concrete properties,
- Concrete mechanical properties (typically at 28 days to 56 days age), and
- Long-term properties of concrete (typically in excess of 56 days age).

The influence of GGBFS in concrete is considered in some detail for each of the areas mentioned above in Tables 2, 3 and 4 respectively. For each area, the specific influence of GGBFS in concrete is described for each key concrete test parameter. Observations presented in Tables 1, 2 and 3 are general in nature. The Australasian (Iron and Steel) Slag Association recommends specific testing on GGBFS, other constituents and resulting concretes to verify observations in specific applications.

Table 2: Influence of GGBFS on Early Age Properties of Concrete		
Concrete Parameters	**Aust. Standard**	**Typical influence of GGBFS in Concrete**
Slump	AS1012 Part 3	Similar to other concrete types and can be designed to suit application Reduced slump loss
Air Content	AS1012 Part 4	No significant influence
Set Time	AS1012 Part 18	Can increase depending on inclusion level - can usually be designed to suit any application
Density	AS10112 Part 5	
Bleed	AS1012 Part 6	
Temperature Rise	AS1012 Part 89	Can be significantly reduced when replacing higher levels of Portland cement
Comp Strength	AS1012 Part 89	Can have a reduced strength gain at early age. Matched early age compressive strengths can be achieved through mix design and .admixtures

Table 3 - Influence of GGBFS on Mechanical Properties of Concrete (28 day to 56 day age)		
Concrete Parameters	**Australian Standard**	**Typical Influence of GGBFS in Concrete**
28 day Comp. Strength	AS1012 Part 9	Can be effectively included into concretes up to 100 MPa
Indirect Tensile Strength	AS1012 Part 10	Usually a function of compressive strength and the benefits of GGBFS flow through to this parameter
Flexural Strength	AS10912 Part 11	Usually a function of compressive strength and the benefits of GGBFS flow through to this parameter
Hardened Density	AS1012 Part 12	Limited infliuence on density
Drying Shrink-age	AS1012 Part 13	Whilst concrete drying shrinkage is some-times higher than other concrete types, this is a function of the test method and similar serviceability behaviour is usually observed on site
Elastic Modulus	AS1012 Part 17	Limited influence - Usually linked to compressive strength

Table 4 - Influence of GGBFS on Long-Term Properties of Concrete (post 56 day age)		
Concrete Parameters	**Australian Standard**	**Typical Influence of GGBFS in Concrete**
Long-Term Comp. Strength	AS1012 Part 9	Usually increased long-term strengths due to later age hydration reactions
Creep	AS1012 Part 16	Linked to compressive strengths - Usually reduced (good for design)
Permeability and Pore Structure		Usually reduced
Sorptivity		Usually reduced when compared with other concrete types
Chloride Ion Penetration		Usually significantly reduced when compared with other concrete types

A review of information in Tables 2, 3 and 4 show the significant advantages that can be derived from using GGBFS in concrete from an early age perspective (fresh concrete state), hardening state and hardened states. GGBFS can significantly improve durability properties of concrete under commonly encountered aggressive conditions[1,21].

4. DURABILITY PROPERTIES OF GGBFS CONCRETE

4.1 SORPTIVITY

Ho et al[19] showed that the response of concrete to the rate of water absorption and to interrupted curing can be improved by the incorporation of ground slag. Sorptivity values for slag concretes were found to be similar to plain concretes of higher compressive strength. The rate of water absorption in concrete by capillary action was significantly reduced when 35% GGBFS was used and a water reducing admixture was incorporated. The sorptivity of concrete containing GGBFS was not as adversely affected by interrupted curing as was concrete with Portland cement only as the binder.

4.2 CHLORIDE ION PENETRATION

The resistance to the penetration of chlorides into concrete is dependent mainly on the pore structure of the cement paste and the nature of the products of the binder/water reactions. For blends of GGBFS and Type SL Portland Cement, the resistance to chloride penetration increases with increasing GGBFS proportion. Concrete made using binders containing 60% or more of GGBFS is considered to be highly impermeable to chloride ions[10]. In Figure 1, the soluble ion concentration at depths of 0-10 mm, 20-30mm and 40-50 mm for concrete containing 350 kg/m^3 of Type SL Portland cement and Type SL/GGBFS binders after immersion in seawater for 3 years is shown. The reduction in chloride ion penetration with depth for GGBFS concrete is clearly observable in the data presented.

4.3 SULFATE RESISTANCE

Concrete can be exposed to attack from sulfates from various sources including ground waters, industrial effluent and its by-products, decay of organic matter, sewage, and sea water. GGBFS concretes improve the resistance of concrete to sulfate attack by reducing the permeability of the cement paste matrix and reacting with the calcium hydroxide in the hardened cement paste thus reducing the availability of one of the compounds that are highly susceptible to sulfate attack[10].

Figure 2 shows compressive strengths of mortars cured in seawater compared to mortars cured in tap water. Figure 3 shows corrected linear expansion of mortar bars immersed in 5% Sodium Sulfate solution. Reference mortar bars were stored in tap water. The mortar bars contained an equivalent binder content of 350 kg/m^3 Type SL Portland cement and Type SL/GGBFS binders. The use of cement blends with higher GGBFS contents showed greater resistance to sulfate attack than the lower GGBFS contents[10]. Frearson[13] found that at replacement levels of 60% and above, Type GP/GGBFS mortars were more resistant to sulfate attack than Type GP alone. (Figure 3 shows Type SL cement performing better than the 60% slag mix, contradicting the above comment.)

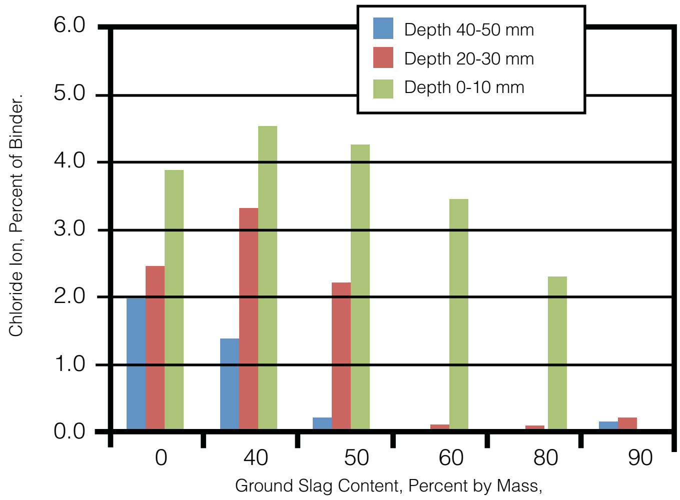

Figure 1: Chloride Ion Penetration after Immersion in Seawater for 3 Years.

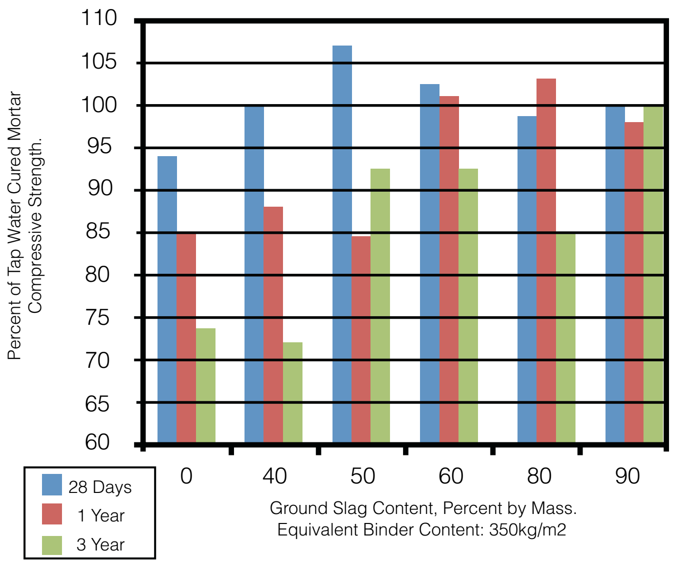

Figure 2. Mortar Compressive Strength Cured in Seawater as a Percentage of Mortar Cured in Tap Water.

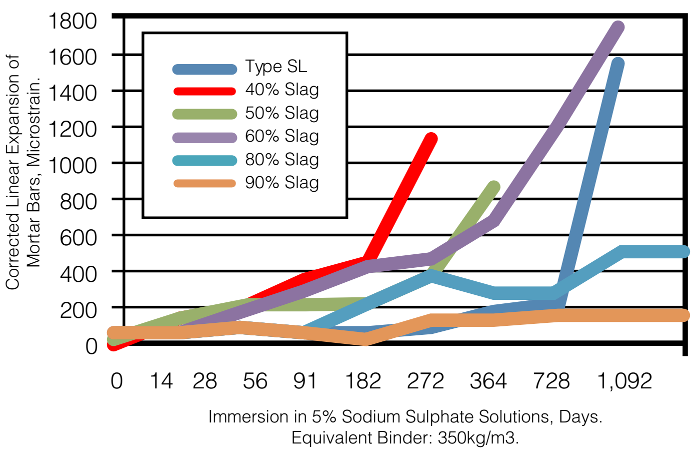

Figure 3. Corrected Expansion of Mortar Bars Immersed in 5% Sodium Sulfate Solution.

4.4 ALKALI-AGGREGATE REACTION (AAR)

Alkali-aggregate reaction refers to the reactions that can occur between the alkalis present in the Portland cement and certain siliceous compounds found in some aggregates. These reactions can cause expansion and cracking in concrete. It has been shown that cements containing GGBFS are effective in reducing the expansion of aggregates that have been found to be alkali-silica reactive. Results obtained using varying proportions of GGBFS from 10% to 50% of the total cementitious binder indicated that GGBFS of 20% and higher resulted in less expansion when compared with the control 100% Type GP cement[14]. With high cement content concrete mixes it was concluded that more than 40% of Type GP Portland cement should be replaced by ground slag to mitigate against the alkali-silica reaction[14].

5. GGBFS AND OTHER SUPPLEMENTARY CEMENTITIOUS MATERIALS

The use of materials such as fly ash and silica fume in combinations with GGBFS and Portland cement provide blended cements and concretes that have been in common use in particular applications for many years[1,2,3]. Some of these concrete mixes gave 28 day compressive strengths in excess of 85 MPa. The use of combinations of these three supplementary cementitious materials with Portland cement in concrete, is technically and practically valid. It has been shown that these materials are very compatible and complementary when used together in concrete. Combinations of these materials are therefore seen as ways to achieve improved performance in concrete such as enhanced durability and strength. The combination to be used will depend on the design requirements of the particular project and the economics and availability of each supplementary cementitious material.

6. CONCLUSIONS

As a result of the significant benefits of the use of GGBFS in concrete, the material has found wide use in many project applications in Australia. Key benefits of concrete incorporating GGBFS include:

- Reduced heat of hydration and temperature rise,
- Increased long-term strength
- Improved concrete durability particularly in reference to:
  - Chloride ion penetration, Sulfate attack, and
  - Alkali-aggregate reaction.

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