australasian (iron & steel) slag association

REFERENCE DATA SHEET 1 - 2011

Blast Furnace Slag Aggregate & Cementitious Products

1. INTRODUCTION

Throughout the world there is an increasing focus on the need to recycle and to more fully utilise co-products of manufacturing processes in an attempt to conserve our finite natural resources. Technical evaluation supported by field experience has shown that co-products such as blast furnace slag have, in many applications, properties suitable to replace or supplement and improve traditional materials used.

This data sheet reviews in some detail the use of slag in cement and concrete either as an aggregate (coarse or fine) or as a binder component in concrete manufacture. Where relevant, published technical literature is referenced for verification and provides additional sources of information for further reading. Particular reference is made to the Australasian (iron & steel) Slag Association's (ASA) publications – 'Guide to the Use of Iron and Steel Slag in Roads' and 'Guide to the Use of Iron Blast Furnace Slag in Cement and Concrete'[1,10].

As there are many types of slag, it should be noted that the term 'slag' used throughout this publication refers specifically to metallurgical slag produced in modern blast furnaces (i.e. blast furnace slag and not basic oxygen steel slag or electric arc furnace slag which are generally referred to as 'steel furnace slags').

Although the term 'recycling' is referred to when slag is used in any of its applications, strictly speaking slag is not a recycled material. As a co-product in the manufacture of iron, blast furnace slag is considered a recovered resource material. The slag has not been previously used but was formed as part of and during the iron making process. Slag has a controlled chemistry and leaves the blast furnace in a molten form free from foreign matter.

2. HISTORY OF IRON PRODUCTION IN AUSTRALIA

There is a long and interesting history of iron smelting in Australia dating back to the mid 1800's[2] . Many companies failed initially in this industry because customers could purchase the lower cost iron ballast from England, which was literally being dumped in the struggling colonies.

The first iron smelted in Australia was at the Fitzroy Ironworks, Mittagong, NSW, in 1848. This was followed by the Eskbank Ironworks and Rolling Mills at Lithgow, NSW, which was constructed by Cobb & Co. in 1875 but was forced to close in 1882. The British and Tasmanian Charcoal Iron Company opened in Tasmania in 1876 but closed soon after. The Lal Lal Ironmaking Company commenced operations in 1881 in Ballarat, Victoria, however the project was short lived. In 1907 William Sandford's blast furnace at Lithgow, NSW, commenced operation only to have the banks foreclose shortly after. The plant was acquired by G & C Hoskins. A second blast furnace was constructed by Hoskins in 1913[2].

The Broken Hill Proprietary Company decided to expand into the manufacture of iron and steel with the establishment of a blast furnace in Newcastle, NSW, in 1915. Hoskins relocated from Lithgow to the Port Kembla seafront with a deep water harbour and in 1928, the Hoskins No.1 Blast Furnace was commissioned. By 1929 BHP's Newcastle plant had grown to three blast furnaces and the company was in such strong position that it acquired the Hoskins Kembla Works in the mid 1930's. Port Kembla, Australian Iron & Steel Ltd., became the largest iron and steel producing complex in Australia. The name was eventually changed to BHP Steel Port Kembla to identify with BHP's other iron and steel plants at Newcastle and Whyalla (South Australia).

Lithgow Steelworks, circa 1920s

The post-World War II years brought about a strong demand for metal products of all types. No.5 Blast Furnace was installed at Port Kembla which produced some 7000 tonnes of iron and 2500 tonnes of slag per day. In 1997, No.6 Blast Furnace was commissioned with slightly higher production than No. 5 Blast Furnace.

Since these early days, iron production has continued to grow with steel demand. Today approximately 80% of all iron and steel slag (ISS) produced is utilised within various civil and construction applications throughout Australia and New Zealand. In 2009 approximately 3.4 Mt (million tonnes) of iron and steel slag products were produced within Australasia with some 2.71 Mt or 80% utilised. More than 20% or 0.671 Mt was used in cementitious applications; 48% or 1.64 Mt was used in non-cementitious and road construction applications and 12% or 0.39 Mt used in general civil or fill applications.

In summary the recovery and reuse of ISS provide significant positive environmental impacts, including resource conservation and importantly, the reduction of greenhouse gas emissions that would otherwise be produced from the processing of virgin resources[16].

In Figure 1, data on sales of milled slag (GGBFS) are shown from the early 1960's to 2009. The uptake of this material can be clearly seen since its first use around 1965 to the current demand in excess of 650,000 tonnes per annum.

Much of the uptake is attributed to significant research and development conducted by various Australian groups focusing on the material's use in concrete[3,4,5].The processing and marketing of iron and steel slag products in Australia has grown to become a substantial industry involving over 3.4 million tonnes per annum. Approximately 2 million tonnes of this total is blast furnace slag which is also a most versatile material in terms of end use.

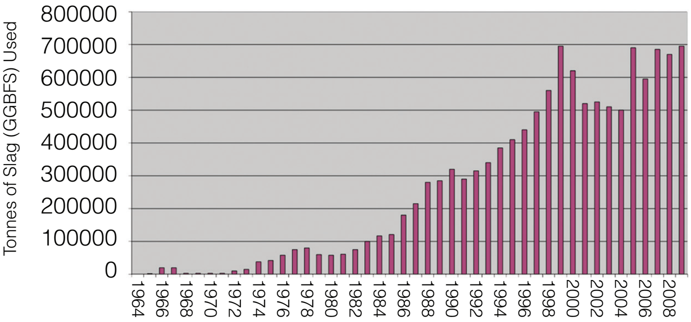

Figure 1 – Sales of GGBFS over time in Australia (Source: Ryan[6], Jones[7] and the Australasian (iron & steel) Slag Association

As long as iron and steel are produced in Australia, slag will be generated as a co-product representing a substantial recoverable and renewable national resource. The utilisation of this resource is an example of improved resource efficiency on a very large scale. Used properly, slag can be beneficial in a wide range of construction applications that include[8,9]:

- Coarse aggregate replacements and supplements in concrete and other applications,
- Fine aggregate replacements and supplements in concrete and other applications,
- Inclusion in the binder for concrete as a supplementary cementitious material; and
- Inclusion as a component in the manufacture of blended cements.

3. TYPES OF BLAST FURNACE SLAG

Blast furnace slag in Australia is currently produced in three forms:

3.1 BLAST FURNACE ROCK SLAG (BFS)

Molten slag on leaving the furnace is directed into ground bays where it air-cools to form a crystalline rock-like material (Figure 2). BFS is suitable for varied uses in building applications as aggregates in concrete, construction of roads in base and sub-base courses either unbound or bound. It can also be mixed with other materials for mechanical stabilising or as a cementing or stabilising binder[10].

Figure 2 – Blast Furnace Rock Slag

When compacted, BFS develops a high degree of mechanical particle interlock resulting in high shear strength partly due to the rough texture (vesicular nature) of the slag. The chemical reactivity of the slag causes it to be self-cementing and produces engineering fill, which over a period of time forms a semi-rigid mass.

BFS can be crushed and screened to a full range of aggregate sizes. BFS should not be simply substituted for natural aggregate in an existing concrete mix without considering differences in grading, particle shape, water absorption and particularly particle density. As for any aggregate, a concrete mix should be specifically designed to suit the characteristics of the aggregate. Therefore, the slightly lower particle density and higher water absorption of slag, due to its vesicular structure, should be taken into account in the mix design.

3.2 GRANULATED BLAST FURNACE SLAG (GBFS)

Molten slag, on leaving the blast furnace is directed into a specialised plant known as a granulator in which high pressure, high volume, cold water sprays to rapidly cool the molten slag resulting in the formation of an amorphous, coarse sand sized material exhibiting hydraulic cementitious properties (Figure 3). Although the principal use of GBFS is in the manufacture of slag blended cement and Ground Granulated Blast Furnace Slag, it can be used as lightweight aggregate where its high fire resistance and insulation properties make it an excellent aggregate for concrete and masonry units where high fire resistance is required. It can also be used in geopolymer concrete, as an additive for glass manufacture, as a lightweight fill and in engineered fill applications.

Figure 3 – Granulated Blast Furnace Slag

3.3 GROUND GRANULATED BLAST FURNACE SLAG (GGBFS)

Granulated Blast Furnace Slag when dried and milled to cement fineness and in the presence of a suitable activator becomes a cementitious binder (Figure 4).

Figure 4 – Ground Granulated Blast Furnace Slag (GGBFS)

Currently, GGBFS is predominately used in the form of blended cement to manufacture concrete or as a direct supplementary cementitious material addition in concrete manufacture. The reportable properties for GGBFS are specified in Australian Standard AS3582.2[11], Supplementary Cementitious Materials for Use with Portland and Blended Cement: Part 2: Slag – Ground Granulated Blast Furnace Slag. The specified properties for slag blended cement are detailed in Australian Standard AS3972[12], Portland and Blended Cement.

4. PROPERTIES OF BLAST FURNACE SLAG CONCRETE

The properties of materials used to manufacture concrete are those in the previously described standard AS3582.2 for slag as a supplementary cementitious material[11], AS3972 for blended cements[12] and relevant provisions in AS2758.1, the Australian Standard for concrete aggregates[13]. Generally, the use of slag aggregates and slag cements in concrete produces plastic properties similar to those resulting from natural aggregates and Portland cement alone. Concrete made with vesicular aggregates, such as slag aggregate, can be successfully pumped, placed and finished[10]. It is, however, recommended that the lower density of slag aggregate is taken into account when designing concrete mixes to ensure that the volume of coarse material is not excessive.

The most commonly specified tests for concrete in projects are detailed in the various parts of AS10[14]. Tests for concrete can be generally classified into three areas:-

- Plastic concrete properties,
- Concrete mechanical properties, typically up to 56 days age, and
- Long-term properties of concrete, typically mechanical properties in excess of 56 days age

The influence of blast furnace slag in concrete is considered in some detail for each of the areas mentioned above in Tables 1, 2 and 3 respectively. For each area, the specific influence of slag 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 & steel) Slag Association (ASA) recommends that specific testing be conducted on slag binders and aggregates, other constituents and resulting concretes to verify properties in specific applications.

In many cases, slag enhances the hardened properties of concretes, generally improving and often surpassing those resulting from concrete made with natural aggregates and Portland cement alone[1,9,10]. In Table 2, a summary of the influence of slag binders and aggregates on typical hardened concrete properties are summarised.

The Association recommends that specific testing be conducted The influence of slag on long-term properties of concrete is summarised in Table 3. High slag content concretes, particularly those containing blended cement with a high proportion of slag, produce high durability performance and are particularly useful for concrete structures in marine and saline environments. When properly used, blast furnace slag has the potential to improve concrete quality, particularly with slag blended cements. Correct cover, compaction and curing are all essential to ensure that the resultant hardened concrete will achieve the required design properties such as strength and durability. The same criteria apply equally to concrete containing natural aggregates and GP or other Portland cements.

Table 1 –Influence of Slag on Early Age Properties of Concrete

Concrete Parameter & Standard	Typical Influence of Slag Aggregate (BFS) in Concrete	Typical Influence of GGBFS in Concrete
Slump AS1012 Part 3	No effect if correct batching and moisture management procedures are in place	No significant effect when following sound mix design procedures
Air Content AS1012 Part 4	No significant effect when compared with good natural aggregate	No significant effect
Set Time AS1012 Part 18	No significant effect when compared with good natural aggregate	Works well with admixtures to achieve required initial and final set times
Density AS1012 Part 5	Can over-yield on equal mass replacement of good natural aggregate	Limited influence on density. Depends on replacement level
Comp. Strength AS1012 Part 9	Same influence as for good natural aggregates	Matched early age compressive strengths can be achieved through proper mix design
Heat of Hydration	May have slight reduction in temperature rise in concrete	Significantly lowered thus reducing the risk of thermal cracking

Table 2 – Influence of Slag on Mechanical Properties of Concrete (28 day to 56 day age)

Concrete Parameter & Standard	Typical Influence of Slag Aggregate (BFS) in Concrete	Typical Influence of GGBFS in Concrete
28 day Comp. Strength AS1012 Part 9	Same as for good natural aggregates	Can be used in high performance concretes (such as 100 MPa characteristic strength)
Indirect Tensile Strength AS1012 Part 10	Same as for good natural aggregates	Slight increase compared to Type GP cement
Flexural Strength AS10912 Part 11	Same as for good natural aggregates	Slight increase compared to Type GP cement
Hardened Density AS1012 Part 12	No significant influence when compared with good natural aggregate	Limited influence on density
Drying Shrinkage AS1012 Part 13	Can reduce drying when compared with inclusion of other aggregates	Can increase concrete drying shrinkage but this may relate to issues with the test method

Table 3 – Influence of Slag on Long-Term Properties of Concrete (post 56 day age)

Concrete Parameter & Standard	Typical Influence of Slag Aggregate (BFS) in Concrete	Typical Influence of GGBFS in Concrete
Long-Term Comp. Strength AS1012 Part 9	Slight increase due to later age hydraulic reactions	Usually increased long-term strengths due to later age hydraulic reactions
Creep AS1012 Part 16	Same influence as for good coarse aggregate	Reduced creep but dependent on compressive strength
Chloride Ion Ingress	Some reduction due to better aggregate/ matrix bond	• Significantly reduced • Excellent option for marine environment concrete
Sulphate Resistance	Slight increase due to better aggregate/ matrix bond	Significantly increased but dependent on replacement rate
Alkali Silica Reaction Resistance	Same influence as for good coarse aggregate	Assists in decreasing AAR but dependent on replacement rate

5. CONCLUSION

The beneficial effects of slag in properly designed concrete can provide significant benefits with respect to:-

- Early age plastic and hardened concrete properties,
- Concrete mechanical properties up to 28 days, and
- Long-term properties of concrete at later ages and long-term durability.

Importantly, the ASA advocates the inclusion of slag materials in concrete where appropriate design, construction procedures, sustainability and other project factors are considered in detail with relevant technically based information is applied. The aim is always to develop ways in which complex project issues can be solved using the beneficial properties of slag materials. More detail on specific issues discussed is available in other ASA data sheets and in references cited in the text.

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