australasian (iron & steel) slag association

REFERENCE DATA SHEET 2 - 2011

Blast Furnace Slag Aggregates

Properties, Characteristics and Applications

1. INTRODUCTION

Being a co-product of iron manufacture in a modern blast furnace, molten blast furnace slag can be processed to produce a variety manufactured products[1]. This reference data sheet gives guidance on the properties, characteristics and application of air-cooled blast furnace slag (BFS) or more commonly known as BFS aggregates.

Molten blast furnace slag is tapped from the furnace into ground bays where it air-cools to form a crystalline rock-like material. When cooled, the BFS is crushed and screened to a full range of aggregate sizes. There has been a significant amount of information published on the properties of BFS aggregates and further details on definitions are available in other technical literature[1,2,3].

Above. Port Kembla, NSW

Discussion of BFS as an aggregate requires a review of how natural and other aggregates are used in concrete and other civil engineering applications. The term 'aggregate' encompasses materials such as sand, gravel and crushed stone, which includes fine and coarse materials. Natural aggregates are mined in quarries situated around basaltic, limestone, granite and other geological deposits. The extracted material is crushed and screened into designated sizes to produce coarse or fine aggregate products. AS2758 describes requirements for aggregate and rock for engineering purposes and is published in a number of parts of which Part 1 discusses concrete aggregates[4]. Aggregates for concrete are essentially defined in this standard by size (an indication of the maximum size of particle present) as follows:

a) Coarse aggregate (nominal size greater than or equal to 5 mm);

b) Fine aggregate (nominal size of less than 5 mm);

c) Heavyweight aggregate (particle density on a dry basis of greater than or equal to 3.2 tonnes/m^3);

d) Lightweight aggregate (particle density on a dry basis of less than 2.1 tonnes/m^3 and greater than or equal to 0.5 tonnes/m^3), and

e) Normal weight aggregate (particle density on a dry basis of less than 3.2 tonnes/m^3 and greater than or equal to 2.1 tonnes/m^3).

Key properties described in AS2758.1 include:

Particle size
Particle Density
Water absorption
Bulk density
Particle Shape
Wet strength
Los Angeles value
Sodium sulfate soundness
Chloride and sulfates
Alkali aggregate reaction
Iron Unsoundness
Falling or dusting unsoundness

The properties described above are discussed in the following sections for BFS aggregates. Table 1 summarises typical results reported for BFS aggregates 10mm and 10-20mm size aggregate products. Methods of sampling and testing of aggregate are described in AS1141[5].

Table 1 – Typical Key Properties

Attribute	Unit	Typical Range for BFS
Bulk Density - Loose	t/m^3	1.20 - 1.30
Bulk Density - Compacted	t/m^3	1.30 - 1.40
Apparent Particle Density	t/m^3	2.75 - 2.85
Particle Density - SSD	t/m^3	2.55 - 2.65
Particle Density - Dry	t/m^3	2.45 - 2.55
Water Absorption	%	3.0 - 4.0
Material < 75mm	%	< 2
Material < 2mm	%	<0.2
Particle Shape - 2:1	%	10 - 15
Particle Shape	%	< 1
Wet Strength	%	90 - 110
Dry Strength	%	95 - 120
Wet/Dry Variation	%	10 - 20
Los Angeles Value		30 - 35
Sodium Sulfate Soundness	%	< 0.5
Light Particless	%	< 5
Weak Particles	%	< 0.5
Sugar		Nil
Iron Unsoundness		Free
Sulfate	%	< 0.2
Chlorides	%	< 0.01

2. PROPERTIES OF BFS AGGREGATES

2.1 PARTICLE SHAPE

Due to the vesicular*. physical structure of air-cooled slag, crushing produces a cubic shape with fewer misshapen particles than found in some natural aggregates. Testing 20mm aggregate to AS2758.1[4] shows that the 3:1 ratio is less than 1% which is significantly lower than 10% specified in AS2758.1[4]. The vesicular nature of slag particles' surface also promotes good particle interlock contributing towards increased flexural strength discussed in section 3.

2.2 WATER ABSORPTION

As a result of the manufacturing process, BFS aggregates are vesicular with individual particles containing an unconnected void structure. This can result in water absorption of 3% to 4% by mass. Natural aggregates typically exhibit water absorptions in the order of 4% or lower. There is no specified maximum value for water absorption in AS2578.1[4]. The maximum value of 2.5% water absorption in some specifications derives from Note 2, Clause 7.3 of AS2578.1[4]. Suppliers of concrete need to ensure that there are operational processes in place during batching of concrete to manage the higher absorption characteristics of BFS aggregates.

Figure 1 - Blast Furnace Slag Aggregate (10mm-20mm size)

Other guidance in the standard notes that vesicular aggregates can be used where performance records are available. There is a long history of the use of BFS aggregates in Australia and around the world. Pre-wetting the aggregates prior to mixing in concrete is recommended[4].

2.3 BULK DENSITY

Due to the vesicular nature and chemical composition of air-cooled BFS aggregates, bulk density values for this material are typically lower than those for natural aggregates. Typical values for 20mm aggregate tested to AS1141.4[6] are 1200 kg/m^3 to 1300 kg/m^3 uncompacted and 1300 kg/m^3 to 1400 kg/m^3 compacted.

2.4 WET STRENGTH

Wet Strength and Wet/Dry Strength Variation specified in AS2758.1[4] is intended to specify aggregate durability for use in concrete. Whilst the test procedure is valuable in assessing natural gravels and aggregates for use in road pavements, it is less significant with vesicular aggregates such as slag. Typical values for BFS aggregates tested to AS1141.22[7] are presented in Table 1. In summary, BFS aggregates wet/dry strength variation is between 10 – 20% and conforms to criteria set down in AS2758.1[4].

2.5 LOS ANGELES VALUE

The Los Angeles Test, AS1141.23[8] is a very severe impact test used to determine the toughness of aggregate particles. Values in Table 1 are 30 to 35 for BFS aggregates. This test does not necessarily reflect the performance of aggregates in concrete. AS2758.1[4] nominates limits for Los Angeles value in Table 5 of that standard. The standard notes that values other than those specified in its Table 5 for natural aggregates are applicable to vesicular aggregates (including BFS aggregates).

2.6 SODIUM SULFATE SOUNDNESS

Dissolved sulfate salts present in sea water and some ground waters can degrade absorptive aggregates by expansive crystallisation within the particles which ultimately causes particle disintegration. BFS aggregates exhibit a high degree of resistance to sodium sulfate attack when tested to AS1141.24[9]. Typical sulfate soundness losses are less than 0.5% by mass which is significantly lower than the most severe classification for aggregates in AS2758.1[4].

2.7 CHLORIDE ION CONTENT

BFS aggregates have chloride ion contents comparable to that of natural aggregates. Tested in accordance with AS1012.20[10], chloride ion contents for BFS aggregates reported in Table 1 are less than 0.01%. Corresponding values for natural aggregates are less than 0.03%.

2.8 SULFATE ION CONTENT

Tested in accordance with AS1012.20[10], the sulfate ion contents in BFS aggregates reported in Table 1 are less than 0.2%. Corresponding values for natural aggregates are less than 0.15%.

2.9 ALKALI-AGGREGATE REACTION

AS1141.65 lists a test method as a means of recognising aggregates that may be alkali reactive[11]. Mineralogical examination of BFS aggregates shows no content of any reactive forms of minerals which could cause alkali- aggregate reactions to occur. Testing BFS aggregates in accordance with AS1141.65 and taking account of ASTM C295-08[12] BFS aggregates are classified "innocuous".

2.10 IRON UNSOUNDNESS

Iron unsoundness, which occurs as disintegration of an aggregate when immersed in water, is highly likely when the slag contains more than 3% ferrous oxide and at least 1% of sulfur. AS2758.1[4] notes that Iron Unsoundness has not been recorded for Australian slag sources. Chemical analyses of BFS aggregates show that ferrous oxide and sulfur contents are significantly below the maximum values noted in AS2758.1[4].

2.11 FALLING OR DUSTING UNSOUNDNESS

When some blast furnace slag cool from the molten state to around 490°C an inversion of ß-dicalcium silicate to the gamma form in the slag may result in disruption of the slag structure. This leads to a condition in the slag known as falling or dusting unsoundness. AS2758.1[4] notes that "No evidence has been found either in Australia or overseas of delayed inversion of beta dicalcium silicate in iron blast furnace slag, or of deterioration of concrete due to the presence of beta dicalcium silicate". During processing particles less than 7 mm may contain falling slag that are used in other applications.

*. Vesicular is a volcanic rock texture characterised by, or containing, many vesicles. The vesicles are small cavities formed by the expansion of bubbles of gas or steam during the solidification of the rock.

Therefore, BFS aggregates in general are deemed to comply with the provisions of AS2758.1[4].

2.12 CHEMISTRY AND MINERALOGY

BFS aggregates are composed of silicates and aluminosilicates, primarily from the melilite group of minerals. Typical oxide analyses are shown in Table 2[13]:

Table 2 - Chemistry and Mineralogy of BFS Aggregates			
XRF Oxide Analysis		**Mineralogy**	
Oxide	**wt. %**	**Phase**	**vol. %**
%Si02	34 - 37	Melilite	65 - 80
%Al203	12 - 15	Glass	5 - 15
%CaO	40 - 43	Larnite	5 - 10
%MgO	4 - 7	Bredigite	5 - 10
%S	0.6 - 0.8	Merwinite	0 - 2
%K2O	0.3 - 0.5		
%FeO	0.4 - 0.8		
%MnO	0.4 - 0.6		
%TiO2	0.7 - 1.5		

3. BFS AGGREGATES IN CONCRETE

3.1 PLASTIC CONCRETE PROPERTIES

Generally, the use of BFS aggregates in concrete produces plastic properties similar to those resulting from natural aggregates. Concrete made with vesicular aggregates, such as BFS aggregate, can be successfully pumped, placed and finished. It is, however, recommended that the lower density of BFS aggregate is taken into account when designing concrete mixes to ensure that the volume of coarse material is not excessive.

3.2 HARDENED CONCRETE PROPERTIES

The hardened properties of concretes containing BFS aggregates are at least equal to those of concretes containing natural aggregates[3]. In many cases hardened concrete properties are improved when BFS aggregates are included in properly designed mixes. Typical data for 40 MPa concrete are presented in Figure 1 for compressive strength versus time (following AS1012.9). Typical data for a 32 MPa concrete are presented in Figure 2 for drying shrinkage versus time (following AS1012.13). Whilst the data in both charts is typical, it is noted that both compressive strength and drying shrinkage values can vary and the Australasian (Iron and Steel) Slag Association advocates investigations on specific materials proposed for use on projects to verify concrete properties. It can be seen in these Figures that concretes made using BFS aggregates are not dissimilar in nature to those made from natural aggregates conforming to AS2758.1.

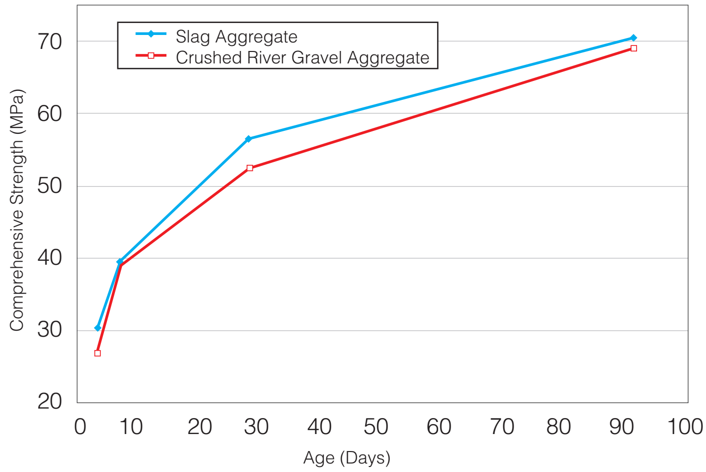

Figure 1. Compressive Strength versus Time

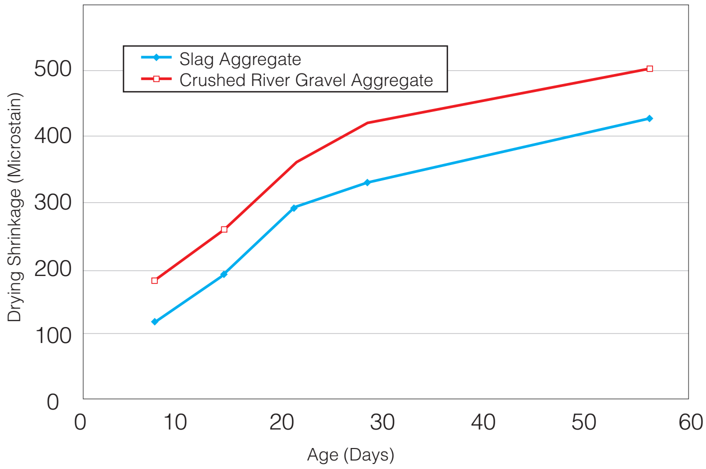

Figure 2. Drying Shrinkage versus Time

In Figure 3, data on flexural strength versus time are presented for 40 MPa grade slag aggregate and crushed river gravel aggregate concrete (following AS1012.11). As can be seen, the respective data are comparable on this criteria.

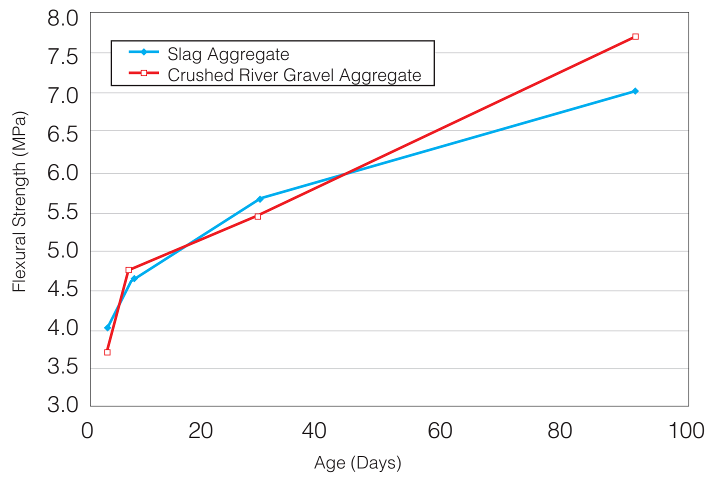

Figure 3. Flexural Strength versus Time

3.3 OTHER CONSIDERATIONS

The vesicular nature of BFS aggregates causes retention of absorbed water by the aggregates after the concrete is placed. As the cement hydrates, this reservoir of water is made available to the curing concrete mass, thus providing the environment required for the achievement of designed properties[14,15,16]. This can result in enhanced hardened concrete properties. 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 absorption of slag should be taken into account in the mix design.

BFS aggregates, due to their vesicular nature, can result in better cement paste-aggregate interaction. Vaysburd[17] reported that concrete with lightweight aggregate developed a contact zone between the cement paste matrix and the lightweight aggregate particles which was different to the zone that formed between the cement matrix and dense aggregate. The zone around the lightweight aggregate was found to be low in porosity and free from microcracks and porous pockets whilst the zone around the dense aggregate was weak and porous due to water being trapped at the underside of the aggregate particle and insufficient packing of the cement paste around the aggregate.

Zhang and Gjorv[18] reported the penetration of cement paste into the pores of lightweight aggregate using scanning electron microscopy techniques. While BFS aggregates are not a true lightweight aggregate, its vesicular nature tends toward the behaviour reported for lightweight aggregates and the data presented in Figures 1 to 3 demonstrates that the higher water absorption of BFS aggregates is not a sign of weakness of the aggregate but rather a beneficial property for concrete performance.

Correct cover, placement, compaction, finishing and curing are all essential to ensure that BFS aggregate concrete will achieve the required design properties such as strength and durability. These same criteria apply equally to concrete containing natural aggregates.

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