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TECHNICAL NOTE

TECH NOTE NO: 35
TITLE: Ground Granulated Blast Furnace Slag
AUTHORS: V. Cervantes, J. Roesler
CONTACT: University of Illinois, Dept. of Civil and Environmental Engineering
1211 NCEL, MC-250 Urbana, IL. 61801
Ph: (217) 265 – 0218, e-mail: jroesler@uiuc.edu
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1. Ground Granulated Blast Furnace Slag

Ground Granulated Blast Furnace Slag (GGBFS) is a by product of the steel industry. Blast furnace slag is defined as "the non-metallic product consisting essentially of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace." [1] In the production of iron, blast furnaces are loaded with iron ore, fluxing agents, and coke. When the iron ore, which is made up of iron oxides, silica, and alumina, comes together with the fluxing agents, molten slag and iron are produced. The molten slag then goes through a particular process depending on what type of slag it will become. Air-cooled slag has a rough finish and larger surface area when compared to aggregates of that volume which allows it to bind well with portland cements as well as asphalt mixtures. GGBFS is produced when molten slag is quenched rapidly using water jets, which produces a granular glassy aggregate.

2. Classification

In accordance with ASTM C989, GGBFS has three strength grades which are determined by their respective mortar strength when they are mixed with equal mass of portland cement. The three grades, 80, 100, and 120, are classified according to their slag activity index which is average compressive strength of the slag-reference cement cubes (SP), divided by the average compressive strength of the reference cement cubes (P), multiplied by 100 (see Table 1).

$$Slag\ Activity\ Index, \% = \frac{SP}{P} \times 100$$

The standard also describes the mixture proportions for each type of cube as well as noting a size requirement of residue left on a No. 325 sieve (45µm) to be 20% and that the air content in the slag mortar not be greater that 12%. The chemical limitations of the standard are that the sulfur and ion sulfate contents can not exceed 2.5%, and 4.0%, respectively.

Table 1: ASTM C 989 standard for the classification of different grade slag

Day Index	Grade Type	Minimum Slag Activity Index % Average of last five consecutive samples	Any individual sample
7 Days	Grade 80	-	-
	Grade 100	75	70
	Grade 120	95	90
28 Days	Grade 80	75	70
	Grade 100	95	90
	Grade 120	115	110

3. Chemistry

Slag is primarily made up of silica, alumina, calcium oxide, and magnesia (95%). Other elements like manganese, iron, sulfur, and trace amounts of other elements make up about other 5% of slag. The exact concentrations of elements vary slightly depending on where and how the slag is produced.

When cement reacts with water, it hydrates and produces calcium silicate hydrate (CSH), the main component to the cements strength, and calcium hydroxide ($Ca(OH)_2$). When GGBFS is added to the mixture, it also reacts with water and produces CSH from its available supply of calcium oxide and silica. A pozzolanic reaction also takes place which uses the excess SiO_2 from the slag source, $Ca(OH)_2$ produced by the hydration of the portland cement, and water to produces more of the desirable CSH making slag a beneficial mineral admixture to the durability of concrete.

4. GGBFS Effects on Flexural and Compressive Strength

GGBFS has a positive effect on both the flexural and compressive strength of concrete after 28 days. In the first 7 days the compressive strength is generally slightly lower than pure 100% Portland cement mixtures. In the 7 to 14 day range, the compressive strength is about equal to the strength of concrete without slag. The real gain in strength is noticed after the 28 day mark especially when 120 grade GGBFS is used. [2]. A 1992 study which showed that the flexural strength of concrete mixes with different slag replacement percentages was between 6.0-6.8 MPa at 14 days [3]. The long term strength of slag cement depends on many factors such as the amount of slag and Portland cement, and water to cement ratio.

5. Slag cement in Self Consolidating Concrete (SCC)

The use of slag as a replacement of cement in SCC mixtures was shown to be effective in a 2003 study. The slag cement content was varied in different SCC mixtures. The SCC mixtures with the slag cement had slump flow and flow times similar to the control mixtures. The compressive strengths for the mixtures with the slag cement met their target strengths by 28 days, reaching 31-46 MPa compressive strength. Cost was also a consideration for this study and the most cost effective mixture had a 60% slag replacement. [4]

6. Shrinkage

One report sates that the shrinkage of GGBFS is similar to the shrinkage of plain concrete and thus dose not require any special engineering or construction requirements [2]. A study in

2003 showed that plain concrete and concrete with silica fume developed drying shrinkage faster than concrete with GGBFS, but that after one year the shrinkage was about the same for all the types of concrete that were tested. With respect to autogenous shrinkage, the study showed that the higher the percentage of slag used, the higher the autogenous shrinkage after 1 year. The total shrinkage, drying plus autogenous, of concrete containing slag was lower than 100% portland cement concrete [5].

7. Alkali-Silica Reactions (ASR)

GGBFS has been known to reduce the degree of which ASR occurs in concrete. The alkali in cement is used by the GGBFS during hydration which prevents the alkali from reacting with the potential deleterious aggregates. In addition, GGBFS typically reduces the permeability of the concrete which in turn prevents the alkalis form migrating through the pores [6].

8. Projects

Slag is prepared in different ways for different applications. Air-cooled slag aggregate has been used to surface NASCAR racetracks because of its friction properties that add stability [6]. GGBFS is primary used as a replacement for cement in concrete mixtures because of its enhancement capabilities to ordinary concrete properties. According to Elliot [2], examples of projects where GGBFS has been used in airfields are:

Baltimore/Washington International, MD
Dulles International, Reston, VA,
George Bush Intercontinental, Houston, TX,
Ronald Reagan National, Washington, DC,
Hartsfield International, Atlanta, GA
Indianapolis International, Indianapolis, IN
JFK International, New York, NY

9. Consumption of Slag

The U.S. consumed 10.5 million metric tons of slag in 2001. The cost of the slag averaged about $10.67 per metric ton, totaling 112 million dollars. 58% of the slag was used in the states of Illinois, Indiana, Michigan, and Ohio. The Mid-Atlantic States of Maryland, New York, Pennsylvania, and West Virginia consumed 29% of the slag and other states which include, Alabama, California, Kentucky, Mississippi, and Utah consumed the last 13% of the slag [6].

10. References

[1] The American Society for Testing and Materials, ASTM, C989-99

[2] Elliot, D. F., Ground Granulated Blast-Furnace Slag for Use in Airfield Pavements, Lone Star Industries, New Orleans, LA

[3] Douglas, E., Bilodeau, A., Malhotra, V. M., “Properties and Durability of Alkali-Activated Slag Concrete,” ACI Materials Journal, V. 89, No 5. September-October 1992. pp 509-516

[4] Lachemi, M., Hossain, K. M. A., Lambros, V., Bouzoubaâ, N., "Development of Cost-Effective Self-Consolidating Concrete Incorporating Fly Ash, Slag Cement, or Viscosity-Modifying Admixtures," ACI Materials Journal, V. 100 No5, September-October 2003., pp 419-425

[5] Saric-Coric, M., Aïtcin, P., "Influence of Curing Conditions on Shrinkage of Blended Cements Containing Various Amounts of Slag," ACI Materials Journal, V. 100 No5, November December 2003., pp 477-484

[6] Kalyoncu, R. S., "Slag-Iron Steel," U.S. Mineral Survey Materials Yearbook – 2001. 2001., pp 70.1-70.3