Sustainable Shotcrete Using Blast-Furnace Slag

By Philip Sawoszczuk, Dr. Michelle Nokken, and Dr. Marc Jolin

Two shotcrete mixtures were designed based on sustainability for use in mining ground support. The sustainable shotcrete mixture contained both fine and coarse pelletized blast-furnace slag aggregates. The control mixture contained regular concrete sand as the fine aggregate and pelletized blast-furnace slag as the coarse aggregate. The cementing materials were the same for both mixtures and consisted of 85% portland cement, 7.3% granulated blast-furnace slag, and 7.7% silica fume. The sustainable shotcrete mixture—composed of a total of 77.71% recycled materials, including slag cement, slag aggregates, and silica fume—achieved an average compressive strength of 4569 psi (31.5 MPa) at 28 days, in addition to a hardened density that was 7.6% lighter than the control mixture. The results indicate the potential and feasibility of the sustainable shotcrete mixture for mining companies as they strive to meet more stringent environmental regulations and expectations.

Introduction

Concrete and shotcrete are consumed at a rate of 11 billion tons (9.98 billion metric tons) per year, making it the most consumed material on Earth.[1] Incorporating waste materials such as blast-furnace slag or silica fume into concrete and shotcrete can go a long way toward reducing concrete's impact on the environment by recycling them into a useful product and replacing new minerals. Disposing of this waste has always been a concern for industry; until very recently, it has been dealt with by the most economic means possible. Unfortunately, the most economical waste disposal methods were often damaging to the environment. Today, laws, regulations, treaties, and public pressure are increasingly forcing all industries to find more environmentally and socially responsible ways to manage waste. As our scientific and technological understanding increases, waste is being refashioned into products looking for a purpose. In this light, with some technical knowledge, waste can be processed and used economically, with little or no environmental impact. Adding to this trend is the growing awareness of the high level of sustainability of the shotcrete process.[2] This article will explore and discuss the performance of two shotcrete mixtures, designed to maximize sustainability while meeting the performance criteria required for underground ground support.

Problem Definition and Research Significance

Industrial wastes can have detrimental impacts to human health, the environment, and to society. Is it possible to use part of these wastes in ground support shotcrete in a sustainable fashion? Pelletized and granulated blast-furnace slag aggregates have not been studied in shotcrete previously and offer a promising channel to increase the recycled material content of shotcrete, as well as making it less dense, offering further benefits to the yield of fresh shotcrete per weight of dry material. The research project will help qualify the feasibility of using these aggregates in shotcrete mixtures for ground support.

Objectives

The goal of this project was to investigate a dry-process shotcrete mixture design that:

1. Recycles various waste products;
2. Meets standard safety criteria for shotcrete materials;
3. Meets performance criteria for underground ground support shotcrete;
4. Meets durability criteria for underground ground support shotcrete; and
5. Meets economic and process feasibility criteria.

Mixture Design Ingredient Selection

Blast-furnace slag from the iron refining industry has been widely used and accepted in the concrete industry, is commercially available, and already has been the subject of shotcrete research as a cementitious ingredient in shotcrete under the form of ground-granulated blast-furnace slag (GGBFS).[3*] It is produced alongside pig iron when iron ore, limestone, and coal are heated in an enormous blast furnace at temperatures reaching around 3450°F (1900°C). As the molten iron sinks to the bottom of the furnace, impurities containing silicates and sulfates are captured by the calcium carbonate of the limestone and float to the top. The pig iron is separated out at the bottom of the furnace, while the slag is skimmed off the top of the molten pig iron.[4-6] After accounting for marketable pig iron recovery, about 10 to 15% by mass of pig iron output is slag.[7] Blast-furnace slag has steadily gained popularity for various uses, making it an economically viable option. GGBFS has been studied, used, and proven to be a useful addition to concrete mixtures as a supplementary cementitious material.[8] Blast-furnace slag has been studied as both a coarse aggregate, as expanded blast-furnace slag,[9] and as a fine aggregate[10,11] under the form of non-ground-granulated blast-furnace slag (n-GGBFS) in concrete mixtures, but not in shotcrete mixtures. This project investigated the feasibility of using blast-furnace slag, in multiple forms, to produce dry-mix shotcrete mixtures with the explicit goals of sustainability and meeting basic performance criteria for underground shotcrete. Blast-furnace slag aggregates and supplementary cementitious material (SCM) are also as safe to use in shotcrete applications as conventional aggregates and cement, thus meeting the safety objective.[12]

Mixture Designs

Dry-mix shotcrete was selected for this project, as it offers users more control over placement parameters. It is better suited for lightweight aggregate mixtures and is a current placement method in many mines.[13] The two mixture designs used in the experimental phase of this project are shown in Table 1, with pictures of the ground blast-furnace slag aggregates in Fig. 1 and their combined gradations in Graph 1.

Fig. 1: Pelletized coarse (1.15 to 9.50 mm [0.05 to 0.37 in.]) (right) and pelletized fine (0 to 2.36 mm [0 to 0.09 in.]) (left) blast-furnace slag aggregates

Graph 1: Comparison of Shotcrete Mixture Design Gradations and ACI 506R Limits

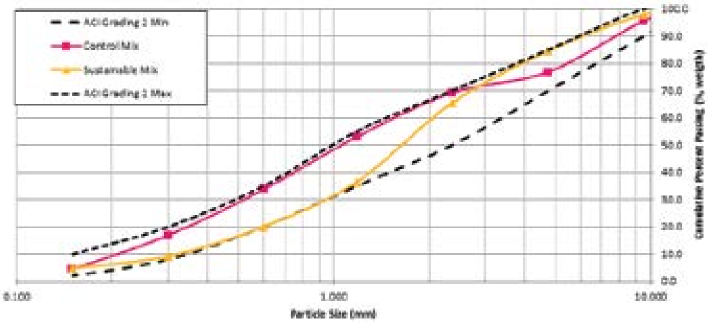


Table 1: Mixture designs for dry-mix shotcretes

	Control mixture		**Sustainable mixture**	
Ingredients	Dry ingredient, (%, weight)	Quantity, lb/yd^3 (kg/m^3)	Dry ingredient, (%, weight)	Quantity, lb/yd^3 (kg/m^3)
Type GU cement	20.40	656 (389)	22.10	649 (385)
GGBFS cement (90% BFS, 10% GU)	1.75	56 (33)	1.90	56 (33)
Silica fume	1.85	59 (35)	2.00	59 (35)
Concrete sand (0.08 to 5.00 mm)	57.00	1831 (1086)	0.00	0 (0)
n-GGBFS fine (0.15 to 2.36 mm)	0.00	0 (0)	59.30	1743 (1034)
BFS coarse (1.18 to 9.50 mm)	19.00	610 (362)	14.70	432 (256)
TOTAL DRY	100.00	3211 (1905)	100.00	2936 (1743)
Water (e/c = 0.45 theoretical)		347 (206)		344 (204)
TOTAL WET		3558 (2111)		3282 (1947)

---

*Note: ACI and ASTM International now use the term "slag" in place of "ground-granulated blast-furnace slag," but to eliminate confusion in this article, we will use the older term GGBFS because we are also discussing pelletized slag as well as the cementitious GGBFS.

Experimental Procedure

The raw materials were dried, weighed, blended dry, and packaged in the laboratory using ovens and the sun for drying, bench-top scales for weighing, a concrete mixer for blending dry ingredients together, and plastic bags for packaging. Roughly 530 lb (240 kg) of each dry mixture was prepared at the King Packaged Materials Facility in Blainville, QC, and shipped to Laval University in Québec City, QC, for testing. The world-class shotcrete testing facility at Laval University features mass balance monitoring for all inputs, including material weight, water, and air, in addition to an accurate rebound measurement system and a fully equipped concrete testing lab. A certified nozzleman placed the samples. An Aliva 246 dry-mix shotcrete machine was used for testing, using 66 ft (20 m) of a 1-1/2 in. (38 mm) inside diameter, 2 in. (50 mm) outside diameter hose, with a double-bubble type nozzle and a water ring immediately at the end of the hose, right before the nozzle. A hydromix assembly was not available during the test period, but would have offered longer and better mixing. The machine, the operator, and the material were all located on a large scale to weigh the outgoing shotcrete material. The material was shot against a steel panel with a beveled edge that hangs from a load cell to measure rebound. The material was also shot into two standard ASTM C1604/C1604M[14] wood panels measuring 24 x 24 x 3.5 in. (610 x 610 x 90 mm) to extract cores for compressive strength, boiled absorption, volume of permeable voids, chloride ion permeability, and density testing.

Fig. 2: Aliva 246, material and operator on scale (top left), double bubble nozzle (top middle), short hydromix nozzle assembly (top right), shotcrete panels (middle left), rebound panel (middle middle) and shooting area overview (middle right), fresh control mixture on rebound panel (bottom left), measuring buildup (bottom middle), shooting control mixture panel (bottom right)

Experimental Results

Table 2 presents the results achieved during the testing phase.

Discussion

The water-cementitious material ratio (*w/cm*) of the fresh shotcrete for the control mixture was 0.33 compared to 0.52 for the sustainable mixture. Both of these were determined by taking the initial mass and then drying freshly shot shotcrete in a microwave until a constant mass is achieved. The ratio is then calculated using the mixture's in-place cementitious content, measured by washout over an 80 µm sieve immediately after shooting. The in-place cementitious content was higher for the control mixture, as a result of the higher rebound. This method does not distinguish between the water consumed to hydrate cement and the water absorbed by the aggregates. Blast-furnace slag aggregates absorb between 6 to 9% water by mass, as compared to 0.6% for natural sand.[12] It follows that a significant part of this water content can be attributed to absorption by the slag aggregates and that the actual *w/cm* is less than 0.52 for the sustainable mixture.

The air flow for the control mixture, at 196 ft^3/min (5.55 m^3/min), was higher and closer to the normal air flow rate for standard shotcrete mixtures with the selected equipment than the sustainable mixture, which was 136 ft^3/min (3.85 m^3/min) or 30.7% less. The reduced air flow rate for the sustainable mixture was a result of unfamiliarity of the shooting performance of the mixture. The all-slag mixture was found to be stable at a higher *w/cm*, masking the requirement for a higher air-flow rate to produce a denser and stronger hardened shotcrete. Because the slag particles are smooth and more slippery within the cement matrix than natural sand, they should decrease the water demand to achieve a proper fresh shotcrete consistency. Yet, because the particles are porous, they tend to absorb more water than natural concrete sand, offsetting the more fluid consistency. The mixing time was also shortened, due to the unavailability of a long hydromix nozzle assembly, resulting in a less than ideal mixing time for either mixture.

Table 2: Test results

Criteria	**Method**	**Control mixture**	**Sustainable mixture**	**ACI 506.5R minimum**[16]	**ACI 506.5R maximum**[16]
Water content to cementitious ratio	U. Laval	**0.33**	**0.52**	0.35	0.45
In-place cementitious (%, mass)	U. Laval	37.1	31.8	—	—
Average air flow, ft^3/min (m^3/min)	U. Laval	195.9 (5.55)	135.8 (3.85)	—	—
PERFORMANCE CRITERIA					
Compressive strength at :					
3 days, psi (MPa)	ASTM C1604[14]	2495 (17.2)	**1697 (11.7)**	2176 (15)	—
7 days, psi (MPa)	ASTM C1604[14]	**4235 (29.2)**	**2698 (18.6)**	4351 (30)	—
28 days, psi (MPa)	ASTM C1604[14]	**5656 (39.0)**	**4569 (31.5)**	5802 (40)	—
Hardened density, lb/yd^3 (kg/m^3)	U. Laval	3600 (2136)	3327 (1974)	—	—
Rebound (%, mass)	U. Laval	**34.7**	14.8	10[*]	30[*]
DURABILITY CRITERIA					
Boiled absorption (%)	ASTM C642[15]	**10.26**	**15.45**	—	8[†]
Volume permeable voids (%)	ASTM C642[15]	**20.20**	**26.69**	—	17[†]
Chloride permeability (coulombs)	ASTM C1202[17]	1032	1843	—	—

[*] Rebound limits defined in ACI 506R, Table 8.1.[13]

[†] These limits are for normalweight aggregates and may not apply to lightweight aggregates, such as slag aggregates.

Note: **Bold** results do not conform to ACI 506.5R, "Guide for Specifying Underground Shotcrete," criteria.[16]

The sustainable mixture had 32%, 36%, and 19% lower compressive strength at 3, 7, and 28 days, respectively, compared to the control mixture. The blast-furnace slag aggregates are more porous, with a specific gravity of 2.3 for the fine aggregates and 1.7 for the coarse aggregates. The natural concrete sand has a specific gravity of 2.7, showing the slag aggregates are less dense.[12] Furthermore, the sustainable shotcrete probably suffered from less compaction and more voids than the control mixture due to lower air-flow rate used to project it, also increasing its overall porosity. According to strength theory, as voids and porosity increase in a material, strength decreases.[1] The sustainable mixture had a 7.6% lower hardened density than the control mixture. The experimental densities were close to those determined mathematically, with 3560 lb/yd^3 (2110 kg/m^3) versus 3600 lb/yd^3 (2140 kg/m^3) for the control mixture and 3280 lb/yd^3 (1950 kg/m^3) versus 3330 lb/yd^3 (1970 kg/m^3) for the sustainable mixture, perhaps indicating that the actual *w/cm* ratio was different than that measured experimentally, due to absorption and adsorption of water on the dried aggregates. Furthermore, the values of boiled absorption, volume of permeable voids, and chloride ion permeability are all higher in the sustainable mixture, indicating it is less dense or more porous.

Even the control mixture values for these criteria are above those proposed by ACI 506.5R, illustrating that the porous coarse slag aggregates alone greatly influence the total porosity and permeability of the final hardened shotcrete. The 42.7% reduction in rebound measured for the sustainable mixture can be partly attributed to the lower air-flow rate used to project it on the steel receiving plate. Future experiments at optimized air-flow rates will provide a better comparison. Both the sustainable and the control mixtures did not meet the ACI 506.5R criteria for compressive strength, boiled absorption, and volume of permeable void limits.[16] According to ASTM C1202, both mixtures are still classified as having low chloride ion permeability.[17]

All these factors illustrate the challenges and future opportunities of studying shotcrete mixtures based on lightweight slag aggregates. The water content and the air flow could be optimized in future experiments to increase success and achieve higher compressive strengths, while reducing permeability and porosity, especially when using lightweight blast-furnace slag aggregates.

Conclusions

Although the experimental phase did not meet performance and durability criteria for a suitable underground ground control shotcrete application as defined by ACI 506.5R, "Guide to Specifying Underground Shotcrete," it did meet the objective of sustainability, achieving an economically and technically feasible mixture composed of 77.7% recycled materials— including slag cement, slag aggregates, and silica fume—with an average compressive strength of 4570 psi (31.5 MPa) at 28 days and an average density 7.6% lighter than the control mixture. The comparatively low rebound of 14.8% on a vertical steel plate can be an additional benefit, increasing the yield of fresh shotcrete per unit of dry shotcrete material, along with the lower density, for the sustainable shotcrete mixture. In general, this article has illustrated the promising and positive aspects of increasing the use of industrial waste materials, such as blast-furnace slag aggregates in dry-mix shotcrete.

References

1. Mehta, P. K., and Monteiro, P. J., *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill, New York, 2006, 659 pp.

2. American Shotcrete Association, “Sustainability of Shotcrete,” Farmington Hills, MI, 2011, 10 pp.

3. Yoshida, S.; Taguchi, F.; Yamanaka, S.; and Sato, H., “Applicability of Shotcrete for NATM Using Blast Furnace Slag Cement,” *Shotcrete for Underground Support X*, ASCE, Whistler, BC, Canada, 2006, pp. 89-98.

4. National Slag Association, “Blast Furnace Slag,” 2009, http://www.nationalslag.org/blastfurnace.htm. (last accessed July 31, 2011)

5. National Slag Association, “Slag: The Construction Material of Choice,” http://www.nationalslag.org/archive/nsa_blast_furnace_brochure.pdf. (last accessed July 31, 2011)

6. Ricketts, J. A., “How it Works: The Blast Furnace,” from the local history of Stoke-on-Trent, England, http://www.thepotteries.org/shelton/blast_furnace.htm. (last accessed July 31, 2011)

7. Kalyoncu, R., “Slag—Iron and Steel,” from the U.S. Geological Survey, http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/790400.pdf. (last accessed Sept. 27, 2013)

8. Hooton, R. D., “Canadian Use of Ground Granulated Blast-Furnace Slag as a Supplementary Cementing Material for Enhanced Performance of Concrete,” *Canadian Journal of Civil Engineering*, 2000, pp. 754-760.

9. Emery, J. J., “Pelletized Lightweight Slag Aggregate,” *Proceedings of Concrete International,* Concrete Society, UK, Apr. 1980, 11 pp..

10. Topçu, I. B., and Bilir, T., “Effect of Non-Ground-Granulated Blast-Furnace Slag as Fine Aggregate on Shrinkage Cracking of Mortars,” *ACI Materials Journal*, V. 107, No. 6, Nov.-Dec. 2010, pp. 545-553.

11. Yüksel, I.; Özkan, Ö.; and Bilir, T., “Use of Granulated Blast-Furnace Slag in Concrete as Fine Aggregate,” *ACI Materials Journal*, V. 103, No. 3, May-June 2006, pp. 203-208.

12. Lafarge North America, “Technical Data Sheets,” Hamilton, Montréal, QC, Canada, 2011, 3 pp.

13. ACI Committee 506, “Guide to Shotcrete (ACI 506R-05),” American Concrete Institute, Farmington Hills, MI, 2005, 40 pp.

14. ASTM C1604/C1604M-05(2012), “Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete,” ASTM International, West Conshohocken, PA, 2012, 5 pp.

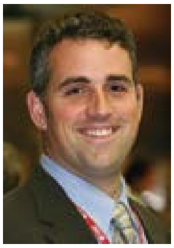
15. ASTM C642, “Standard Test Method for Density, Absorption, and Voids in Hardened Concrete,” ASTM International, West Conshohocken, PA, 2006, 3 pp.

16. ACI Committee 506, “Guide to Specifying Underground Shotcrete (ACI 506.5R-09),” American Concrete Institute, Farmington Hills, MI, 2009, 52 pp.

17. ASTM C1202, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration,” ASTM International, West Conshohocken, PA, 2005, 6 pp.

***Philip Sawoszczuk**, Eng., M.Eng., is a Technical Services Representative for King Packaged Materials Company, Boisbriand, QC, Canada. He received his M.Eng. in civil engineering from Concordia University, Montreal, QC, Canada, in 2013, and his B.Eng. from McGill University, Montreal, QC, Canada, in 2009. His areas of expertise include rehabilitation and preservation of infrastructure, structural engineering, shotcrete, cementitious material science, and durability of concrete. He is a member of OIQ, ACI, and ICRI.*

***Dr. Michelle Nokken**, P. Eng., FACI, is an Associate Professor in the Department of Building, Civil & Environmental Engineering at Concordia University. She received her BASc and PhD degrees from the University of Toronto, Toronto, ON, Canada, in 1999 and 2004, respectively. Dr. Nokken’s research interests are durability of concrete, use of alternate cementing materials and non-destructive testing. Dr. Nokken is a member of ASCE.*



***Dr. Marc Jolin**, FACI, is a Full Professor in the Department of Civil and Water Engineering at Laval University, Québec City, QC, Canada. He received his PhD from the University of British Columbia, Vancouver, BC, Canada, in 1999. An active member of Centre de recherche sur les infrastructures en béton (CRIB), he is currently involved in projects on service life, reinforcement encasement quality, new admixtures, and rheology of fresh shotcrete. Jolin is an ASA member; an ACI Examiner for Shotcrete Nozzleman Certification (wet- and dry-mix processes); Chair of ACI Committee C660, Shotcrete Nozzleman Certification; and Secretary of ACI Committee 506, Shotcreting.*