EcoSmart™ Concrete Project
A Concrete Contribution to the Environment™

STUDY OF GS-CEM AND OTHER SLAG-BASED PRODUCTS

Source: Portland Cement Association

Pre-Feasibility Review of the Potential for
Using Slag-Based Products in Concrete

Prepared for:
Action Plan 2000 on Climate Change – Minerals and Metals

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1. Executive Summary

The following report evaluates the potential for using slag-based products in concrete in order to reduce the greenhouse gas (GHG) emissions associated with the production of Portland cement (PC). Preliminary investigation into the use of high volumes of ground granulated blast-furnace slag (GGBFS) in common concrete applications was carried out, and a pre-feasibility review of the use of ground cement slag (GS-Cem) in concrete as a supplementary cementing material (SCM) was undertaken.

GGBFS-based high volume slag (HVS) concrete is currently used in other parts of the world, and is limited to specific applications in Canada. The main reasons for using slag in concrete at high levels of Portland cement replacement are related to durability, including increased resistance against sulphate attack, lower heat of hydration, and protection against alkali-aggregate reactivity. HVS concrete appears to have a number of technical challenges, including potentially longer setting time and slower strength gain, as well as limited availability across the country due to location of domestic sources and transportation distances to some concrete markets. Considering the potential access to international sources of slag, the opportunity exists and it has been proven technically feasible to increase the replacement of Portland cement by GGBFS up to 80% in more common applications.

For the GS-Cem material, the pre-feasibility review of technical data indicated that there is the potential to use this material in concrete as an SCM, and that it may improve some concrete properties. However, the review of environmental data indicates that the GHG benefit of using GS-Cem is not as great as that of using fly ash. Furthermore, the price of GS-Cem on the market is similar to the price of Portland cement, while performance-wise, GS-Cem should be priced similar to fly ash.

In the course of GS-Cem evaluation, another Teck Cominco product, Hard-Cem, has come to light. Although not an SCM, Hard-Cem is produced from the same barren slag as GS-Cem, and can be used as an effective concrete hardener.

From this evaluation, EcoSmart has concluded that while it may consider utilizing Hard-Cem in high volume fly ash (HVFA) concrete in future case study projects, it will not continue further work on GS-Cem. On the other hand, the potential for greater reductions of GHG emissions from the concrete industry through the use of HVS concrete is a concept that EcoSmart is likely to continue developing, using its experience with increasing the use of HVFA concrete in Canada.

2. Introduction

The use of Portland cement (PC) in concrete has significant greenhouse gas (GHG) implications, as the manufacture of each tonne of Portland cement generates approximately 0.9 tonnes of CO_2 emissions[1]. However, the "GHG signature" of concrete can be reduced by partial replacement of Portland cement with supplementary cementing materials (SCM). Typical SCMs include fly ash (FA), ground granulated blast-furnace slag (GGBFS), and silica fume (SF), ground limestone, natural pozzolans and metakaolin.

2.1. Production and Use of GGBFS and GS-Cem

2.1.1. Production and Use of GGBFS

GGBFS (a by-product of the steel manufacturing process) is regulated by the Canadian Standards Association (CSA), is uniform in composition, and is widely accepted as an SCM (it is sometimes referred to as slag cement). However, the research into the use of high volume slag (HVS) in concrete has not been as extensive as the use of high volume fly ash (HVFA) in concrete has been. Not surprisingly, the application of HVS concrete in the field is very limited, and typically only used to achieve special properties in concrete (e.g., to provide resistance against sulphate attack, lower heat of hydration, and protection against alkali-aggregate reactivity). Furthermore, Portland cement replacement by GGBFS has been limited to levels less than 40% (by mass)[2], while it is known that GGBFS can replace Portland cement by up to 80%[3].

Another limiting factor for the widespread use of HVS concrete is the geographic availability of slag. GGBFS is primarily available in the Eastern parts of Canada and the U.S., with no or limited local sources in the Central and Western parts of North America. As it is uneconomical to transport slag over large distances, and the resulting GHG emissions from transportation would reduce the environmental benefit of using slag to replace Portland cement, other (non-steel) sources of slag may be worth investigating, particularly in the West.

2.1.2. Production and Use of GS-Cem:

The exploration of industrial by-products as potential SCMs in concrete has identified ground slag cement (GS-Cem), a by-product of lead smelting. The prime ingredient in GS-Cem is barren slag, which is produced by Cementec Industries Inc. (Cementec) from the Trail Operations of Teck Cominco Limited (Tech Cominco). Slag is primarily comprised of silica and limerock and is used in the smelting process to collect impurities. Heavy metal impurities are subsequently removed from the slag, which is then quenched in water. The resulting barren slag is a granulated glassy material exhibiting potentially pozzolanic properties.

GS-Cem is produced by finely grinding the barren slag and mixing it with Econo-Set, a proprietary product that enhances early strength development, bleed water control, and concrete finishability. According to Teck Cominco, GS-Cem could replace up to 20% of the Portland cement in concrete without significantly reducing concrete performance.

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[1] Malhotra, 1999.
[2] Insaar, February 2004.
[3] SCA, 2003. (Bulletin No. 13: Suggested Specifications.)

Therefore, EcoSmart undertook the investigation of the potential of GGBFS-based HVS concrete as well as the potential of using GS-Cem in concrete as an SCM.

2.2. Study Objectives

The objectives of this study are:

1. to prepare a preliminary slag scoping study that defines the scope, outline, and deliverables for a full study on the use of GGBFS as an SCM in concrete;
2. to recommend the approach to a full slag scoping study;
3. to establish the validity of the concept of developing GS-Cem as a Portland cement alternative at the 20% replacement level;
4. to compile and summarize existing information from the supplier and undertake additional tests, if necessary, to produce a clear overview of the "promise and challenges" of the concept; and
5. if the results of 3. and 4. are positive, to further explore the technology involving small scale production at a pilot plant and application of the technology in a case study.

2.3. Scope of Report

This study was conducted as a pre-feasibility review of the potential for using slag-based products in concrete. The report focuses on the potential of using GGBFS at high Portland cement replacement levels in concrete, and on the potential of using GS-Cem as an SCM in concrete. This report outlines these technologies, the application of these technologies in concrete, and their economic and environmental implications. Existing information is compiled, including supporting tests and analysis. This report also documents the process undertaken by EcoSmart, the input of the cement and concrete industry, and the potential courses of further action. Finally, the outcome of the pre-feasibility review is indicated.

2.4. About EcoSmart

The objective of the EcoSmart™ Concrete Project (EcoSmart) is to minimize the GHG signature of concrete by optimizing the replacement of Portland cement in the concrete mixtures with SCMs while maintaining or improving cost, performance, and constructability. EcoSmart is an industry-government partnership generating and transferring knowledge on reducing the CO_2 emissions from the construction industry.

3. Background

A number of SCMs are recognized by the Canadian Standards Association (CSA), including fly ash, ferrous slag (specifically GGBFS), silica fume, and natural pozzolans. Unlike GGBFS, GS-Cem is not explicitly covered by the CSA Standard. However, GS-Cem has been tested and demonstrated to satisfy the chemical and physical analysis requirements of CSA A3001 for alternative SCMs, and its characteristics are comparable to those of Type S SCM, and specifically, GGBFS. [4, 5]

Despite the stringent regulation of GGBFS, the availability of standards and guidelines for its use in concrete, and a technical replacement limit of up to 80%, its use in concrete in Canada has been moderate (up to 40% during the summer months, and 10-15% during the winter months). [6] Higher replacement levels are specified mainly to improve certain

[4] Cementec Technical Bulletin #2
[5] AMEC, April 2003.
[6] Insaar, February 2004.

properties of concrete, such as to provide resistance against sulphate attack, to lower heat of hydration, and to provide protection against alkali-aggregate reactivity. The drawbacks of using HVS concrete include increased requirement for quality control and trial concrete tests to avoid potential reductions in early strength gain, and potential problems related to freezing and thawing and de-icing salt scaling. Currently, there is no organized effort in Canada to systematically increase Portland cement replacement by slag beyond the current moderate levels or to use HVS concrete in common applications.

As indicated in Section 3.3, a number of investigations and studies have been undertaken to assess the pozzolanic properties of GS-Cem and its performance in ordinary concrete. At the onset of the EcoSmart study, the GS-Cem technology appeared to have a number of advantages, including market introduction of a cementitious material with low climate change implications; reuse of a waste product; resolution of Trail's slag stock pile issues; and production of a more durable concrete. However, the technology also presented some challenges, including energy intensity of grinding the hard barren slag; the high estimated cost of GS-Cem (in the range of the cost of Portland cement); the reluctance of the cement/concrete industry to adopt the concept; and the untested performance concrete containing GS-Cem in combination with other SCMs (such as high volumes of fly ash).

3.1. Definitions

Portland cement (PC) is a hydraulic cement produced by pulverizing Portland cement clinker, usually in combination with calcium sulphate (gypsum). Portland cement clinker is a partially fused ceramic material consisting primarily of hydraulic calcium silicates and calcium aluminates.[7]

Supplementary cementing material (SCM) is a pozzolanic material that contains high proportions of silica and in some SCMs, alumina. When used in concrete as partial replacement of Portland cement, it reacts with unreacted calcium hydroxide from the hydration of Portland cement to form calcium silicate hydrates – the desired end product of Portland cement hydration. SCMs include fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), natural pozzolans (NP), and metakaolin (MK).

Ground granulated blast-furnace slag (GGBFS) is produced by grinding the glassy granular material formed when molten blast-furnace slag is rapidly cooled or quenched from approximately 1500oC. This slag is the by-product of iron production, where iron oxide, limestone and dolomite, and coke combined in a molten state. GGBFS is comprised mainly of silicon, calcium, aluminum, and magnesium oxides. The high calcium oxide of GGBFS (CaO 30-45%) gives GGBFS its hydraulic (cementitious) properties. [8]

Ground slag cement (GS-Cem) is a specialty Type S SCM manufactured in Calgary, Alberta, from finely ground metallurgical slag, blended with a proprietary additive Econo-Set. The slag component of GS-Cem is produced by Teck Cominco in Trail, British Columbia, in lead smelting operations through a slag fuming process, which produces a barren slag that is rich in reactive silica and chemically active metal oxides. Unlike other SCMs, GS-Cem is an unregulated product. However, according to Cementec, GS-Cem fully conforms to the standards outlined in the CSA A23.5 (now CSA A3000) and is classified as Type S SCM[9], [10].

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[7] ACI Manual of Concrete Practice, 2003, ACI 116R-12-14.
[8] ACI Manual of Concrete Practice, 2003, ACI 233R.
[9] Cementec Product Sheet: GS-Cem
[10] Cementec Technical Bulletin #2

3.2. Use of Slag-Based Products in Canada

3.2.1. Use of GGBFS in Canada

The use of GGBFS in Canada has been documented in the 2003 report on the "Current Situation of SCMs in Canada" prepared by NRCan/CANMET. The report indicates that the utilization of available slag can be increased if the demand for GGBFS is increased. [11] However, slag is not available in all regions of Canada. Therefore, in addition to a number of technical barriers, there is also an economic barrier that includes the availability of slag at a reasonable price across the country. Fortunately, technical barriers can be overcome with additional R&D, improvements in quality control, performing field trials, and educating the construction sector. [12] However, the long transportation distances to regions far away from slag sources not only increase the cost of the slag, but transportation-related GHG emissions diminish the environmental benefits of slag use in concrete.

3.2.2. Use of GS-Cem in Canada

Currently in Canada, GS-Cem has been used in a range of concrete applications (primarily in Calgary, Alberta) since 1997[13] and a number of field trials have been conducted[14]. However, at present, this material is not widely used commercially. No other sources of GS-Cem have been identified.

3.3. Investigations of Pozzolanic Potential of GS-Cem

While the hydraulic (cementitious) properties of GGBFS are undisputedly the result of the high CaO content of this material (the same primary reactive agent present in Portland cement), the pozzolanic potential of GS-Cem is less obvious.

Investigations of the cementing properties of Teck Cominco's slag began in 1992, when CANMET results of tests on the barren slag showed promise. Subsequently, in 1995, Agra Earth and Environmental (now AMEC Earth and Environmental Limited (AMEC)) and Trow Engineering tested ground barren slag of various fineness (Blaine), and determined that at Blaines up to approximately 400 m^2/kg the pozzolanic qualities and compressive strengths were lower than those of fly ash and comparable fly ash concrete mixes (at Portland cement replacement levels of 20-40%). However, at Blaines higher than approximately 500 m^2/kg, the compressive strengths of the ground barren slag were higher and the setting times shorter than those of comparable fly ash concrete. Ordinary Portland cement (OPC) concrete was still found to be superior in these tests[15]. (It should be noted that the Blaine of typical Portland cement is at minimum 280 m^2/kg [16], and is normally in the range of 300-500 m^2/kg [17], while the Blaine of fly ash can range from 170-1,000 m^2/kg [18]. For comparison, the Blaine of GGBFS is in the range of 400-450 m^2/kg[19].)

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[11] Bouzoubaâ and Fournier, 2003.
[12] Insaar, February 2004.
[13] AMEC , April 2003.
[14] Teck Cominco, March 2002.
[15] Teck Cominco, March 2002.
[16] Lehigh Heidelberg Cement Group, website.
[17] Portland Cement Association, website.
[18] U.S. Department of Transportation, website.
[19] Insaar, February 2004.

Following the barren slag testing, in 1996, Pildysh Engineering (now Cementec) began experimenting with various additives to develop the ground barren slag into an SCM. By late 1999, a product called GS-Cem had been formulated and used in concrete in a number of field trials. The optimum Portland cement replacement with GS-Cem was determined to be in the range of 15-20%, with good concrete performance in terms of setting time, compressive strength, finishability, bleed water control, durability (particularly under freezing and thawing exposure), and alkali-silica reactivity. Additional tests demonstrated good sulphate resistance of GS-Cem concrete[20].

During 2001 and early 2002, following preliminary investigations and discussions with Teck Cominco, EcoSmart undertook as part of its mandate to follow up and further investigate the technical, economic and environmental potential and challenges of developing this source of slag, and if the results were positive, to initiate a case study using GS-Cem concrete.

In January 2003, a stakeholders meeting was held in Alberta with representatives of Teck Cominco, Cementec, the engineering and architectural communities, the cement and concrete industry, and the research community. The purpose of the meeting was to investigate the suitability and acceptability of this material by the cement and concrete industry, and to identify potential challenges of introducing GS-Cem on the concrete market[21]. It was decided that the stakeholders would review the available technical information, and that the cement and concrete industry would identify potential challenges, including any remaining testing that would be needed for this material to be fully compliant with all applicable standards. Initial concerns from the cement and concrete industry pointed to the potential that GS-Cem would be used to replace fly ash in concrete instead of the intended cementitious Portland cement, because of the pozzolanic nature of GS-Cem [22].

In April2003, AMEC produced a comprehensive report verifying the applicability of concrete test data generated in Alberta to concrete produced in British Columbia. The results of the AMEC study were generally positive for concretes containing 15-20% GS-Cem as a Portland cement replacement. [23] More details of these findings are presented in Section 4.1.

While investigating GS-Cem's use as an SCM, another Cementec product, called Hard-Cem, was presented to EcoSmart. Hard-Cem is used as an integral concrete hardener with superior abrasion resistance properties. It is produced from the same barren slag from the Teck Cominco operations as the slag used to produce GS-Cem. However, the slag is ground less finely for Hard-Cem production than for GS-Cem production, and blended with other proprietary additives. Hard-Cem's performance has been extensively tested, and the material was used in the concrete floor for Transcontinental Printing warehouse in Calgary. AMEC also produced a comprehensive report in 2003 reviewing the suitability of Hard-Cem for use in concrete as a partial fine aggregate (fine sand) replacement. [24, 25] More details of these findings are presented in Section 4.3. Presently, one EcoSmart case study project, namely the Metro Skate Park in Burnaby, BC, is using Hard-Cem in combination with fly ash in the concrete. The main considerations in selecting the Hard-Cem product for this project included a smooth surface finish, abrasion resistance, and darker colour to reduce glare. The project is under construction at the time of writing of this report, and detailed technical performance information is not

[20] Teck Cominco, March 2002.
[21] EcoSmart, January 15, 2003.
[22] EcoSmart, May 14, 2002.
[23] AMEC, April 2003.
[24] Cementec Industries Inc., website.
[25] AMEC, May 2003.

available. However, the landscape architect and contractor have reported satisfaction with the workability of the concrete and the quality of the surface finish[26]. Design considerations and concrete specifications may be found in the existing case study report[27].

Following the review of the available information and discussions with stakeholders, EcoSmart began identifying potential case study projects where GS-Cem and/or Hard-Cem could be used. The two projects for which GS-Cem use was investigated were: the Vancouver Wharves (which Teck Cominco uses for bulk shipping their materials), and the Seymour and Capilano Water Treatment Plant (a regional infrastructure project). However, these projects did not become GS-Cem case studies for reasons including cancellation of the Vancouver Wharves project, decision to optimize the level of Portland cement replacement by substituting it with fly ash only, identifying a more appropriate demonstration project in BC that would benefit more from the properties of GS-Cem, among others.

The following sections of the report provide more details of the findings from the EcoSmart initiative.

4. Technical Evaluation

4.1. Performance of High Levels of GGBFS in Concrete

The reactivity of GGBFS is similar to that of OPC. However, it has been observed that the setting time of slag concrete is longer, and the early strength is lower compared to OPC concrete. This performance deficit is evident at low Portland cement replacement levels (e.g., 25%), and it is reasonable to expect that this characteristic would worsen at higher replacement levels. However, modifications to the concrete mix design, such as the reduction of water-to-cementing materials ratio (W/CM), particularly with the addition of superplasticizers, may improve these characteristics. Other factors that influence the setting time and strength gain of slag concrete include the grade of the slag, its fineness and source. [28]

At conventional Portland cement replacement levels (up to 40%), bleeding does not appear to be a problem. At higher replacement levels, particularly at low curing temperatures, the extended setting time could have an unfavourable effect on bleeding. Similarly, at conventional replacement levels, the workability of concrete improves; higher replacement levels may require additional testing to confirm this characteristic. [29]

When using high volumes of slag in air-entrained concrete, the air-entraining admixture dosage may need to be increased, primarily because slag is finer than Portland cement. The duration of curing likewise needs to be extended for HVS concrete, since the rate of formation of strength-producing hydrates is slow[30], and the concrete mixtures are likely to contain less mixing water at the onset (i.e., as discussed above, lower W/CM may be required to achieve higher early strengths).

The permeability of well-cured HVS concrete is significantly reduced. Likewise, the heat of hydration of concrete containing slag is reduced. However, the effect on the

[26] Personal communication, Jeff Cutler, August 16, 2004. Personal communication, Henry Boschman, July 27, 2004. EcoSmart site visit July 27, 2004.
[27] Space2place, March 2004.
[28] ACI Manual of Concrete Practice, 2003, ACI 233R.
[29] Insaar, February 2004.
[30] Insaar, February 2004.

associated thermal cracking needs further investigation, because it appears that the tensile strength and tensile strain at failure of concrete at early ages decreases with increased slag content. [31]

Durability characteristics are largely unaffected or are improved by the use of GGBFS, especially at high Portland cement replacement levels. Properties such as resistance to sulphate and salt water attack, and resistance to alkali aggregate reactivity are substantially improved at the 65% replacement levels[32]. For good performance under repeated freezing and thawing cycles, Portland cement replacement with slag can range between 25-80% when W/CM is 0.45, however, for concrete exposed to de-icing salts, even with W/CM of 0.45, slag levels should be limited to 25-50%[33].

In general, the performance characteristics of HVS concrete are largely inferred from the performance of concrete where 40-50% of Portland cement is replaced with GGBFS. Therefore, there is a significant need to verify these inferences in field applications of HVS concrete.

Internationally, a number of countries (such us the UK, Japan, Australia, Finland and the US) introduce slag as a separate ingredient at the ready-mixed concrete plant. On the other hand, other countries (such as Holland, France and Germany) intergrind slag with clinker at the cement plant to produce an interground slag cement. Although the international use of slag in concrete at the 60-85% level has been documented, detailed performance data from specific applications is not readily available. [34] Therefore, concrete producers in Canada can be confident that wider use of HVS concrete is feasible; however, field performance data must be generated here in Canada to increase the practical knowledge of the Canadian concrete industry.

4.2. Performance of GS-Cem in Concrete as an SCM

GS-Cem has been shown to improve most mechanical and durability properties of plastic and hardened concrete. However, the benefits of using GS-Cem as an SCM in terms of improved concrete properties are limited to Portland cement replacements up to 20%. Improved concrete properties are also exhibited by concrete containing up to 20% GS-Cem and 20% fly ash for a total Portland cement replacement of 40%. [35]

In general, the use of GS-Cem does not increase the water demand of concrete, and reduces bleeding in fresh concrete. The setting time of GS-Cem concrete is comparable to that of OPC concrete at standard curing temperatures, and shorter than that of 20% fly ash concrete. The early strength development (up to 7 days) is slower for GS-Cem concrete than OPC concrete, but comparable to that of fly ash concrete. After 28 days, the strength of GS-Cem concrete is higher than both fly ash concrete and OPC concrete. [36]

GS-Cem was shown not to increase the drying shrinkage of concrete, and was shown to improve the de-icing salt scaling of concrete. Earlier evaluation by AMEC indicates that at the 15-20% Portland cement replacement levels, GS-Cem concrete improves the sulphate resistance of concrete. [37]

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[31] Insaar, February 2004.
[32] Insaar, February 2004.
[33] SCA, 2003. (Bulletin No. 13: Suggested Specifications.)
[34] Insaar, February 2004.
[35] AMEC, April 2003.
[36] AMEC, April 2003.
[37] AMEC, April 2003.

As with some fly ash concrete, GS-Cem concrete may require a higher dosage of air-entraining admixture than OPC concrete[38].

The colour of GS-Cem concrete may be an issue even at the 20% Portland cement replacement level. Unlike Portland cement, which is grey, and fly ash, which is beige, GS-Cem is black. Typically, lighter cementing materials have a higher value (e.g., for use in architectural concrete), and it is easier to introduce them in the concrete industry.

4.3. Performance of Hard-Cem in Concrete as a Hardener

The main use of the Hard-Cem product is as an integral concrete hardener. It serves as a substitute for conventional surface-applied hardeners, commonly referred to as dry-shake hardeners. Hard-Cem appears not to have any detrimental effects on the performance of concrete, and may improve a number of its properties. As confirmed by an AMEC review, Hard-Cem has modest elasticizing effect, potentially allowing for a reduction in the water demand of concrete that may result in increased compressive strength. Hard-Cem has also been shown to reduce bleeding in the plastic concrete. Perhaps the greatest advantage of using Hard-Cem as a hardener rather than dry-shakes is that it can be used with air-entrained concrete in exterior exposure conditions. [39]

Concrete containing the recommended dosage of 40 kg/m^3 of Hard-Cem (replacing an equal volume of fine sand) exhibits enhanced abrasion resistance over OPC concrete. In addition, improved surface performance has been observed during de-icing salt scaling tests and freeze-thaw durability tests. [40]

Typical applications for Hard-Cem include industrial warehouses and shop floors, parkades, ramps, bridges, intersections, interchanges, dams, dykes, spillways, stilling basins, flumes, pipes, penstocks, hydro-turbine chambers, revetments and breakwaters, precast concrete pipe and other products.[41] As indicated in Section 3.3, landscape and flatwork applications such as skate parks are also good candidates for the Hard-Cem product.

5. Economic Evaluation

The location of the sources of the two types of slag discussed in this report, and the cost of transportation of large volumes of materials over long distances, essentially define the market for each. GGBFS is currently produced and used mainly in Central Canada[42] while GS-Cem is produced only in one location in Western Canada.

Detailed cost analysis would be required to determine the impact of using high volumes of GGBFS in concrete in specific projects. Some economic considerations identified in the Slag Scoping Study by Insaar Services include the level of Portland cement replacement, amount of admixtures added (e.g., superplasticizers and/or silica fume), and the transportation distance[43].

In Western Canada, where GS-Cem is manufactured, no other types of slag are readily available. Therefore, the market price for SCMs is determined by the price of fly ash, which is readily available from Alberta and north-western states in the U.S. The price of fly ash mainly depends on the transportation distance and method, and ranges between

[38] AMEC, April 2003.
[39] AMEC, May 2003.
[40] AMEC, May 2003.
[41] Cementec Industries Inc., website.
[42] Insaar, February 2004.
[43] Insaar, February 2004.

$40 and $80 per tonne depending on the location of the source and the end-use market[44]. The pricing for GS-Cem is $130 per tonne in the Calgary market, which is more in line with the price of Portland cement in that region than with fly ash[45].

5.1. Cost of Transportation

5.1.1. Transportation Costs for GGBFS

The vast distances between Canadian markets and sources of potential materials often determine the feasibility of using certain materials, particularly waste products such as slag. The distances between sources of GGBFS in Central Canada and the concrete market could be nearly 4,500 km. Opportunities exist for international imports of slag from overseas by ship to areas in the West where local slag sources do not exist. However, infrastructure costs of storage and distribution of the quantities of materials that would make such imports economical have thus far been prohibitive.

5.1.2. Transportation Costs for GS-Cem

Likewise, the remoteness of the Teck Cominco slag is a major challenge for using GS-Cem in concrete as an SCM. The cost of transportation of the barren slag to Calgary for processing, and subsequent transportation of the GS-Cem product to the market where it could be used in concrete construction increases with distances traveled. The distance from Trail to Calgary is approximately 600 km, and from Calgary to Vancouver, it is approximately another 1,000 km. Comparatively, the distance to transport fly ash from Edmonton to Vancouver is approximately 1,200 km. Therefore, under the existing processing arrangement, it would not be feasible to bring the price of the GS-Cem product in line with the price of fly ash. In addition to transportation costs, there are also processing costs that include grinding, quality control, and performance testing of GS-Cem concrete, particularly since GS-Cem is an unregulated product. The distances between the potential BC market for GS-Cem in Vancouver and material sources in Trail and Calgary (as well as fly ash sources in Edmonton) are illustrated in Figure 1.

[44] Phiz Engineering, March 2004.
[45] Teck Cominco, March 2002.

Figure 1: Distances between Production Site, Processing Site, and Potential Market for GS-Cem

5.2. Value Comparison of GS-Cem and Other Cementing Materials

A comparison of the relative value of GS-Cem and other cementing materials, such as Portland cement, fly ash and GGBFS is summarized in Table 1.

In essence, the following observations can be made. The reactivity of GS-Cem is higher than that of fly ash but lower than that of Portland cement and slag (i.e., relative pozzolanic reactivity of 0.95, 0.85, 1.00, and 1.00 respectively) [46]. GS-Cem also has a much darker colour than Western fly ash, GGBFS and Portland cement. Therefore, the value of GS-Cem as an SCM is more comparable with that of fly ash than that of Portland cement or GGBFS. However, GS-Cem cannot compete with Portland cement, GGBFS or fly ash for the following reasons:

- the reactivities of Portland cement and GGBFS are higher,
- the distances between sources of materials and concrete markets are too vast,
- the production of fly ash in Alberta already exceeds the demand,
- the price of fly ash (FOB) at a power plant in Alberta is low (from $8 - $12 / tonne),
- fly ash does not require additional processing, and
- the GHG benefit as an SCM in concrete is greatest with fly ash.

Furthermore, the use of yet another SCM by the ready-mixed concrete supplier presents an additional cost for a separate silo for GS-Cem, requiring an additional capital investment. This might affect the price of concrete, increasing the costs of construction and making concrete less competitive than other construction materials.

[46] AMEC, January 14, 2003.

Table 1: Summary of Value Comparison of SCMs

Property/Characteristic	GS-Cem	Fly Ash	GGBFS
Reactivity (relative to Portland cement)	0.95	0.85	1.00
Colour (relative to Portland cement)	Darker	Lighter (Western fly ashes)	Lighter
Transportation distance from SCM source significant to concrete markets	Vast	Reasonable (where fly ash sources exist)	Reasonable (where fly ash sources exist)
Price on the market (relative to Portland cement)	Similar	Significantly lower	Significantly lower
Additional processing of industrial by-product into SCM	Energy intensive	None (where good quality fly ash exists) Some (where lower quality fly ash exists)	More than fly ash but less than GS-Cem
GHG benefit (reduction/tonne of Portland cement replaced, excluding transportation-related emissions)	0.7	0.9	0.8
Ease of introduction at ready-mixed concrete plants	Requires an additional silo (in addition to Portland cement and fly ash silos that may be at plant)	Requires an additional silo (in addition to Portland cement silo that may be at plant)	Requires an additional silo (in addition to Portland cement silo that may be at plant)

Therefore, unless drastic change occurs in the current price or quality of fly ash, GS-Cem will have difficulty penetrating the SCM market.

6. Environmental Evaluation

6.1. Environmental Performance of GGBFS

The Slag Scoping Study conducted by Insaar Services examined the GHG emissions impact of partially replacing Portland cement with GGBFS and the health and safety considerations for humans and the environment.

The processing of steel slag into GGBFS requires about 90% less energy than that required to produce Portland cement. Depending on the source of energy for grinding the slag, similar savings in GHG emissions can be expected. [47] Therefore, replacing one tonne of Portland cement with GGBFS would result in savings of approximately 0.8 tonnes of GHG[48]. Transporting the slag from the source to the market would generate

[47] Insaar, February 2004.

[48] 0.9 tonnes of GHG emissions per tonne of Portland cement (see Section 2) x 90% savings in GHG emissions by replacing Portland cement with GGBFS = 0.8 tonnes of GHG emissions saved per tonne of Portland cement replaced.

additional GHG emissions, which could be significant at large distances (e.g., 0.0162 kg CO_2 per tonne of GGBFS per kilometre transported by rail[49], resulting in approximately 0.07 CO_2 tonnes per tonne of GGBFS transported over 4,500 km).

The Insaar study does not identify any increased risk of GGBFS to human or environmental health and safety relative to that posed by Portland cement. Small amounts of hazardous heavy metals (as glassy silicates) may be found in GGBFS; however, in the hydrated form in concrete, these toxic substances are unlikely to pose a threat of leaching. [50] Similar precautionary measures should be taken when handling GGBFS as with Portland cement.

6.2. Environmental Performance of GS-Cem

A review of the environmental considerations of GS-Cem use in concrete as an SCM was conducted by Hemmings & Associates LLC in 2003. The review included evaluations of both the barren slag and GS-Cem product.

It was found that both the barren slag and GS-Cem have good chemical stability and low solubility, and are not expected to leach trace metals into the environment. The trace metals that are present in the barren slag are sequestered within either the glassy or crystalline phases. Given the additional stabilization and sequestration characteristics of cement-based products, including GS-Cem concrete, the probability of leaching hazardous components has been determined to be very low. [51]

The review also indicated that due to the existing knowledge gaps concerning the potential leachability of aged and weathered concrete demolition rubble containing the slag as an SCM, no definitive statement could be made about potential related risks without further study[52].

The use of waste slag in concrete as an SCM has several environmental benefits. Firstly, the need for landfill disposal of the slag can be reduced or eliminated. And secondly, by replacing a portion of the Portland cement in a concrete mix with GS-Cem, reductions in virgin raw materials, energy consumption and GHG emissions may be achieved. According to Teck Cominco and Cementec, the production of each tonne of GS-Cem generates approximately 0.21 tonnes of CO_2 per tonne of GS-Cem. GHG emissions also result from transporting the barren slag from the smelter in Trail to the processing plant in Calgary and from transporting the GS-Cem product from Calgary to the market (e.g., Vancouver) (see Section 5.1 for transportation distances). [53], [54] Therefore, without accounting for transportation-related GHG emissions, the net GHG emission reduction from the replacement of Portland cement by GS-Cem is in the order of 0.7 tonnes per tonne of cementing material (given that the manufacture of each tonne of Portland cement generates approximately 0.9 tonnes of CO_2 emissions[55]). The use of GS-Cem has a lower GHG emission reduction potential than fly ash, which typically does not require additional processing.

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[49] VCR, 2004.
[50] Insaar, February 2004.
[51] AMEC, April 2003.
[52] AMEC, April 2003.
[53] Teck Cominco, March 2002.
[54] Teck Cominco and Cementec, May 14, 2002.
[55] Malhotra, 1999.

6.3. Environmental Performance of Hard-Cem

The environmental review of the Hard-Cem product has generally been limited to the evaluation of barren slag and GS-Cem conducted by Hemmings & Associates LLC in 2003. Similar environmental performance can be expected with Hard-Cem as with GS-Cem since the source of the "raw" material is the same in both cases. However, substituting slag in the form of Hard-Cem for a dry-shake hardener would not result in the GHG emission reductions that the use of GS-Cem does when it partially replaces Portland cement. In the case of Hard-Cem, fine sand is replaced in the concrete mix with dry-shake hardener, which does not have significant, if any, GHG emission reduction advantages. On the contrary, depending on the location of the sources of fine sand and dry-shake hardener, the GHG emissions may actually increase for concrete containing Hard-Cem, since Hard-Cem needs to be transported over large distances (see Section 5.1).

7. Conclusions

A concerted effort is required to develop a strategic approach for increasing the use of HVS concrete in common applications, particularly in regions where GGBFS is readily available. Based on its experience with increasing the use of HVFA concrete, the EcoSmart group is in a good position to coordinate the HVS concrete effort. With the continued production and use of virgin steel in Canada, and possibility of importing slag from international sources, the opportunity exists to significantly reduce the GHG emissions from Portland cement production by making HVS concrete a common construction material.

The factors involved with production and transportation of the GS-Cem product, namely the high energy intensity and cost of grinding the very hard Teck Cominco slag to sufficient fineness for use as a Portland cement replacement and subsequent transportation of the material to a processing plant and then to the market, tend to indicate that GS-Cem is not a viable cement alternative in the BC concrete market. The Hard-Cem product, manufactured from the same Teck Cominco slag but not requiring as much grinding, appears to be a more promising use of the Teck Cominco waste. Therefore, the EcoSmart group will not expand further effort in implementing GS-Cem in field applications, but may consider implementing Hard-Cem as a hardener in HVFA concrete in suitable applications. Likewise, Teck Cominco has decided to shift their focus from producing GS-Cem to producing and marketing Hard-Cem[56].

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