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# SOS : An Optimization System for the Sustainable use of Supplementary Cementing Materials in Concrete

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**Abstract**:

The paper reports on a major initiative to increase the use of Supplementary Cementing Materials (SCMs) in construction, and thus provide a more sustainable and greener construction industry – through the use of lower quantities of Portland cement. This project -- involving 3 non-governmental organizations (led by Ecosmart), 3 universities, 2 cement companies, 4 government organizations and 9 engineering and construction companies – aims to develop a web-based computer application to provide online expert guidance concerning all aspects of, and the optimum use of, SCMs at all stages of construction – through concept, structural design, materials selection and proportioning, to construction management and implementation.

## 1. Introduction

Supplementary cementing materials are widely used in Canada and other countries for the partial replacement of cement in concrete and/or in small additions to improve workability (1-5 e.g.). The SCMs most commonly used include fly ash and ground granulated blast furnace slag. These materials react to form additional cementing compounds (primarily calcium-silicate-hydrates) that help to improve the quality of a wide-variety of construction materials. The nature of the chemical reactions occurring, and whether the reaction is pozzolanic or self-cementitious, depends upon the characteristics of the SCM selected for use.

With proper engineering and construction practice, SCMs help produce stronger, more durable concrete. The use of SCMs in concrete diverts the material from being disposed in landfill sites. Because SCMs are waste products of other processes, they are much less expensive at source than Portland cement; due to transportation and other commercial influences the market price of SCMs vs. Portland cement, in some cases, does not reflect this. Replacing cement with SCMs also helps to reduce GHG emissions through reduction in the amount of Portland cement required. In Canada, almost one tonne of $CO_2$ is emitted for each tonne of cement produced; worldwide, according to the International Energy Agency, cement production accounts for 7% of total global $CO_2$ emissions. The replacement of cement with SCMs also reduces the emission of other Criteria Air Contaminants (CACs) such as NOx and SOx, associated with cement production, by the same proportion. Several publications attest to the relationship between the volume of cement production and GHG emissions (6-12, e.g.).

On the other hand, historically there have been some negative events that have slowed SCM use in the construction industry. For example, poor quality fly ashes that existed in the 70s and 80s resulted in a much higher water-demand when they were used in concrete. Similarly, because of impurities in some fly ashes, their use resulted in unpredictable quantities of air-entrainment for concrete exposed to freeze-thaw conditions. There have been claims that the use of fly ash with unusually high sulphate levels contributed to the premature deterioration of concrete foundations. Concrete scaling problems that occurred during early experiments on the use of fly ash in flatwork (sidewalks and curb & gutter) resulted in many municipalities banning the use of fly ash in such applications – even though the problem was not confirmed to be due to fly ash use. Fly ash concrete has the reputation of requiring adequate curing practices in order to produce a satisfactory product – practices that are sometimes not followed.

With the advent of classified fly ashes (where the inferior larger particles are removed) and more refined quality controls on fly ash production and distribution, the reputation for fly ash use has improved greatly in the last decade. Currently, a large proportion of all ready-mix concrete supplied in Canada contains fly ash in some proportion. Anecdotal evidence suggests that about 10% of the cementitious material used for concrete in Canada is currently in the form of SCM – in other words, without the use of SCMs, cement demand would be about 10% higher. Canada produces about 13 million tonnes of cement per year for construction (11); without SCMs more than 14 million tonnes of cement would be required for construction, and the annual $CO_2$ emissions associated with concrete production in Canada would be almost one million tonnes higher.

Over the last several years, various forms of research in Canadian laboratories and in other countries show the practicality of replacing much higher levels of cement by SCMs . There are many case studies and pilot projects performed across Canada since 1999 that show the potential for going up to and beyond the 50% plateau for replacement of cement by SCMs (4,5). It is important to emphasize that not all concrete mixes can use replacement levels as high as 50%, and that careful engineering and design are always necessary to ensure that SCMs are used appropriately. Nonetheless, case studies clearly demonstrate the potential for a much greater average use of SCMs in concrete in Canada. The group of industrial advisors gathered in advance of the SOS (SCM Optimization System) project – developers, architects, engineers, contractors, researchers and cement and concrete producers – agree that a target to replace, on average, 25% of cement with SCMs is within reach. With expected growth in construction over the next decade, this would reduce, by 2012, Canada's $CO_2$ emissions by about 2.4 million tonnes per year and CAC emissions such as NOx and SOx by about 8 kilotonnes each.

Although the technology to use a replacement level of 50% is now well established and field tested, greater efforts are required to achieve the proposed average 25% replacement level. There are several reasons for this. One is that the construction industry is – appropriately – reluctant to take risks: it only adopts new technologies widely when they have been tried and tested. The industry perceives risk because of past failures with SCM use. Another is the very diverse, even fragmented, nature of the construction industry, which involves a large number of very different organizations. Some of these are major multi-national companies, like the cement producers that are already working towards increased SCM use because they see the technological, environmental and economic benefits, but they also see the dwindling supply of raw materials that are required to make Portland cement. Others in the industry are quite small, including architects, engineers, and ready-mix concrete producers. Considerable effort and the appropriate decision-supporting tools are required to guide these diverse groups towards the use of higher levels of SCMs, while increasing confidence and reducing risk.

An important factor in the success of most of the pilot projects to date has been the involvement of industry and laboratory/research experts in persuading the developers, architects, engineers and builders that high levels of SCMs can safely be used. These same experts have also been closely involved in monitoring the construction process to ensure that correct practices are followed, and to guide the use of what is still a new technology to most people in the industry. Ideally, all construction projects should have the benefit of this sort of advice, but most projects can not afford the cost of such guidance, even if there were enough experts to provide it. Clearly, personal treatment is not practical on a large scale. Web-based advice and expert guidance is the next best thing.

Industrial advisors have therefore recommended the development of an enabling technology that will effectively make expert advice on SCM usage readily and economically available. SOS is a computer-based expert system that will make the accumulated and ongoing experience and expertise available to the entire construction industry – information and guidance obtained directly from the experience of expert-advisors and others, and also that which is embedded in the relevant literature. Such a system, once developed will be extremely valuable to all facets of the construction industry in Canada -- owners, engineers, contractors, concrete-suppliers, etc. – and, with appropriate extension, can promote the use of SCMs throughout North America and the world.

## 2. Project Objectives

The SCM Optimization System (SOS) is a decision-making system that enables the reduction of the quantity of Portland cement in concrete by determining the optimum level of replacement by supplementary cementing materials. The primary objective of the SOS project is:

> to assemble and package the scientific and technical knowledge, experience and intellectual property currently owned by the members of the partnership and that have been used in numerous SCM case studies, and make these readily available to industry through a computer-based advisory / expert system.

The intention is that developers, builders, suppliers, architects and engineers purchase the model and access to the database – which will be continuously updated with new scientific, technical and project data – and use it to determine the optimal level of SCMs for their projects. The model will take into account climate, structural specifications, construction requirements, quality of locally available materials, and numerous other parameters to determine not only optimal SCM levels but also cost savings and benefits in reduced GHG and criteria air contaminant (CAC) emissions. The model will give advice and guidance about suitability for purpose, selection of materials, mix proportions, construction practices, code requirements, economic and technological alternatives, and mitigation of risk. In addition, the model will interface with other software programs commonly used by industry.

The technology of replacing Portland cement with SCMs in concrete offers numerous benefits such as increased strength, durability and resistance to chemical attacks. At the same time, the technology presents some challenges, such as longer setting time or the risk of carbonation and increased rate of corrosion. Optimizing the amount of SCM in concrete is a complex process that involves numerous interrelated – and often contradictory – parameters and a vast range of stakeholders, each with their own priorities and objectives, as illustrated in Figure 1.

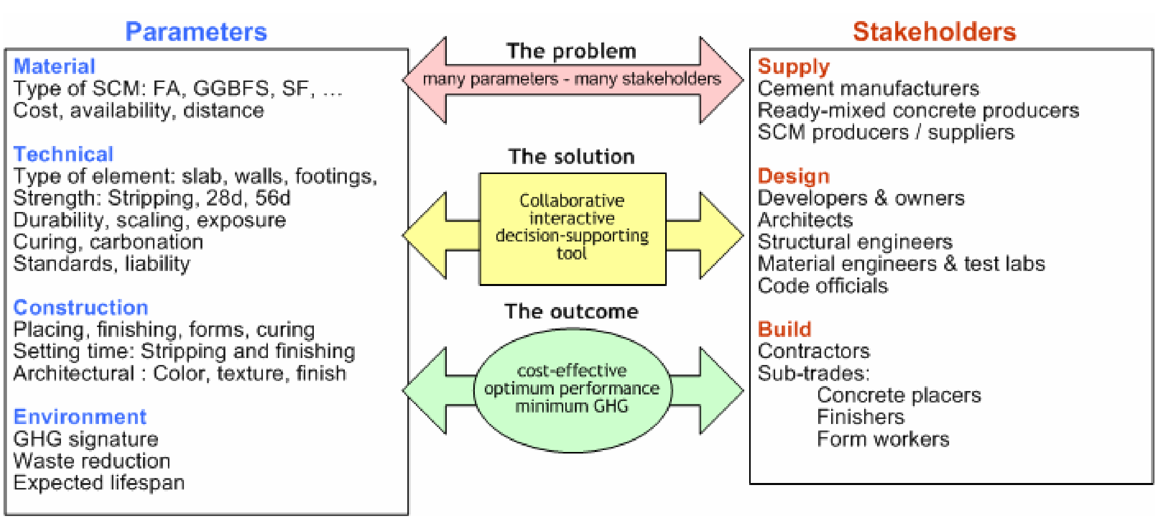


Figure 1: Optimization Parameters and Stakeholders

The SOS is born out of a need for an enabling technology to optimize the replacement of Portland cement in concrete through a systematic, collaborative, interactive process that takes into account the complexity of both sides of the equation: (1) the scientific, technical, economical, and environmental parameters and (2) the multi-stakeholder decision-making process related to concrete and construction in general. Referring to Figure 1:

a) Building with concrete depends on many parameters (in the left box) that have different, often conflicting- priorities for the many stakeholders (in the right box) involved in a project.
b) The proposed solution is to develop a collaborative decision-supporting tool allowing the stakeholders to interactively optimize these parameters.
c) The objective is to determine for a particular project the concrete with the lowest cost, - optimized for all stakeholders- the highest technical performance and the lowest GHG signature.

The SOS is intended to address four overarching goals for sustainable technology in Canada:

**Sustainable Development**: use of high levels of SCMs through the SOS will be a major contributor to making the construction industry more sustainable. The SOS will provide a way to use material with a significantly lower environmental impact, resulting in reduced energy consumption and air emissions.

**Demonstration of New Technologies**: the SOS will be an essential step in extending the current demonstration of the new technology of high volume SCM concrete in a few case studies to the wider Canadian – and US – market, and hence, will foster sustainable development.

**Foster and Encourage Cooperation and Capacity**: the SOS will bring together a wide range of organizations working in the construction field –researchers, contractors, materials suppliers, developers, architects, engineers regulators and not-for-profit organizations (e.g., the EcoSmart Foundation Inc.). All these players will have an enhanced capacity to advance the sustainable development objectives within the construction industry.

**Dissemination of New Technology**: the primary purpose of SOS is to diffuse the new technology by making it easier to implement on a wide range of applications and readily accessible to all parties involved in a construction project. The SOS is a tool for diffusing the knowledge from innovators and early adopters to the industry.

This enabling technology represents an articulated need and a real value for industry:

- <u>Value for designers (developers, architects and engineers)</u>
    - reduces decision complexity
    - minimizes liability
    - assures appropriate, scientifically based, quality design
    - helps meet “green” objectives and achieve LEED credits
    - reduces design time and cost

- <u>Value for universities and research labs</u>
    - provides a platform for transferring results of research to industry
    - creates opportunities for new research
    - collaborate to the development of a leading-edge product

- <u>Value for contractors</u>
    - Develop new and more efficient building methodologies
    - Improve competitiveness
    - Improve technological knowledge in concrete

- <u>Value for suppliers (cement and concrete producers</u>
    - increases the demand for SCMs in concrete
    - addresses current cement and raw-materials shortages

- allows $CO_2$-neutral production increase of cementitious material
- reduces the demand for energy-intensive, costly production of Portland cement
- reassures customers (concrete specifiers and owners)
- assures quality end product
- assists with training of individual concrete producers
- supplies the expertise required to change standards and construction practices

## 3. Contribution to Sustainability and Lowering of Greenhouse Gas Emissions

Development of more sustainable concretes that use higher proportions of waste materials is an important pollution prevention measure. Its primary focus is the reduction of GHG emissions associated with cement production through the partial replacement of cement in concrete by SCMs. A further benefit is the reduction of other pollutants, especially Criteria Air Contaminants (CAC), as described below. Additionally, SCM technology conserves natural raw materials and fossil fuels used in cement production, and thereby reduces the environmental impacts related to their extraction and transport. SCMs have the potential to reduce emissions in proportions similar to the percentage used to replace Portland cement (3).

Emissions associated with Portland cement manufacturing may include the following, although some of the pollutants may not be present in significant amounts at some manufacturing plants. The list of emissions has been provided in the Environment Canada, 2004 reference (3).

Greenhouse gases (GHGs):

- carbon dioxide equivalent ($CO_{2\ eq}$)

Criteria air contaminants (CACs):

- particulate matter (total PM or PMT, $PM_{10}$, and $PM_{2.5}$);
- nitrogen oxides (NOx, i.e., $NO_2$, $N_2O$);
- sulphur oxides (SOx, i.e., $SO_2$);
- carbon monoxide (CO); and
- very minor amount of volatile organic compounds (VOC)

Other substances:

- acidic compounds (e.g. hydrogen chloride (HCl), hydrogen fluoride (HF), sulphuric acid ($H_2SO_4$));
- ammonia ($NH_3$) (in some cases);
- metals (e.g., arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and nickel (Ni)); and
- organic compounds.

It is important to emphasize that the concrete technology, which, when adopted, directly reduces demand for Portland cement, and hence reduces GHG and other emissions associated with cement production, is now well-developed, while the integrated design approach that the project wants to achieve is still an innovation. The SCM Optimization System is an enabling technology. Once the SOS is in place and successfully demonstrated and deployed, it will greatly accelerate the rate at which the SCM concrete technology is accepted and adopted by the construction industry. The complexity of the interrelated technical and economical parameters and the multi-stakeholder decision-making process currently makes it extremely difficult and expensive to implement this technology outside closely monitored demonstration projects.

## 4. Technology Implementation Plan

The technology will assemble and package the scientific and technical knowledge, experience and intellectual property that have been developed over many years, and used in numerous SCM case studies (supported by EcoSmart and others), and make these readily available to industry through a computer-based advisory / expert system. Developers, builders, architects and engineers will use the model to determine the optimal level of SCMs for their projects. The model will take into account climate, structural specifications, construction requirements, quality of locally available materials, and numerous other

parameters, to determine not only optimal SCM levels but also cost savings and environmental benefits. These relationships are illustrated in
Figure 2.

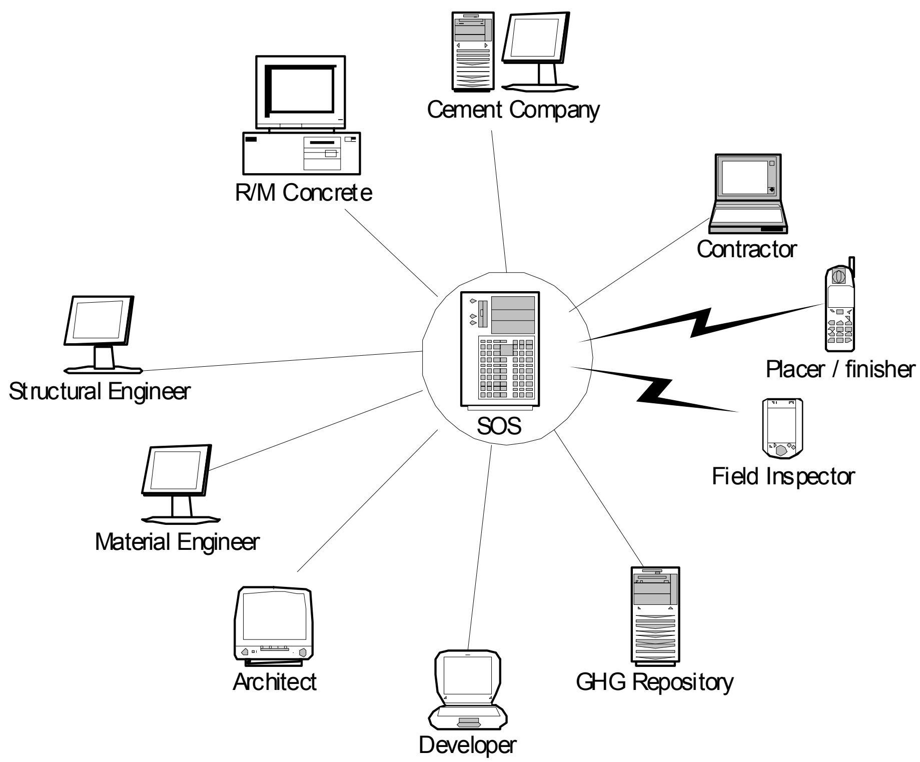


**Figure 2: SOS Network**

The SOS will affect several aspects of building construction:

- Cost: SCMs are often more economical than the Portland cement they replace or their use is made necessary by a shortage of Portland cement. Users of the SOS will be able to optimize SCM content according to cost criteria.
- Design: The optimum use of SCM improves the quality, durability and overall performance of concrete. Ready-mix operators and engineers will have an easy and fast way to determine the optimum level of SCMs for desired performance specifications.
- Construction: Effect on construction schedules (and concomitant costs) is often perceived as a barrier to increased use of SCMs. Contractors will be able to identify additional costs or schedule issues related to particular levels of SCM, and also to receive direction and advice on how to overcome construction difficulties and avoid pitfalls (e.g. curing methods).
- Green building: Sustainability is increasingly becoming a key specification in new projects due to more stringent federal sustainability requirements as well as the growing adoption of LEED® (Leadership in Energy and Environmental Design) Green Buildings Rating System in Canada. Emphasis on sustainability and the environment will grow drastically in the next 10-20 years; this tool will help accelerate that growth. Developers, building owners and architects will be able to establish embodied GHG signature targets and calculate LEED credits built into the SOS. By providing ways to meet these requirements, the SOS will also give a competitive advantage to contractors bidding on such projects.
- Collaboration: The SOS will facilitate a collaborative decision-making process bringing significant benefits and economy to the project. One very important aspect of the SOS is that all modules related

to the use of SCM in concrete will be viewable by all sectors of the industry. This fosters increased education about SCM concretes of all participants and will lead to increased collaboration among the sectors to ensure that projects are completed to the satisfaction of all stakeholders.

- Repository: The SOS will provide a repository for the results of new research and case studies, and therefore, fast-track transfer of knowledge and expertise.

## 5. Conceptual Architecture of the SOS Application

Considering the requirements, it is envisaged that SOS will have a 3-tier architecture, namely, the presentation tier, middle tier and the data access and storage tier.

- Presentation Tier: The trend in the software industry today is to use thin clients such as a web browser as the presentation tier. No logic related to the application is included other than logic for presentation routines and processing of user input (the alternative is to use a thick client that will process some data at the user's computer). The presentation tier will consist of web forms including controls for user interaction with the system and graphical components to display results.
- Middle Tier: Almost all processing of data will take place in the middle tier. All software modules needed for the functioning of the system will be included in this tier. The middle tier will interact with the data access and storage tier depending on the requests made by the user in the presentation tier.
- Data Access and Storage Tier: This tier is the data storage facility (i.e. the database) that will provide the services for data access, filtering, and storage.

The modules in the middle processing tier should be able to communicate with each other to carry out system functions (i.e. to provide expert guidance and optimisation). Some examples of modules in the middle tier are Mix Proportioning Module, Fresh Concrete Properties Module (setting times, workability and curing requirements), Durability Module, Benefits Module (LEEDS credits, GHG mitigation), and Economise Module (material and production cost analyses). These modules will consume data input by the user and data stored in the database and produce results for the user's consumption and for archiving. The data storage tier can be effectively represented by a relational database such that all information needed for optimising SCM use can be stored and retrieved effectively.

The SOS system can be implemented either in the Sun Java platform or the Microsoft's .NET platform. However, considering the performance, stability, standards and available technical resources, it is thought that a .NET solution would be appropriate. The above 3-tier architecture of the SOS and the modules can be efficiently implemented using ASP.NET technology (Figure 3). The ASP.NET supports programming of the presentation tier and the middle tier (using HTML and any .NET language such as Visual Basic.NET, C# and J#). In addition it is possible to use legacy code compiled as a DLL in an ASP.NET application (if such useful modules are available). ASP.NET also provides application security services and makes the development process quicker. For deployment of an ASP.NET application a Web Server – Windows 2000 Server (or greater) running Microsoft Internet Information Server (IIS) – is needed with ASP.NET 1.1 Framework installed. If Microsoft's .NET platform is selected for implementing SOS, development and testing of individual components of SOS should be done using Visual Studio .NET. The data access tier (the relational database) should be implemented on the Microsoft SQL Server platform for seamless integration for the ASP.NET data access using ADO.NET technology.

## 6. Feasibility

Various SCM concrete projects have been successfully demonstrated in a variety of case study projects over the period 2000-2005. More than 20 case studies have been produced and documented, such as the Computer Science Building at York University (Toronto), the Mountain Equipment Co-op store (Montreal), the Bayview apartment building (Vancouver), and the Little Mountain Reservoir (Vancouver). (See the EcoSmart web site www.ecosmart.ca for more details on these projects.) Further, there is widespread acceptance and understanding of the use of SCMs at relatively low replacement levels throughout

Canada. Therefore, it is clear that the use of SCMs at high levels is feasible, provided industry accepts the results of demonstrations to date.

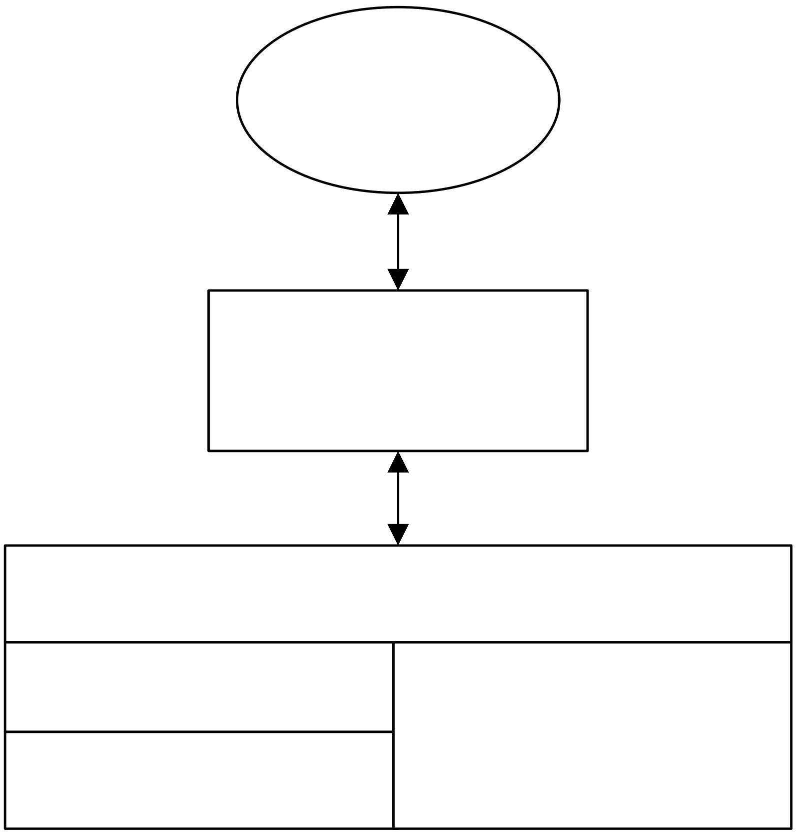


Figure 3 – ASP.NET Architecture
(Paul D. Sheriff, "Upgrading to Microsoft "NET", PDSA Inc., USA)

However, the technical advisors, who represent a very broad cross-section of the construction industry, including major cement producers, are adamant that industry must have the tools to give it confidence and technical support in the design levels of SCMs that they are being asked to use. Demonstrations to date have had the benefit of personalized expert guidance from academics and industry professionals who have worked closely with EcoSmart in developing and managing these demonstrations. This level of expert involvement and knowledge has given developers and builders involved in the demonstration projects the confidence they need – in a very conservative industry – to embark on what, to them, is a relatively unknown approach to making and using concrete.

It is not practical for this detailed level of expertise to be provided on all projects, both because of cost and the relatively small number of experts available. Advisors have therefore recommended that we develop a commercial advisory system that will be simple to use, can draw on a continuously updated data bank of expertise and knowledge, and will help determine for a given project the optimal level of SCM replacement.

The successful demonstration of such a decision-supporting tool will bridge the gap between the current stage where the technology has been successfully applied to a few case study projects and the stage where it is widely adopted by the market. Its adoption will bring returns to the investors and major benefits in terms of reduced GHG and CAC emissions. These benefits will come initially in Canada, but in due course, we intend to expand the sale and use of the system to North America and the world. (According to our industry advisors, no such system exists in North America. Canada is a leader in the use of SCMs and is well-positioned to be the first to put this kind of a system on the market.)

## 7. Summary

Development and use of the SCM Optimization System (SOS) in Canada is expected to reduce $CO_2$ emissions by 2.4 million tonnes per year by 2012. Worldwide, successful deployment of the SOS could shrink total $CO_2$ emissions by at least two orders of magnitude more, while at the same time reduce the need to dump fly ash and slag, decrease the investment needed in new cement plants, reduce the strain on supplies of raw materials, lower the cost of construction, and increase the long-term durability of concrete.

## 8. References


1. Bouzoubaâ, N. and Fournier, B. "Current Situation of Supplementary Cementitious Materials (SCMs) in Canada," CANMET Report MTL 2003-4 (TR), Natural Resources Canada, Ottawa, April 2003.
2. CSA A23.1. "Concrete Materials and Methods of Concrete Construction," 2004.
3. Environment Canada, Minerals and Metals Branch of the Pollution Prevention Directorate. "Foundation Report on the Cement Manufacturing Sector," December 2004.
4. Malhotra, V.M. "Eight CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete," Conference Proceedings, Las Vegas, U.S.A., pp. 73-87, May 23-29, 2004.
5. Malhotra, V.M. and Mehta, P.K. "High-Performance High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories", Marquardt Printing Ltd., Ottawa, Canada, August 2002.
6. Reid Crowther & Partners Ltd., July 1998. Environmental Review Tilbury Cement Plant Pollution Prevention Plan, Volume 1. (Prepared for the GVRD.)
7. US Bureau of the Census. "Total Midyear Population for the World: 1950-2050," data updated September 30, 2004, http://www.census.gov/ipc/www/worldpop.html, accessed Dec. 17, 2004.
8. Vagt, Oliver. "Mineral and Metal Commodity Reviews - Cement 2002," http://www.nrcan.gc.ca/mms/cmy/content/2002/17.pdf, accessed Dec. 17, 2004.
9. Venta, G.J., Bouzoubaâ, N. and Fournier, B. "Production and Use of Supplementary Cementing Materials in Canada and the Resulting Impact on Greenhouse Gas Emissions Reductions," Eight CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Supplementary Papers, Las Vegas, U.S.A., pp. 73-87, May 23-29, 2004.
10. Vanderborght, Bruno and Brodmann, Urs. "The Cement CO2 Protocol: CO2 Emissions Monitoring and Reporting Protocol for the Cement Industry. Guide to the Protocol, Version 1.6," WBCSD Working Group Cement, October 2001, http://www.wbcsdcement.org/sub_c02.asp, accessed on Dec. 15, 2002.
11. World Cement. "World Cement Production 2002-2003," July 2004, http://www.palladian-publications.com/Cement/WC_regional_review_july04.htm, accessed Dec. 30, 2004.
12. Yuan, Ying-shu, Shah, Surendra P. and Lü, Heng-lin (Editors). "Proceedings of the International Conference ICACS 2003, 17-19 September 2003, Xuzhou, China," (RILEM Publications), 2 Vol., 1592 pp., ISBN: 2-912143-41-1, http://www.rilem.net/rppro32.html, accessed Dec. 17, 2004.