THE POTENTIAL USE OF NATURAL POZZOLANS IN BRITISH COLUMBIA AS SUPPLEMENTARY CEMENTING MATERIALS

Prepared for

The EcoSmart™ Concrete Project

Prepared by

CMP TECHNOLOGIES LTD.

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EXECUTIVE SUMMARY

A review of the available technical information indicates that natural pozzolans from several sources in British Columbia have been tested and found to satisfy relevant Canadian and American standards for supplementary cementing materials. However, only two of these sources are currently active, and there is only a limited amount of information available on the chemical, physical and pozzolanic properties of the material from each. There is no indication that the natural pozzolans from any of the identified sources in British Columbia have any apparent technical advantage relative to the fly ashes being imported into the province and used as portland cement replacement materials.

A comparative evaluation has been carried out of the environmental burden associated with the acquisition, processing and transportation of natural pozzolans available from sources in British Columbia and fly ashes imported from Washington State and Alberta. This evaluation is based on energy consumption or requirement, which is often used as a surrogate for greenhouse gas emission and combustion related pollution, particularly in relation to transportation. This evaluation indicates that, in terms of the present supplementary cementing materials market in British Columbia, there would be no environmental benefit derived from using a natural pozzolan instead of fly ash.

A preliminary cost estimate, based on a central processing facility for natural pozzolans located in Hope, suggests that the delivered cost of a natural pozzolan suitable for use a supplementary cementing material will be of the same order of magnitude but possibly higher than the price of fly ash in the Greater Vancouver Area market. The unit cost values used to develop this estimate are considered to be conservative, but do not include the capital costs of the equipment and infrastructure at the central processing facility. Transportation of ‘raw’ natural pozzolan material from its source to a processing facility is probably the major expense associated with the production of a portland cement replacement material from the natural pozzolans available.

At the present time, therefore, there does not appear to be any technical, environmental or economic reason to develop the natural pozzolan sources in British Columbia identified in this study for use as supplementary cementing materials. Consequently, it is recommended that no further investigation of this issue be carried out by the EcoSmart™ Concrete Project until it can be demonstrated that there is a demand for portland cement replacement materials in the province that cannot be satisfied by the importation of fly ash form Washington State and/or Alberta at an acceptable cost.

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INTRODUCTION

Study Objectives and Scope

The primary objective of the EcoSmart™ Concrete Project is to minimize the greenhouse gas (GHG) emission signature of portland cement concrete by maximizing the replacement of portland cement in concrete mixtures with supplementary cementing materials while maintaining or improving cost, performance and constructability. As part of its mandate, EcoSmart™ therefore has the requirement to investigate the feasibility of using natural pozzolans from sources in British Columbia as cement replacement materials. To satisfy this requirement, EcoSmart™ has retained an independent consultant, CMP Technologies Ltd., to carry out a study and prepare an overview report summarizing the currently available information on the potential use of natural pozzolans from deposits in British Columbia as supplementary cementing materials.

The objectives of the study are therefore to:

1. assess the potential use of natural pozzolans from deposits in British Columbia for use as supplementary cementing materials in portland cement concrete; and,
2. determine whether further study of this issue is justified.

In accordance with the terms of reference, the scope of the study is limited to a review of existing information resulting from previous work by the portland cement and ready-mixed concrete industries, private consultants, and government and research organizations on natural pozzolans as supplementary cementing materials, with particular emphasis on previous studies of natural pozzolans from British Columbia deposits. The technical, environmental, and economic benefits and costs of using naturally pozzolanic materials from provincial deposits are compared with those associated with the use of fly ash from coal-fired thermal electrical power plants as a supplementary cementing material in British Columbia.

Study Team

The study was carried out by CMP Technologies Ltd., and employed the following personnel:

Robert J. Gray, Ph.D., P.Eng., President, CMP Technologies Ltd.

James W. Atwater, P.Eng., Associate Professor, Dept. of Civil Engineering, University of British Columbia

W. Scott Dunbar, Ph.D., P.Eng., Associate Professor, Dept. of Mining Engineering, University of British Columbia

Dr. Gray had primary responsibility for the direction and completion of the study. He was also responsible for identifying, collecting and assessing all information related to the technical aspects of the use of natural pozzolans as supplementary cementing materials. Mr. Atwater was responsible for the evaluation of the potential environmental benefits and costs of the use of natural pozzolans relative to those accruing from the use on fly ash as a partial replacement for portland cement. Dr. Dunbar was responsible for the evaluation of the potential economic viability of using natural pozzolans as supplementary cementing materials in British Columbia.

The qualifications and experience of the members of the study team will be made available from EcoSmart™ upon request.

Study Methodology

The study consisted of the following activities:

1. identification of information on natural pozzolans, in general, applicable to the study objectives using appropriate databases;
2. collection of the applicable information where it was readily accessible;
3. review of the collected information and assessment of its relevance to the study objectives;
4. identification of sources in British Columbia of natural pozzolans which are potentially suitable for use as supplementary cementing materials;
5. identification of organizations and/or individuals who have knowledge of the potentially-suitable natural pozzolan sources;
6. collection and review of information on the potentially-suitable natural pozzolans;
7. assessment of the technical, environmental and economic benefits and costs of the potentially-suitable natural pozzolans;
8. comparison of the benefits and costs of the potentially-suitable natural pozzolans with those of fly ash; and,
9. summation of the results of the study in a final report.

A list of individuals who were contacted by the study team and provided information for the study is included as Appendix A to this report. The study team wishes to acknowledge the assistance provided by these individuals.

BACKGROUND

Definitions

The Canadian Standards Association (CSA) standard for supplementary cementing materials, CSA A23.5-98, defines a pozzolan, a natural pozzolan, and a supplementary cementing material as follows:

> pozzolan – a siliceous or alumino-siliceous material that, in finely divided form and in the presence of moisture, chemically reacts at ordinary room temperatures with calcium hydroxide released by the hydration of portland cement to form compounds possessing cementitious properties

natural pozzolan – a natural material which may also be calcined and/or processed (e.g., diatomaceous earth, meta kaolin, rice husk ash, volcanic ash, or calcined shale)

supplementary cementing material - a material that, when used in conjunction with portland cement, contributes to the properties of hardened concrete through hydraulic or pozzolanic activity or both.

These definitions are generally consistent with those of other standards organizations and can be used with confidence when reviewing information from national and international sources on these materials.

Supplementary Cementing Materials in Canada

A recent summary report prepared by CANMET [Bouzoubaâ and Fournier, 2003] identifies four types of supplementary cementing materials currently being used in the construction industry in Canada: fly ash; ferrous and non-ferrous slag; silica fume; and, metakaolin. These materials are 'artificial' pozzolans in that they do not occur naturally but are by-products of industrial processes (fly ash, slag and silica fume) or are specially manufactured (metakaolin). The report notes that approximately 2.2 million tonnes of fly ash are produced in Canada annually and are potentially suitable for use as supplementary cementing materials. Approximately 70 per cent of this fly ash, or approximately 1.5 million tonnes, is produced in Alberta, most of which is excess to demand in that province and available for export.

The CANMET report shows that fly ash is by far the most commonly-used supplementary cementing material in British Columbia, with approximately 140,000 tonnes being consumed in 2001. Both Type F and Type CI fly ash are used in the province, with Type F material imported from the Genesee power plant in Alberta, and Type CI material from the Sheerness and Sundance power plants in Alberta and the Centralia power plant in Washington State. The amount of portland cement replacement by fly ash in concrete mixtures in the province varies with the intended use or application of the mixture, construction considerations and ambient temperature conditions, but more than 80 per cent of ready-mixed concrete contains fly ash with replacement rates typically around 25 per cent according to the report.

The report also notes that blended cements constitute a very small portion of the total cement production in Canada, with silica fume the most commonly-used supplementary cementing material blended with portland cement.

Types of Natural Pozzolans

In a review of natural pozzolans as supplementary cementing materials, Mehta [Mehta, 1987] classified these materials into four categories on the basis of their principal lime-reactive constituents: unaltered volcanic glass; volcanic tuff; calcined clay or shale; and, raw or calcined opaline silica. Mehta notes that most natural pozzolan deposits contain more than one lime-reactive constituent, and that their composition and properties vary widely.

Volcanic glasses, such as rhyolitic pumicites, pumice and obsidian, derive their lime-reactivity mainly from their very high composition of unaltered aluminosilicate glass. Volcanic tuffs, such as zeolitic minerals, consist of volcanic glass altered under hydrothermic conditions, and derive their lime-reactivity from a base exchange reaction between calcium (lime) and alkalis in the tuff. Natural clays or shales containing substantial proportions of kaolinite-type or montmorillonite-type clay minerals, or combinations thereof, require calcination at temperatures in the range of 540 C to 980 C to induce optimum pozzolanic activity. During calcination, which may occur naturally or may need to be carried out as part of a processing operation, the clay minerals decompose to form an amorphous or disordered aluminosilicate structure that reacts readily with lime at ordinary temperatures. Opaline materials, including diatomaceous earths and silica gel, are very reactive to lime, but typically have a very large surface area which may result in a very high water demand or requirement when these materials are used in portland cement concrete mixtures. It is also often necessary to calcine these materials.

Previous Investigations of Natural Pozzolans in British Columbia

The CANMET report referred to previously [Bouzoubaâ and Fournier, 2003] notes that naturally pozzolanic materials - natural shales, diatomaceous earth and pumice - are found in British Columbia, but are not currently being used in concrete production. It also notes that attempts were made to commercially exploit some of these natural materials in the late 1970s and early 1980s, but these attempts met with limited success.

The first recorded investigation of a natural pozzolan as a supplementary cementing material in British Columbia was in 1960, when a shale (siltstone) material from a deposit east of Port Alberni, on Vancouver Island, was processed and then tested in accordance with then-current ASTM specifications [British Columbia Research Council, 1960].

In 1978, a number of potential sources of natural pozzolans in the province were identified and investigated by the Mineral Sciences Laboratory of Energy, Mines and Resources (EMR) Canada [Hora *et al*, 1978]. The study concentrated on potential sources considered to be within an economic transportation distance of the Greater Vancouver Area, the largest market for portland cement concrete in BC. Furthermore, attention was focused on materials rich in volcanic glass and on diatomaceous earths, which would not require heat treatment to be pozzolanic. Ten potential sources were identified, but four were not investigated because of the unfavourable size of the deposit or its poor location. The location of the remaining six sources and the type of material contained in each are summarized in Table 1 below, and the locations shown in Figure 1.

In the section of the Hora *et al* report describing the natural pozzolan source immediately west of Quesnel, it is noted that poorly-exposed deposits of similar materials have been reported at several locations between Quesnel and Kamloops. In addition, reference is made to a previous study by the federal Department of Mines and Technical Surveys [Malhotra and Zoldners, 1964] of material from another site located southwest of Quesnel at Narcosli Creek.

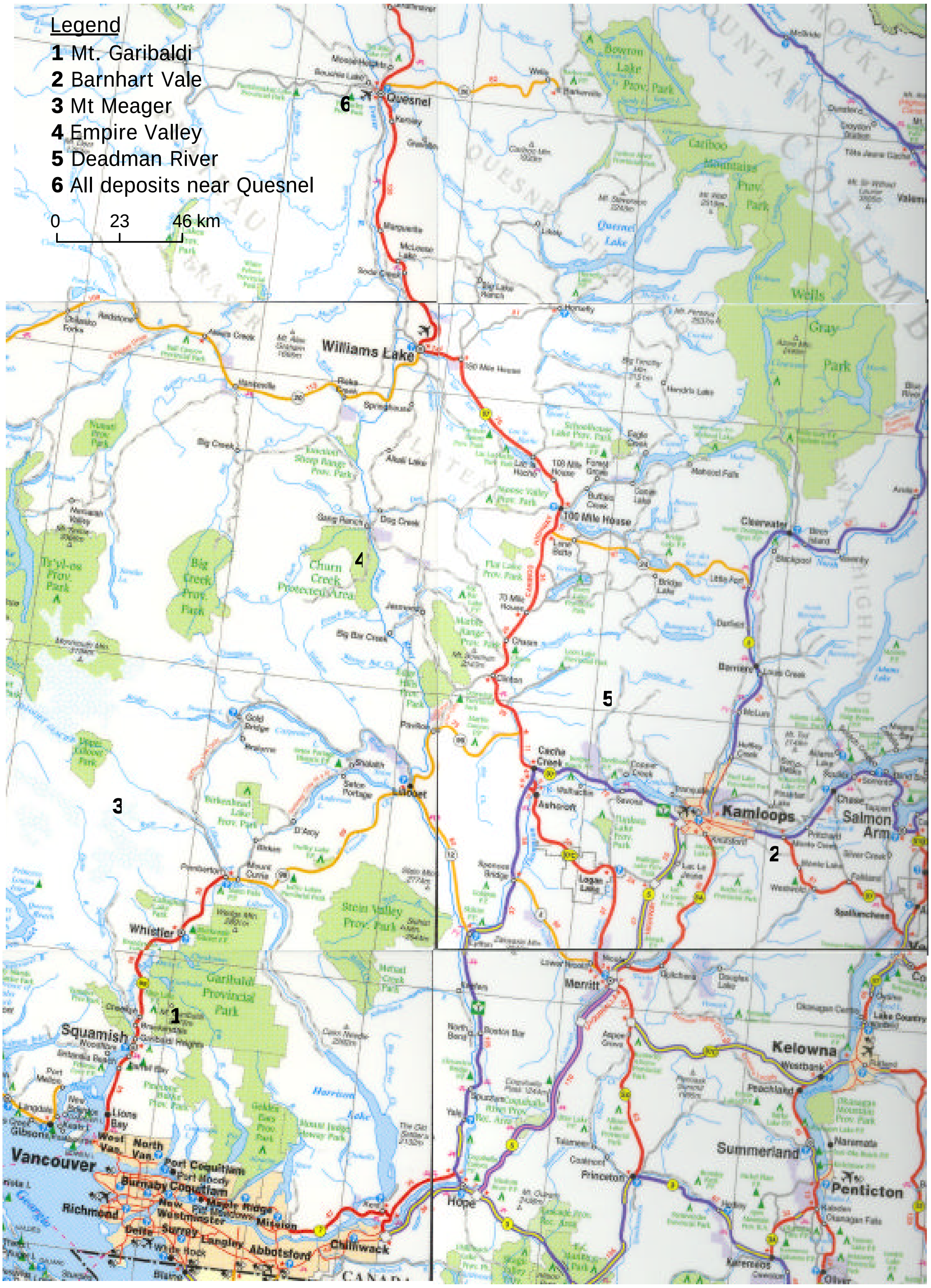

Figure 1: Location of Selected Natural Pozzolan Deposits in British Columbia

Table 1: Natural Pozzolan Sources in British Columbia [Hora *et al*, 1978]

Source	Location	Type of Material
Mt. Garibaldi	15 km northeast of Squamish	obsidian
Barnhart Vale	22 km east of Kamloops	rhyolite tuff
Mt. Meager	65 km northwest of Pemberton	pumice
Empire Valley	90 km north of Lillooet	porphyritic obsidian
Deadman River	60 km northeast of Ashcroft	volcanic ash and clayey tuff
Quesnel	immediately west of Quesnel	tuffaceous clay and clay-shale

The Government of British Columbia, Ministry of Energy and Mines website has a listing of Industrial Minerals Operations and Projects active in the province during 2000 and/or into 2001. This list includes several mines, quarries and/or prospects/developments that contain types of materials, such as zeolites, which may be pozzolanic in nature and have been used successfully as supplementary cementing materials in other parts of the world. No information was found on materials from any of the deposits included in this listing other than those described above.

TECHNICAL EVALUATION

Introduction

Raw or processed natural pozzolans have been used by mankind for construction purposes for thousands of years. Mortars and concretes using a mixture of lime and a natural pozzolan - typically a volcanic ash or tuff - were developed and used by the Greeks (700-600 BC), and later the Romans (150 BC), to build durable, water-containing structures such as aqueducts and water-storage tanks. Several reviews of the historical development and use of these types of materials are available and should be consulted for further information [Mehta, 1987; ACI Committee 232, 2000].

Natural pozzolans are still commonly used in many parts of the world, but now as secondary rather than primary cementing materials. An excellent review of the use of these materials as supplementary cementing materials can be found in the recent ACI Committee 232 report “Use of Raw or Processed Natural Pozzolans in Concrete” [ACI Committee 232, 2000]. The main technical advantages of the use of natural pozzolans in concrete mixtures include [Mehta, 1987]:

- improvement in workability
- reduced heat of hydration and risk of thermal cracking
- increased water tightness
- improved durability in sulphate and acidic environments
- enhanced resistance to cracking by alkali-aggregate reaction

However, the actual improvement imparted by a particular pozzolanic material to a particular concrete mixture is strongly dependent on the chemical composition and physical properties of the pozzolan, which vary significantly both within and between the different types of material.

Specifications, Standards and Test Methods

The use of supplementary cementing materials, in general, and natural pozzolans, in particular, in Canada and The United States is currently governed by the following specifications, standards and test methods.

CSA A23.5-98	Supplementary Cementing Materials
CSA A456.1-98	Chemical Test Methods for Hydraulic Cement, Supplementary Cementing Materials, and Cementitious Hydraulic Slag
CSA A456.2-98	Physical Test Methods for Hydraulic Cement, Supplementary Cementing Materials, and Cementitious Hydraulic Slag
CSA A456.3-98	Test Equipment and Materials for Hydraulic Cement, Supplementary Cementing Materials, and Cementitious Hydraulic Slag
CSA A362-98	Blended Hydraulic Cement
ASTM C618-03	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan as a Mineral Admixture in Concrete
ASTM C311-02	Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete
ACI 232.1R-00	Use of Raw of Processed Natural Pozzolans in Concrete

CSA Standard A23.5-98 is the Canadian national specification for supplementary cementing materials, and addresses the chemical and physical requirements for specific types of these materials, including fly ash and natural pozzolans. It also specifies how these materials are to be sampled and tested.

The mandatory physical and chemical requirements in the CSA standard are minimal, and provide little information on the potential performance of these materials in portland cement concrete mixtures. There is, however, a set of optional requirements which address some of the more important characteristics of these materials with respect to their interaction with portland cement and their probable effects on concrete.

The American specification for supplementary cementing materials, or ‘mineral admixtures’ as they are known in The United States, ASTM C618, has a greater number of mandatory chemical and physical requirements than the Canadian standard. It includes three requirements which are not included or not mandatory in the CSA standard, i.e., (i) minimum total silica, alumina and iron oxide content, (ii) minimum strength activity index with portland cement, and (iii) maximum water requirement or demand, but are commonly measured and reported when these materials are being evaluated for use in Canada. It also has a mandatory limitation on the variability of the fineness and density of the materials.

Although early studies showed that there is little direct correlation between the total silica, alumina and iron oxide content of a pozzolan and its pozzolanic properties [Mehta, 1989], the intent of this specification requirement is to ensure that sufficient potentially reactive constituents are present in the material. Similarly, the strength activity index, which is based on the relative strength of 50 mm mortar cubes made using a fixed portland cement-pozzolan ratio, is considered as only an indicator of reactivity with portland cement and does not necessarily foretell the potential compressive strength of concrete mixtures containing the pozzolan. The water demand requirement is also based on mortar, and not concrete, properties.

Pozzolan fineness is one of the mandatory physical requirements in both the CSA and ASTM specifications, through a limitation on the amount of material retained on the 45 ìm (No. 325) sieve. The quantity of the pozzolan finer than this sieve has been found to be related to its reactivity with cement. It is therefore important that this property be measured and considered when assessing the pozzolanic nature of a material or comparing its reactivity with another.

The standards and specifications listed above do not necessarily indicate the nature or extent of the effect of supplementary cementing materials on the properties of portland cement concrete mixtures containing them. For this reason, most concrete technologists would be resistant to the use of a particular pozzolanic material until they had successfully produced and tested concrete mixtures containing the pozzolan and their portland cement, aggregates and admixtures.

Fly Ash

As noted previously, fly ash is by far the most commonly-used supplementary cementing material in British Columbia. The fly ash used in the Greater Vancouver Area is Type CI from sources in either Alberta (Sundance) or Washington State (Centralia), and material from both sources has been tested extensively over the past several years. These products have been found to consistently satisfy relevant CSA and ASTM requirements. As a consequence, concrete producers in the area are confident that they can use these materials to produce concrete mixtures satisfying CSA strength, durability and uniformity requirements at portland cement replacement levels of up to 40 per cent [Bouzoubaâ and Fournier, 2003].

A typical sample of the fly ash used in the British Columbia has a total silica, alumina and iron oxide content of about 80 per cent, a fineness of about 25 per cent retained on the 45 ìm (No. 325) sieve, a strength activity index with portland cement of about 90 per cent, and a water requirement or demand of about 95 per cent of the control mix [Caruth, 2003].

Natural Pozzolans Available in British Columbia

As previously noted, a testing program was carried out by the British Columbia Research Council [British Columbia Research Council, 1960] on a shale (siltstone) material from a deposit east of Port Alberni. A single pilot run of test material was prepared by quarrying, crushing, calcining and then grinding raw material from the deposit. The tests showed that the material generally exceeded the requirements of the then-current ASTM specification, i.e., ASTM C402-58T, "Tentative Specifications for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete", and was an 'excellent' pozzolan.

The test material was also used to prepare several concrete mixes. Of particular interest was the finding that the compressive strength levels of concrete mixes containing up to 30 per cent replacement of portland cement by the pozzolan equaled those of cement-only mixes at or before 90 days. In addition, when used as a cement replacement, the pozzolan increased the impermeability of concrete, and hence its sulphate resistance, and decreased the bleeding.

The report notes that work was to continue on evaluating the properties and uses of this material as a natural pozzolan, but no further information was identified by the study team.

Representative samples of material were collected from the six sources of natural pozzolans investigated by EMR Canada in 1978 (Table 1), and analyzed and tested to determine their chemical composition and physical and pozzolanic properties in accordance with then-current CSA and ASTM standards, i.e., CSA Standard CAN3-A266.3-78, "Pozzolanic Mineral Admixtures for Use in Portland Cement Concrete", and ASTM Standard C618-78, "Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete". Samples from most of the sources satisfied the chemical requirements of both standards, but only samples from the Mt. Garibaldi (obsidian), Mt. Meager (pumice), and Empire Valley (porphyritic obsidian) deposits satisfied all of the physical requirements [Hora *et al*, 1978].

The investigators concluded that the obsidian from Empire Valley had the most promising pozzolanic properties, followed by the pumice from Mt. Meager and the obsidian from Mt. Garibaldi. However, the Mt. Meager deposit was considered to have the best potential for further detailed technical and commercial study because of its easy access to the Greater Vancouver Area market relative to the other two deposits. Some additional testing of the pumice material from this deposit has since been carried out by the current mineral lease-holder, Great Pacific Pumice Inc. Mortar cube testing by Fenicem Minerals Inc. [Starling, 2002] with portland cement replacements of 25 and 50 per cent by both mass and volume showed pozzolanic activity index values of greater than 100 per cent at ages of 28 and 90 days, and it was noted that the consistency of the pumice mixes 'appeared' to be higher than that of the pure cement mixes. However, the fineness of the material used in the Fenicem tests was not reported.

A natural pozzolan from a volcanic deposit at Narcosli Creek, located approximately 20 km southwest of Quesnel, was first tested by the Mines Branch, Federal Department of Mines and Technical Surveys in 1964 [Malhotra and Zoldners, 1964], as noted previously. The material was described as a scoriaceous vesicular lava rock of andesitic composition, which could be classified as pumicite. When ground to a fineness of 7 per cent retained on the 45 ìm (No. 325) sieve, the sample of material tested had a pozzolanic activity index with portland cement of 100 per cent.

Production of this material on a commercial basis began in 1979, and it was used by some ready-mixed concrete producers in the British Columbia interior over the next few years in several projects, including a sewage treatment plant in Prince George and a section of roller compacted concrete pavement on the haul road for the Bullmoose Mine in Tumbler Ridge. The material was extensively tested in the early 1980s by the lease-holder of the deposit, Quesnel Redi-Mix Cement Co. Ltd., and by the British Columbia Ministry of Transportation and Highways (BC MOTH). In general, it was found to meet then-current CSA and ASTM standards for natural pozzolan materials, i.e., CSA Standard CAN3-A23.5-M82, “Supplementary Cementing Materials and their Use in Concrete Construction”, and ASTM C618-80, and to produce a variety of portland cement concrete mixes with satisfactory properties.

Testing for the lease-holder was carried out by Gordon Spratt & Associates Ltd. and B.H. Levelton & Associates Ltd. Concrete trial mixes were prepared and tested by B.H. Levelton & Associates using the natural pozzolan material, delivered to them in a ground condition, and they were able to produce several types of concrete - residential, high-strength cast-in-place and precast, and architectural, for example - that satisfied typical specification requirements. Apparently there were no problems with water demand for these mixes, but there were no control mixes cast with 100 per cent portland cement. Of particular interest, uniformity testing carried out on samples delivered to their laboratory, generally in accordance with the frequency requirements of CSA Standard CAN3-A23.5-M82, indicated good to very good uniformity [B.H. Levelton & Associates, 1983].

In 1984, Hardy Associates (1978) Ltd. conducted a series of tests on two materials from this deposit, identified as a ‘red’ pozzolan and a ‘grey’ pozzolan on the basis of their colour, on behalf of BC MOTH [Hardy Associates (1978) Ltd., 1984]. The materials were sampled on several occasions at the production facility by personnel from Hardy Associates and tested for variability, conformance to the CSA standard for pozzolans, and effect on several concrete properties.

The testing program carried out by Hardy Associates found that the ‘red’ pozzolan material did not satisfy the requirements of CSA Standard CAN3-A23.5-M82 with respect to moisture content and increase in drying shrinkage. In addition, when used in concrete mixes, this material resulted in a significant increase in water demand and a decrease in 28-day compressive strength when compared to mixes containing only portland cement or to mixes containing similar additions of fly ash. The increase in water demand also resulted in an increase in drying shrinkage of the concrete mixes containing this material.

The ‘grey’ pozzolan was found to satisfy the chemical and physical requirements of the CSA standard for a Type N pozzolan. There was also some increase in water demand when this material was used in concrete mixes, but at addition levels of up to about 10 per cent the corresponding increase in water-cementing materials ratio was more than off-set by an increase in compressive strength at 28 days. The tests indicated that the optimum ‘dosage’ for this material was between 5 and 10 per cent of the total cementitious materials content in the concrete mix, i.e., portland cement plus pozzolan, but at such concentrations the 28-day compressive strength may be increased by approximately 5 per cent only. Furthermore, the ‘grey’ pozzolan did not perform as well as the fly ash used in the control mixes - at all ages up to 28 days and all levels of pozzolanic material content, the compressive strength of the fly ash mixes was higher than that of the natural pozzolan mixes.

Uniformity testing of both the ‘red’ and the ‘grey’ pozzolan was also carried out by Hardy Associates, as previous testing had indicated some variability in fineness and activity index. It was noted that these characteristics are somewhat interdependent. Samples were obtained by Hardy Associates personnel from storage silos at the production facility, and it was found that the ‘grey’ pozzolan was more consistent than the ‘red’, in both fineness and activity index.

The deposit of naturally calcined clay/shale material immediately south of Quesnel is currently being developed by the owner of the property on which it sits, Canada Pumice Corporation. Material from the deposit has been tested and apparently satisfies current CSA and ASTM standards for natural pozzolans [Wear, 2003].

In summary, a review of the available technical information indicates that natural pozzolans from several sources in British Columbia have been tested and found to satisfy relevant CSA and/or ASTM specification requirements for use as supplementary cementing materials. However, only two of these sources are currently active, i.e., the pumice deposit at Mt. Meager and the naturally calcined clay/shale deposit at Quesnel, and there is only a limited amount of information available on the chemical, physical and pozzolanic properties of the material from each of these deposits. A much more extensive testing program would therefore need to be carried out to determine if natural pozzolans from these sources can satisfy current and future technical requirements and market demands for supplementary cementing materials in the province. Any such testing program should be particularly directed at evaluating the effects of these materials, at a range of practical replacement levels, on the fresh and hardened properties of various types of portland cement concrete mixtures, i.e., residential, structural, precast and architectural. This program should be expanded to include natural pozzolans from any other known or still unknown sources in the province if it is or can be shown that such materials satisfy the CSA and ASTM requirements for supplementary cementing materials.

The results of such a testing program will also enable direct comparison of the technical benefits of the materials from these sources with those of the fly ashes currently being imported into the province. Approximate reactivity values for various types of supplementary cementing materials reported by Morgan [Morgan, 2003] indicate that natural pozzolans in general are less efficient than fly ash in replacing portland cement in concrete mixtures.

ENVIRONMENTAL EVALUATION

There are two major environmental benefits associated with the substitution of pozzolanic materials for portland cement in concrete mixtures. The first is a reduction in greenhouse gas emissions associated with the production of the material - portland cement carries a carbon dioxide (CO_2) burden of about 1 tonne per tonne produced [Bouzoubaâ and Fournier, 2003] - and the second is a reduction in the energy required for production - portland cement has an energy requirement of about 4 gigajoules (GJ) per tonne produced [EcoSmart™, 2003]. However, in those situations where natural materials such as clay or shale have to be calcined to develop or enhance their pozzolanic character, some of the significant greenhouse gas benefit of substitution would possibly be lost.

A third possible benefit is the reduction in the environmental impact associated with the extraction of the raw materials needed to produce portland cement, which may not be realized if pozzolanic materials have to be quarried.

It is generally considered that the environmental costs of acquiring and processing fly ash are so low relative to those of producing portland cement (see Table 2 following, for example) that replacement of a portion of the portland cement in a concrete mix with the equivalent amount of fly ash results in a CO_2 reduction roughly equal to the portion of cement replaced.

In the following comparison of the environmental burden associated with the acquisition, processing, and transportation of natural pozzolans with that of fly ash, three assumptions are made:

1. environmental impacts beyond the primary level are not considered, i.e., the impact related to the manufacture of equipment used to produce and transport the materials is not considered;
2. jurisdictional boundaries are not considered; and,
3. no portion of the impact associated with the extraction, transportation and burning of the coal in a thermal generating plant is assigned to the fly ash thereby produced. The rational for this assumption is that there is no change in the environmental impact of those operations regardless of whether the fly ash is simply disposed of or is utilized as a supplementary cementing material. It could be argued that there would be a small positive benefit at the disposal point if the fly ash is used as a cement substitute, but this also is ignored.

Four factors are typically considered in such a comparison: water pollution, air pollution, mass of solid waste requiring disposal, and energy consumption. The easiest comparisons to make are in respect to energy consumption or requirement, which is often used as a surrogate for greenhouse gas emission and combustion related air pollution, particularly in relation to transportation.

Relative energy requirements for the acquisition and processing of cementing materials - portland cement, fly ash, and natural pozzolans - in 1978 are shown in Table 2 below [Hora *et al*, 1978]. The information in this table indicates that at that time the energy consumed in acquiring and processing a natural pozzolan prior to transport was of the same order of magnitude but roughly twice as much as that consumed in acquiring and processing a fly ash - approximately 0.80 GJ/ton compared to 0.44 GJ/ton. The difference is essentially due to the need to grind the natural pozzolan material to an appropriate fineness level. These energy values are dated and generic, and they could therefore be brought up to date and refined as it is expected that both drying and grinding efficiencies have since improved. However, fly ash is now being removed by electrostatic precipitators and not scrubbers, as it probably was in 1978, so drying it would not be required. Hence it is very unlikely that more current processing values would change the relative magnitude of the respective total energy requirements.

Table 2: Relative Energy Requirements in Preparation of Cementitious Materials [Hora *et al*, 1978]

Process/ operation	Energy Requirement in 10^3 BTU/TON (10^6 J/TON)		
	Portland Cement	Fly Ash	Natural Pozzolans
Quarrying	110 (116)	50 (53)	50-100 (53-106)
Drying	320 (338)	320 (338)	320 (338)
Grinding (Raw Material)	310 (327)	-	300 (317)
Burning	6140 (6478)	-	-
Finishing and Blending	520 (549)	50 (53)	50 (53)
Total	7400 (7808)	420 (444)	720-770 (761-814)

The natural pozzolans from the two currently active sources in British Columbia, a pumice (Mt. Meager) and a naturally-calcined clay/shale (Quesnel), apparently are suitable for use as supplementary cementing materials without need of beneficiation, although there are several processes available for increasing the reactivity of such materials [Shi, 2001]. However, one of the fly ashes currently being supplied into the British Columbia market is being classified to improve its particle size distribution [Lecuyer, 2003]. The energy requirement for beneficiation of this fly ash is not known, but it is unlikely to be significant.

Although the difference in acquisition and processing energy consumption discussed above, about 0.35 GJ/ton, or about 0.40 GJ/tonne, less for fly ash than for a natural pozzolan, is based on outdated values, it can be used to obtain some indication of the relative transportation advantage fly ash has over any natural pozzolan. This energy consumption difference is roughly equivalent to 1400 km of rail transport, 580 km of highway truck transport or 160 km of urban truck transport, based on fuel consumption values of 0.0075 L/km-tonne, 0.0180 L/km-tonne and 0.0633 L/km-tonne for each transportation method respectively, and a diesel fuel energy equivalent of 0.03868 GJ/L for all three [VCR Inc., 2002; Barton, 2000]. For fly ash from the power plants at Centralia (Washington State) and Sundance (Alberta), the two current sources of fly ash for the Greater Vancouver Area market, the transportation energy consumption is about 0.14 GJ/tonne and 0.33 GJ/tonne, respectively. These figures are based on 280 km of rail transport from Centralia to a terminal in New Westminster and 25 km of urban truck transport thereafter, and 800 km of rail transport from Sundance to a terminal in Langley and 40 km of urban truck transport thereafter. Therefore, the transportation energy consumption for both fly ash sources is of the same order of magnitude but less than the advantage fly ash has over natural pozzolans in energy consumption for material acquisition and processing alone. Hence, any source of natural pozzolans would have to be located very near the Greater Vancouver Area market to overcome the initial energy consumption benefit of fly ash.

As well, in order to utilize the identified natural pozzolans there may be additional direct environmental impacts associated with further site preparation and access road construction, principally habitat destruction and sediment run-off. On an ongoing basis there will also be a potential water pollution issue, i.e., suspended solids associated with site run-off and the waste stream coming from the grinding operation. The exact magnitude of those impacts is site specific and only qualitatively described, but it is sufficient to assume that they will exist.

In summary, therefore, in terms of the present supplementary cementing materials market in British Columbia, and given the available data, there would be no environmental benefit derived from using natural pozzolans instead of fly ash. In fact the opposite is likely the case.

ECONOMIC EVALUATION

As indicated in the previous section of this report, the development of a natural pozzolan source to produce a material suitable for use as a supplementary cementing material generally requires acquisition (quarrying and possibly crushing) and processing (drying, grinding, and possibly beneficiation and/or blending) of the material. The capital cost of the required equipment and infrastructure could be as much as $500,000 for a small operation requiring only drying and grinding equipment [Wear, 2003]. For a larger processing facility including equipment for material handling and storing, as well as drying and grinding, the current capital cost could be as much as $2.5 million, on the basis of a 1989 study [Ainsworth-Jenkins Holdings Inc., 1989]. For a single producer, the initial capital cost may therefore constitute a significant barrier to the development of his material source.

One possible method for dealing with this potential barrier is to construct a processing facility at a central location. The underlying assumption is that natural pozzolans of the same type from one or more sources can be processed at one facility, which would need to include the following equipment:

- delivery stations to stockpiles
- grinding mill (ball mill)
- conveyers for blending from stockpiles
- storage silos for processed and blended pozzolans
- quality control laboratory

Potential sources of natural pozzolans in British Columbia within an economic transport distance from the Greater Vancouver Area are listed in Table 1 above. In order to obtain a cost estimate for production of a supplementary cementing material from natural pozzolans potentially available at these sources, it is assumed that a processing facility would be located in or near Hope. This assumption will be discussed later. The approximate road transport distances from these sources to Hope are given in Table 3 below.

Table 3: Distances from Natural Pozzolan Sources in British Columbia to Hope

SOURCE	APPROXIMATE DISTANCE TO HOPE (KM)
Mt. Garibaldi	150
Barnhart Vale	180
Mt. Meager	265
Empire Valley	250
Deadman River	220
Quesnel*	450

* Includes all sources in or near Quesnel

An approximate cost estimate for the processing of supplementary cementing material from these sources is given in Table 4 below. The quarrying cost assumes that the deposit is unconsolidated and can be transferred to a truck for transport by means of a front-end loader or similar equipment. The crushing and grinding costs are estimated using the Bond equation [Wills, 1997] assuming that the material is to be reduced from about 12.5 mm in size to 45 ìm. The energy requirement for drying is taken from Table 2 above; the cost of the energy is conservatively estimated at $0.10/kwh. To be conservative, the transport distance from the source to the processing facility is assumed to be 300 km.

Table 4: Cost Estimate for Processing at a Central Location (Hope)

cost Item	Cost per tonne
Quarrying ($5.00-$7.00/tonne)	$7.00
Crushing and grinding to 45 μm ($3.00/tonne)	$3.00
Drying (100 kwh/tonne @ $0.10/kwh)	$10.00
Road transport (300 km @ $0.15/tonne-km)	$45.00
Total cost	$65.00

The estimated total cost for processing a natural pozzolan at a central location in Hope is therefore $65.00 per tonne, exclusive of the capital costs of the facility. In addition, there will be the cost of transportation of the processed natural pozzolan to the Greater Vancouver Area, say 100 km, or $15.00 per tonne (using the road transport cost of $0.15/tonne-km in Table 4.) So the total cost of the processed natural pozzolan in the Greater Vancouver Area would be about $80.00 per tonne.

The current price of fly ash in the Greater Vancouver Area is about $75.00 per tonne, including transportation [Almeida, 2003]. Any alternative supplementary cementing material should therefore cost less than this or provide significant additional benefits to compete in this market. The above cost estimate suggests that the delivered cost of a processed natural pozzolan will be of the same order of magnitude but possibly higher than the cost of fly ash. However, it should be emphasized that the unit cost estimates used to develop this estimate are conservative.

The above cost estimate does not include the capital costs of the equipment and infrastructure at the processing facility. These capital costs would have to be recovered from a markup on the above operating costs and depreciated over some time period. From the point of view of capital costs, fly ash has a considerable advantage since the infrastructure required for its production is in place and likely is partially or completely assigned to the power production at the source thermal generating plant.

Table 4 shows that transportation of ‘raw’ material from its source to a processing facility is probably the major expense associated with production of a supplementary cementing material from the natural pozzolans available. Perhaps more than one processing facility should therefore be considered. One possibility is a facility in the Squamish-Pemberton area. A site in Cache Creek might also be considered if it is proved possible to acquire and blend the volcanic tuffs from the Barnhart Vale and Deadman River sources. The main principle of processing site location would be to minimize the distance that low value material, i.e., quarried natural pozzolan, must travel.

The location of processing facilities and the type of equipment at these facilities should be a major component of any further study. Also, at some of the natural pozzolan deposits, quarrying can only occur during the spring and summer months. Thus, the amount of inventory of certain types of natural pozzolan to be stored at a processing facility or elsewhere would also be of interest. A transport contract, in which one trucking contractor visits several sites and delivers natural pozzolan to the processing facility (or facilities), might also be considered as a means of reducing transport costs.

CONCLUSIONS

Previous studies have identified several possible sources of naturally pozzolanic materials in British Columbia that are potentially suitable as supplementary cementing materials for portland cement concrete mixtures. Samples from several of these sources have been tested and found to satisfy past and, in some cases, current Canadian (CSA) and American (ASTM) standards for natural pozzolans and/or supplementary cementing materials. However, only two of these sources are currently being exploited, the pumice deposit at Mt. Meager and the calcined clay/shale deposit at Quesnel. The status of the other potential sources is unknown at this time.

The CANMET report on supplementary cementing materials [Bouzoubaâ and Fournier, 2003] identified and discussed a number of existing barriers, real and perceived, to increased usage of such materials in the concrete industry in British Columbia, and presented suggestions for overcoming these barriers. The barriers for fly ash, as listed in Table 17 of the report, are identified as:

- Policy Barriers
    - None

- Technical Barriers
  - Constructibility (lower early strength and setting time) particularly in cold weather
  - Simple substitution of cement with fly ash on a kg for kg basis can result in substandard HVFA (high volume fly ash) concrete which will then have an impact on the credibility of the system
- Economic Barriers
  - None at current price
- Other Barriers
  - The relatively new position of the ready-mix industry in which they wish to produce concrete as a "manufactured product" (like steel). On this basis, they control the proportioning internally and the amount of SCM (supplementary cementing material), if any, is unknown. The question then arises whether there is any incentive on their part to expand the use.

There is no reason to believe that the introduction and use of natural pozzolans as supplementary cementing materials in British Columbia would not be subject to the same barriers, as well as several possible additional ones.

On a policy basis, the Canadian national standard on portland cement concrete, CSA A23.1-00, "Concrete Materials and Methods of Concrete Construction", does not prevent or restrict the use in concrete mixtures of supplementary cementing materials which conform to the requirements of CSA Standard A23.5. The CANMET report indicates that the specifications of most, if not all, provincial and municipal authorities in British Columbia now follow the lead of the national standard. However, it is still probable that specifications produced by some jurisdictions and/or consulting engineering firms in the province for specific projects do not allow or limit the use of supplementary cementing materials.

However, if specifications were to require the use of a certain type and amount of supplementary cementing material in the concrete mix(es) for a project, then a possible policy barrier could arise from the provisions of Clause 16 of CSA A23.1-00, Alternatives for Specifying Concrete. In the case where the owner, or his representative, specifies both the type and the amount of cementing materials to be used, identified as Alternative (2) Prescription in the clause, he assumes responsibility for the mix proportions and properties of the concrete mixture. That is, the concrete supplier is responsible for neither the proportions (Alternative (1) Common) nor the performance (Alternative (3) Performance) of the concrete.

Where only the type, but not the amount, of supplementary cementing material is specified by the owner or his representative, the concrete would be supplied under Alternative (1) Common. However, the concrete supplier would not want to supply concrete under this alternative unless the risk of not meeting the specified performance criteria (quality, yield and strength) with even a minimum amount of the specified supplementary cementing material (say 5 per cent) was acceptable to him. The technical evaluation conducted out as part of this study indicates that considerably more testing would have to be carried out on the natural pozzolans currently available in British Columbia before a concrete supplier would be confident enough in their use to supply concrete containing them under this alternative.

It was previously noted that the CANMET report on supplementary cementing materials in Canada briefly discussed the current situation with respect to blended cements. The potential use of a natural pozzolan from one or more of the British Columbia sources identified in this study as a cementing component in a blended cement was not investigated in any detail because of the anticipated strong resistance by concrete producers to the use of such materials. Ready-mixed concrete producers in particular are resistant to the use of a blended cement since it reduces their ability to vary the content of the supplementary cementing material in concrete mixes to satisfy specification and market requirements.

A preliminary comparative analysis of energy requirements for acquisition, processing and transportation indicates that the environmental benefits that can be derived from the use of natural pozzolans as portland cement replacement materials are of the same order of magnitude as those for fly ash, but possibly significantly less. There would not appear, therefore, to be any environmental benefit to developing the known sources of natural pozzolans in British Columbia to produce supplementary cementing materials relative to the current situation of importing fly ash for this purpose.

The economic evaluation carried out as part of this study indicates that the delivered cost of a processed natural pozzolan to the Greater Vancouver Area will be of the same order of magnitude but possibly higher than the current price of fly ash. Several assumptions are made in this evaluation, and there is a very limited amount of available cost data. The capital costs of the equipment and infrastructure needed for processing the material are not included in the analysis, but the operating cost estimates are considered to be conservative. It is noted that fly ash has a considerable initial advantage again in that the infrastructure required for its production is in place and the capital costs are likely assigned to the electrical power production at the source thermal generating plant.

The economic evaluation also shows that the major expense in the delivered cost of a natural pozzolan is likely to be that of transportation of the relatively low value 'raw' material to a processing facility, and therefore the main objective of selecting a site for such a facility would be to minimize the distance that this material must be transported.

In summary, the preceding technical, environmental and economic evaluations indicate that natural pozzolans from certain deposits in British Columbia may have potential use as supplementary cementing materials in portland cement concrete mixtures. However, until there is a proven demand for supplementary cementing materials in the province that cannot be satisfied by importing fly ash from Washington State and/or Alberta at an acceptable cost, there does not appear to be any technical, environmental or economic reason to develop the natural pozzolan sources in the province for this purpose. At this time, therefore, further study of the potential use of natural pozzolans from deposits in British Columbia as supplementary cementing materials is not justified.

RECOMMENDATIONS

It is recommended that no further investigation of the potential use of natural pozzolans from deposits in British Columbia as supplementary cementing materials be carried out by the EcoSmart™ Concrete Project until it can be demonstrated that there is a demand for such materials in the province that cannot be satisfied by the importation of fly ash from Washington State and/or Alberta at an acceptable cost.

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Appendix A:

Individuals Who Provided Information to the Study Team

The following individuals were contacted by the study team and provided information that was helpful in completing the study and preparing this final report. Their assistance is gratefully acknowledged.

John Anthoine, P.Eng.	Lafarge North America Inc./ Construction Materials Division
Garth Carefoot	Great Pacific Pumice Inc.
Jim Caruth, P.Eng.	Pozzolanic International Limited
Steve Geddes	British Columbia Ministry of Transportation/ Engineering Branch
Tom Gibson	Lehigh Northwest Cement Limited
Gene Lecuyer, P.Eng.	Lafarge North America Inc./Cement Division
D.R. Morgan, Ph.D., P.Eng.	AMEC Earth & Environmental
John Rutherford, P.Eng.	Ocean Construction Supplies Ltd.
R. (Ron) J. Savelieff	Lehigh Northwest Cement Limited
Thomas Scuffi	Quesnel Redi-Mix Cement Co. Ltd.
Brian Wear	Canada Pumice Corporation
Dave Zakarius	United Concrete & Gravel Ltd.