Preliminary Slag Scoping Study for EcoSmart™ Concrete

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"Preliminary Slag Scoping Study" for EcoSmart™ Concrete

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Summary

This report gives the details of the preliminary scoping study of slag cement in order to facilitate a full-scale study on the high volume use of slag in EcoSmart™ concrete. The report provides a summary of the current status of use of slag cement and identifies work that would be required to introduce effectively the high volume slag (HVS) in the relevant structural applications.

The byproducts from the steel industry that are useful in making concrete include ground granulated blast furnace slag (GGBFS) and also, potential use of electric arc furnace slag (EAFS). These materials are used as supplementary cementing materials (SCM) for partial replacement of cement in concrete. SCMs are less energy intensive materials to produce, as they are industrial byproducts and when combined with energy intensive normal Portland cement to make concrete, it helps in reducing the environmental impact, particularly in terms of reducing greenhouse gas (GHG) emissions. A need has been identified for a comprehensive study on the use of high volume slag in concrete structures including a review of technical performance, environmental benefits and impacts, economical analysis, quality control requirements and related issues. This report includes discussions on these issues.

It is expected that the steps described here will provide a framework for a full-scale study that would facilitate in the development and use of HVS as a supplementary cementing material. Increased use of slag in concrete would result in positive impact on the environment. The approach described should form the basis for developing guidelines for demonstration projects, supported by technical evaluation and testing where required. A concerted effort is required to carry out and monitor such projects with HVS.

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1.0 INTRODUCTION

Use of supplementary cementing materials (SCM) is becoming common in the concrete industry /1- 4/*. These include fly ash, slag, condensed silica fume etc. SCMs are waste by-products requiring very little, if any, additional energy to produce, and when combined with energy intensive normal Portland cement to make concrete, it helps in reducing the environmental impact. This report mainly deals with the use of high volume slag (HVS) in concrete.

The report provides a background for the scoping study and identifies various issues related to slag, the barriers for the introduction of the use of high volume slag in field applications, and the approach needed to overcome such barriers.

2.0 BACKGROUND

The by-products from the steel industry useful in making concrete include ground granulated blast furnace slag (GGBFS) and potentially the use of electric arc furnace slag (EAFS). These materials are used as supplementary cementing materials (SCM) for partial replacement of cement in concrete. Other applications of slag (in granulated form), such as in lightweight-concrete as aggregates, are not part of this report.

In spite of the availability of guidelines, standards and code of practices for use of slag cement in concrete /5-7/, it is noted that the use of high volume slag in concrete has been limited in the EcoSmart™ concrete /8/. The reason has been attributed mainly to the lack of initiative in developing a strategic approach for introduction of slag blending in the concrete. Also, it is noted that the impact on the reduction in the green house gas (GHG) emission may not have been fully realized as a result. In comparison, use of high volume fly ash as SCM in concrete has taken a lead role mainly because of significant expertise gained both in the research findings and in the field applications, including effective communications at various levels of the industry. EcoSmart Project has been responsible for taking the initiative in generating knowledge from the field applications.

Therefore, a need has been identified for a comprehensive study on the use of high volume slag in concrete applications including technical performance, environmental benefits and impacts, economical analysis, quality control requirements and related issues.

Replacement of normal Portland cement with various amounts of slag cement is becoming common to produce concrete under field conditions, although the amount used during winter months is less. The practice is generally acceptable in the Ontario area. The reason for this is possibly due to the proximity of the sources of slag in Ontario. Also, large organizations like the Ministry of Transportation of Ontario allow the use of slag-cement up to a maximum of 25%. Ontario Power Generation/Hydro-One (formerly Ontario Hydro) had restricted its use to specific projects.

Higher amounts slag replacement is sometimes specified to achieve special properties of the concrete i.e., to provide resistance against sulphate attack, lower heat of hydration, to provide protection against alkali-aggregate reactivity etc. However, higher percentage of slag in the concrete requires pre-testing of the concrete in order to evaluate technical difficulties i.e., slow strength gain. The current effort is focused towards the review of the various issues related to the use of high volume use of slag in concrete.

* See list of References

3.0 SCOPE

The scope of this preliminary "Scoping" study is limited to identifying the issues related to the current use of slag in concrete, developing a strategic approach to determine the barriers for higher amounts of slag usage and that for overcoming such barriers. The approach identified here should provide a guide to the development for a full-scale study for the use of high volume slag in EcoSmart™ concrete.

4.0 CURRENT STATUS

The data gathered by CANMET on the current status of SCM /4/ include various aspects of all the SCM's available across Canada. As far as the slag is concerned, it is mentioned that the utilization of available slag can be increased if the demand is increased. In Canada most of the ready mix operation uses slag as a separate ingredient mixed with the other concrete constituents at the plant. It is reported that up to 40% replacement is provided by the ready mix industry during summer months while it drops down to 10% to 15% in the winter months.

The barriers identified in the CANMET report are policy, technical, and economic. The policy barriers include banning or limiting the use of slag in the construction specifications for provincial, municipal and other large agencies. The technical barrier includes, slower than normal strength gain of concrete. Also, it was noted that there is a perceived concern for freezing/thawing and salt scaling resistance properties of slag blended concrete. With good quality control at low water to cementing materials ratio and adequate air entrainment, there is no reason for such concern. The economic barriers include availability of slag at a reasonable price across the country.

A concerted effort has been suggested to promote the use of slag through R&D to improve the early age strength, a strict quality control as well as field trial testing and conducting technical workshops. Except for these suggested activities, the Canadian SCM-inventory developed by CANMET provide sufficient knowledge to the degree to which slag is currently being used as SCM.

It would therefore appear that the industry is self-controlled from a technical point of view and comfortable with the current level of usage. The main reason for the lower percentage replacement during winter months is the slow setting time and slower strength gain at low temperatures. The benefits from the environmental perspective are less obvious in such low percentage usage.

It is therefore apparent that effort is required to overcome the barriers and find ways and means to increase the volume of slag replacement in the current concrete industry. The following sections deals with these issues with high volume usage.

5.0 TECHNICAL AND ENVIRONMENTAL CONSIDERATIONS

For the purpose of this report GGBF slag replacement of more than 40% is considered as high volume application in concrete with normal Portland cement as activating agent. Currently the upper limit of use is given in CSA A 362 for blended cement at 70%. However, there is no limit given in the CSA specifications dealing with concrete (CSA A 23.1 and A23.5), where slag is mixed as a separate ingredient at the ready-mix plant. Suggested slag replacement up to 50% is given by Slag Cement Association (SCA) for most of the structural applications with as much as 80% for certain specific applications /25/. In European studies, discussed later under section 5.5, applications up to 85% replacement has been reported. The technical considerations for use of high volume slag replacement are described below, along with the environmental related issues.

The following sections 5.1 to 5.5 deal with the use of GGBFS in combination with Portland cement as the activating agent. Activation of slag is also possible with agents other than cement. These are discussed in section 5.8.

5.1 Chemical and Physical Properties

It is known that modern blast-furnace technology produces very low variability in the compositions of both the iron and slag from a single source /6/. The range of chemical composition from source to source are given in references /6, 9/. The variability of the Canadian slag between three sources, as reported in reference /9/, generally falls within the expected range given in ACI reference /6/, except for the MgO content in one source and that of Fe_2O_3 for another source were marginally outside the upper range.

Under normal conditions, the effectiveness of the slag is measured from the performance of slag in combination with cement rather than the actual composition of the slag. The specification limits given in the CSA standards /5/ are based on research and field experience and are adequate for quality control and acceptance purposes. The requirements for the blended cement (CSA A 362) include sulphur trioxide (SO_3), sulphide-sulphur (S), loss on ignition and insoluble residue, while for slag cement alone (CSA A 23.5) limits on SO_3, S and optional moisture content are given. The physical properties include autoclave expansion/contraction, slag activity index and the fineness.

There are no reasons to believe that the same limits would not be applicable for higher volume usage in concrete. The items that could be an issue are the level of vitrification (or glass content) and the degree of fineness. It is known that higher levels of both provide enhanced slag activity when combined with Portland cement which could be of benefit at high replacement levels. However, it is also noted that a wide range of glass content is acceptable for reliable performance /9/. It is important to note that ACI 233 Committee /6/ recognized the complexity of the slag hydration and noted that due to the complexity of the influencing factors, attempts to relate the hydration of GGBFS to simplified chemical moduli failed to provide adequate evaluation criteria. In practice direct performance evaluations of workability, strength characteristics, and durability are the most satisfactory measures of the effectiveness of GGBFS use.

Therefore, no apparent barrier exists for higher volume usage with respect to the chemical and physical properties, except that the assurance of the consistency of the slag from the source of supply would be important. The increased fineness of grinding would help to enhance the activation of slag at higher percentage replacement but the energy intensive process involving additional cost would negate some of the benefits with respect to the environmental impact. Further evaluation is required to optimize the level of fineness to provide satisfactory performance at higher slag-replacement level, if required.

5.2 Properties of Unhardened Fresh Concrete

The properties of the fresh concrete that would be most affected due to the use of high volume slag in concrete are described below. The data are for replacement level of 50% as reported in CANMET publication /1a/ and that in the ACI guidelines /6/. Except for the dosage rate of air-entraining admixture, as noted below, no test data were readily available for higher replacement levels. The possible implications of using higher percentages of slag are discussed.

5.2.1 Mix proportions

Mix proportions would depend on the chemical compositions, fineness, and specific gravity of the proposed slag. Therefore, laboratory trial investigation is required to establish the mix proportions with the normal Portland cement, aggregates and chemical admixtures to be used for any proposed project. This is especially true with higher replacement levels of slag. The specific gravity of slag ranges from 2.85 to 2.95, compared to 3.15 for Portland cement. This difference generally results in a higher volume of paste

in concrete for a given replacement of cement by slag on a weight basis than it would have without the slag. Therefore, at high replacement level this will affect the rheology of the mixture requiring adjustment to the amount of aggregates. Increased paste content provides better workability without increasing the water content but may not result in higher strength for HVS concrete. This has been discussed later under section 5.3.2, where it is noted that low water to cementing materials (W/CM) ratio does not necessarily provide increased strength. It would therefore appear that the increased slag content although has water reducing capability compared to Portland cement it may not be beneficial from strength point of view. The workability issue has been further discussed under section 5.2.5.

5.2.2 Time of setting

The partial replacement of cement with slag generally increases setting time of concrete. The final setting could be delayed significantly depending upon the ambient temperature and the amount of replacement. Lower temperatures would further extend the setting time. At 18°C, concrete with 25% slag replacement, up to 3.5 hours delay in setting time has been reported /44/.

5.2.3 Bleeding

Bleeding is the collection of water at the surface due to settlement of aggregate particles during early stages of setting. Excessive bleeding is undesirable. Most of the available data indicate that because of the high fineness of the slag, bleeding is not a problem. However, changes in the fineness of the slag may require re-evaluation at higher level of replacement particularly at low temperatures. Extended time of setting at low temperatures could play a role in the bleeding capacity.

5.2.4 Effect of admixtures

The superplasticizing and air-entraining admixtures are expected to be as effective in slag blended concrete as they are in normal Portland cement concrete. However, the dosage rates would require adjustment and optimized in order to achieve the desired result for high level of replacement. The compatibility of the admixtures requires evaluation prior to their use in the concrete /22/. Further, it has been reported that a patented non-chloride based accelerating admixture has been developed to enhance the early age properties of slag blended concrete /22b/. Effectiveness of such accelerating admixture with HVS requires further evaluation.

5.2.5 Slump and workability

Improvements in workability requiring less vibration during placement have been observed with slag blended concrete. The summary of data given in ACI document /6/ indicates that the improvement is due to the surface characteristics of the slag particles having smooth dense slip planes. As the percentage of slag increased, the W/CM ratio had to be reduced to maintain workability properties same as the control concrete without slag. This observation requires confirmation under field conditions with high replacement level /1a/.

5.2.6 Rate of loss of slump and entrained air

The rate of loss of slump and air is comparable to the normal Portland cement concrete without slag. However, in order to maintain the same level of air content a higher dosage of the admixture is required for HVS, mainly because of the higher fineness of the slag. CANMET tests /1a/ indicated almost three fold increase of air-entraining admixture dosage to maintain 5% air in the concrete with slag.

As noted earlier, most of the observations on the properties of the fresh concrete are based on 50% replacement level. Therefore, the effect of higher percentage level of replacement would require further evaluation under laboratory and field conditions, discussed under section 6.3.

5.3 Properties of Hardened Concrete

Most of the data reported /1a, 6/ are for the replacement level up to 50%, although some limited data are available for replacements to 70%. Applications higher than 70% have been mentioned for specific projects but detailed technical data were not available for review. The following discussions refer to the areas of further study and data collection that would be required for use of higher replacement levels.

5.3.1 Curing

It is known that concrete containing slag is more affected by poor curing conditions than concrete without slag /1a/. Especially at higher than 30% replacement levels where slow formation of strength-producing hydrates occur, the effect is more pronounced /6/. The concrete must be kept in a proper moisture and temperature during early stages for development of strength and durability potential. Therefore, extended curing time would be required depending on the ambient and concrete temperatures, the type and amount of cement used, and the level of percentage replacements. Further study is required to identify various parameters and their effects on concrete with higher replacement levels.

5.3.2 Compressive strength

The compressive strength development of slag mixed concrete depends primarily on the source of slag, fineness, activity index, and proportions of slag used in the concrete mixture. Generally, the strength development is slower at early ages, but between 7 and 28 days, the strength approaches that of the control concrete without slag with later age strengths being higher than the control. It has been reported that this trend may not always be true, particularly with low W/CM ratios concrete, where the slag concrete strength tends to stay somewhat lower than the control concrete even after one year of curing /1a/. The reason for such lower strength is not very clear, as all specimens were cured the same way under laboratory conditions therefore the curing conditions do not appear to be a cause. The fineness of the grind of the Canadian slag used in the study, may be a contributing factor. The fineness of Canadian slag is generally lower than that of the US sources.

At higher percentage replacement (65%) of US slag, the later age strength tends to be higher than that which would be achieved with 50% replacement and lower than that of 40% but in all cases the strength was higher than the control concrete. The results were for a high-grade slag from USA source reported with W/CM ratio being constant /6/. It is, therefore, important to perform laboratory investigation for each source of slag to develop age versus strength relationship.

Increased fineness of slag and addition of silica fume as a ternary blend appears to be promising in obtaining strength increase /1a/. Also use of superplasticizing and accelerating types of chemical admixtures may provide rapid strength gain with high percentage of slag. Further evaluation is required in this area to identify the types of admixtures suitable for such applications and the optimum use of silica-fume.

5.3.3 Flexural strength

In general, at seven days and beyond, the flexural strength of concrete with slag is comparable to, or greater than the corresponding strength of control concrete /6/. The data reported in the literature are for up to 65% replacement under laboratory conditions. Confirmation of this result at higher replacement levels in both laboratory and field is required.

5.3.4 Modulus of elasticity

At the same strength level, there is no significant difference between the modulus of elasticity of slag concrete and that of the control concrete. The relationship between elastic modulus and age is similar to that of compressive strength and age. Under normal temperatures, slag blended concrete develops modulus more slowly than the control concrete. The higher the replacement levels the slower the rate of increase. Project specific requirement will dictate the level of replacement.

5.3.5 Drying shrinkage

In the short term, the drying shrinkage of concrete with 50% GGBFS mix appears to be somewhat lower than that of the control concrete. However, in the long term, the relative shrinkage was higher under sealed curing conditions. It is also noted that under a drying environment after a curing period of 14 days, the shrinkage is appreciably higher with GGBFS concrete. This leads to the belief that not enough is known of the behavior of GGBFS concrete under drying conditions. This area will require more study to establish the effect of curing on shrinkage of GGBFS concrete, especially with higher level of replacements.

5.3.6 Creep

Compared to the control concrete, it is reported that the total creep of slag mixed concrete could be somewhat higher at 60% relative humidity at room temperature, but the basic creep tends to be lower /1a/. This effect could have implications in large sections where the interior would have less tendency for stress relief from creep effect than the outer region of the section. The limited data available indicate conflicting results /6/, therefore, better understanding of the stress/strength ratio and the age of loading along with the later age strength gain characteristics are required for higher level of replacements of GGBFS.

5.3.7 Permeability

The permeability of well-cured concrete containing slag is greatly reduced when compared to concrete without slag. This is mainly due to the improvement in the porosity and the pore size distribution as a result of the secondary reaction of slag with calcium hydroxide and alkalis released during Portland cement hydration. As the slag content is increased permeability decreases, benefiting the overall performance of the concrete. Project specific requirements will dictate the level of replacement.

5.3.8 Temperature rise and thermal cracking

The temperature rise occurs due to the heat of hydration of cement at early ages when the heat is not allowed to dissipate fairly rapidly, such as in the case of mass concrete. During cooling, restrained sections would crack if the tensile strain capacity of the concrete were exceeded.

Experience gained in the past indicated that slag mixed concrete would help in reducing peak temperature during early age curing of the mass concrete. The heat evolved is dependent on the Portland cement used and the activity of the slag. However, it was noted that the ambient conditions under which the concrete is placed and cured are also controlling factors to prevent thermal cracking in the concrete. It is the gradient between the interior and the outside temperature controls such cracking. In some instances, significant cracking was noticed in tower bases made with 30% slag replaced concrete /11/.

From limited investigation /12/ it appears that both the tensile strength and the tensile strain at failure for concrete at early ages decreased with increasing slag content. Therefore, the benefit of reduced temperature rise on thermal cracking of concrete may be offset by the lower tensile strength and strain

capacity at early ages. Further study is required with higher replacement levels in order to determine the temperature rise characteristics and the associated thermal cracking potential for restrained concrete.

5.4 Durability Related Issues

5.4.1 Freeze/thaw (F/T) and deicing salt scaling

As with all Portland cement concrete, proper air content and bubble spacing is necessary for adequate protection against F/T. Slag mixed concrete is no exception. At higher replacement levels the dosage of air- entraining admixture would be higher. Also, a properly air entrained with low water to cementing materials ratio concrete shows good resistance to salt scaling. Therefore, optimization of the air content and the water to cementing materials ratio is required under field conditions. The air content requirements for F/T resistance and deicing salt scaling are given in CSA standard /5b/. Although CSA A23.1 standard does not give any limit on slag replacement for concrete exposed to deicing salts, Slag Cement Association suggests limiting it between 25% and 50% with W/CM ratio of 0.45 /25/.

5.4.2 Resistance to sulphate and sea water attack

Concrete made with slag generally improves its resistance to sulphate attack, though the concentration of sulphate surrounding the concrete would control the amount of replacement. The resistance to sulphate attack improves with higher replacement level (65%). At lower replacement levels (20% to 50%), a low alumina content (less than 11% of Al_2O_3) in the slag is suggested to achieve adequate resistance /23, 28/.

Similarly in sea water which contains sulphates, a well cured low water to cementing materials ratio concrete containing a high replacement level of slag performs very well /24/. Crystallization of salt, resulting in pressure build-up in the pores has been identified as a deterioration mechanism of the concrete. However, the salt crystallization occurs to concrete sections above the sea water level due to capillary action of salt water and subsequent evaporation. A low permeability of the slag concrete would prevent such penetration of salt water. Therefore, there are no barriers for using higher percentage replacement for achieving seawater attack or sulphate resistance properties of the concrete.

5.4.3 Resistance to alkali aggregate reactivity (ASR)

The use of slag in concrete generally reduces expansion due to any potential reactivity of aggregates. It has been reported that a replacement level of 40% to 65% virtually eliminated expansion. It has been reported /6/ that the improved resistance to ASR is influenced by (a) reduced permeability, (b) change in alkali-silica ratio, (c) dissolution and consumption of the alkali species, (d) direct reduction of available alkali in the system, and (e) reduction of calcium hydroxide to support the reaction.

5.4.4 Resistance to corrosion of reinforcing steel

The passive alkaline environment of the concrete provides protection to the reinforcing steel. The protection is controlled by the rate at which moisture, oxygen, chloride ions can penetrate and destroy the passive environment. The loss of protection can occur as a result of either chloride ingress or carbonation. It has been reported /6/ that a slight reduction in the pH of pore solution in the concrete with slag does not have a negative impact on the passivity of the reinforcing steel. Use of GGBFS in good quality-concrete, reduces permeability, thus reducing the penetration of corrosion causing agents. Some concerns were expressed regarding potentially harmful effects of sulphide-sulphur in the slag, but the maximum acceptable amount specified in the CSA standards is adequate for most practical applications. Therefore, resistance to corrosion of reinforcement is not an issue with the high volume use of slag in a good quality concrete.

5.4.5 Carbonation

The rate of carbonation of slag cement concrete has been reported to be higher than that of Portland cement concrete especially at high slag replacement levels /1a/. Based on the limited test data, the reason has been attributed to changes in the pore size distribution in the paste fraction of the concrete /24/. However, field performance in European studies indicated otherwise in some instances /10/. Therefore, further understanding is required in this area for high level replacement.

5.5 Expertise Abroad

The use of GGBFS and fly ash in concrete was reviewed by the Working Party of the Concrete Society, UK, in early '90s and a state-of-the-art report was produced /10/**.** Studies in early '80s and later technical research papers were published on various aspect of the GGBFS use /15-20, 38/**.** These papers indicate significant advancement in the use of high volume slag in specific projects. The composition of slag from UK sources as reported in reference /10/ falls within the rage of values given for North American slag that includes Canadian slag /6/. The fineness, for both UK and Canadian slag, is in the range of 400-450 m^2/kg as reported in references /10, 44/. Therefore, in general, the UK findings on the performance of slag would be applicable to the Canadian context, except for the local conditions e.g., aggregates, cement, admixtures etc.

Since the introduction of slag as a separate cementitious material in late '50s in South Africa, the addition of GGBFS at the concrete mixer along with Portland cement has been accepted as a common practice in UK, Japan, Australia, Finland /6, 10/, including the USA and Canada. Although, many countries e.g., Holland, France, and Germany have developed the use of slag in the form of inter ground slag cement /1a, 10/. The economics of inter-grinding aspect in Canadian context has been discussed later under section 6.5.1.

The practice of using slag as a separate ingredient, mixed at the ready mix plant, provides the flexibility of proportioning the mix to suit the specific project need. The general level of slag replacement in UK is 30% to 50%. A number of applications were identified where 60% to 70% replacements were used. These were mostly where requirements include resistance to sulphate attack, and lower early age heat generation in underground slabs. A few projects were also reported where 75% to 85% replacements were used, mainly in the mass concrete and for sulphate resistance purposes. However, no project specific technical data were given for such applications.

It would, therefore, appear that in terms of the gap in knowledge, as with the experience of UK, Germany and France /10, 38/ for more than a decade, we are not able to draw on field performance of high volume use of slag in actual structures.

5.6 Comments on the technical issues

None of the technical issues discussed in sections 5.1 to 5.4 and the expertise abroad in section 5.5 indicate any fundamental barrier for use of higher percentage slag replacement in concrete than the current level. The slow rate of strength gain is probably the single greatest limitation for high volume use of slag limited by the fineness of the available slag. The concrete industry prefers cements that would behave more or less like normal Portland cement (i.e., Type 10). The currently available slag would not provide such properties at higher volume replacement levels. The use of superplasticizing/accelerating admixtures in combination with silica-fume has not been fully investigated to overcome the slow strength gain properties.

Some of the technical issues require better understanding to determine the limitations while most of them demand project specific performance evaluation. The issues requiring better understanding and that of the project specific evaluation are discussed under section 6.3.

5.7 Comparison with Current Initiative Related to Fly Ash Use

The current initiative and the knowledge management system developed and introduced by EcoSmart Concrete Project /39/ for fly ash are equally applicable to the use of slag in concrete. The benefits and challenges listed for fly ash use would be similar to that of the slag. The use of slag provides increased workability, less bleeding, enhanced long-term strength, reduced permeability, increased durability, reduced thermal stress and early age cracking, and increased resistance to sulphate. The GGBFS is environmentally sound as listed by United States, Environmental Protection Agency /45/ under Comprehensive Procurement Guidelines for use in concrete where reference is made to ASTM /28/ standards and ACI recommendations /6/.

At lower percentage of cement replacement (up to 40%), the slag performs well and is acceptable within the current industry practice in Canada, except that during the cold season, a lower replacement level is utilized. At higher replacement levels of slag, attention should be drawn to the limitations, mainly the slow strength gain at early ages and associated shortcomings, such as extended setting time, undesirable bleeding during cold weather placing of concrete. These limitations could be severe in some instances depending on the mix compositions and the job conditions. As Mehta /36/ pointed out that due to the simplicity of the technology high volume fly ash and/or slag concrete is expected to have a high impact on the concrete industry. Therefore, testing and evaluation are required for successful use of HVS.

The CANMET work on high volume fly ash included a complete range of evaluation of properties for fresh and that of the hardened concrete under laboratory conditions /21/. Following laboratory evaluation simulated structural elements were made representing various sizes of members i.e., wall, columns etc. The key to the success was to use low water to cementing material ratios with superplasticizing admixture. Similar approach would be required for high volume slag. The applied research, case study, and effective communications would be the approach for continued effort to introduce high volume slag in the concrete industry.

5.8 Activation of Slag with Agent Other than Portland cement

Activation of slag without Portland cement has been reported in bench scale study in the laboratory using mortar specimens /13a/. The process is not common and mostly at the research stage. Various types of activating agents have been systematically evaluated. These include sodium hydroxide, sodium carbonate, sodium silicate and combinations thereof. These studies provide a reasonably comprehensive view of the phenomenon associated with activation of slag. The results are encouraging for many of the concrete making properties. However, no laboratory scale concrete study has been reported. Therefore, the system requires extensive study and evaluation to overcome various concrete related issues. It has been mentioned that the chemical activators are expensive and may have undesirable side effects. The cheapest and safe activator for slag is Portland clinker with some additional gypsum /13b/. At present no such R&D activities could be found readily in Canada. Therefore, further discussion of these processes is not warranted.

5.9 Slag from Electric Arc Furnace

Investigation of the commercial use of electric arc furnace slag (EAFS), a steel mill waste requires further study. This is in line with the recent R&D work planned by the Commonwealth Scientific & Industrial Research Organization (CSIRO) in Australian, through its Sustainable Material Engineering (SME) Group /14/. At the present time, no such R&D work is in progress that could be readily found in Canada.

5.10 Environmental Impact, GHG Reduction and Safety Issues

It is reported that slag cement requires nearly 90% less energy to produce than an equivalent amount of Portland cement /25/. Therefore, a significant benefit can be realized from purely energy point of view by partially replacing Portland cement with slag cement.

The cement industry is identified as among those industries that emit the greatest amount of green house gas (GHG) /32/, mainly due to the calcination of limestone. Therefore, any reduction in the amount of calcination will reduce the GHG. The utilization of SCM to the greatest amount that can be safely blended with the Portland cement would, therefore, reduce the GHG.

The Slag Cement Association (SCA) reported /25/ that each tonne of slag cement used to substitute for a tonne of Portland cement in the production of concrete, reduces GHG by one tonne. The value of one tonne appears to be approximate. A more precise value has been calculated in the CANMET report /33/ where it indicates that each tonne of cement produces about 0.91 tonnes of CO_2 during manufacturing process. Therefore, allowing for the grinding of the blast-furnace slag to produce slag cement, somewhat less than 0.91 tonnes would be the reduction of GHG for each tonne of slag used. The factor for grinding effect has been estimated to be 0.07 tonnes /4/. Therefore, the estimated GHG reduction would be 0.84 tonnes per tonne of replacement of cement with slag. Similar estimate could be arrived from the energy consumption point of view, that is slag requires only 10% of energy to produce than Portland cement, therefore, 90% of 0.91 tonnes equals to 0.82 tonnes of CO_2 would be saved per tonne of Portland cement replaced. The estimate does not include CO_2 release due to transportation, estimated to be 0.022 tonnes per 1000 km of transportation by truck and rail /4/.

The health and safety issues associated with the use of slag cement would be no different from the practices currently followed for Portland cements in construction, including the requirements for MSDS (Material Safety Data Sheet) for the product. Recent MSDSs from the cement companies /46/ indicate that Portland cement and the Slag cement are similar from the point of view of dusting and toxicity. It is noted that both contains trace amounts of free crystalline silica with caution against prolonged exposure, and poses no unusual toxicity to plants or animals. It is also noted that GGBFS may contain small amounts of hazardous heavy metals, usually in solution in the glassy silicates, derived from limestone flux used in steel making. In hydrated form in concrete, the heavy metals unlikely to pose threat to leaching. Presence of any radioactive substance is not identified therefore it is not an issue. Therefore, once the concrete containing slag is hardened, it does not appear to be of concern for releasing any harmful substances in the air or in the ground.

The occupational health and safety regulations for construction projects and that of industrial establishments would be applicable /34/. The regulations could vary according to the jurisdictions across the country, the reference cited above are for the Ontario Ministry of Labour.

6.0 FIELD APPLICATIONS AND COMMERCIAL CONSIDERATIONS

6.1 Standards, Specifications and Code of Practices

The standard specifications for slag cement in some of the European countries (Finland: National Building Code, Sweden: PFS 1985:2, UK: BS 6699, Russia: ON722108) includes additional chemical and physical requirements compared to Canadian standards: CSA A 23.5, and A 362. These additional requirements, not necessarily given in all the standards cited, include limitations on Magnesium oxide (MgO), Chloride (Cl^-), sum of oxides ($CaO + SiO_2 + Al_2O_3$), CaO as free lime, specific surface area (or fineness), soundness, glass content etc.

ASTM standard C989 includes various grades of slag depending on the slag activity index, whereas Canadian standard only requires minimum 28 days slag activity index of 80%. ASTM C989 also suggests higher numerical grade of slag for high volume use to improve early strength performance, however, it cautions against the use without performing tests with job site materials and conditions. Canadian standard A363 also includes requirements for cementitious hydraulic slag where there are requirements for meeting minimum strength without the addition of Portland cement.

The Canadian standards and the National Building Code (NBC) of Canada along with the ACI guidelines are adequate for the current use of slag in the concrete industry. The implications of the additional requirements noted in other standards require further review and understanding from the Canadian perspective for use with HVS. In order to meet the performance criteria, the project specific guidelines may include some of the additional requirements cited above. This should be further reviewed.

The current standards for concrete require 28 days strength for design purposes. However, later age strengths to meet specific project requirements are permissible in the CSA A23.1, as such, HVS concrete would be acceptable provided structural requirements are met. Appendix B of CSA A 23.5 provides a guideline for use of supplementary cementing materials that in turn refers to ACI 233 document /6/. The ACI document currently suggests over 50% replacement for sulphate and low heat requirements but stops short of providing guidance as to the range that would be acceptable for particular applications. The full scale study recommended in this report may provide data for such guidance for Canadian slag and it would be a step forward if CSA A 23.5 includes guidelines for HVS applications.

Further, CSA A23.1 requirements are adequate for the current level of slag replacement (up to 40%), however, with HVS the requirements such as curing, exposures, early age strength etc., need to be better defined. The technical committee of CSA A23.1 is currently working on this subject. It is suggested that EcoSmart Concrete Project monitor progress of the committee work, and that EcoSmart provide information to support the activities of the committee, where required.

6.2 Construction Practices and Quality Control Issues

6.2.1 Construction Practices

Various aspects of the construction process are commented on where high volume replacement may have an impact. The comments are based on the CSA standards /5/, ASTM /27/, ACI guidelines /6, 37/, European practices /10/ and the author's experience during placement of over 150 large size transmission tower foundation bases /11/. Some of the shortcomings associated with slow strength gain of HVS concrete could be avoided by rescheduling the construction activities to allow for the concrete to gain adequate strength or use of suitable admixtures (i.e., superplasticizer/accelerating) to enhance the strength as suggested later in section 8.0. The other alternatives to overcome the shortcomings could include re-designing the mixture proportions and lower the water to cementing material ratio significantly as suggested in ACI document /6/.

(a) Transportation: The current practice of ready-mix concrete transportation is acceptable with high volume slag (HVS) concrete. The slow setting time of HVS may help in transporting over long distances. Pumping of HVS concrete does not appear to be a problem, however, if used; admixtures to facilitate pumping may require compatibility evaluation.

(b) Placing, compacting and finishing: In general, HVS provides enhanced workability, pumpability, ease in compacting and finishing. However, field evaluation is recommended to confirm these properties at higher level of replacement. During lower temperature periods the extended working time of HVS concrete may result in delays in finishing.

(c) Bleeding: As reported in the UK study /10/, bleeding is generally not a problem with slag concrete at 40% or less replacement levels. However, because of the extended setting time the bleeding could pose difficulties with HVS concrete, particularly at low placing and ambient temperatures. The job specific conditions should be considered to evaluate the possibility of excessive bleeding and its impact on the finishing time.

(d) Form-work: The form-work removal time could be significantly extended due to the slower rate of early age strength gain properties of the HVS concrete. For the same reason, the placing rate may have to be decreased. If the placing rate is to be maintained same as the concrete without slag, the form-work pressure could increase requiring re-evaluation.

(e) Plastic cracking: Plastic cracks can occur in concrete in the first few hours after placement. The potential for cracking may increase due to the settlement of HVS concrete during a slow setting time period. The job specific conditions should be considered to evaluate the possibility of plastic cracking.

(f) Colour: The colour of exposed concrete with slag is lighter than normal Portland cement concrete, while the interior of concrete with slag, not exposed to air, generally retains a blue-greenish colour for a considerable time. If colour is of concern, this should be reviewed further.

(g) Curing: Curing requirements should be evaluated for job specific conditions. As discussed in section 5.3.1, for HVS extended curing time would be required depending on the ambient and concrete temperatures, the amount of cement used and the level of percentage of cement replacement with slag. To attain proper strength and durability, curing should follow the procedures given in ACI specification for curing concrete /37b/. It is mentioned that during cold weather, the concrete requires protection against direct uneven heating and carbonation due to the exposure to combustion heater exhaust. As suggested in section 5.3.1, further study is required to identify various parameters and their effects on concrete with higher replacement levels.

(h) Early age thermal cracking due to heat of hydration: For large sections of concrete structures, where early age thermal cracking is of concern, the potential for such possibilities should be evaluated for HVS concrete, since the existing data with Canadian slag is not sufficient to draw any definitive conclusions. This aspect has been discussed under section 5.3.8 where it is noted that under restrained conditions the gradient between the interior and the outside temperature controls such cracking. The interior temperature rise would be reduced with HVS but depending on the amount of slag replacement, it may provide insufficient tensile strength and strain capacity to prevent cracking at early age. Therefore, maximum acceptable temperature rise needs to be evaluated for a particular job.

6.2.2 Quality Assurance and Control Practices

The quality assurance and control practices currently in place for the concrete industry are equally applicable to HVS concrete. However, some additional assurance would be necessary for the combinations of Portland cement and the slag to provide the properties required for the particular application, and that it would meet the requirements of the appropriate CSA or ASTM standards. Therefore, evaluation of job site materials is required prior to and during the construction phase. Once satisfactory evaluation has been carried out the frequency of testing could be reduced. However, if the source of materials were changed re-evaluation would be required.

6.3 Evaluation under Laboratory and Field Simulations

It has been mentioned under section 5.6 that none of the technical issues discussed indicate any fundamental barrier for use of higher percentage slag replacement in concrete than the current level. However, it has been pointed out that better understanding of some of the properties is required including

that of project specific performance evaluation for HVS. The following items describe the laboratory and field evaluations to address these two issues:

6.3.1 Laboratory Evaluation

Currently available slag sources in Canada have not been fully evaluated at high percentage levels in combination with normal Portland cement. As noted earlier, currently up to 40% is used by the industry during warmer months. Therefore, the laboratory evaluation should address replacement levels of greater than 40% i.e., 50%, 60%, 70% and 85% to determine the changes in the properties for fresh and that of hardened concrete. Further, in order to provide adequate early age strength to the concrete with lower replacement levels (i.e., 35% to <50%) during colder months, evaluation for strength enhancement properties should be conducted.

Following the evaluation of materials and mix proportions for making HVS concrete, emphases should be placed on achieving increased rate of early age strength gain and acceptable later age strength for each replacement level. The possible approach would be to evaluate use of silica-fume and/or superplasticizing, accelerating admixtures. The temperature of the concrete during mixing and the ambient conditions would play an important role, and therefore should be taken into consideration. A series of trial tests would be required to obtain the optimum proportions and to determine the effect of temperature.

The evaluation of the concrete should address the following properties for each replacement level:

For fresh concrete properties: Effects on time of setting, bleeding, slump and workability, loss of slump and air content.

For hardened concrete: Effects on curing conditions (moisture, temperature etc.), compressive and flexural strengths, drying shrinkage, creep, tensile strain capacity and temperature rise to evaluate thermal cracking potential, resistance to freeze-thaw and salt scaling along with parameters of entrained air-void system, and the rate of carbonation.

6.3.2 Field Simulations

The field evaluation should be carried out on selected mixes identified under laboratory evaluation. The transfer of technology from the laboratory to the field should be initially carried out on simulated structural elements, including relatively thick and thin sections. The simulations should be carried out using ready-mix concrete. In addition to the normal quality control tests, confirmatory tests are required for time of setting, rate of slump and air content loss, admixture dosage rate and the effect on entrained-air. Also, for thick sections, temperature rise characteristics need to be monitored. Testing core samples periodically should be conducted to monitor the long-term performance and to evaluate the service life of the simulated structure. The guidelines for such evaluations are given in the reference cited /29-31/. As mentioned under section 6.4, the test data from field and laboratory are limited for concrete with Canadian slag at >50% replacement level.

6.4 Demonstration Projects

In late '70s and '80s at least thirty-two projects were listed, made with cementitious hydraulic slag from Standard Slag Cement Company, Ontario /40/. Except for one project discussed below, the test data from these projects are sketchy but appears to have been made with 25% to 50% slag replacements.

A significant structural application of 50% slag concrete that the author could review was a raft foundation slab for Belmont Development Project in York Mills Place, Toronto, built in 1982. The data provided by the Standard Slag Cement Company, show that the 1.52 meter thick, 30.4 m x 36.57 m slab

contained a total cementing materials of 330 kg/m^3 (of which 165 kg/m^3 slag cement) with water to cementing material ratio of 0.48. No superplasticizing or air-entraining admixtures were used. The objective was to provide low heat cement hydration properties. At placement, the concrete and the ambient temperatures were about 15°C and 21°C respectively. The maximum temperature recorded for the concrete at mid depth of the slab was 41°C during early stages of hydration. The temperature rise was deemed acceptable for lowering the risk of thermal cracking as required by the project specification. The concrete strength at 7 days was 26.3 MPa, while it achieved 90 days strength of 47.3 MPa.

A few other notable projects listed with significant quantities of concrete with slag cement were:

- Stelco Steel Mill at Nanticoke, Ontario, 300,000 m^3 of equivalent low heat (termed as 20S) and that of sulphate resistant (termed as 50S) cements, started in 1978 and believed to be completed in mid '80s.
- Defasco #2 Hot Mill Reheat Furnaces, Hamilton, Ontario, 40,000 m^3 of equivalent type 20S built in 1985 to 1986.
- Raw Water Reservoir and Pumping Station, Kitchener-Waterloo, Ontario, 10,000 m^3 of Type 50S. The date of construction is not given but believed to be late '80s or early '90s.

Other projects with slag replacements of up to 35% have been reported with partial success for providing protection against early age thermal cracking for large size (4 m x 4 m x 2 m thick) tower foundation bases (over 150 in numbers) for the then Ontario Hydro /11/. Also, success stories of Scotia Plaza office tower in Toronto, have been identified on the Lafarge web-site /26/ where up to 30% slag replacement was used.

Various replacement levels of slag cement for structural applications have been suggested by the Slag Cement Association's promotional CD /25/. It is noted that most of the concrete structural components could use up to 50% replacement while a few have been identified where 60% to 80% can be used. The high levels of replacement mainly deal with footings, mass concrete, and applications for low permeability, sulphate resistance and/or mitigation of alkali-aggregate reaction. The suggested replacement levels require review for applications in the demonstration projects with Canadian slag.

The selection of demonstration projects requires careful consideration in order to evaluate the short- and long-term performance of HVS. The selected projects should include concrete with various levels of strength requirements i.e., foundation slab, above ground slab exposed to the weather, structural members such as columns, beams and slabs. The concrete mixes evaluated under laboratory and field studies should form the basis for the selection of mix proportions. Guidelines should be developed for making, placing and finishing of the concrete. A detailed record should be kept for quality control tests and the properties of the concrete making materials. A suggested framework for the implementation of demonstration projects involving a team effort is given below (Section 6.5.2) under Consultation with the Industry and the Implementation team.

6.5 Commercial Issues

6.5.1 Economic and Liability Issues

Economic Issues: It is recognized that the sources of slag currently in use are mainly in central Canada. Therefore, the cost of transportation across the country would impact on the cost of construction. However, cost effective import from sources outside Canada is a possibility. The HVS use may require either higher fineness of the grind or use of specialty admixtures with or without silica fume to meet the construction requirements. Both these processes would add to the cost of concrete with the former being more sensitive to environmental impact. Mehta /36/ provided some guide to the cost escalation of 2% due to addition of superplasticizer, and to 5% if silica fume is also used. Therefore, the cost benefits obtained from using HVS would depend on the level of replacement in the concrete, amount of admixtures and the

haulage distance involved. A detailed cost analysis would be required to fully evaluate the technical and environmental impacts for specific projects. The inter-grinding of slag with cement clinker at the cement manufacturing plant is another possibility. However, the current industry practice in Canada does not support that approach. As noted in section 5.5, the flexibility of proportioning the mix to suit the specific project need is the driving force. Therefore, the economics of such significant change would require further study.

Liability issues: The construction industry is very complex involving many engineering professionals, manufacturing and process sectors, including high degree of human interaction. Therefore, liability issues are difficult to define in simple terms.

A pecuniary obligation is often attached with the liability issues involving negligence and/or improper discharge of responsibility. Any construction material and system carries a liability to the extent governed by the codes and standards. The National Building Code (NBC) of Canada provides directions for fulfilling the code requirements to minimize failure risks. The risk would be higher for materials, systems and process that are not common or being newly introduced in the industry. The code allows the use of such uncommon or new systems provided "Equivalency" is demonstrated (NBC: Section 2.5). At present, because of the insufficient field experience, the HVS could be classified as a "new material and system" for the construction industry in Canada. Therefore, an attempt has been made to highlight the responsibilities associated with the use of HVS for various sectors of the industry involved in the manufacturing, design and applications.

For slag, the manufacturing processes involve:

(a) Iron making: where quality control of iron maintains the quality of the slag produced,
(b) Granulation: monitored by measuring glass content and cementitious performance,
(c) Processing additions: to target chemical compositions prior to feeding the mill where check is made by chemical analysis of the slag, and
(d) Finally, the grinding mill operations: controlled by the feeding rates that determine the fineness etc. and shipping.

Similarly, for Portland cement a number of processing steps is involved before the final product is made and shipped for use by the industry. At each step, a quality control system is in place to verify the quality of the product.

The concrete is produced at the ready-mix plant by mixing concrete making materials (i.e., aggregates, admixtures, and water) with Portland cement and slag at required percentages and delivered to the job site. The quality of the concrete is governed by the design requirements and that of the requirements of CSA standards for concrete. The concrete is placed and finished by the construction crew following appropriate specifications and workmanship standards.

The architect/engineer's responsibility would be to make sure that all records at each step of the process (i.e., design, specifications, and construction), are transparent and traceable, including proven performance through appropriate tests and/or evaluation of the materials and systems. As required by the health and safety act, the owner should be able to determine that every precaution reasonable under the circumstances has been taken to ensure satisfactory performance of the materials and the system specified for the project. This includes inspection and following proper QC procedures. The contractor, the construction crew and the supplier of the concrete should be fully aware of the limitations and the consequences of the new approach required for the use of the HVS and take full responsibility.

The current practices within the industry appear to work well. There are no reasons to believe that the same would not apply for HVS use in concrete. From a material and performance point of view, nothing is

more important than the assurance that all parties involved in the manufacture process, design, and construction have taken appropriate measures to ensure compliance with the applicable standards and practice with full responsibilities. As discussed under section 6.1, the proposed activities of the Canadian Standard Committee on concrete to include requirements of HVS and that of suggested guidelines for applications would add to the assurance and reduce the risk factor.

The product and construction risk management, and the attached liability issues are a subject of continuous study. A good source of information is listed under reference /35/.

6.5.2 Consultation with the Industry and the Implementation Team

It will require a concerted effort to review and implement the use of high volume slag in the concrete industry. The following is a suggested framework for consultation and implementation strategy, involving formation of a technical committee, technical project team and project coordinator for specific projects.

It is anticipated that successful implementation of projects would lead to effective introduction of HVS in the industry through the efficient mechanism of generating knowledge and dissemination that already exists with EcoSmart Concrete Project with in-put from the Technical Committee where required.

(a) Technical Committee: The members of the Committee should work in an advisory capacity, provide recommendations to the EcoSmart Concrete on an on-going basis and identify potential projects where high volume slag could be used. The members should come from the various sectors of the concrete industry, including representatives from Cement Association, Slag Association, Ready-mix Concrete Association, admixture/cement/slag/steel producers, structural engineers, architects and contractors.
(b) Technical Project Team: The implementation and monitoring of any specific project should be the responsibility of a technical project team. The team members should be selected based on their expertise in specific areas. The project team should focus on the technical and environmental aspects and on developing field guidelines for specific projects. The team should provide guidance, review the work carried out by the Project Coordinator and develop a monitoring plan for in-service performance evaluation of concrete.
(c) Project Coordinator: A project coordinator should be assigned to each specific project for liaison with the structural engineers, the concrete suppliers and making sure of the proper implementation of procedure. An as-built summary report for the project specific concrete should be submitted to the Project Team for review with recommendations for future course of action as required for performance evaluation.

7.0 Scope of the Full-Scale Study

The scope of the full-scale study should cover the use of slag to the greatest extent feasible, technically and economically, backed by laboratory and field evaluation of various percentages of slag replacement. In order to achieve this, the focus should be on overcoming the challenges facing the concrete industry using higher volume of slag replacement as outlined under section 8.0.

8.0 Outline of Challenges and Recommended Approach to the Full-Scale Study

The previous sections provided a brief description of technical along with other issues, to identify and evaluate the various aspects of using HVS in the ready-mix concrete. Overall, it would appear that the use of Canadian slag in the current industrial setting faces three challenges. These are described below:

(a) To overcome the current low replacement level of slag (10% to 15%) in colder months for structural applications. The objective would be to bring it up to 50% replacement level where possible

irrespective of the season. The structural applications should include exposed or unexposed walls, columns, beams, and slabs, including pre-stressed concrete and pavements etc.

(b) To evaluate the performance with slag replacement levels >50% to 65%. These are generally recommended for foundation slabs, underground footings and walls, for low permeability, sulphate resistance and mitigation of alkali-aggregate reactivity requirements in concrete. Therefore, early-age minimum strength along with other practical properties i.e., setting time, bleeding etc., at cold temperature would be the criteria for acceptance.

(c) To evaluate the performance with slag replacement level >65% to 85%. These are generally recommended for mass concrete and underground massive foundation slabs etc. The critical issue here is the reduction of temperature rise due to heat of hydration to prevent potential for thermal cracking.

To overcome the challenges, the approach should focus on the evaluation of additives such as superplasticizing and/or accelerating admixtures and silica fume to enhance the early age strength and other relevant properties of the concrete with slag. Also, slag ground to a higher fineness than currently available would enhance the early age strength, though involving additional cost. The inter-grinding of slag with Portland cement clinker would be another approach that would requires further study as suggested under section 6.5.1. The variables should include concrete placing and curing temperature. Also, the performance of high-grade slag as per ASTM standard C 989 may be used for comparison along with the control reference concrete without slag.

Based on the above approach, a technical review is required along with developing a detailed testing and evaluation program. Appropriate laboratory testing, field evaluation and the implementation of demonstration projects as described in sections 6.3, and 6.4 should follow this.

9.0 Deliverables

The deliverables for the full-scale study should encompass the following three items:

(a) A detailed report on the full scoping study based on the suggested scope and approach given in sections 7.0 and 8.0 of this report respectively.

(b) Carry out laboratory and field simulation studies, analyze test results and provide recommendations as outlined in section 6.3.

(c) Provide technical in-put for implementation of the demonstration projects. Evaluate the performance of the concrete and produce reports with recommendations, as outlined in section 6.4.

10.0 Timeline and Budget

It is estimated that three years would be the time frame to complete item (a) and (b) as given in section 9.0. This would be followed by item (c) where the timeline would be controlled by the demonstration project requirements.

The budget for item (a) and (b) is estimated at $300K, assuming that the supplier of materials and those having stake in the project would provide many of the support services. The estimate is based on projected 40 weeks of engineering time and 25 weeks of technician time over a period of three years. The budget for the item (c) should be decided later depending on the demonstration project scope.

11.0 Available Expertise in Canada

No public organizations in Canada that are currently involved in R&D with HVS could be readily identified. Some of the project specific activities are believed to be carried out by the cement producers but test data are scarce. Technical reports have been published on recent research carried out at the Canadian universities (i.e., University of New Brunswick, University of Toronto and University of

Sherbrooke). These research studies involve evaluation of slag as supplementary cementing material to evaluate alkali-aggregate reactivity /41/, chloride diffusion studies /42/ and up to 80% slag replacement for curing conditions studies /43/.

In order to undertake a full-scale study for HVS use, a wide range of expertise would be required. Such expertise may include materials, structural and field applications aspects. The expertise could be drawn from the consulting engineering sector and the Universities.

12.0 Concluding Remarks

It would appear that it is possible to use slag replacement level in excess of the current practice of 40%, up to as much as 85% in select applications. The main barrier is the requirement for extensive evaluation and pre-testing of the currently available slag and the normal Portland cement combinations with specialty additives in order to develop and meet the project specifications. The approach given in this report for laboratory and field evaluation for high volume slag use in concrete would provide a guide for developing the full-scale study. In order to achieve the overall success, it is recommended that a team approach be considered to evaluate the various aspects of the high volume use of slag, be it material, structural, and/or field applications.

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