Transportation Association of Canada

Best Practices Guide for the Use of Recycled Materials in Transportation Infrastructure

June 2013

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Abstract

Historically, the methods that have been used for evaluating the engineering and environmental suitability of new potentially recyclable materials have varied significantly across jurisdictions. As a consequence, both an ‘applicant’ (who might be an agency, constructor or supplier) who desires to use a recycled material, and a ‘decision maker’ (owners, specifiers or designers) who must determine the suitability of the application, in many cases do not have a clear or consistent approach (an evaluation framework) that can be used to proceed with such an evaluation.

The objective of this document is to provide a guide for use by agencies in identifying the various types of recycled materials and technologies which are available to them, along with their most practical/successful uses in transportation infrastructure applications.

The focus of the document is on waste and industrial by-product materials that are suitable as replacements for natural aggregates in transportation infrastructure projects. Twenty-two materials have been evaluated and grouped into six main categories: asphalt concrete, portland cement concrete, granular base and subbase materials, embankment and fill construction, stabilized bases and flowable fills.

Keywords

Materials

- Aggregate
- Bituminous mixture
- By-product
- Concrete
- Evaluation (assessment)
- Fly ash
- In service behaviour
- In situ
- Recycling (Mater)
- Road construction
- Slag
- Tyre

Supplementary Information

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EXECUTIVE SUMMARY

The objective of this document is to provide a guide for use by agencies in identifying the various types of recycled materials and technologies which are available to them, along with their most practical/successful uses in transportation infrastructure applications.

In order to develop a comprehensive document representative of the current use of recycled materials in transportation infrastructure projects in Canada, the experiences and expertise of regional transportation stakeholders was gathered to define the current national best practices. In addition, a literature review of international recycling best practices was completed, with those relevant to Canadian practitioners included in the document. All of the information which was gathered was then synthesized into five principal sections.

Summary of Canadian Survey

An integral component of this best practices development was the survey of Canadian transportation stakeholders. The main purpose of the survey was to identify the various types of recycled materials and technologies which are being used in various jurisdictions across Canada, as well as their most practical/successful use in transportation infrastructure applications. The results of the survey have been summarized in this section along with the recycling experiences using various materials and by-products.

Recommended Framework for Evaluating the Engineering and Environmental Suitability of Recycled Materials

Historically, the methods that have been used for evaluating the engineering and environmental suitability of new potentially recyclable materials have varied significantly across jurisdictions. As a consequence, both an 'applicant' (who might be an agency, constructor or supplier) who desires to use a recycled material, and a 'decision maker' (owners, specifiers or designers) who must determine the suitability of the application, in many cases do not have a clear or consistent approach (an evaluation framework) that can be used to proceed with such an evaluation.

A recommended standardized evaluation framework is provided to assist agencies in evaluating the suitability of recycled materials. The evaluation framework is based on AASHTO PP 56-06 which is considered to be the most suitable in the Canadian context.

Recycled Materials Currently in Regular Use in Transportation Infrastructure Projects

There are a number of waste and industrial by-product materials that are currently being used successfully on a regular basis as replacements for natural aggregates across Canada. A quick reference table (Table 5) has been developed which allows users to review these successful uses, as well as determine the most appropriate application for each individual material based on Canadian experience using a green, yellow and red colour coding. Each of the materials presented in this section are then cross-referenced to the detailed material sheets provided in Appendix C.

Potential Recycled Materials Not Currently Used in Transportation Infrastructure Projects

There are also a number of waste and industrial by-product materials that not currently being used in transportation infrastructure projects across Canada but may be considered for use based on positive experience in other international jurisdictions. A quick reference table (Table 6) has also been developed which allows the user to review the potential uses as well as the experience of other jurisdictions using a green, yellow and red colour coding. Each of the materials presented in this section are then cross-referenced to the detailed material sheets provided in Appendix C.

Canadian Research and Development

This section provides an overview of recent and current Canadian Research and Development showing the activities being completed in various provinces across Canada in 2012. In addition, the regional trends in the research have been assessed and are described based on the six main applications in transportation infrastructure which have been used throughout including:

- Asphalt Concrete Pavement;
- Portland Cement Concrete Pavement;
- Granular Base and Subbase;
- Embankment or Fill;
- Stabilized Base; and
- Flowable Fill.

Appendices

Integral to this document are the detailed Recycled Material Data Sheets which are provided in Appendix C. These data sheets are formatted to provide the reader with: a description of the specific material; an analysis of how it is generated and the quantities generated; typical sources across Canada; descriptions on how it can be used in transportation infrastructure and in what quantities; typical engineering properties; toxicity or environmental impacts; and any technical limitations to using the specific material.

The focus of the document is on waste and industrial by-product materials that are suitable as replacements for natural aggregates in transportation infrastructure projects. Twenty-two materials have been evaluated and grouped into six main categories: asphalt concrete, portland cement concrete, granular base and subbase materials, embankment and fill construction, stabilized bases and flowable fills. Each material that has been evaluated has at least one possible use in these categories with some of the materials suitable for use in several of the categories as outlined in the quick reference Tables 5 and 6.

The materials which have been evaluated as part of this document, as well as those deemed potentially suitable and unsuitable, are based on current Canadian municipal and agency experience and should not be considered as conclusive as the technology and potential uses of current and potentially new waste and by-product materials continues to develop. Any materials that have been omitted in this document simply indicates that there is insufficient Canadian experience to currently permit its use based on existing processing techniques or technology, or that insufficient information is available to sufficiently evaluate the material.

1. INTRODUCTION

1.1 Background

The demand for construction aggregates for the construction of transportation infrastructure continues to grow across Canada. At the same time, the traditional natural sources for these aggregates – sand and gravel pits and stone quarries – close to market are becoming depleted and it is becoming increasingly more costly to produce and transport aggregates. The approvals process for new pits and quarries, coupled with the 'Not In My Backyard' consensus, has made it very difficult to develop new local 'close to market' sources. The use of recycled materials provides a potential alternate source of construction aggregate, while also reducing costs and promoting environmentally and resource sustainable development in our communities.

The major uses for aggregates such as stone, sand and gravel are in roadway base and subbase and as aggregates in portland cement concrete and hot-mix asphalt mixtures, with 70 to 75 percent on average of the total aggregate consumption estimated to be used in these applications across Canada. Canada has over one million kilometres of paved and unpaved roadways (CIA, 2011) and considering the approximate quantities of construction aggregate required for various common uses (Table 1), it is clear that the majority of the primary aggregates are used in the construction of this important civil/transportation infrastructure. The substitution of primary aggregates with recycled aggregates thus provides an opportunity to make a significant impact in the conservation of this critical resource.

Table 1 Approximate Quantities of Construction Aggregate Required for Various Common Uses (MNR, 2009)

COMMON USES	(TONNES)
1 km of Six-Lane Road (freeway)	51,800
Typical Highway Bridge/Overpass	33,700
Average Brick House	440
Average School	13,000
Large Office Block	16,000

Since the seventies, there has been an ever-increasing awareness in Canada and internationally for the need for sustainable development and preservation of non-renewable aggregate resources. The most significant current North American references include the FHWA *User Guidelines for Wastes and Byproduct Materials in Pavement Construction* (FHWA, 1998 which had a major update in 2008 and continues to be maintained) and *Framework for Evaluating Use of Recycled Materials in the Highway Environment* (October 2001, which was superseded by the AASHTO *Recommended Practice for Evaluating the Engineering and Environmental Suitability of Recycled Materials*, 2006), with the European state-of-the-technology described in *Recycled Materials in European Highway Environments: Uses, Technologies, and Policies* (FHWA, 2000). In conjunction with these guidelines, the use of recycled and by-product materials in transportation infrastructure construction has continued to grow, along with an increasing number of recycled and recyclable products and applications. Somewhat typical of the genesis of transportation infrastructure materials recycling across Canada, the timing for implementation of various recycling process/techniques in Ontario is outlined in Table 2. Recycling has and continues to make a significant contribution to aggregates conservation and reduced landfill disposal requirements in major Canadian metropolitan areas.

Table 2 Implementation of Various Transportation Infrastructure Technologies in Ontario (Kazmierowski, 2009B)

RECYCLING TECHNOLOGY	YEAR IMPLEMENTED
Central Plant Recycling	Late 70's
Milling, Partial Depth	Early 80's
Full Depth Reclamation	Mid 80's
Cold In-Place Recycling	1989
Hot In-Place Recycling	1990
FDR with Expanded Asphalt	2000
CIR with Expanded Asphalt	2003

Recycling had renewed international focus in the late eighties and early nineties, however this time it was not due to dramatic energy cost increases but due to the introduction of the concept of sustainability. Sustainability can be defined as "a system which creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" (EPA, 2012). The concept of sustainability originally gained prominence with the publishing of the Brundtland Commission Report in 1987. However, the widespread adoption of sustainability came when John Elkington coined the term "triple bottom line" in the late nineties.

Figure 1 Sustainability's Triple Bottom Line

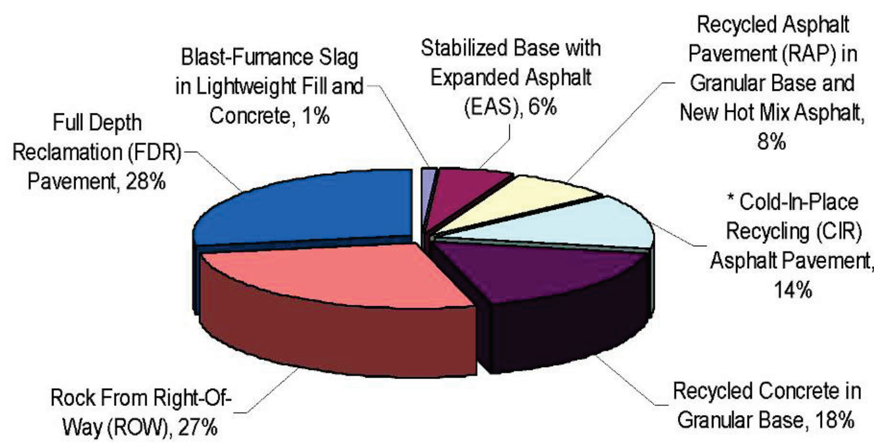
The triple bottom line describes the co-dependency of economic growth, environmental stewardship and social progress in sustainable development which is shown graphically in Figure 1. This figure illustrates that sustainability is only achieved when all three pillars of the triple bottom line are satisfied.

Today, we are faced with not only a demand by infrastructure users to promote environmental stewardship, but also face the prospect of ever increasing energy costs. As such, more and more agencies are now considering a triple bottom line approach to infrastructure development. The use of recycled and by-product materials in transportation infrastructure is the key to providing sustainable development as when materials are reused to their highest potential they not only provide cost savings, but also reduce the amount of material which is disposed of in landfills as well as reduce the amount of natural aggregates that must be mined to support infrastructure development.

Today's focus on sustainability has resulted in a significant increase in the types of recycled materials and recycling technologies used in transportation infrastructure. As an example, during the period between 2005 and 2008, about 42 million tonnes of aggregates was reportedly used on MTO contracts for primary and secondary highway and related transportation infrastructure construction, of which 8.3 million tonnes (20 percent) consisted of recycled materials (Kazmierowski, 2009A); the various recycled aggregate types considered, along with the prevalence of their use, are shown in Figure 2. In Ontario, this implementation represents an increase from an estimated 3 percent in 1990 (JEGEL, 1995). If this rate of recycled aggregate used were extrapolated to both municipalities and agencies across Canada, this would represent over 53 million tonnes of recycled aggregate used annually.

Unfortunately, this general extrapolation does not fully capture the actual volumes of recycled aggregate that are currently being used across Canada. While many of the provincial agencies have progressive waste policies and specifications that allow for the use of recycled and by-product materials in construction, these agencies are only responsible for a fraction (approximately 10 percent) of the paved and unpaved roadways in each province. While many municipalities adopt provincial specifications for the construction of their roads, it has been speculated (ECO, 2006) that most lower-tier municipalities only permit a small portion of recycled materials to be used due largely to lack of experienced recycling contractors and in-house technical expertise.

Figure 2 Distribution of Recycled Aggregates Use in Ontario (2005 to 2008) (Kazmierowski, 2009A)



Total Tonnage: 8.3 million

* Includes Cold-In-Place Recycling with Expanded Asphalt Mix (CIREAM)

Another consideration is the under-reporting by some jurisdictions of the amount of reuse/ recycling of excess materials on the jobsite. While not considered recycling by some, the reuse of excess materials across Canada accounts for the conservation of very large quantities of virgin aggregates. As an example, the joint Ontario Ministry of Transportation (MTO) and Ontario Ministry of the Environment ‘wasteless highway’ initiative in the early nineties resulted in a framework for the evaluation and use of potentially excess materials to enable highway design and construction personnel to reuse and recycle materials generated during road construction and maintenance projects (JEGEL, 1995). As a result of this initiative, the reuse and recycling of excess materials on the jobsite as well as existing pavement granular base and subbase materials, either as granular subbase or subgrade fill material, is a standard, ongoing excess materials management activity that is generally not captured by agencies and municipalities when determining the quantities of recycled aggregates used on an annual basis. In addition, efforts are taken to ensure that materials such as topsoil and unsuitable subsoils are used on site in landscaping and non-structural applications rather than disposing in landfill.

Many jurisdictions have developed their own guidelines and specifications for the use of recycled materials; however, despite the continuing evolution in specifications, material processing methods, quality control practices and design, many agencies and municipalities continue to prohibit or restrict the use of some recycled materials, largely due to lack of experience or an unfavourable past experience.

As clearly demonstrated by the foregoing comments, the development of a comprehensive Best Practices Guide is important to assist Canadian practitioners in the selection and implementation of the most appropriate and sustainable use of recycled materials in transportation infrastructure, all while reducing costs, energy consumption and the emission of greenhouse gases which are all vitally important in today's transportation infrastructure development environment.

1.2 Objectives

The overall objective is to provide a document for use by agencies in identifying the various types of recycled materials and technologies which are available to them, along with their most practical/successful uses in transportation infrastructure applications. In addition, the use of various recycling technologies is studied in terms of the effect on climate change, green construction practices, sustainability and economic/environmental considerations.

The specific project objectives are to:

- Identify recycled materials currently used in transportation infrastructure projects;
- Determine which recycled materials can be technically and economically used in transportation infrastructure projects in various Canadian jurisdictions;
- Evaluate the amounts of recycled materials which can be practically incorporated into various infrastructure applications;
- Identify environmental concerns for recycled materials used in transportation infrastructure projects; and
- Identify current and future sources of recyclable materials.

1.3 Approach, Methodology and Organization

At the outset of the project, a list of potential interview candidates was developed from agencies and municipalities who were considered to be familiar with the technical and practical aspects of the current state of recycling in their locals. The list of potential interview candidates was developed from contacts in municipalities, provincial and federal transportation agencies, industry and international technical organizations to report on aggregate recycling processes and methodologies in other jurisdictions and to determine research activities currently underway to promote increased use of recycled materials. This included all Canadian provinces as well as experts from international technical committees of the World Road Association (PIARC), and the Organization for Economic Cooperation and Development (OECD).

Prior to conducting interviews with prospective candidates, a concise set of interview questions was developed which was reviewed and approved by the Project Steering Committee. The interview questions addressed the specific experience of each agency/organization with respect to various uses of recycled materials experience and technologies. The questions also addressed current research/innovation in the field, evaluated factors which encourage or discourage recycled material use, along with exploring other technical, economic and environmental factors. A copy of the interview questions is provided in Appendix D.

Prospective candidates were contacted and briefed on the scope and objectives of the project in order to determine if they were the most suitable representative from their organization to complete the survey. In cases where the participant was not available to complete the survey within the survey timeline, another respondent within the specific agency was identified and contacted to complete the survey. All of the prospective candidates were given the option to complete the survey on paper or electronically, or alternately, via phone interview or in person.

To assist respondents in properly completing the survey, candidates were provided with a Questionnaire Primer. The intent of the Primer was to provide more background information on the types of information that were being sought for the survey, along with common descriptions and definitions to assist the candidates in identifying specific recycled materials use within their jurisdictions. A copy of the questionnaire primer is also provided in Appendix D.

A comprehensive review of the technical literature, as well as a jurisdictional scan of existing legislation/regulations/policy and technical standards pertaining to the use of recycled materials in transportation infrastructure projects was also completed. This included comprehensive searches of national and international pavement and transportation information databases in order to develop an indexed project-specific database of the most current relevant reuse and recycled materials references.

The information from the survey, jurisdictional scans and literature review were compiled by geographical area and by key attributes. This information was then synthesized into five sections as follows and detailed in subsequent sections of the Best Practice report.

- **Summary of Canadian Survey** A detailed analysis of results of the information gathered during the survey is provided. The information was compiled by geographical area and in regard to key attributes such as: climate (temperature, precipitation); municipality size (large or small); environmental considerations (regulations, for instance); and characteristics of use (where recycled products can be used, percentages incorporated, potential impacts (positive and negative) on engineering properties, and future recyclability).
- **Recommended Framework for Evaluating the Engineering and Environmental Suitability of Recycled Materials** A summary of the AASHTO Recommended Practice PP 56-06 which was developed to provide a clear and consistent approach to determine the suitability of using various potential recycled materials by various agencies. The associated appendix provides the Framework in detail including standardized checklists which are helpful in the evaluation.
- **Recycled Materials Currently in Regular Use in Transportation Infrastructure Projects** There are a number of waste and industrial by-product materials that are currently being used successfully on a regular basis as replacements for natural aggregates across Canada. A quick reference table has been developed which allows users to review these successful uses, as well as determine the most appropriate application for each individual material based on Canadian experience using a green, yellow and red colour coding. Detailed material sheets have been provided in Appendix C and have been developed in such a way that they can be printed out individually for convenient use by potential users.
- **Potential Recycled Materials Not Currently Used in Transportation Infrastructure Projects** There are also a number of waste and industrial by-product materials that not currently being used in transportation infrastructure projects across Canada but have a potential for use based on positive experience in other international jurisdictions following a proper evaluation. A quick reference table

(Table 6) has also been developed which allows the user to review the potential uses as well as the experience of other jurisdictions using a green, yellow and red colour coding. Similar to the previous section, a summarized description of their uses has been provided with detailed material sheets provided in Appendix C.

- **Canadian Research and Development** This section outlines current Canadian research activities as well as provides areas of potential research.

2. SUMMARY OF CANADIAN SURVEY

An integral component of this best practices development was the survey of Canadian transportation stakeholders. The main purpose of the survey was to identify the various types of recycled materials and technologies which are being used in various jurisdictions across Canada as well as their most practical/successful use in transportation infrastructure applications.

In order to determine the current recycling practices in transportation infrastructure projects across Canada, four general categories were identified as important areas of interest for the purpose of this study. The categories included information on the types of materials which are currently being recycled, positive and negative experiences with the use of various recycled materials along with typical associated costs for their use, an examination of policies and specifications which were found to promote recycling in various jurisdictions and current research and development promoting the recycling of materials in transportation infrastructure.

To help clarify the questions and to provide more information on the context of the survey, a Questionnaire Primer was provided along with the Survey. The Primer mirrored the Survey and provided definitions of the various recyclable materials along with their typical uses. The Primer was intended to facilitate the completion of the Survey as well as improve and standardize the quality of the responses.

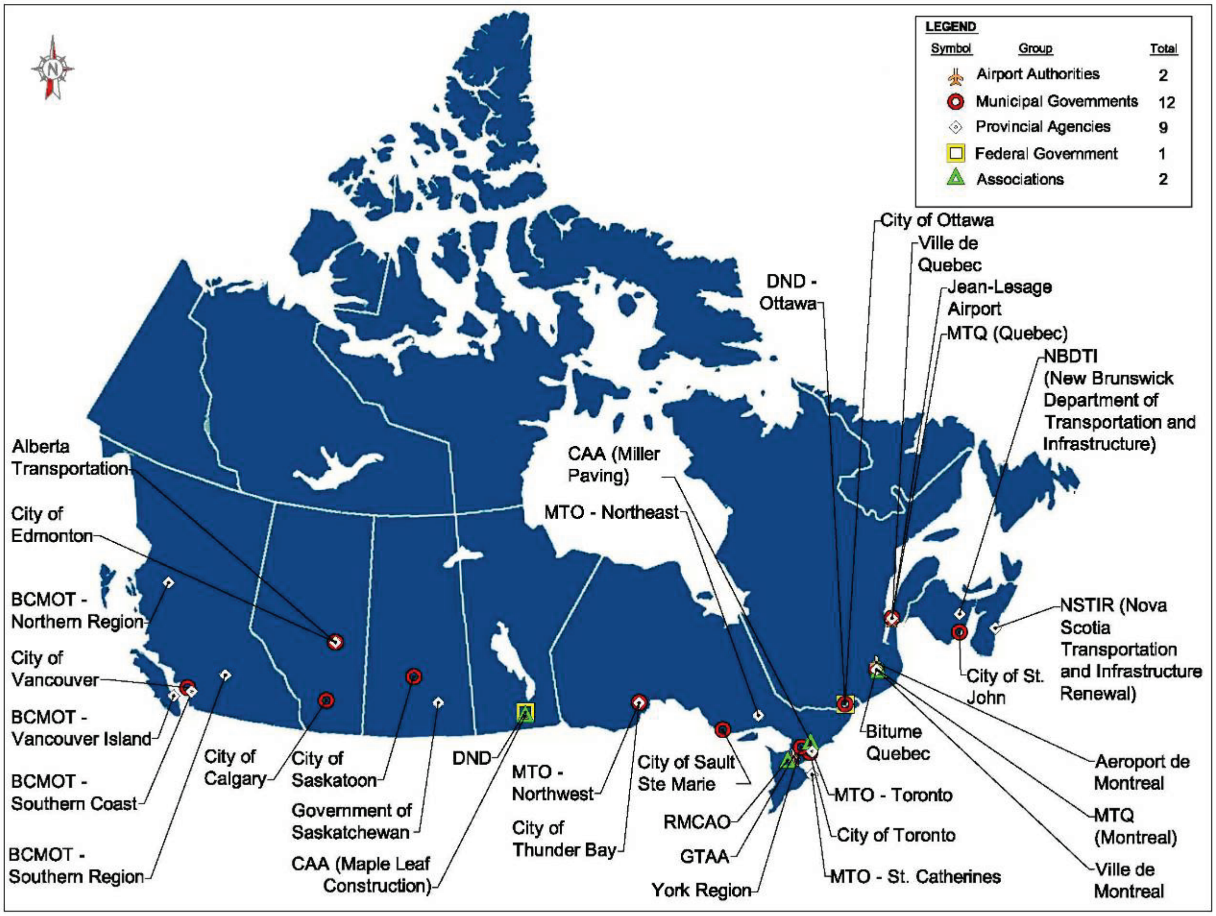
The Survey was sufficiently concise (16 questions) that it could be readily completed by the candidate but allow the flexibility to augment the question responses with as much additional/detailed information as was readily available. The survey response was excellent with 25 respondents out of the 40 candidates which were initially contacted, representing a diverse cross-section of transportation infrastructure stakeholders including airport authorities, industry associations, Federal Government departments, Municipal Governments and Provincial Agencies from regions across Canada. The grouping of the respondents provided in Table 3 with the geographical distribution of respondents is shown in Figure 3.

Table 3 Distribution of Survey Respondents

GROUP	MAP SYMBOL	TOTAL
Provincial Agencies	Diamond	9
Municipal Governments	Circle	11
Airport Authorities	Airplane	2
Federal Government	Square	1
Industry Associations	Triangle	2

The survey questionnaire has been provided for reference in Appendix D along with a detailed analysis of the responses in matrix format. The survey responses are summarized and discussed in the following sections.

Figure 3 Geographical Distribution of Survey Respondents



2.1 Types of Materials Currently Being Recycled

In order to evaluate the types of materials which are currently being recycled in transportation infrastructure projects across Canada, the survey questions were divided based on three major recycling categories: in-situ recycling; materials being recycled in bulk applications and materials being recycled in cementitious applications.

2.1.1 In-Situ Recycling

In the context of transportation infrastructure, in-situ recycling techniques are almost uniquely associated with the recycling of existing pavement structure materials (asphalt concrete, portland cement concrete and road base and subbase materials) as bulk construction aggregate in some form of roadway and/or airport (service roadway, taxiway, runway or apron) rehabilitation or reconstruction. The processes which are typically employed across Canada and which were evaluated in the survey included: Cold In-Place Recycling (with emulsion or equivalent); Hot In-Place Recycling; Full Depth Reclamation with (Foamed) Expanded

Asphalt; Partial Depth Recycling with Expanded Asphalt; In Place Pulverization/Reprocessing; and Rubblization of Portland Cement Concrete Pavements.

Over the past 30 years, the use of in-situ recycling techniques has increased dramatically across Canada as a means to maintain the current infrastructure during periods of decreasing operating budgets. The survey results indicated that nearly all respondents (92 percent) have used one form or another of in-place recycling in 2010 representing about 13 million m^2 of road and/or runway/taxiway rehabilitation work. If this is extrapolated for all locations across Canada, this would translate into approximately 42 million m^2 of recycled pavement. The only respondents who indicated that they did not use any form of in-place recycling in 2010 were the Department of National Defence, Greater Toronto Airports Authority and the City of Vancouver, who tend to favour processes where materials were recycled at a central plant location.

The most frequently used in-situ recycling techniques in 2010 were cold in-place recycling, full depth reclamation with expanded asphalt, partial depth reclamation with expanded asphalt and in-situ pulverization/reprocessing which was used by approximately 40 to 60 percent of survey respondents and accounted for 11 of the 13 million m^2 of road and/or airport in-situ recycling in 2010. These in-situ recycling techniques were generally used across Canada except for in British Columbia which primarily completed hot in-place recycling over other in-situ recycling techniques and in Saskatchewan, where it was reported that despite efforts to complete full depth recycling with foamed asphalt, there was little interest by contractors to accept this option.

Nineteen percent of the survey respondents indicated the use of either hot in-place recycling and/or rubblization of portland cement concrete. The main issues inhibiting more frequent use of these processes included the lack of suitable equipment owned by local contractors and, in the case of rubblization, the absence of portland cement concrete pavements.

2.1.2 Materials Being Recycled in Bulk Applications

There are a number of residual or by-product materials that have been used in bulk aggregate related uses as substitutes for natural aggregates. Twenty-two potentially recyclable residual or by-product materials were identified and provided in the survey to determine the current usage across Canada as well as an option to identify other materials that may have not been included in the survey. Out of the 22 potentially recyclable residual or by-product materials, thirteen materials were identified as being regularly or occasionally used by the various survey respondents. The remaining nine materials were identified as being used only on a trial basis; their use having been restricted due to past performance issues or have not previously been considered for use. One material – silica fume – was identified by survey respondents as a material that was being used on a trial basis but not included in the list.

The majority of respondents (96 percent) either regularly or occasionally use reclaimed asphalt pavement (RAP) or reclaimed concrete material (RCM) products in their transportation infrastructure, indicating that the use of these materials is well established in most areas across Canada. The applications where these materials are permitted however, was observed to vary in the survey response. RAP material, for instance, is not permitted in new hot-mix asphalt by the Department of National Defence, but it may be used as a granular base or subbase material for pavements. The Ready Mix Concrete Association of Ontario (RMCAO) indicated that while there are provisions for up to 10 percent of RCM usage in new portland cement concrete mixes, that its use as an alternative concrete aggregate is not extensive.

A moderate number of respondents (40 to 65 percent) either regularly or occasionally use or have ongoing trials for the use of roofing shingle scraps or tear-offs and scrap tires as bulk construction aggregates in various products. The survey results indicate that the use of these materials is generally still in the trial process throughout Canada with the exception being the Saskatchewan Department of Highways which indicated the regular use of scrap tires for the past six years. However, Bitume Québec and the MTQ indicated that scrap tires have been used in trials in the Province in the past which were deemed unsuccessful.

Nationally, there is an infrequent use (16 to 28 percent) of blast furnace slag, coal fly ash, quarry by-products, waste glass and waste ceramics as bulk construction aggregates. Blast furnace slag, coal fly ash and quarry by-products were generally indicated as being in regular or occasional use with waste glass and waste ceramics generally classified as trial products with the exception of in Ontario where their use is permitted in Provincial Specifications.

There is a limited use of nonferrous slags (Ontario, granular materials), steel slag (Saskatchewan and Quebec) and Wood (New Brunswick and Quebec). It should be noted that the use of steel slag and wood has been restricted in Ontario due to performance issues with previous use.

Construction and demolition wastes are not generally used in transportation infrastructure construction with the exception of the City of Saskatoon which is reported that it is using these materials on a trail basis. It is likely however that the use of construction and demolition wastes such as RCM are not being well documented as aggregate processing operators typically do not source separate RCM delivered from transportation infrastructure operations from construction and demolition projects and hence these materials typically end up commingled in the same material processing stockpiles. Alternately, it is possible that agencies specifically only recycle portland cement concrete materials from existing transportation infrastructure projects due to concerns with potential contamination of concrete by potentially deleterious C&D wastes (drywall for instance) that which can contribute to poor performance when used in bound and unbound applications. However, facilities such as the City of Edmonton's Construction and Demolition Waste Recycling Facility have the capability of processing and sorting loads of mixed C&D wastes into their constituent materials. The potential success of these types of facilities will improve the quality of RCM from C&D projects and will be quite positive in terms of increased reuse and recycling of these materials.

One third (32 percent) of survey respondents reported the recycling of baghouse fines (asphalt plant dust). This reuse of baghouse fines across Canada is likely higher than that reported by the survey respondents as the recovery and reuse of baghouse fines is a standard process for hot-mix asphalt plants that employ fabric filter baghouse emission control systems.

2.1.3 Materials Used as Substitutes in Cementitious Applications

In addition to recycled materials used in bulk applications, there are a number of residual or by-product materials that may be used as substitutes in cementitious applications. Seven potentially recyclable residual or by-product materials were identified and provided in the survey to determine the current usage across Canada.

The survey indicated that 40 percent of respondents use crumb rubber in hot-mix asphalt mixtures (RMA). It should be noted that this excludes Department of National Defence facilities and the three major airport authorities (Jean-Lesage, GTAA and Aeroport de Montréal), all of which indicated that RMA is not used in their infrastructure. In British Columbia, crumb rubber is not used over concerns that it inhibits future hot in-place recycling, with the crumb rubber potentially 'gumming up' the milling teeth of the recycling unit. The City of Québec (in the 1990's) as well as Alberta Transportation (2002 to 2008) conducted trials of hot-mix asphalt with crumb rubber with poor performance which has resulted in this material not being used in these jurisdictions. In Ontario, trials using dry process crumb rubber were completed between 1980 and 1995. The results of the monitoring of these pavement sections indicated that 75 percent of the trial sections had a service life of 10 years or less, which is lower than the expected service life of conventional pavements (MERO, 2009). The predominant pavement distresses that were observed in these pavement sections were moderate to severe ravelling, rutting, cracking and potholes.

Blast furnace slag (slag cement) and roofing shingles were also reportedly used by 28 percent of the survey respondents. The use of blast furnace slag is well established in central and eastern Canada, however its use is not as prevalent in the rest of Canada. The use of roofing shingles (mainly manufactured shingle modifier) is also well established with it currently being used in provinces and municipalities across Canada.

There is very little documented use by survey respondents of granulated copper/nickel slag, sulphur, cement kiln dust and lime kiln dust across Canada. This is likely due to a lack of availability in many jurisdictions and high transportation costs. these materials are not covered in the Canadian cement standard, CSA A 3000. In addition, due to changes in the manufacturing process and disposal cost considerations, materials such as lime kiln dust and cement kiln dusts are being diverted back into their respective processing streams for reuse rather than disposal.

The use of sulphur in hot-mix asphalt mixtures has been restricted in British Columbia due to the fumes created when an asphalt pavement is hot in-place recycled and associated worker complaints. Research on the use of sulphur in hot-mix asphalt indicates that hydrogen sulphide can be created when there is prolonged exposure to both sulphur and bitumen at elevated temperatures, however this can be mitigated by the use of sulphur pellets incorporating hydrogen scavengers which limit the creation of hydrogen sulphide (SEAM, 2008). Low level exposure to hydrogen sulphide exceeding permissible exposure limits can result in irritation of the nose and throat, headache, dizziness, nausea, and nervousness (MSDS, 1995).

Aside from the processing and handling challenges, there were health and safety concerns which arose from the prolonged exposure of the sulphur to the bitumen at elevated temperatures. The bitumen can function as a hydrogen donor leading to hydrogen sulphide generation.

Whilst odour and vapour emissions from the hot paving mixtures during road construction were in compliance with legislated health standards, they were a regular source of worker complaints. In the late 1990s, the development began of solid sulphur pellets, which could be readily added to asphalt paving mixtures, eliminating the expense and hazards associated with hot, liquid sulphur use and significantly decreasing the fumes and odours emanating from the paving mixture. This is primarily due to the fact that the pellet is added to the HMA rather than the binder, thus ensuring that the sulphur is exposed for only a relatively short time to the hot bitumen. Fume mitigation is further enhanced by the incorporation of a hydrogen scavenger in the sulphur pellets. These modified sulphur pellets have been marketed as SEAM TM Asphalt Mix Modifier. However, when using hot in-place recycling techniques, or recycled hot-mix asphalt mixtures which contains either SEAM or sulphur modified asphalt mixes, the sulphur can again be exposed to prolonged heating, and the same health and safety issues can occur. The potential for reducing future recyclability should be taken into consideration when determining the suitability of using sulphur in hot-mix asphalt mixes.

2.2 Experiences and Economics

2.2.1 Consideration of Recycling During the Design Process

When considering various recycling options during design, the two most important aspects indicated by respondents are potential cost savings (92 percent) and social/environmental considerations (84 percent) such as ‘going green’. This is not surprising given the fact that the environment and our impact on it is a very prevalent 'hot' topic in current conversation. However, given that most agencies are dealing with increasingly large transportation infrastructure networks with more conservative budgets, an agency may find it difficult to 'go green' if it means spending scarce funds.

It was interesting to note that 42 percent of respondents indicated that various recycling options are considered due to superior material properties and/or performance. While some recycling projects are considered by some agencies to simply be waste diversion (linear landfills), there are many agencies that have had positive recycling experiences which have provided a net benefit to their transportation infrastructure. As an example, the experience in Nova Scotia, Quebec, Ontario and Alberta has shown that full depth reclamation with expanded asphalt allows the agency to improve the strength of underlying materials so that a full depth rehabilitation can be completed to accommodate increased traffic loading without increasing the existing grades (in some cases reducing the overlay requirements). This results in a rehabilitated pavement structure with the service life of a reconstructed pavement at less than half of the cost.

Eight percent of the respondents indicated that recycled materials are considered due to a lack of suitable virgin aggregate. One example of this is in Saskatchewan, where premium construction aggregate is limited and the supply of electric arc furnace steel slag from a source which is near to a major urban area provides needed premium construction aggregate.

Sixteen percent of respondents indicated that there is legislation or regulations in their district which makes the use of recycled materials more favourable while 20 percent or respondents indicated that there are regulatory barriers such as leachate quality and air emission quality that discourage their agencies from using more recycled materials in transportation infrastructure projects.

2.2.2 Example Cost Savings

Cost savings are a major impetus for the use of recycled material in transportation infrastructure. The experience of the survey respondents is outlined in Table 4.

Table 4 Example Cost Savings for Various Recycled Materials

RECYCLED MATERIAL	EXAMPLE COST SAVINGS
Crushed Concrete as Granular Material[1]	30 to 50%
Hot In-Place Recycling	40%
RAP in Hot-Mix Asphalt	10% (15% RAP Addition) \$2 - \$8 per tonne of HMA 20% (40% RAP Addition in Binder Course)
Full Depth Reclamation with Foamed Asphalt	1/3 the Cost of Reconstruction
Shingles in Hot-Mix Asphalt	\$4 per tonne of HMA

1) Reported by all four Airport Authority Respondents

2.2.3 How Appropriate Recycling Materials and Technologies are Determined

There are many factors to consider when determining whether to use a specific recycled material or recycling technology. Some of the factors that agencies consider based on the survey results are:

- Not all technologies and materials may be available in rural areas which may limit options;
- Quantity and availability of materials and recycling technologies;
- Impact to workers' health and safety;
- Time increases or savings for a particular material or process;
- Staff or Consultant experience administering and supervising construction;
- A particular material can be recycled without additional cost or deleterious effects;
- Field trials and performance data is available either in a jurisdiction, from another similar jurisdiction or from trusted sources (TAC or CTAA, for instance);
- Discussion with industry representatives to see what materials and technologies are available and which may be considered for trial construction;
- Availability of existing technical standards or guidelines; and
- Trial projects are identified based on technologies promoted by local contractors.

2.2.4 Issues That Discourage Recycled Material Use

The two main issues that survey respondents indicated that discourage agencies from using more recycled materials in transportation infrastructure projects are materials or processes that increase costs (68 percent) or have a reduced performance (64 percent). As both of these factors can equate to an increased cost, if taken together it is a concern of nearly 85 percent of respondents. Again, this should be expected given that while most agencies would like to 'go green' (previously 85 percent of respondents indicated this was an impetus for their agency), agencies may not be able to consider green practices if it means consuming a greater amount of already scarce operating funds.

Another important factor preventing further recycled material use is either a lack of experience and/or equipment by local contractors (52 percent) and a lack of confidence (experience) by agencies due to either to a lack of technical literature or performance data on various processes. While there has been a steady, ever-increasing use of recycled and by-product material in transportation infrastructure construction over the past 30 years, the equipment, experience (both contractor and agency) and technical literature (standards, and performance data) has only been growing regionally. This highlights the importance of associations like CTAA, CUPGA, ARRA, CAC, OHMPA, PCA and TAC to continue to provide recycling information and promote technology transfer to all regions across Canada.

It is understandable that some recycled or by-product materials may not be available in some jurisdictions as the primary by-product manufacturers (slag producing industries, for instance) may not be in the region and the cost to transport these materials would be prohibitive. This is likely why 32 percent of respondents indicated that the supply of material prohibited its use. This is however not always the case. In some jurisdictions, the supply of material is not available due to the by-product material being diverted to another, sometimes more practical use such as foundry sand use in the manufacture of cement. In other cases, the by-product material may be diverted to another process simply because of an established use, not necessarily the best use such as scrap tires being used as a fuel by cement producers. Regardless, a stable supply of the recycled or by-product material is crucial when making a decision to invest millions of dollars on capital purchases of recycling equipment.

Another issue that can discourage the use of certain recycling processes is the amount of time required to complete the process (such as the 14-day curing period required for cold in-place recycling with emulsion). In locations such as an airport runway or a busy roadway/ intersection, if the recycling process takes more time than the traditional process (mill and overlay, for instance), then recycling could be considered to be not feasible.

In some jurisdictions, regulatory barriers to the use of certain recycled or by-product material may discourage, or in some cases prevent, the use of excess or by-product materials in transportation infrastructure projects. It can be quite complicated to obtain the necessary approvals and permits to use a certain recycled or by-product material and this can result in time/schedule delays for the completion of the project as well as associated additional costs when compared to natural aggregates. Consequently, it is important that proponents ensure that they have a strong understanding of local regulations and requirements prior to proposing the use of a particular excess or by-product material during construction to ensure that the appropriate regulations are followed.

2.3 Policies That Promote Recycling

The majority of respondents indicated that they did not currently have a formal policy requiring the recycling of excess or by-product material except for the MTO (Strategic Direction #4), MTQ (Volume I: 10 on Sustainable Development), with the City of Edmonton, GTAA and Aéroport de Montréal having Environmental Management Systems in accordance with ISO 14001 as shown in Figure 4. The City of Calgary (Concrete and RAP) and Nova Scotia Department of Transportation (RAP) have material specific recycling policies.

Figure 4 Example Canadian Agency Policies that Promote Recycling

The opinion of the survey respondents was divided on how to encourage the increased use of recycled materials during construction. One group indicated that the use of recycled and by-product materials in place of virgin aggregates should be market driven based on the potential for cost savings to the project. The other group felt that in order to stimulate the capital purchases and training required to start using more recycled material in their construction projects, some form of recycling policy or incentive was required.

Some of the policy or incentive ideas suggested by the survey respondents (listed in order of frequency of response) are listed below:

- Directly state in a policy or contract documents that certain materials must come from recycled or by-product sources;
- Public recognition system such as: LEED; or MTO Green Pave Initiative;
- Increase tipping fees for materials that are considered to be recyclable;
- Provincial or Federal regulation identifying ‘limited source materials’ (gravels, asphalt and concrete, for instance) which must be recycled if possible; and
- Incentives in the bidding process.

3. RECOMMENDED FRAMEWORK FOR EVALUATING THE ENGINEERING AND ENVIRONMENTAL SUITABILITY OF RECYCLED MATERIALS

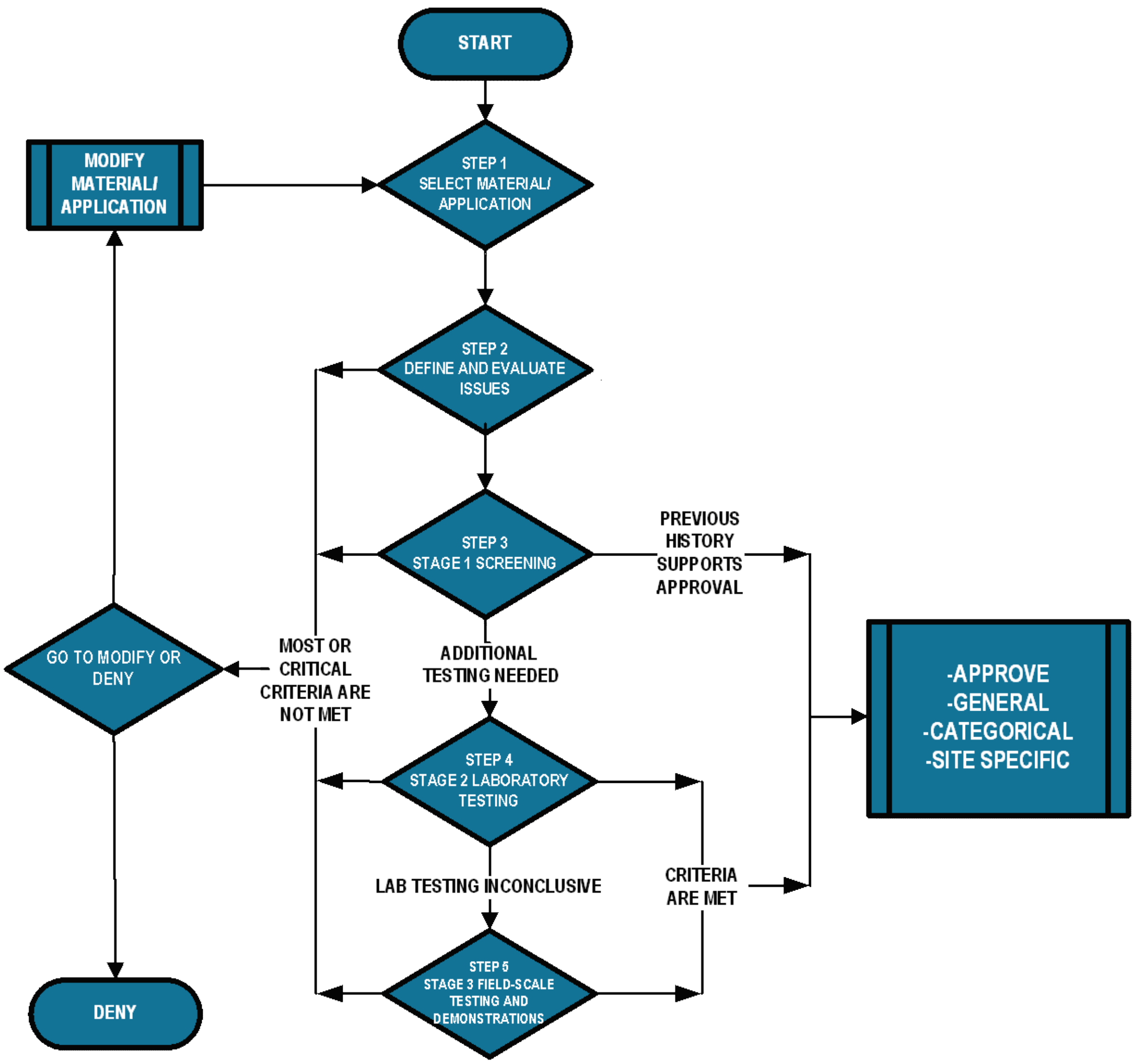
There are a number of well-documented 'success stories' for established uses of recycled materials in transportation infrastructure projects including most notably reclaimed asphalt pavement (RAP) and reclaimed concrete material (RCM) which are currently being used across Canada. However, historically, the methods that have been used for evaluating the engineering and environmental suitability of such materials have varied significantly in each jurisdiction. As a consequence, both an 'applicant' (who might be an agency, constructor or supplier) who desires to use a recycled material, and a 'decision maker' (owners, specifiers or designers) who must determine the suitability of the application, in many cases do not have a clear or consistent approach (an evaluation framework) that can be used to proceed with such an evaluation.

The evaluation framework described in detail in AASHTO Designation: PP 56-06 *Recommended Practice for Evaluating the Engineering and Environmental Suitability of Recycled Materials* (reference) was developed from the FHWA *Framework for Evaluating Use of Recycled Materials in the Highway Environment* (FHWA, 2008). The framework is generally described below, and for the purposes of this particular study, is considered to be the most suitable in the Canadian context.

3.1 Summary of the Framework

The evaluation framework is illustrated in a flowchart format presented in Figure 5. There are five steps in the framework as outlined below.

Figure 5 Implementation of Various Transportation Infrastructure Technologies (Adapted from FHWA, 2008)



Step 1 – Select Recycled Material and Application

The first step in the process is to select a recycled material and an application (use of RAP in hot-mix asphalt, for instance) and complete a standardized application process which is then forwarded to the appropriate evaluator or decision maker. In many cases the evaluator or decision maker(s) will be the provincial transportation and/or environmental agencies.

Step 2 – Define and Evaluate Issues
The second step is to collect all relevant engineering and environmental information to the decision-making process. This includes all related historical data, engineering and recycled material property data, environmental, health and safety data, implementation limitations, construction and processing issues, and costs.

The purpose of this step is to determine if there are any issues that may warrant more detailed examination and more specifically any issues that may prohibit approval of the recycled material for use. Checklists to ensure that the proper information is collected for such an evaluation are described in detail in the AASHTO *Recommended Practice for Evaluating the Engineering and Environmental Suitability of Recycled Materials* and these checklists have been adapted/modified to reflect the Canadian context and are provided in Appendix E.

Step 3 – Stage 1 Screening Evaluation
The purpose of the Stage 1 screening is to determine whether the recycled material in question can be approved (or rejected) based on previous history of use or positive experience in another jurisdiction. A Stage 1 approval means that sufficient information to justify acceptance of the proposed material and application has been provided for the proposed recycled material and application. The applicant will typically be required to demonstrate that the proposed recycled material is sufficiently similar to reference materials (similar specifications or material requirements in other jurisdictions, for instance) to warrant approval.

A Stage 1 screen should include an assessment of all existing data including:

- engineering data;
- environmental health and safety data;
- known recycling issues and concerns;
- implementation concerns;
- political issues;
- economic issues; and
- regulatory issues.

A series of screening checklists, evaluation procedures, and evaluation criteria for this type of evaluation are described in the AASHTO *Recommended Practice for Evaluating the Engineering and Environmental Suitability of Recycled Materials* and have been modified/adapted to reflect the Canadian context and are provided in Appendix E.

Step 4 – Stage 2 Laboratory Evaluation
A Stage 2 laboratory evaluation is recommended if the Stage 1 review determines that existing information is insufficient to either accept or reject the proposed recycled material use. The Stage 2 laboratory evaluation is intended to characterize the engineering and materials properties as well as the environmental, health, and safety properties of the proposed recycled material and its ultimate product.

To undertake a Stage 2 laboratory evaluation, it is recommended that:

- a test plan be prepared that delineates the samples to be tested and the tests to which the sample will be subjected;
- acceptable specifications or performance criteria be identified that can be used as a means for evaluating the results of the test plan; and

- the data be statistically evaluated to determine if specifications are met or if performance is similar to appropriate reference materials.

The most critical steps in a Stage 2 evaluation are the development of the test plan and establishment of performance criteria. The AASHTO Recommended Practice provides a description of engineering and environmental parameters that will typically be of interest to decision makers when evaluating the use of proposed recycled materials in specific applications and provides detailed lists of applicable laboratory test methods that can be used in the evaluation. The detailed lists have been modified/adapted to reflect the Canadian context and provided in the Appendix E.

Step 5 – Stage 3 Field Scale Testing and Trial Sections
If the decision maker is not able to either accept or reject a material after review of the results from both Stage 1 and Stage 2 evaluations, then Stage 3 field testing and trial sections may be warranted. Stage 3 is intended to provide field-scale data on engineering and material properties as well as environmental, health, and safety properties of the proposed recycled material and its ultimate product. The results of the field testing are typically compared with established performance criteria or with reference materials (control section, for instance).

To undertake a Stage 3 evaluation, it is recommended that:

- a demonstration test plan be prepared that delineates the field monitoring requirements;
- acceptable specifications or performance criteria are identified to evaluate results of the field demonstration; and
- the data be statistically evaluated to determine if specifications are met or if performance is similar to that of appropriate reference materials.

3.2 Evaluation and Approval

The approval process, depicted in the lower right-hand inset in Figure 5, is an integral part of the recommended evaluation framework. As shown in the Figure, approval can occur during any of the three Stages of the evaluation process. Approval or rejection is dependent on the performance of the recycled material in the proposed application compared with appropriate engineering criteria and specifications of reference materials.

3.3 Economic Analysis

The decision on when or when not to use a potential recycled material will in most cases depend on the cost of using the recycled material compared with the cost of using a conventional material. Notwithstanding its technical suitability, the cost of using a recycled material must generally be competitive with that of a conventional material or there will be resistance to using it.

There are three costs that are of interest when evaluating the cost of using a recovered material in transportation infrastructure applications:

- The cost of the material.
- The cost of installation when using the material.
- The life-cycle cost of the application when using the material.

Each of the above costs could be relevant when examining the potential cost-benefits of using a recycled material. When evaluating the cost of the material and the cost of installation, the decision maker must take into account the fact that the cost of the material and installation may change once the material has been approved and in regular use. For instance, the cost of the material may increase if it is a waste which then becomes a salable product, while the cost of the installation may decrease once contractors are more familiar with incorporating the product during construction or more local suppliers emerge reducing transportation distance. The specific situations where material, installation, and life-cycle costs would be relevant, and the components or elements that are needed to estimate these costs, are presented in the following sections.

Not included in the above analysis are 'soft' costs – for instance, the savings that may result from diverting an excess or waste material from landfill/disposal, energy savings, and societal benefits of 'green' construction.

3.3.1 Cost of Material

Once a recycled material is introduced into the marketplace it will have a cost or price that a prospective user would pay to have the material delivered to site. The purchaser of the material could be a public agency, contractor, or material supplier. The seller would normally be the recycled material generator or producer. If the recycled material is equivalent to a conventional material in expected design, construction, and performance, then the cost of material may be of primary interest when comparing the cost of using a recycled material with a conventional material. The cost (delivered price) of a waste or by-product can be calculated as follows:

$$D_P = P_{RM} + C_{PR} + C_{ST} + C_{LD} + C_{TR} + P \qquad \text{(Eq.1)}$$

where,

- D_P = Delivered price,
- P_{RM} = Price of the raw material (F.O.B.),
- C_{PR} = Cost of processing the material,
- C_{ST} = Cost of stockpiling the material,
- C_{LD} = Cost of loading the material,
- C_{TR} = Cost of transporting the material, and
- P = Profit.

3.3.2 Cost of Installation

A prospective user may be more interested in the total cost of installation than simply the delivered price of the material. This would be the case when the cost of design, construction, and testing or inspection when using the recycled material differs from the cost of these items when using a conventional material. The cost of installation includes the delivered material price (DP), as well as the additional elements, outlined below.

The cost of installation when using a recovered material can be calculated as follows:

$$C_{IP} = C_{DR} + D_P + C_C + C_{TI} \qquad \text{(Eq. 2)}$$

where,

- C_{IP} = Cost of installation of proposed material,
- C_{DR} = Cost for design of application with the recovered material,
- C_C = Cost for construction with the recovered material, and
- C_{TI} = Cost of testing and inspection for the proposed application.

3.3.3 Life-Cycle Cost

The cost of the material itself and the cost of installation provide a prospective user with a comparative analysis of the cost of using a recycled material versus a conventional material. However, if the introduction of a recycled material alters the maintenance requirements or expected service life of the application, then a life-cycle cost analysis should be completed to provide an assessment of the cost of using the recovered material over a typical design life versus that of a conventional material.

The life-cycle cost of a recovered material application can be calculated using a variety of economic approaches. The approach recommended in this Best Practices Guide is based on the calculation of an annual effective cost resulting from the proposed application. This annual cost can be calculated using the following equation:

$A_{CP} = C_{IP} \times CRF(i,n) + C_{AM}$ .... (Eq. 3)

where,

- A_{CP} = Annual life-cycle cost using proposed material,
- CRF(i,n) = The capital recovery factor with an interest rate of i percent and a product life of n years, and
- C_{AM} = Cost of Annual Maintenance.

To compare the life-cycle costs, the two applications must be compared over an equivalent period of time. A comprehensive analysis may require the introduction of infrastructure rehabilitation or new installation costs to achieve a suitable comparative analysis over equivalent time periods.

In many cases, due to the lack of long-term historical data regarding the expected service life and maintenance requirements associated with the use of recycled materials in transportation infrastructure projects, life-cycle cost estimates are typically difficult to complete.

3.4 Framework Limitations

The guidelines presented in the AASHTO Recommended Practice attempts to provide an overall comprehensive evaluation framework that decision makers in various jurisdictions can use in evaluating recycled materials use in various transportation infrastructure applications. The complexity associated with defining evaluation procedures and criteria demands that the evaluator select the best test methods and criteria subject to local conditions, and that the criteria and test methods be continually updated as new information is made available.

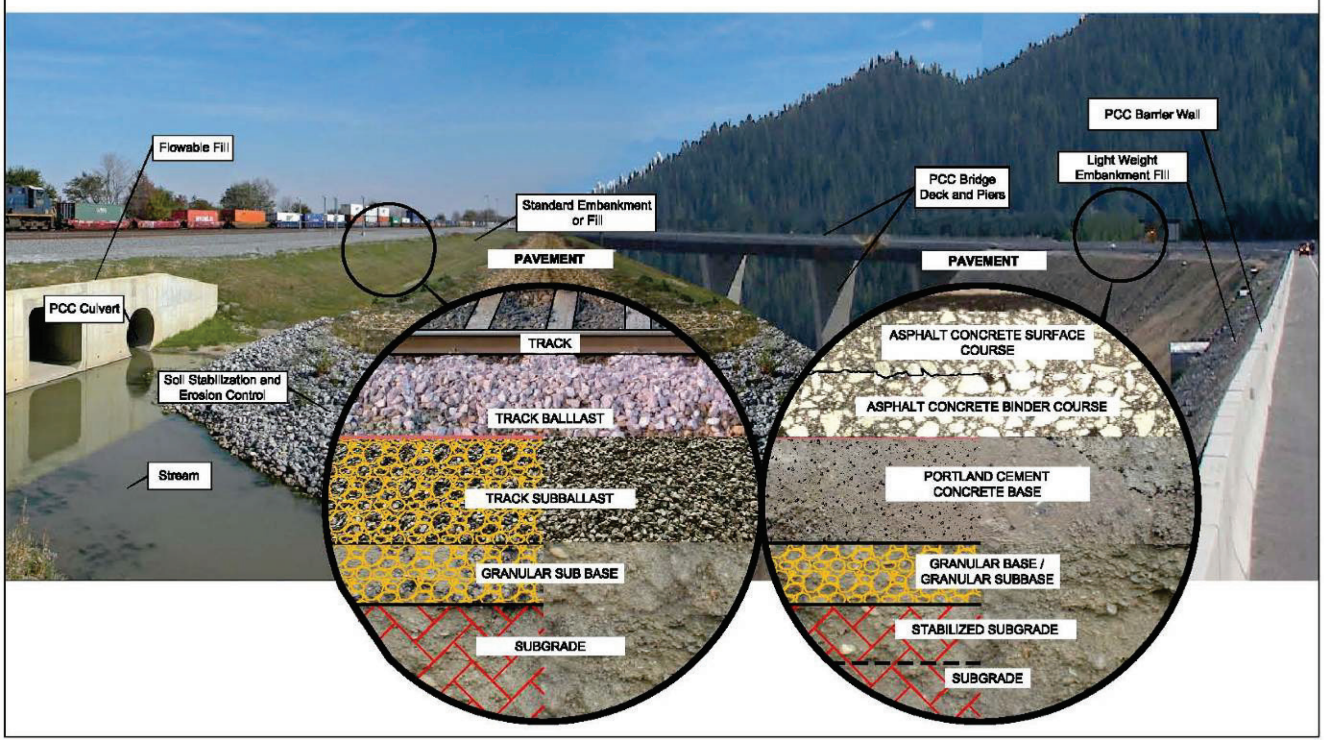
The multidisciplinary engineering and environmental effort involved in implementing the steps outlined in the AASHTO framework requires that engineering and environmental agencies in each jurisdiction forge cooperative efforts, pooling the necessary resources to undertake the necessary evaluation effort. Only through such cooperative efforts can these complex issues receive proper attention, ensuring the appropriate use of recycled materials in the transportation infrastructure environment.

4. RECYCLED MATERIALS CURRENTLY IN REGULAR USE IN TRANSPORTATION INFRASTRUCTURE PROJECTS

Waste and industrial by-product materials have been used as replacements for natural aggregates in a number of different applications. However, their use in transportation infrastructure projects can be grouped into six main bulk materials categories: asphalt concrete, portland cement concrete, granular base and subbase materials, embankment and fill construction, stabilized bases and flowable fills.

A general overview of each of these six categories has been prepared to describe how natural aggregate materials are used and provide an indication of where waste and by-product materials may be incorporated. In addition, a graphical representation of the various relevant components in transportation infrastructure is provided in Figure 6.

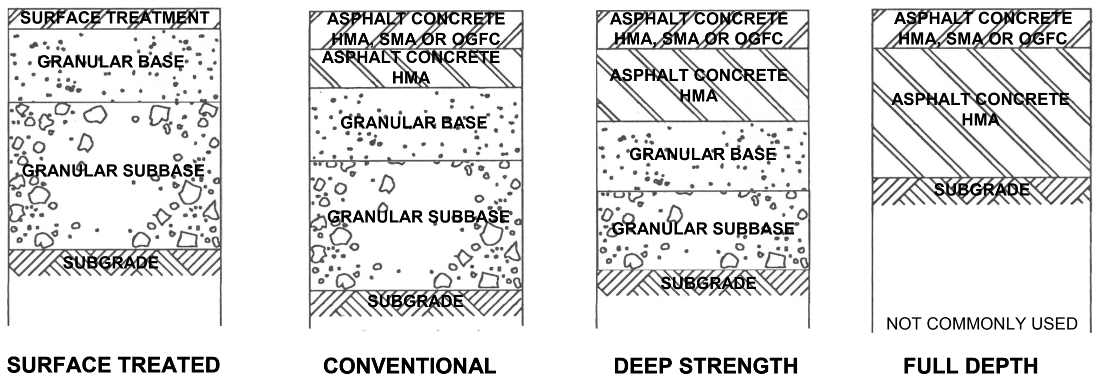
Figure 6 Various Transportation Infrastructure Components



Asphalt Concrete Pavement

Flexible pavements, also know as asphalt concrete pavements, typically consist of a combination of hot or cold mix asphalt concrete surface and binder course layers over either stabilized or unstabilized granular base and subbase layers. For low volume rural roads, bituminous surface treatments are often used to provide a waterproof barrier at the surface of the pavement as well as to bind the aggregate particles together for dust control and to reduce granular base erosion. The thickness of the various components depends on the quality of the subgrade and the quality of the materials used in the pavement structure and will vary depending on the structural requirements to support the design traffic loading. Asphalt concrete is typically composed of a mix of aggregate (92 – 96 percent), asphalt cement (4 to 7 percent) and mineral filler (1 to 2 percent, where required). The typical flexible pavement types are illustrated in Figure 7.

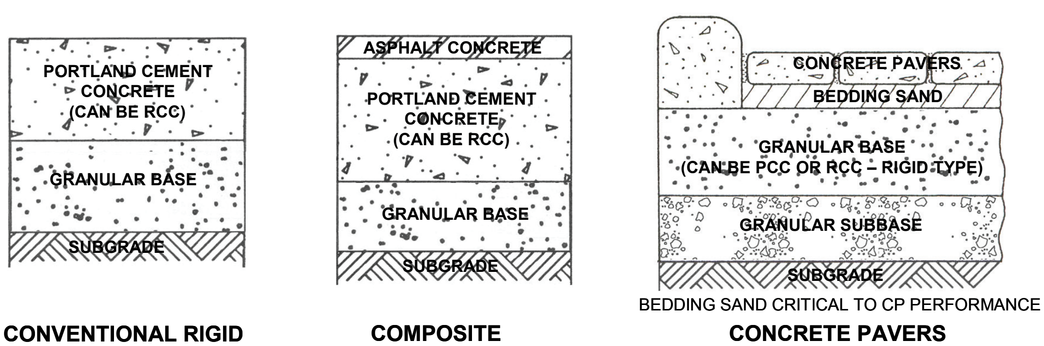
Figure 7 Typical Flexible Pavement Types



Portland Cement Concrete Pavement

Portland cement concrete pavements typically consist of an unreinforced, dowelled or continuously reinforced portland cement concrete layer (such as jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP)) overlying a granular base and/or subbase layers (or in some cases placed directly over subgrade). In some cases, the PCC layer may be overlain by either asphalt concrete (composite pavement) or interlocking concrete pavers. The thickness of the various components depends on the quality of the subgrade and the quality of the materials used in the pavement structure and will vary depending on the structural requirements to support the design traffic loading. Portland cement concrete pavements are typically composed of about aggregate (85 to 90 percent by volume of the mix) and portland cement paste (10 to 15 percent by volume). The typical rigid pavement types are illustrated in Figure 8.

Figure 8 Typical Rigid Pavement Types



Granular Base and Subbase

Aggregate materials are used in pavement structures in order to distribute the load applied by traffic to the subgrade, as well as to provide drainage and frost protection for the pavement structure. Granular base materials typically contain higher amounts of crushed stone, are densely graded and the amount of dust (material passing the 75 µm sieve) is controlled to ensure proper drainage. Granular subbase materials are generally not as well graded as granular base materials and will contain coarser particles, however the amount of dust is also controlled to ensure proper drainage. While some agencies specify granular subbase materials with high crushed stone content (Ontario Granular B Type II that is 100 percent quarried bedrock, for instance) for high performance pavements (to reduce structural rutting), granular subbase specifications typically allow the use of sand and gravel materials which may not have a crushed particles requirement. Granular base and subbase use in pavement structures is illustrated in Figures 7 and 8.

Embankment or Fill

An embankment typically refers to a volume of material that is constructed for the purpose of raising the grade of a roadway (or railway). A fill refers to a volume of material that is constructed in order to backfill a natural or man-made hole or depression. Embankments and fills are constructed of a variety of materials (most often what is locally available) including soil, granular materials including excess base and subbase materials or rock which are generally required to be placed at a maximum of 2H:1V side slopes depending on the angle of repose of the embankment material (some rock fills can be as steep as 1.25H:1V).

Graded embankment designs typically use coarser materials near the bottom or base in order to facilitate drainage and prevent saturation. The top portion of an embankment is usually constructed of higher-quality, well-compacted material to meet the design requirements of the overlying pavement layers. The remainder of the embankment is constructed with fill material which meets applicable specification quality requirements. Typical embankment and fills are illustrated in Figure 6.

Stabilized Base

The term ‘stabilized base’ refers to a blend of aggregate (either granular base or subbase) which is bound using cementitious materials (such as portland cement, lime, asphalt cement or emulsion) and is capable of being compacted using standard construction compaction equipment and which may increase in strength over time.

This process is used to enhance the properties of the granular base or subbase material in order for these layers to be able to support increased traffic loadings while reducing the load which is transferred to the underlying subgrade. Stabilized base and subbase materials are routinely used for both flexible and rigid pavements.

Flowable Fill

Flowable fill refers to a self compacting mixture of fine aggregate or filler, water, and cementitious material(s), which is used as a backfill in lieu of compacted granular materials or soil. The benefits of flowable fill mixtures are that they are capable of filling all voids in irregular excavations and hard to reach places (such as under and around pipes), they are self-levelling, and they harden to a strength greater than typical granular materials within a few hours of construction without the need for supplemental compaction. Flowable fill is also known in other jurisdictions to as unshrinkable fill, controlled low strength material (CLSM), controlled density fill (CDF), and lean concrete slurry.

A common use for flowable fill materials is in the restoration of utility trenches below pavement structures where the low strength allows it to be re-excavated if needed and it has the ability to flow into areas of the pavement that may have been undermined during excavation. These mixes are typically off-loaded directly into the utility trench from a conventional ready-mix concrete truck, can be placed in one lift from the bottom of the trench to just below the pavement structure and they do not require compaction resulting in a very rapid restoration. Flowable fill has also been used to fill abandoned buried culverts and chambers in lieu of removal and restoration.

4.1 Materials Currently in Regular Use

Twenty-two potentially recyclable residual or by-product materials were identified and reviewed to determine the state of the practice for these materials across Canada. After completing a survey of key Canadian stakeholders, 13 of the 22 materials were identified as being regularly or occasionally used in various jurisdictions across Canada.

An in-depth study was completed on each of the thirteen residual or by-product materials in order to determine the Canadian and international best practices for each of these materials. The information that was gathered was used to develop detailed material sheets that were organized to provide the users with important information such as:

- A general description of the material;
- How it is generated and in what quantities;
- Typical sources of the material;
- Description of how the material can be used;
- Engineering properties of the material;
- Toxicity or environmental concerns with its use; and
- Technical limitations to its use.

The detailed material sheets were developed in such a way that they can be printed out individually for convenient use by potential users. The detailed material sheets for each material are provided in Appendix C.

In addition to the detailed material sheets, a quick reference table has been developed in order to quickly determine which materials may be appropriate for their project based on current best practices. The quick reference table is presented in Table 5 and provides a list of the thirteen residual or by-product materials that are currently being regularly or occasionally used in various jurisdictions across Canada. The most appropriate application for each individual material is indicated using a green, yellow and red colour coding as follows:

- A green highlight indicates that the application is currently technically and environmentally acceptable for use as replacement for natural aggregate.
- A yellow highlight indicates that the application has a potential for use but there are currently some technical, environmental or economic factors that must be considered.
- A red highlight indicates that the application has previously been trialed or had some potential for use but significant technical, environmental or economic factors preclude its current use.

Table 5 Recycled Materials Currently in Regular Use across Canada that are Suitable as Replacement for Natural Aggregates in Transportation Infrastructure Applications

Recycled or By-product Material	Asphalt Concrete Pavement	Portland Cement Concrete Pavement	Granular Base and Subbase	Embankment or Fill	Stabilized Base	Flowable Fill	
Baghouse Fines	green						C-1
Blast Furnace Slag	green	green	red	yellow			C-2
Coal Fly Ash	green	green		yellow	green	green	C-4
Nonferrous Slag	yellow		yellow	yellow			C-11
Quarry By-products	green	green				green	C-12
Reclaimed Asphalt Pavement	green		green	yellow	green		C-13
Reclaimed Concrete Material	yellow	green	green	green			C-14
Roofing Shingle Waste	green		green				C-15
Scrap Tires	green	yellow		yellow	green		C-16
Silica Fume		green					C-18
Steel Slag	yellow		yellow				C-19
Waste Glass and Ceramics	yellow	yellow	green				C-21
Wood Waste				green			C-22

5. POTENTIAL RECYCLED MATERIALS NOT CURRENTLY USED IN TRANSPORTATION INFRASTRUCTURE PROJECTS

In addition to the thirteen materials that are currently in regular or occasional use in various jurisdictions across Canada, there were also nine materials that were either under evaluation at the time of this study, their use having been restricted due to past performance issues or had shown potential for reuse in other international jurisdictions.

As with the materials in Section 4, a quick reference table has also been developed for these potentially recyclable materials in order to allow Guide users to quickly determine which materials may be appropriate for their project based on current best practices. The quick reference table is presented in Table 6 uses the same green, yellow and red colour coding as used previously as follows:

- A green highlight indicates that the application is currently technically and environmentally acceptable for use as replacement for natural aggregate.
- A yellow highlight indicates that the application has a potential for use but there are currently some technical, environmental or economic factors that must be considered.
- A red highlight indicates that the application has previously been trialed or had some potential for use but significant technical, environmental or economic factors preclude its current use.

Table 6 Potential Recycled Materials Not Currently Used in Transportation Infrastructure Applications

Recycled or By-product Material	Asphalt Concrete Pavement	Portland Cement Concrete Pavement	Granular Base and Subbase	Embankment or Fill	Stabilized Base	Flowable Fill	Related Appendix
Coal Bottom Ash/Boiler Slag			yellow	yellow			C-3
Construction and Demolition Debris	yellow	yellow	yellow	yellow			C-5
Flue Gas Desulphurization Scrubber Material						green	C-6
Foundry Sand	red	green		red	red	red	C-7
Kiln Dusts	green				yellow		C-8
Mineral Processing Wastes	yellow	yellow	yellow	yellow	yellow	yellow	C-9
Municipal Solid Waste Combustor Ash	yellow		yellow				C-10
Sewage Sludge Ash	yellow						C-17
Sulfate Wastes			yellow	yellow	yellow		C-20

6. CANADIAN RESEARCH AND DEVELOPMENT

The number of recycled and by-product materials as well as the quantities that can be used in transportation infrastructure construction is increasing every year due to ongoing, improvements and new technologies which are developed through research and development. Canadian agencies, universities and associations have been world leaders in the development and improvement of these technologies often collaborating in research, field trial and performance assessment.

In this section, an overview of recent and current Canadian Research and Development will be presented showing the activities being completed in various provinces across Canada.

Alberta Transportation
(Transportation Department, 780-427-2731)
Sulphur in Hot-Mix Asphalt (Completed in June 2011)

- Evaluation Due to Contract Change Initiated by Contractor.
- Trial completed on Highway 659 east of the town of Bonnyville.
- The use of a sulphur asphalt mixture (Shell Oil process known as Thiopave) in place of the specified asphalt concrete mixture.
- Sulphur odours and irritation has been an issue in the past with sulphur in asphalt mixes. However, Shell claims to have made improvements in this regard by adding an organic Warm Mix Asphalt (WMA) additive to lower the mixing temperature to below 140°C therefore reducing resulting odours.
- No major issues were reported with the odours with the lower mix temperatures however they were still noticeable. No difference in pavement performance was observed between the Thiopave and regular asphalt concrete pavement placed on the project.
- Longer term performance monitoring to take place in the future.

City of Calgary
(Transportation Department, 403-268-2846)
Rubber in Use of Rubber Asphalt (Completed)

- Developed 6 successful rubber asphalt projects
- 58,000 recycled tires were used and 22,300 tonnes of Rubber Asphalt were produced.
- Overall, all projects exhibit good performance under heavy traffic.
- Does not appear to maintain long-term noise reduction qualities.
- Does not appear to stop all reflective cracking.

City of Calgary
(Transportation Department, 403-268-2846)
Full Depth Reclamation (FDR) (Completed)

- Completed on Hwy 22X between 37 Street and 85 Street SW.
- The Hwy 22X Full Depth Reclamation/Foamed Asphalt Stabilization project was the first of its kind for the City of Calgary.
- Specific Components that were researched were the performance of FDR base.
- The section was successful, in 6 years of service, no repairs have been necessary.

City of Edmonton
(Transportation Services, 780-496-4245)
Full Depth Reclamation/Stabilization using foamed bitumen (Completed between 2001 and 2002)

- Construction of a demonstration project using foamed bitumen in the full depth reclamation of three locations in the City of Edmonton.
- Full depth reclamation utilizing foamed bitumen as a stabilizer used on the project sites resulted in dramatic increase in the structural strength of the roadway section.
- The stabilized material resulted in a smooth hard and relatively durable surface suitable for temporary detour traffic.
- Ongoing deflection and performance monitoring of the sites will provide an opportunity to determine any increase or decrease in the overall strength of the pavement structure and the contributing strength of the stabilized layer as well as help access the long-term performance of the stabilized material.
- Results Published in CTAA Proceedings 2003.

City of Edmonton
(Transportation Services, 780-496-4245)
Cold-in-Place Asphalt Recycling (Ongoing)

- One project constructed using Cold-in-Place recycling technologies.
- Have not as yet completed the evaluation and as such nothing can be submitted about this project at this time.

City of Edmonton
(Transportation Services, 780-496-4245)
Effects of Recycled Shingles in Hot Mix Asphalt (Ongoing)

- Currently working on a study of the effects of recycled shingles in hot mix asphalt.
- Have not as yet completed the evaluation and as such nothing can be submitted about this project at this time.

Government of Saskatchewan
(Highways and Infrastructure, 306-787-4888)
Experience with Rubber Asphalt in Southern Saskatchewan (Various research projects completed between 2005 and 2010)

- Research emphasized the importance of density and volumetrics for rubber asphalt concrete paving and demonstrated that the rubber asphalt concrete is even more sensitive to those factors than conventional asphalt concrete.
- The use of rubber asphalt provided the opportunity to reduce the design thickness by about 30%. This was proven to be beneficial in areas with limited access to quality aggregate.
- Some projects had poor performance due to low density and high air voids.
- Final results of various projects published in CTAA proceedings from 2007-2011.

Government of Saskatchewan
(Highways and Infrastructure, 306-787-4888)
Cold-In-Place Recycling (No current research underway)

- Historically, a number of small limited trials were undertaken, some of which may not fit the definition of Cold-In-Place recycling.

Government of Saskatchewan
(Highways and Infrastructure, 306-787-4888)
Third Generation Hot-in-Place Recycling (HIR) Technology (Project is planned to commence in 2012)

- No trials have been conduced yet.
- One project may be undertaken in 2012 using HIR.
- A consultant has been commissioned to monitor the project from an emissions and environmental aspects perspective.

City of Toronto
(Contact information not available)
Use of Waste Glass and Ceramics as Construction Aggregate (pilot projects completed in 2003 and 2004)

- Pilot study project using waste glass blended with 50 mm minus crushed concrete for use as granular subbase for road construction. Second pilot project using waste ceramic material in crushed concrete granular base.
- No construction or performance related issues were observed due to the use of these recycled roadway bases.
- Evaluation is ongoing.

Greater Toronto Airport Authority
(Restoration and Development of Facilities, 416-776-3394)
Use of Warm Mix Asphalt on Groundside Facilities (Construction to begin in May 2012)

- Sasobit additive to be used in the warm mix as well as RAP (percentage unknown at this time).

Ministry of Transportation of Ontario
(Materials Engineering and Research Office, 416-235-3733)
Tire Derived Aggregate (TDA) – Recycled Engineered Material for MTO Highway Embankment Construction (Ongoing)

- Used TDA as a recycled engineered material to construct highway embankments at Boundary Road crossing Highway 401 in Cornwall, Ontario.
- Evaluation is ongoing.

Determining Quantity of Recycled Asphalt Cement in Hot Mix Asphalt (Ongoing)

- Study being conducted by the University of Waterloo CPATT on the use of recycled asphalt cement in hot-mix asphalt mixtures.
- Funding jointly provided by the MTO and OHMPA.
- Evaluation is ongoing.

Best Practices Guide for Recycling Ground Rubber Tire into HMA, Interlayers and Chip Seals (Ongoing)

- Study being conducted by Dr. Gary Hicks from California State University in Chico.
- Study being assisted by the University of Waterloo CPATT and Queens University.
- Funding provided by OTS.
- Evaluation is ongoing.

Evaluation of Rubber Modified Asphalt Mixes Paved in Ontario Trial Sections (Ongoing)

- Study being conducted by the University of Waterloo CPATT on the performance of trial sections which were constructed using rubber modified asphalt mixes.
- Funding jointly provided by the OTS and MTO.
- Evaluation is ongoing.

Effect of Warm Mix Additives on Asphalt Cement and Asphalt Mixture Quality (Ongoing)

- Study being conducted by Queens University.
- Funding jointly provided by the MTO, OTS and Asphalt Cement/Warm Mix Suppliers.
- Evaluation is ongoing.

New Brunswick Department of Transportation and Infrastructure
(Research and Design)
Recycled Tires as Lightweight Fill (Completed in 2008)

- Tire Derived Aggregate (TDA) is a beneficial material that can be used as lightweight fill for highway embankment projects constructed on weak clays.
- Use of TDA in this project resulted in significant cost savings to the Department of Transportation.
- This project studied the impact of lower unit weight fills (using tire derived aggregate) on embankments.
- Construction using TDA for Stage 1 went according to plan. The TDA was relatively easy to load, transport, place and compact using traditional earthmoving equipment. The use of trailers equipped with "floating" floors was very advantageous.
- Results of the geotechnical instrumentation for Stage 1 have shown that the in-place TDA is lightweight (TDA Unit Weight = 7.9 kN/m3) with internal TDA temperatures within acceptable and predicted limits.

Halifax Regional Municipality
(Research, 902-490-6872)
Tire Derived Aggregate (TDA) Embankment Project in Ragged Lake, Nova Scotia (Ongoing)

- Design was completed in 2011, construction is planned for 2012. The research/evaluation component will be completed during the construction phase of the project in summer/fall 2012.
- The design involved a city bus access ramp embankment using TDA. The project will utilize approximately 800,000 scrap tires generated in the province in Nova Scotia. This project will be the first TDA transportation project in NS.
- The information collected from the field is expected to add to the local TDA performance database for embankment construction.

7. CLOSING REMARKS

Canadian leadership in reuse and recycling of excess construction materials such as RAP and RCM, and waste/by-product materials such as slags, is well established, as represented by participation in OECD, FHWA and other international initiatives dating back to the Seventies. Emphasis on the “triple bottom line” at the design stage to match physically and environmentally suitable recycled materials with appropriate applications that promote sustainability, both in terms of non-renewable natural resources and management of excess or waste materials, has the ability to both influence infrastructure construction, maintenance and rehabilitation practices and satisfy performance and life-cycle cost objectives.

As the use of recycled materials is such an integral component of sustainable transportation infrastructure, there is considerable, ongoing Canadian and international research and development of various recycled and by-product materials and processes. Consequently, while this document has been developed to present the current state-of-the-technology at the time of its publication, it should be considered to be a ‘living document’ that should be regularly reviewed and updated periodically to reflect changes in materials, availability, processing technology and innovations. Additionally, the development of this document has demonstrated the need for a central Canadian ‘repository’ of information on and specifications for the use of recycled materials in transportation infrastructure projects that can be readily accessed by agencies and practitioners.

APPENDIX A

DEFINITIONS, ACRONYMS AND TECHNICAL TERMS

A1. DEFINITION OF TERMS

The definitions are mainly based on AASHTO, USEPA and TRB standards and practices that provide a fuller range of terms and notes on use.

acceptance sampling and testing – sampling, testing, and the assessment of test results done to determine whether or not the quality of produced material or construction is acceptable in terms of the specifications.

accuracy – the degree to which a measurement, or the mean of a distribution of measurements, tends to coincide with the true population mean.

asphalt binder – an asphalt-based cement that is produced from petroleum residue either with or without the addition of organic modifiers.

asphalt modifier – any organic material of suitable manufacture, used in either new or recycled condition, which is dissolved, dispersed or reacted in asphalt cement to enhance its performance.

base – the layer or layers of material placed on a subbase or subgrade to support a surface course.

bias – an error, constant in direction, common to each of a set of values, which cannot be eliminated by any process of averaging – an error, constant in direction, that causes a measurement, or the mean of a distribution of measurements, to be offset from the true population mean.

cement kiln dust – cement kiln dust (CKD) is the fine-grained, solid, highly alkaline waste removed from cement kiln exhaust gas by air pollution control devices.

coke – coke is the most important raw material fed into the blast furnace in terms of its effect on blast furnace operation and hot metal quality. The coke-making process involves carbonization of coal to high temperatures (1100°C) in an oxygen deficient atmosphere in order to concentrate the carbon.

cold recycling (cold asphalt pavement recycling) – full or partial depth reuse of old asphalt concrete pavement (can be used for surface treatment, and can include treated and untreated base) that is either processed in-place (by cold in-place recycling train or full-depth in-place asphalt pavement reprocessing method, CIR) or at a central plant, typically with the addition of emulsified asphalt (or other additive such as cutback asphalt, lime or cement) and sometimes new aggregate to achieve desired cold mix quality, followed by placement and compaction.

construction and demolition wastes – construction and demolition (C&D) materials consist of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D materials often contain bulky, heavy materials, such as concrete, wood, metals, glass, and salvaged building components.

control limits (upper, lower) (also called action limits) – boundaries established by statistical analysis for material production control using the control chart technique. When values of the material characteristics fall within these limits, the process is “under control.” When values fall outside the limits, there is an indication that some assignable cause is present causing the process to be “out of control”.

controlled process (also called process under statistical control) – a production process in which the mean and variability of a series of tests on the product remain stable, with the variability due to chance only.

crumb rubber – recovered from scrap tires or from the tire retreading process. It is used in road construction and in a number of athletic and recreational applications.

deleterious effect – harmful effect to health.

deleterious materials – undesirable contaminants, such as soft shale, coal, wood, or mica, which are found in a blended aggregate.

dolomitic – when the rock contains 30 to 45 percent magnesium carbonate, it is referred to as dolomite, or dolomitic limestone.

flowable fill – flowable fill mixtures are usually comprised of combinations of cement, water, fine aggregate, and fly ash or slag.

foamed asphalt – a mixture of undried, cold RAP and/or aggregate that is bound together by mixing it with a foamed asphalt binder formed by injecting a metered amount of cold water into a stream of hot asphalt binder in a mixing unit.

foundry sand – foundry sand is the term given to high quality silica sand which is used in foundries to aid in the ferrous (iron and steel) and nonferrous (copper, aluminum, brass and bronze) metal casting and moulding process.

full depth reclamation (FDR) – full thickness of existing asphalt concrete is processed and recycled, usually by mixing/blending with underlying granular base/subbase or subgrade – full depth reclamation may also include stabilization using foamed asphalt, cement or lime.

greenhouse gases – gases that trap heat in the atmosphere are often called greenhouse gases.

hot in-place recycling (HIR) – hot reworking of the surface of an aged asphalt pavement (typically 50 – 75 mm) using preheaters and a heat reforming machine, typically with the addition of a rejuvenator, aggregate or new hot mix (HMA) to restore the condition of the scarified old asphalt pavement, and sometimes with an integral surface course overlay, all suitably placed and compacted in a single or multi-pass process.

landfill – means a waste management facility at which waste is disposed of by placing it on or in land, but does not include a land treatment facility, a surface impoundment pond, a salt cavern or a disposal well.

LEED – Leadership in Energy and Environmental Design (LEED) consists of a suite of rating systems for the design, construction and operation of high performance green buildings, homes and neighborhoods.

lift – when placing and compacting soils, aggregates and hot-mix asphalt, a lift is any single, continuous layer of material that receives the same compactive effort throughout during a single work operation.

lightweight fill – lightweight fill materials such as geofoam, foamed concrete, expanded clays and shales etc. Lightweight fill materials are used to limit settlement and increase stability through the use of materials with lower densities than conventional fill materials.

lime kiln dust – lime kiln dust (LKD) is the fine-grained, solid, highly alkaline waste removed from lime kiln exhaust gas by emission control devices.

long-life asphalt – an asphalt pavement designed and constructed to last longer than 50 years without requiring rehabilitation, and needing only periodic surface renewal (termed “perpetual pavement” by the APA).

lower tier municipalities – when there is another level of municipal government like a county or region involved in providing services to residents. Counties have fewer responsibilities than regions, as the lower-tier municipalities within the counties typically provide the majority of municipal services to their residents.

material – any substances specified or necessary to satisfactorily complete the contract work.

maximum (aggregate) size – a sieve size which is one size larger than the nominal maximum size.

milling – removing the surface of an asphalt concrete pavement, using a traveling machine equipped with a transverse rotating cutter drum (milling head with tips), typically 25 to 75 mm in depth.

nominal (aggregate) size – a sieve size which is one size larger than the first sieve to retain more than 10 percent of the aggregate.

nonferrous slag – A by-product of smelting ore such as copper, nickel, and phosphorus slags that is suitable for use as a granular base, generally exceed specifications for embankment and fill construction.

pavement distress – external indicators of pavement deterioration caused by loading, environmental factors, construction deficiencies, or a combination thereof – typical distresses are cracks, rutting, and weathering of the pavement surface.

pavement performance – the history of pavement condition indicators over time or with increasing axle load applications.

pavement structure – the combination of subbase, base, paving geotextiles, and surface courses placed on a subgrade to support and distribute the traffic load to the roadbed.

performance graded asphalt cement (asphalt binder) (PG or PGAC) – an asphalt cement for which the physical properties can be directly related to field performance by engineering principles – performance graded binders are defined by a term such as PG xx-yy – the first number, xx, is the high temperature grade and indicates the asphalt cement possesses adequate physical properties up to at least xx°C – the second number, -yy, is the low temperature grade and indicates the asphalt cement possesses adequate physical properties in pavements down to at least -yy°C.

pH value – the pH value is an intrinsic value of all aqueous solutions: Each aqueous solution has a pH value.

pit and quarry – a pit "An excavation made for the purpose of removing aggregate without the use of explosive". A quarry is "An excavation, requiring the use of explosives, made for the purpose of removing consolidated rock from the environment".

polymer modified binder (PMB) – polymer modified asphalt (PMA) – asphalt cement that has had its physical and chemical properties modified/enhanced by the addition of a polymer – PMA provides enhanced durability, improved rutting resistance at high temperatures, and increased resistance to low temperature cracking.

quality assurance (QA) – all those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service – quality assurance addresses the overall problem of obtaining the quality of a service, product, or facility in the most efficient, economical, and satisfactory manner possible – within this broad context, quality assurance involves continued evaluation of the activities of planning, design, development of plans and specifications, advertising and awarding of contracts, construction, and maintenance, and the interactions of these activities.

reclaimed asphalt pavement (RAP) – removed and/or processed flexible pavement materials which are composed of a mix of asphalt cement and aggregates.

reclaimed concrete material (RCM) – removed and/or processed old Portland cement concrete (PCC).

recycled hot mix (RHM) – removal (surface milling or full depth) of old asphalt concrete (reclaimed asphalt pavement, RAP), processing, heating and mixing in a hot-mix plant (batch, drum or drum/batch) with new aggregates and new asphalt cement (softer grade or with recycling agent), relaying and compacting to meet specifications for conventional hot-mix asphalt concrete (HMA).

recycled shingle mix – is a recycling process of discarded asphalt roofing shingles to produce shingle mix.

reliability – the degree to which a test produces consistent or dependable results – test reliability is increased as both precision and accuracy are improved – reliability can also refer to product reliability, defined as (1) the degree of conformance or failure of the specific product to meet the consumer's quality needs; and (2) the probability of a product performing without failure of a specified function under given conditions for a specified period of time – in (1) and (2), reliability is that aspect of quality assurance which is concerned with the quality of product function over time.

roadbed – the graded portion of a highway prepared as a foundation for the pavement structure and shoulders.

roller pass – one trip of a roller in one direction over any one spot.

rubblization – in-place processing of old concrete pavement whereby the existing concrete pavement is broken into small pieces using specialty equipment.

soft cost – soft costs are the expenditures necessary to plan, design, and manage the project, while hard costs are the expenditures required for construction.

stabilization process – road stabilization is the process of rehabilitating pavement to make it stronger and more durable.

steel slag – steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces.

subbase – the layer or layers of material placed on a subgrade to support a base.

subgrade – the top surface of a roadbed upon which the pavement structure, shoulders, and curbs are constructed.

suitable material – rock or earth material that will provide stable foundations, embankments, or roadbeds, and is reasonably free of organic matter, roots, muck, sod, or other detrimental material – suitable material may require drying or adding water, root picking, and other methods of manipulation before use. Suitable material includes the classifications of material for which the project was designed.

tire derived aggregate – tire derived aggregate (TDA) is an engineered product made by cutting scrap tires into pieces.

tolerance limits – limits that define the conformance boundaries for a manufacturing or service operation.

toxicity – is the degree to which a substance can damage a living or non-living organisms.

unshrinkable fill – means a mixture of aggregates, cementing material and water, with or without chemical admixtures, that hardens into a material with higher strength than soil but less than 0.4 Mpa compressive strength at 28 days, that can be removed with hand tools.

unsuitable material – material not capable of creating stable foundations, embankments, or roadbeds – unsuitable material includes muck, sod, or soils with high organic contents.

verification – testing or inspection by the consumer or his agent to verify the accuracy and representativeness of material provider QC.

warm mix asphalt – warm-mix asphalt technologies allow the producers of asphalt pavement material to lower the temperatures at which the material is mixed and placed on the road.

work – the furnishing of all labour, material, equipment, and other incidentals necessary to successfully complete the project according to the contract.

A2. ACRONYMS FOR AGENCIES AND ASSOCIATIONS

AASHTO – American Association of State Highway and Transportation Officials <*www.transportation.org*>.

ACI – American Concrete Institute <*www.concrete.org*>

ACPA – American Concrete Pavement Association <*www.pavement.com*>

AI – Asphalt Institute <*www.asphaltinstitute.org*>

APA – Asphalt Pavement Alliance <*www.asphaltroads.org*>

ARRA – Asphalt Reclamation and Recycling Association <*www.arra.org*>

ASTM – American Society for Testing and Materials <*www.astm.org*>

CAC – Cement Association of Canada <*www.cement.ca*>

CCIL – Canadian Council of Independent Laboratories <*www.ccil.com*>

CGSB – Canadian General Standards Board <*www.pwgsc.gc.ca/cgsb*>

CIM – Canadian Institute of Mining < *www.cim.org*>

CIRCA – Association of Canadian Industries Recycling Coal Ash < *www.circainfo.ca* >

CSA – Canadian Standards Association <*www.csa.ca*>

C-SHRP – Canadian Strategic Highway Research Program<*www.chsrp.org*>.

CTAA – Canadian Technical Asphalt Association <*www.ctaa.ca*>

DND – Department of National Defence <*www.forces.gc.ca*>

FCM – Federation of Canadian Municipalities <*www.fcm.ca*>

FHWA – Federal Highway Administration <*www.fhwa.dot.gov*>

FPP – Foundation for Pavement Preservation <*www.fp2.org*>

GTAA – Greater Toronto Airport Authority <*www.torontopearson.com*>

ICPI – Interlocking Concrete Pavement Institute <*www.icpi.org*>

MAC – Mining Association of Canada < *www.mining.ca* >

MOE – Ontario Ministry of Environment < *www.ene.gov.on.ca/environment* >

MTO – Ontario Ministry of Transportation <www.mto.gov.on.ca>

MTQ – Ministère des Transports du Québec <www.mtq.gouv.qc.ca>

NAPA – National Asphalt Pavement Association <www.hotmix.org>

NBDTI – New Brunswick Department of Transportation and Infrastructure <www.gnb.ca/0113/index-e.asp>

NCHRP – National Cooperative Highway Research Program <*www4.trb.org/trb/crp.nsf*>

NGSMI – National Guide to Sustainable Municipal Infrastructure <*www.infraguide.ca*>

NRC – National Research Council <www.nrc.ca>

NSL – National Slag Association <*www.nationalslag.org* >

OECD – Organization for Economic Cooperation and Development <www.oecd.org>

OHMPA – Ontario Hot Mix Producers Association <www.ohmpa.org>

OPS – Ontario Provincial Standards <www.raqsb.mto.gov.on.ca/techpubs/ops.nsf/OPSHomepage>

PIARC – The World Road Association. Original title: Permanent International Association of Road Congresses (PIARC/AIPCR) <www.piarc.org/en>

PCA – Portland Cement Association <www.cement.org>

RMCAO – Ready Mix Concrete Association of Ontario <www.rmcao.org>

SHRP – Strategic Highway Research Program <www.cshrp.org>

TAC – Transportation Association of Canada <www.tac-atc.ca>

TRB – Transportation Research Board <www.trb.org>

USEPA – United States Environment Protection Agency <www.epa.gov>

A3. TECHNICAL TERMS

AADT	annual average daily traffic
ACBFS	air cooled blast furnace slag
Ba	barium
BOF	basic oxygen furnace
Ca	calcium
CBR	California bearing ratio
CCP	coal combustion products
CCPR	cold central plant recycling
CIR	cold in-place recycling
CLSM	controlled low strength material
Cr	chromium
CRCP	continuously reinforced concrete pavement
Cu	copper
EAF	electric arc furnace
ESALs	equivalent single axle loads
FGD	flue gas desulphurization
FWD	falling weight deflectometer
GB	granular base
GBE	granular base equivalency
GGBFS	ground granulated blast furnace slag
GSB	granular subbase
HDBC	heavy-duty binder course
HIR	hot in-place recycling
HMA	hot-mix asphalt
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
LCB	lean concrete base
LCCA	life cycle cost analysis

LOI	loss on ignition
LSBC	large stone binder course
MSDS	material safety data sheet
Ni	nickel
OGDL	open graded drainage layer
OGFC	open graded friction course
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PCC	Portland cement concrete
PCCP	Portland cement concrete pavement
PCI	pavement condition index
PG	performance graded
PGAC	performance graded asphalt cement (binder, PGAB)
PMA	polymer modified asphalt cement (binder, PMB)
PMPGAC	polymer modified performance graded asphalt cement (binder, PMPGAB)
PTE	passenger tire equivalents
RAP	reclaimed asphalt pavement
RAS	recycled asphalt shingles
RCM	reclaimed concrete material
RHM	recycled hot-mix
RMA	rubber modified asphalt
SMA	stone mastic asphalt (termed stone matrix asphalt in US)
TDA	tire derived aggregate
TGB	treated granular base (with cement for instance)
TSR	tensile strength ratio (tensile strength of conditioned subset/tensile strength of dry subset
VOC	volatile organic compounds
Zn	zinc

APPENDIX B

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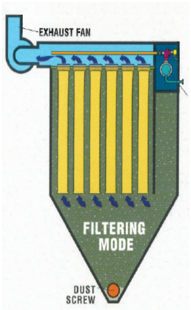
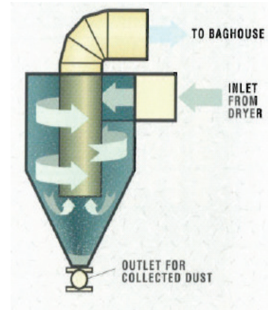
APPENDIX C

Data Sheets for Recycled Materials



AZTEC, 2008

C-1 - BAGHOUSE FINES

A fabric filter baghouse is an integral component of a dry-collector emission control system used at many hot-mix asphalt production facilities. The baghouse is used to trap and remove very fine aggregate and dust particles from the exhaust gases produced during aggregate drying in hot-mix asphalt production. Many modern asphalt production facilities are equipped to then return some or all of the recovered fines either directly into the mixer or they are diverted and stored in separate silos for future use as mineral filler.

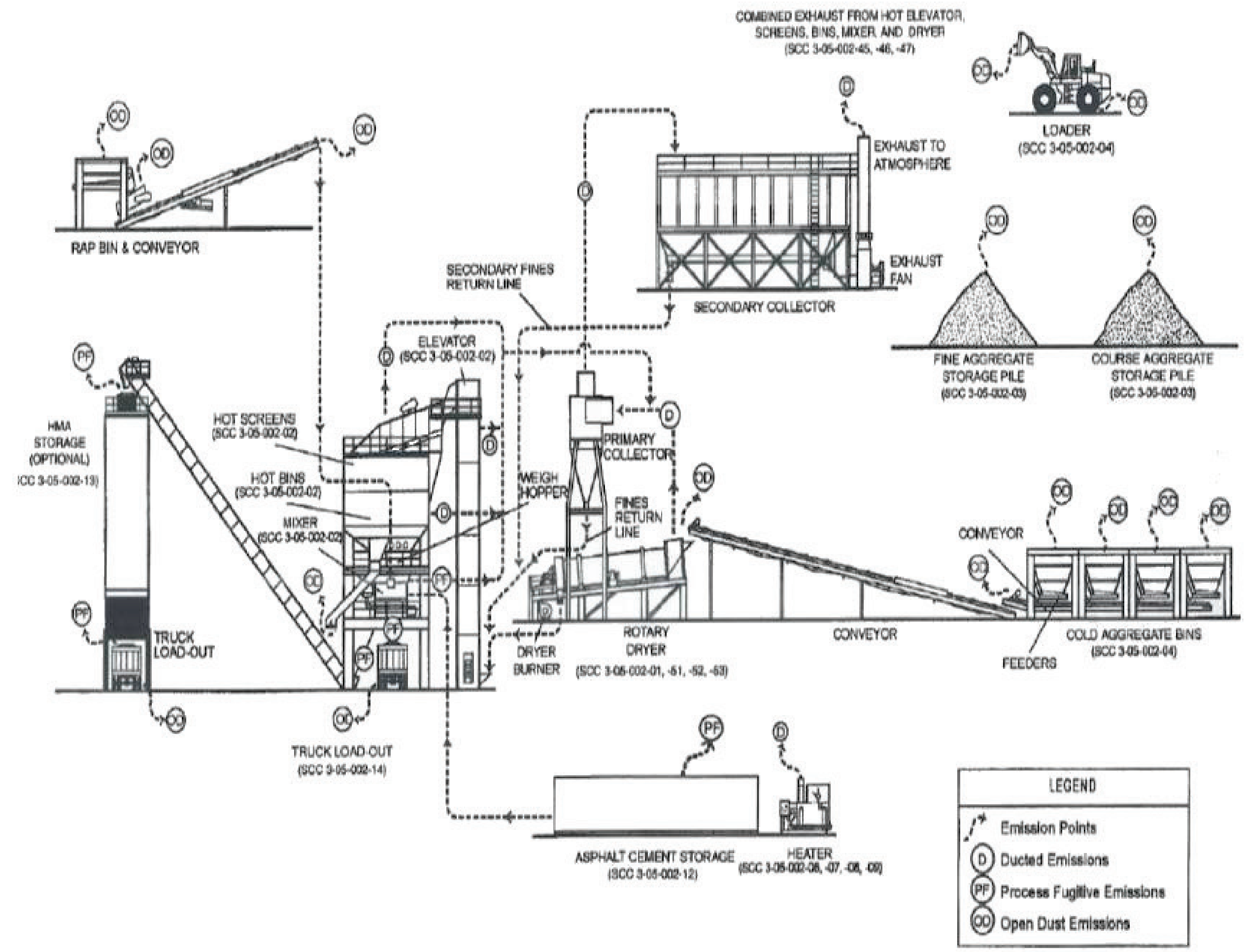
How it is generated/quantities generated

During hot-mix asphalt production, the hot, dust-laden gases which are produced in the dryer are passed through a primary collector (such as a knock-out box or cyclone) then is directed to a secondary fabric filter baghouse which consists of a set of fabric dust collectors which remove over 99 percent of the fine dust particles from the exhaust gases prior to releasing them into the environment. It is common for most hot-mix asphalt plants which employ baghouses as secondary collectors also employ primary collection devices (such as cyclones) in order to remove the coarser particles in the exhaust gases prior to delivery to the secondary collector baghouse.

The two most common types of hot-mix asphalt production plants are drum mix and batch plants. In drum mix plants, the hot-mix asphalt aggregates are taken from the cold stockpiles and conveyed into the drum at the proportions outlined in the hot-mix asphalt mix design. In the drum, the aggregates are first dried and then mixed with asphalt cement as the aggregates approach the end of the drum. In drum plants, the drying and blending with asphalt cement is a continuous process. In batch plants, the aggregates are taken from the cold stockpiles and fed into a dryer, followed by a screening process which divides the aggregates into different size fractions. The various aggregate size fractions are stored in separate hot bins until they blended in the appropriate proportions with asphalt cement in a pugmill mixer. Simplified diagrams showing the drum mix and batch plant asphalt production processes as well as outlining the introduction of the recycled fine materials is shown in Figures C1-1 and C2-2.

As baghouse fines are recycled directly into the mix at the hot-mix asphalt plant, the quantity produced is difficult to estimate. The United States Environmental Protection Agency estimates that 1,225 kg of fine material (passing 10μm, pr PH-10) is created for every 100,000 tonnes of hot mix asphalt produced per year for Batch Mix Plants and 1,043 kg for every 100,000 tonnes of hot mix asphalt produced per year for Drum Mix Plants (EPA, 2000). These figures can be used as a general guideline to determine the amount of baghouse fines that are generated in a particular plant based on the tonnes of hot-mix asphalt which is produced and assuming that the plant in question employs a dry-collector emission control system.

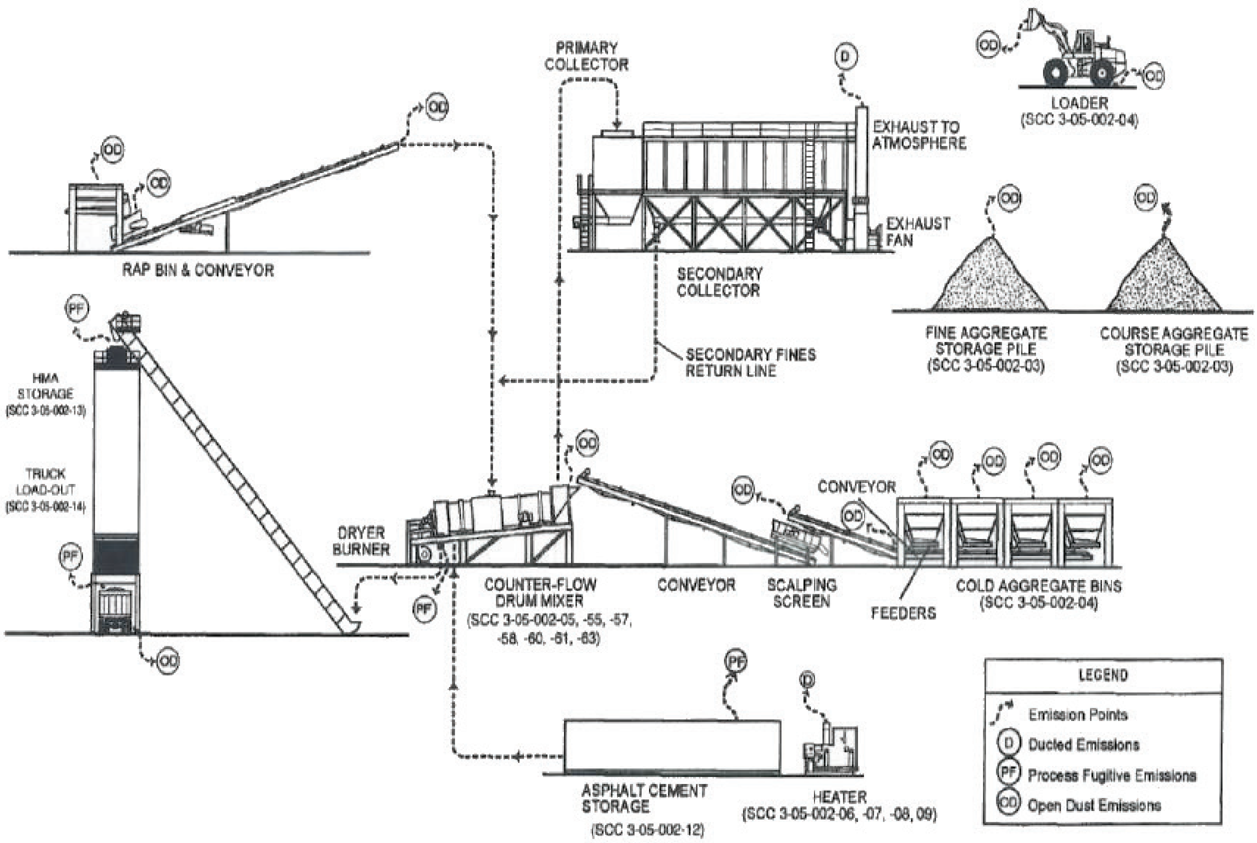
Figure C1-1 General process flow diagram for batch mix asphalt plants (EPA, 2000)



Typical sources

As baghouse fines are generated as a by-product in the production of asphalt concrete mixtures, baghouse fines can be found wherever a hot-mix asphalt plant equipped with dry collector, fabric filter baghouse emission control system is employed. As shown in Figures C1-1 and C2-2, most of the fine materials collected in baghouses are used by hot-mix asphalt producers by returning the collected fines to the hot-mix asphalt production stream in the asphalt mixing plant.

Figure C2-2 General process flow diagram for counter-flow drum mix asphalt plants (EPA, 2000)



In what forms can Baghouse Fines be used and in what quantities

The only established commercial use of Baghouse fines is its reuse as the mineral filler portion of an asphalt concrete mixture. The percentage of mineral filler varies based on the type of asphalt concrete mixture but is typically 2 percent (can be as much as 5 percent) by mass of the total asphalt concrete mixture.

It should be noted that the fines collected from the baghouses will have similar, if not the same, properties as the aggregates which are used in the hot-mix asphalt production of a particular plant and as such it is recommended that these fines should only be incorporated into mixes containing the same aggregate types from which they were derived since the engineering properties of baghouse fines generated from different aggregate supplies can vary, sometimes quite significantly.

Engineering Properties of Baghouse Fines

The collection of baghouse fines and their reuse in hot-mix asphalt is considered to be a routine process. Since these fines are derived from naturally occurring aggregates, the properties of the dust portion of these aggregates are similar to those of commercial mineral fillers such as stone dust or hydrated lime.

Baghouse fines are usually very fine-grained, however, plants without a primary collector or cyclone could have as much as 6 percent of the collected material with a maximum particle size of 0.600 mm according to AASHTO research (AASHTO, 2007). Baghouse fines are typically classified into a coarse fraction and a fine fraction, with the dividing size being the 75µm sieve. It has been observed that the percentage of dust particles passing the 75µm sieve can range quite considerably from plant to plant depending on the type(s) of dust collection systems employed. For instance, the dust produced by plants without a primary collection system can have less than 50 percent of the material passing the 75 µm sieve, compared to plants with a primary collection system which can have 90 to 100 percent of the collected particles finer than 75 µm sieve.

While there has been a limited amount of research completed on the performance of hot-mix asphalt materials incorporating baghouse fines, a 1978 research report completed by the Asphalt Institute Research Report (AI, 1978) concluded that baghouse fines are suitable for use in asphalt mixtures as long as the quality of the parent aggregate is satisfactory.

The typical physical and chemical properties of baghouse fines are shown in Table C1-1 (adapted from FHWA, 2008).

Table C1-1 Typical range of physical properties of baghouse fines

GROUP	GRADATION OF PASSING (MM)				SPECIFIC GRAVITY	SPECIFIC SURFACE* (M^2/G)	HYGROSCOPIC MOISTURE (%)	LIQUID LIMIT	PLASTICITY INDEX
	0.600	0.300	0.075	0.01					
Maximum	100	100	100	78	2.87	2.18	1.9	39	4
Minimum	95	82	28	4	2.57	0.06	0.2	NL	NP
*Measured by air permeability					NL=Nonliquid; NP=Nonplastic				

Toxicity or environmental concerns/impacts

Baghouse fines are typically alkaline with pH values ranging from 7.2 to 10.8 for gravel, granite or traprock aggregates and pH values ranging from 11.0 to 12.4 for limestone and dolomitic aggregates. However, when incorporated into hot-mix asphalt, these alkaline dusts are completely blended and form part of the hot-mix asphalt matrix and should not have any toxicity or environmental concerns.

Technical Limitations

As mentioned previously, the fines collected from baghouses will have similar, if not the same, properties as the aggregates which are used in the hot-mix asphalt production of a particular plant. As such, it is recommended that these fines should only be incorporated into mixes containing the same aggregate types from which they were derived since the engineering properties of baghouse fines generated from different aggregate supplies can vary, sometimes quite significantly.

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C-2 – BLAST FURNACE SLAG

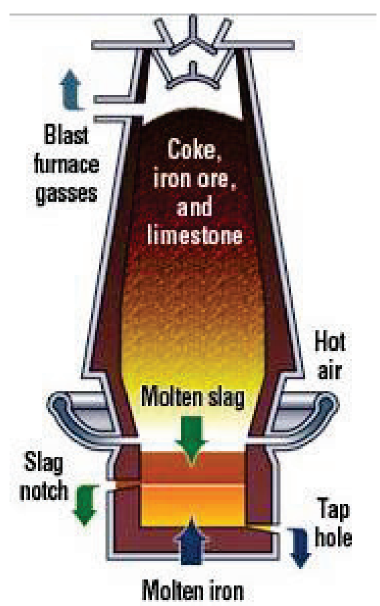
Blast furnace slag is the term given to the non-metallic co-product which is produced in the process of iron manufacturing. Blast furnace slag is formed when iron ore, iron pellets and/or iron scrap are mixed with coke and a flux (limestone and/or dolomite) and are melted together in a blast furnace. When the process has been completed, the lime in the flux has been chemically combined with the non-metallic components of the iron ore (aluminates and silicates) along with the coke ash to form blast furnace slag.

During the period of cooling and hardening from the molten state, different forms of blast furnace slag can be produced depending on the process used to cool the molten slag. There are four distinct methods of processing the molten slag which each produces a unique slag material. The typical slag materials include air-cooled blast furnace slag (ACBFS), expanded slag, pelletized slag and granulated (water quenched) blast furnace slag.

How it is generated/quantities generated

During the production of iron, the combustion material (coke and flux) and ore (iron ore, iron pellets and/or iron scrap) are supplied from the top of the blast furnace chamber while hot air is provided from the bottom of the chamber forcing a chemical reaction to take place throughout the ore as shown in Figure C2-1. The molten slag is less dense than the iron and floats to the top of the blast furnace where it is channelled out through the slag notch and diverted to one of four distinct processing methods depending on the slag material that is desired to be produced.

Figure C2-1 Schematic of a Blast Furnace (NSA, 2011)



Air Cooled Blast Furnace Slag (ACBFS)

Air cooled blast furnace slag is produced when the molten slag is poured into beds and allowed to cool under ambient conditions. Once cooled, the slag crystallizes into hard lumps that are then crushed to produce lightweight, angular, roughly cubical pieces with a minimum of flat or elongated fragments. The rough, porous texture of ACBFS gives it a greater surface area than other aggregates and provides an excellent bond with portland cement and high stability in bituminous mixtures.

Expanded Blast Furnace Slag

Expanded blast furnace slag is produced when controlled quantities of water are used to accelerate the cooling and solidification of the molten slag. The action of the water and the resulting steam produce a solidified slag with an open cellular structure which is then crushed and screened for use as a lightweight structural aggregate. Expanded slag is distinguishable from ACBFS due to its relatively high porosity and low bulk density. Expanded blast furnace slag is angular and cubical in shape, with very few flat or elongated particles.

Pelletized Blast Furnace Slag

Pelletized blast furnace slag is produced when the molten slag is directed onto an inclined vibrating feed plate where it is quenched with water causing the slag to foam. Prior to the slag solidifying, it is then directed onto a revolving finned drum which causes the formation of spherical droplets. The process can be controlled to quench more slowly in order to produce construction aggregate or quench more quickly creating a more vitrified slag which is used in cementitious applications.

Granulated Blast Furnace Slag

Granulated blast furnace slag is produced when water is injected into the molten slag using high pressure water jets, quenching the molten slag almost immediately and forming small, vitreous particles the size of sand grains. The cementitious properties of the granulated blast furnace slag are determined by the temperature at the time of quenching as well as the composition of the slag source. After the granulated blast furnace slag is formed, it must be dewatered, dried and ground in standard mills in order to form very fine cement-sized particles for use as a partial replacement or additive to portland cement.

The Canadian Slag Association estimates that 1.5 million tonnes of blast furnace slag were produced in Canada in 2009 (CSA, 2009)

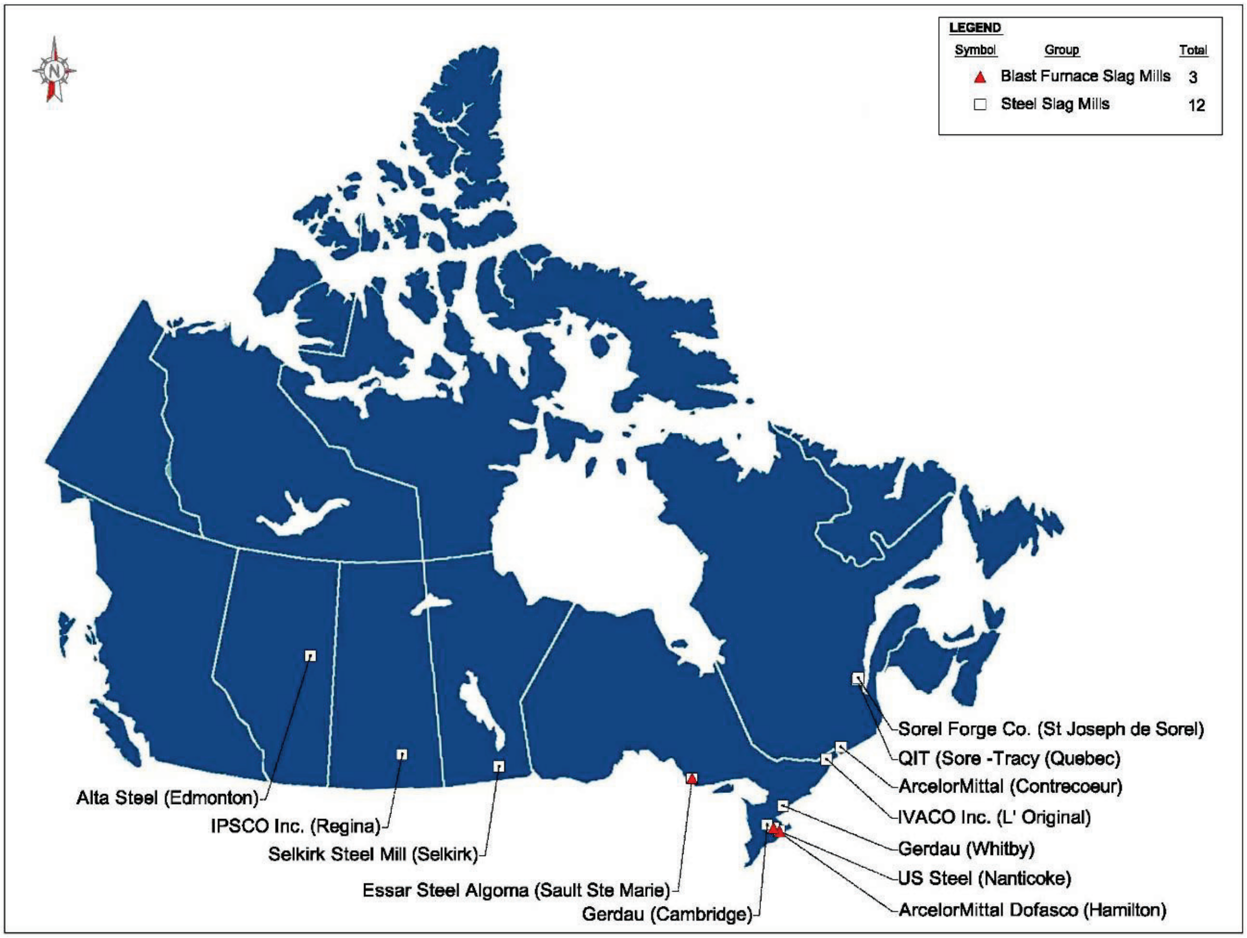
Typical sources

As blast furnace slag is a by-product generated in the production of iron, blast furnace slags can be found wherever an iron blast furnace is located. Currently, there are three active blast furnace slag mills in operation in Canada and all three facilities are located in Ontario. Figure C2-2 shows the typical sources of blast furnace slag in Canada. The various types of blast furnace slags would typically be obtained directly from the blast furnace operators.

In what forms can Blast Furnace Slag be used and in what quantities

Blast furnace slags can be used in bulk applications as aggregates in the construction of granular bases for roadways, as lightweight aggregate for embankments, as aggregate in hot-mix asphalt, or as a supplementary cementitious material in portland cement concrete mixes.

Figure C2-2 Location of Blast Furnace Slag Mills in Canada



Air cooled blast furnace slag (ACBFS) is considered by many agencies as an equal replacement for conventional aggregate in granular base construction. For example, in Ontario, air cooled blast furnace slag can be used as a complete replacement for natural aggregates in granular base (OPSS Granular A, M and S) and granular subbase (OPSS Granular B Type I and Type II) materials. ACBFS can also be used to replace natural aggregate on embankments providing a lightweight fill with a high internal angle of friction. In both cases, the only additional design consideration that is required is to ensure that the ACBFS materials are not placed below grade or in locations where it may come in contact with stagnant or slow moving water as this can result in unpleasant sulphurous odour and water discolouration (florescent green leachate).

Air cooled blast furnace slag is also considered by many agencies as an equal replacement for conventional coarse and fine aggregate in hot-mix asphalt production subject to the hot-mix asphalt consistently meeting all of the design and aggregate physical requirements that are specified by the agency. It should be noted that it can be difficult to meet most agencies Micro-Deval Abrasion loss requirements due primarily to exaggerated loss cause by the sharp edges of the slag breaking off, and in these cases some agencies, such as the MTO, allow for other tests (TRB, 1995) in lieu of the Micro-Deval Abrasion loss test to determine if the ACBFS is acceptable (OPSS 1003, 2006). Another design consideration is that the high porosity of the ACBFS contributes to higher absorption than conventional aggregates leading to an increased asphalt cement demand (up to 3 percent) which increases the cost of these mixes. This increased cost is somewhat offset by the higher yield (higher volume of hot-mix asphalt per tonne) during transportation due to the lower unit weight of the mix.

Blast furnace slag is most typically ground and granulated (ground granulated blast furnace slag GGBFS) and used as a supplementary cementitious material in portland cement concrete, either as a mineral admixture or as a component of blended cement as this process is considered to be the highest, best use of the slag (grinding slag for cement requires only about 25 percent of the energy needed to manufacture portland cement). However, air cooled blast furnace slag can also be used as an aggregate in portland cement concrete. GGBFS can be substituted for portland cement on a 1:1 basis. Canadian practice allows for substitution levels up to 70 percent, however typical North American substitution levels range between 30 and 45 percent of the cementing materials in the mix (CEMENT, 2011). It should be noted however, that research has indicated that the resistance to scaling decreases with GGBFS addition rates over 50 percent and supplementary scaling resistance testing should be completed when considering addition rates above this level.

Engineering Properties of Blast Furnace Slag

The engineering properties of air cooled blast furnace slag are considered by many agencies to be the same as natural aggregates. Some of the typical physical and mechanical properties of the various types of blast furnace slag are shown in Table C2-1 (Emery, 1980).

Table C2-1. Typical Physical and Mechanical Properties of Blast Furnace Slag

PROPERTY	SLAG TYPE		
	AIR-COOLED	EXPANDED/ GRANULATED	PELLETIZED
Specific Gravity	2.0-2.5	-	-
Compacted Density (Kg/m^3)	1120-1360	800-1040	840
Absorption (%)	1-6	-	-
Angle of Internal Friction (°)	40-45	-	-
Los Angeles Abrasion (%)	35-45	-	-
Sodium Sulphate Soundness Loss (%)	12	-	-
Hardness (Moh's Scale)	5-6	-	-
California Bearing Ratio (CBR,%)	Up to 250	-	-

The chemical composition of blast furnace slag is generally applicable to all types of blast furnace slag production and has been shown to be quite consistent and favourable in composition over time as outlined in Table C2-2. When ground, the chemical composition and glassy nature of vitrified slags (particularly GGBFS) react similarly to portland cement to produce cementitious hydration products. The hydration process of GGBFS is slower than portland cement but can be enhanced by the presence or addition of calcium hydroxide, alkalies and gypsum. Blast furnace slag is mildly alkaline with a pH of 8 to 10 and its leachate does not present a corrosion risk to either embedded steel or steel in pilings.

Table C2-2. Typical Composition of Blast Furnace Slag (Emery, 1980)

CONSTITUENT	PERCENT							
	1949		1957		1968		1985	
	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE
Calcium Oxide (CaO)	41	34-48	41	31-47	39	32-44	39	34-43
Silicon Dioxide (SiO_2)	36	31-45	36	31-44	36	32-40	36	27-38
Aluminum Oxide (Al_2O_3)	13	10-17	13	8-18	12	8-20	10	7-12
Magnesium Oxide (MgO)	7	1-15	7	2-16	11	2-19	12	7-15
Iron (FeO or Fe_2O_3)	0.5	0.1-1.0	0.5	0.2-0.9	0.4	0.2-0.9	0.5	0.2-1.6
Manganese Oxide (MnO)	0.8	0.1-1.4	0.8	0.2-2.3	0.5	0.2-2.3	0.44	0.15-0.76
Sulphur (S)	1.5	0.9-2.3	1.6	0.7-2.3	1.4	0.6-2.3	1.4	1.0-1.9

Another interesting property of blast furnace slags is that they have lower thermal conductivities than conventional aggregates due to their more porous structure. This property makes this type of slag ideal for use in fireproofing as well as in applications such as frost tapers (transition treatments in pavement subgrades between frost susceptible and non frost susceptible soils) or pavement base courses over frost-susceptible soils.

Toxicity or environmental concerns/impacts

Where blast furnace slag aggregates have been submerged in the presence of stagnant or slow moving water, the leachate from the slag has been observed to be discoloured and have a sulphurous odour. The stagnant water was observed to exhibit high concentrations of calcium and sulphide with a pH as high as 12.5 (NSL, 1995). Aging of blast furnace slag stockpiles (minimum of 1 month) has been shown to delay the formation of the yellow leachate, however the discoloured leachate was still observed to form if the slag was left in contact with stagnant water over an extended period (NSL, 1995). National Slag Association conducted a study in 1995 which concluded that the blast furnace slag leachate met existing USEPA requirements and would not pose a threat to human or plant life (National Slag Association, BFS Brochure).

In Ontario, placing air cooled blast furnace slag is subject to specific placement guidelines and a potential user is also required to obtain a Ministry of Environment (MOE) site notification prior to its use.

Technical Limitations

Due to the aesthetic environmental concerns regarding the discolouration and odour of ACBFS aggregates submerged in stagnant or slow moving water, these aggregates should only be used above grade as granular base in the pavement structure and must be adequately separated from water courses to prevent immersion.

The use of blast furnace slag in hot-mix asphalt mixtures is restricted in Ontario due to past difficulties in obtaining a consistent density of the hot-mix aggregate. This variation in aggregate density caused high variability in the mix asphalt cement content and led to these mixes not meeting acceptance criteria.

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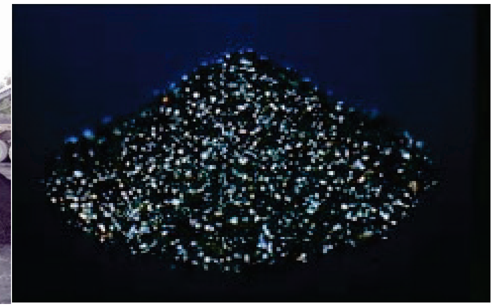


C-3 COAL BOTTOM ASH AND BOILER SLAG

Coal bottom ash and boiler slag are coarse, granular, incombustible by-products resulting from the combustion of pulverized coal in thermal power generation plants. They are two of the four main coal combustion products, along with fly ash and flue gas emission control system material which are produced at thermal generation plants. Coal bottom ash is formed when the pulverized coal is burned in a dry bottom boiler. About 80 percent of the unburned material is removed as ash in the hot combustion gases (flue gas) and recovered as fly ash, while the remaining 20 percent of the unburned material is collected in the bottom of the combustion chamber (bottom ash). Boiler slag is formed when molten ash is removed from the bottom of the boiler and quenched in water which instantly forms pellets. The pellets are then taken away for further processing.

How it is generated/quantities generated

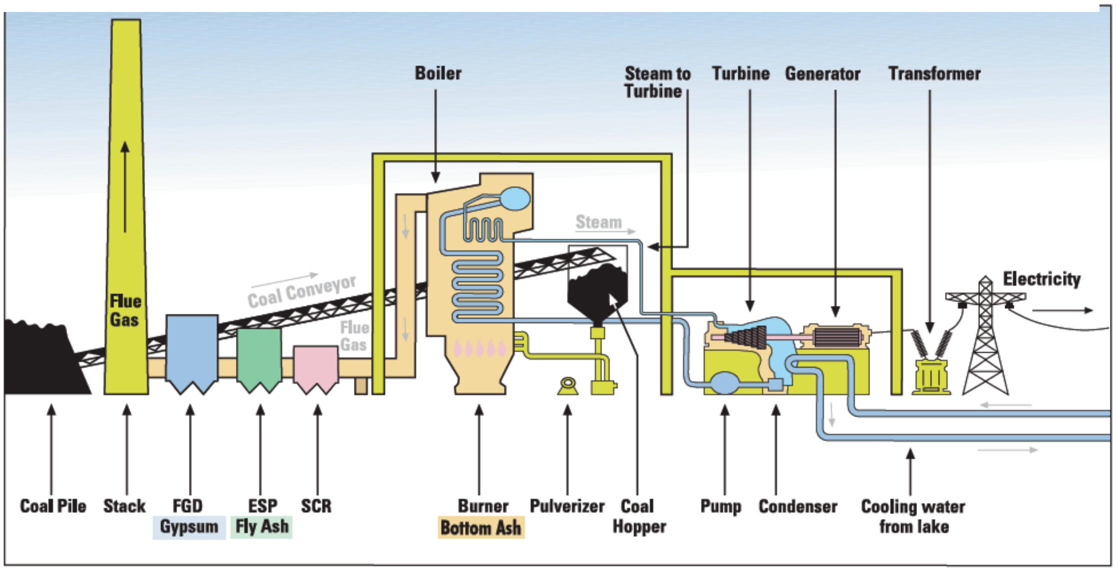
Coal bottom ash and boiler slag are most commonly generated during the production of electricity at coal-fired thermal generation plants. Coal bottom ash and boiler slag are produced using different boiler furnace recovery methods. The type of bottom ash or boiler slag produced varies based on the ore composition and combustion technique employed. An illustration of a typical thermal generation plant along with the various by-products which are produced is shown in Figure C3-1.

Coal Bottom Ash

The most common type of burning furnace in thermal power generation plants is the dry bottom pulverized coal boiler. In this type of boiler, pulverized coal is burned to create steam which powers the thermal power generation plant's turbines, creating electricity. Depending on the type of coal and boiler involved, about 15 to 30 percent of the resultant unburnt material falls to the bottom of the coal furnace and is collected as bottom ash (the remaining fine ash is entrained in the flue gases and is captured later in the process). Coal bottom ash is typically collected in a water-filled hopper at the bottom of furnace where it is removed by either mechanically (augers or moving chains) or by pressure (high pressure water or air jets) to a sluiceway which transports the bottom ash to a separate processing facility for dewatering and further processing into different products. There has been very limited reuse of coal bottom ash in Canada (6 percent) and it has been limited primarily to cement and road base/subbase applications (approximately 50/50 split (CIRCA 2010)). The reuse of coal bottom ash is much more common in the United States (43.5 percent (CIRCA 2010)) with the most common use as structural fill and in embankments (47 percent).

The most recent production estimates for coal bottom ash in Canada are from 2007 and indicated an annual production of 1.6 million tonnes (CIRCA 2010).

Figure C3-1 Typical Thermal Generation Plant Flow Chart (courtesy of www.opg.com)



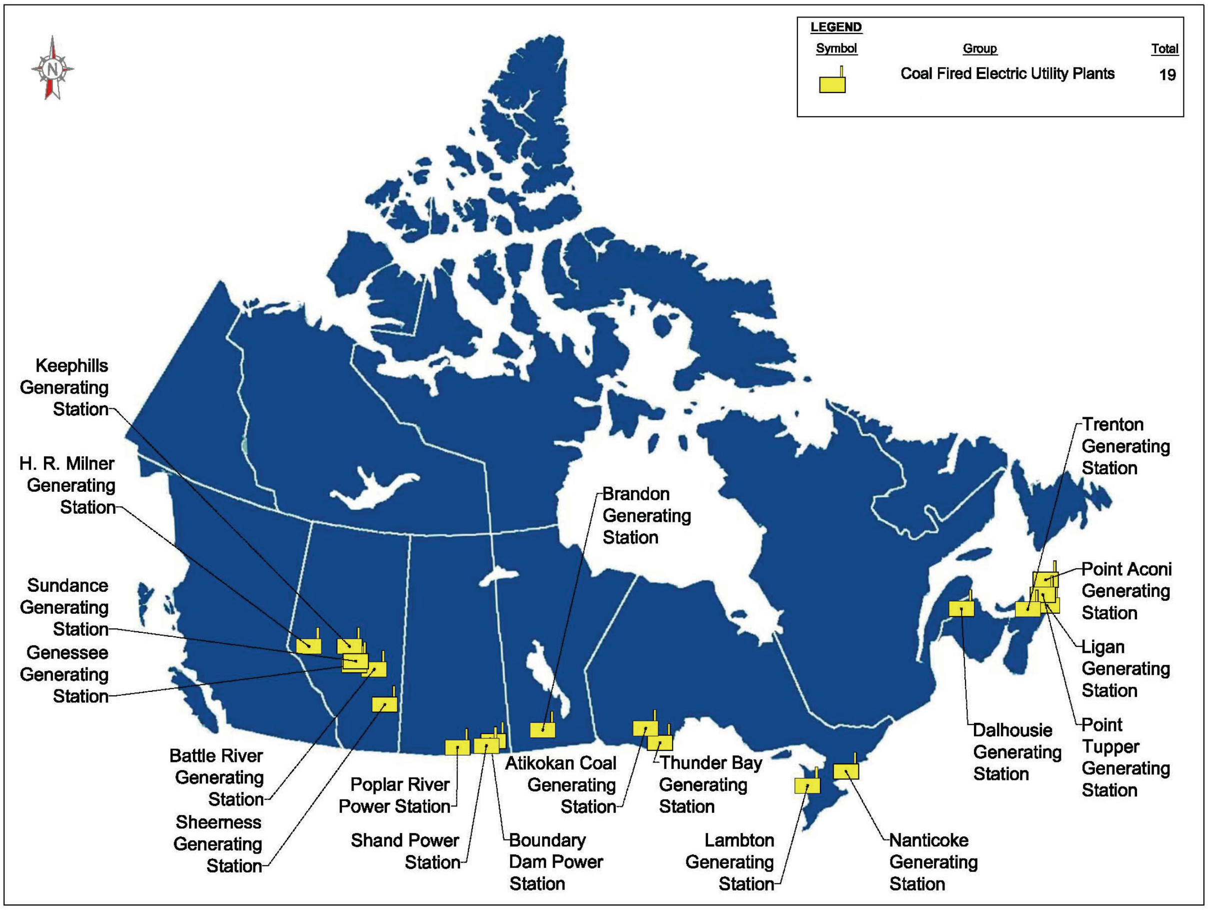
Boiler Slag

Wet bottom boilers, which produce boiler slag, have a higher investment and maintenance cost than dry bottom boilers which results in this type of boiler being built less often despite the fact that the slag by-product is highly desirable and all boiler slag (United States) that is produced is used in other products (ACC, 2010). There are two main types of wet-bottom boilers: slag-tap; and cyclone. The main differences are that a slag-tap boiler burns pulverized coal (with 50 percent of the ash retained as boiler slag) while a cyclone boiler burns crushed coal (with 70 to 80 percent of the ash retained as boiler slag). In both furnace types, the ash is kept in a molten condition and removed though a tap which allows the molten slag to drain into a water-laden hopper which immediately quenches the hot slag and pelletizes the slag. The slag is then transported for dewatering and processing (crushing and screening) for use primarily as blasting grit or roofing granules.

Typical sources

As coal bottom ash and boiler slags are a by-product in the generation of electricity from thermal generation plants, these by-products can be found at coal fired electric generating facilities such as electrical utilities and to a lesser extent, some major industries which employ coal-fired electric plants. Currently there are 20 active coal fired electric generating facilities in operation in Canada. Figure C3-2 shows the typical sources in Canada. Coal bottom ash and boiler slag products would typically be obtained from commercial ash vendors as electric utilities do not tend to market the materials themselves.

Figure C3-2. Location of Coal Fired Electric Utilities in Canada



In what forms can Coal Bottom Ash and Boiler Slag be used and in what quantities

Coal Bottom Ash

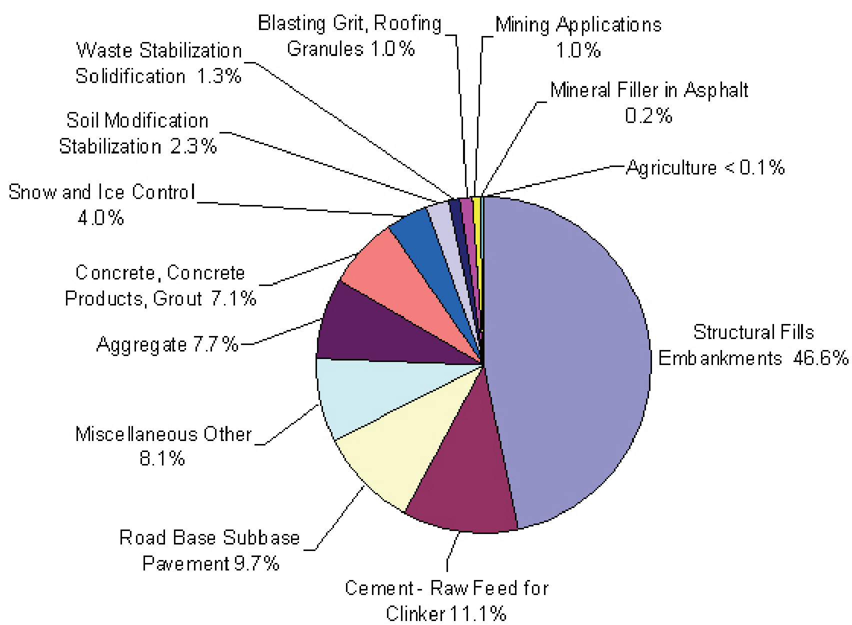
Photograph C3-1 Coal bottom ash in the form of fine aggregate (ACAA, 2011)

When coal bottom ash is produced, the heavier particles that remain after combustion are similar in form and composition to fine aggregates like sand and gravel as shown in Photograph C3-1. When used as an aggregate substitute in transportation infrastructure projects, this means that more natural materials can be saved for other uses which extends the service life of current virgin sources and delays the need to find new sources.

There has been very limited reuse of coal bottom ash in Canada according to Natural Resources Canada research (6 percent (CIRCA, 2010), and its use has been limited primarily to cement production (primarily clinker) and road base/subbase applications (approximately 50/50 split (CIRCA 2010)). None of the survey respondents indicated that coal bottom ash is currently permitted for use in their jurisdictions, with only the City of Edmonton indicating that it was being used on a trial basis. The reuse of coal bottom ash has gained much more attention in the United States (43.5 percent (CIRCA 2010)) with beneficial uses continuing to rise and if it continues, having the potential to utilize all of the bottom ash produced in the United States. Some common applications of coal bottom ash in the United States are shown in Figure C3-3.

Figure C3-3 indicates that the most common use of coal bottom ash in the United States is in structural fills and embankments, however it also indicates a number of other successful uses in transportation infrastructure such as road bases, construction aggregates, aggregates in hot-mix asphalt, and base stabilization.

Figure C3-3. Common Applications of Coal Bottom Ash in the United States (ACAA, 2011)



In 2007, Natural Resources Canada reported that approximately 48,000 tonnes of coal bottom ash were used in granular base/subbase applications compared to over 740,000 tonnes used in the United States. In granular base/subbase applications, the pre-processed coal bottom ash may require short-term stockpiling (typically less than two days) in order to further reduce the material moisture content in order to be at optimum for placement and compaction. During this process, the coal bottom ash should also be screened to remove any agglomerations (popcorn particles) and to determine its particle size distribution. While some bottom ash sources may meet agency granular base/subbase specifications without processing, blending with conventional aggregates may be required. Coal bottom ash can be handled and stored using the same methods and equipment used for conventional aggregates.

Coal bottom ash which has been properly screened to remove any agglomerations is generally sufficiently well graded for use as a partial aggregate replacement in hot-mix asphalt mixes. It should be noted however that bottom ash particles are less durable than conventional aggregates and would be considered better suited for binder course, shoulder and cold mix applications for low volume secondary roads than in wearing course mixes. It is recommended that no more than 30 percent of natural aggregates be substituted with bottom ash based on studies conducted in the United States (TRR 1973). It is also recommended that 1 to 1.5 percent lime addition be used to minimize the moisture susceptibility of mixes incorporating bottom ash (MTL, 2005).

Research conducted in the United States has shown that fly ash stabilized base courses have been successfully implemented incorporating up to 65 percent bottom ash or boiler slag aggregates by mass and portland cement mixes may contain up to 95 percent bottom ash or boiler slag with no undue performance dropoff (TRR 1973). Again, it is important for the performance of these mixtures to ensure that agglomerations have been removed prior to their incorporation and that they have been processed in such a fashion that they do not contain elevated levels of pyrite.

In 2006, the American Coal Ash Association reported that approximately 3.6 million tonnes of bottom ash were used in structural fill and embankment applications while there was no similar reported use in Canada in the same period based on Natural Resources Canada research. Some of the properties of bottom ash that make it useful in embankment and fill applications are: it is lightweight; it is free draining; it has a higher angle of internal friction than conventional aggregates; and it is typically not susceptible to either liquefaction or frost heave. As with other uses, the use of coal bottom ash in embankment and fill applications is considered to be an unencapsulated use and areas near shallow groundwater or drinking aquifers should be given careful consideration prior to use.

Boiler Slag

There is no documented regular use of boiler slag in Canada although it has successfully been used in the United States where it is considered to be a high value-added product which is almost completely consumed on an annual basis (ACC, 2010). None of the survey respondents indicated that coal boiler slag is currently permitted for use in their jurisdictions. Photograph C3-2 shows the texture of coal boiler slag while the typical uses of boiler slag in the US are shown in Figure C3-4 (ACAA, 2011). As shown in Figure C3-4, the main use of boiler slag is in blasting grit and roofing granules with secondary uses as structural fills and in embankments and as a mineral filler in asphalt. Boiler slag is not typically used as granular base due to other, higher value uses.

Photograph C3-2 Coal Boiler Slag in the form of fine aggregate (ACAA, 2011)

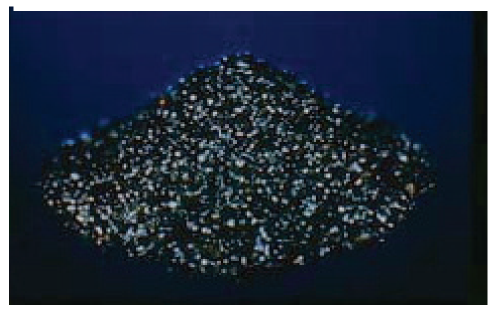
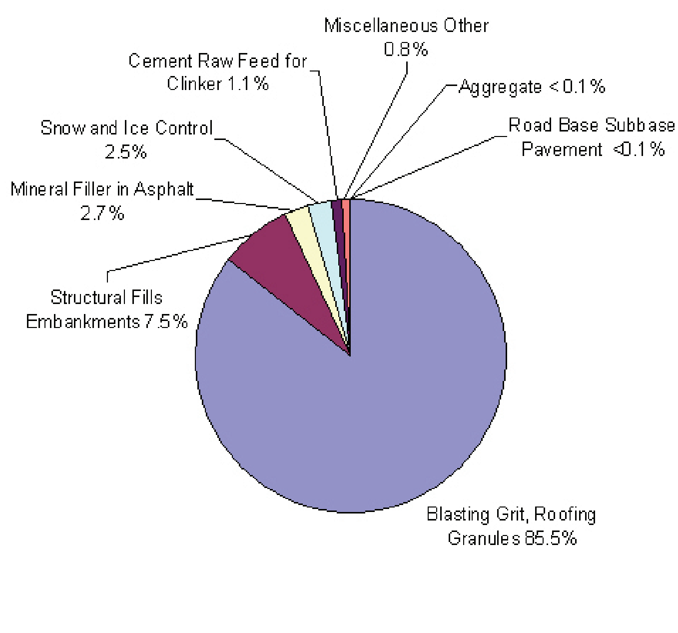


Figure C3-4. Common Applications of Coal Boiler Slag in the United States



Some of the properties of boiler slag that make it useful in embankment and fill applications are: it is lightweight; it is free draining; and it is typically not susceptible to either liquefaction or frost heave. As with other uses, the use of boiler slag in embankment and fill applications is considered to be an unencapsulated use and areas near shallow groundwater or drinking aquifers should be given careful consideration prior to use.

Coal boiler slag which has been properly screened to remove any deleterious particles is generally sufficiently well graded for use as an aggregate replacement in hot-mix asphalt mixes. Unlike coal bottom ash however, boiler slag is considered suitable for use in all hot-mix asphalt applications. Boiler slag also has an affinity for asphalt which increases anti-stripping characteristics.

Engineering Properties of Coal Bottom Ash and Boiler Slag

While coal bottom ash and boiler slag can be processed and constructed using standard construction equipment, they each have unique engineering properties and characteristics which may be considered beneficial for some applications.

Some of the typical physical and mechanical properties of the coal bottom ash and boiler slag are shown in Table C3-1 (Adapted from FHWA, 2008).

Table C3-1. Typical Physical and Mechanical Properties of Coal Bottom Ash and Boiler Slag

PROPERTY	COAL COMBUSTION PRODUCT	
	BOTTOM ASH	BOILER SLAG
Specific Gravity	2.1 – 2.7	2.3 – 2.9
Dry Unit Weight (kN/m^3)	7.1 – 15.7	7.4 – 14.2
Plasticity	None	None
Absorption (%)	0.8 – 2.0	0.3 – 1.1
Internal Angle of Friction (°)	38 – 42	38 - 42
Optimum Moisture Content (%)	12 – 24	8 - 20
Los Angeles Abrasion Loss (%)	30 – 50	24 – 48
Sodium Sulphate Soundness Loss (%)	1.5 – 10	1 – 9
Hydraulic Conductivity (cm/sec)	1 x 10-3	1 x 10-3
California Bearing Ratio (CBR, %)	21 – 110	40 – 70

Bottom ashes and boiler slags are both fine grained materials with angular particles and porous surface textures. A typical grain size analysis indicates that bottom ashes consist of 50 to 90 percent passing the 4.75 mm sieve while boiler slags have 90 to 100 of the material passing the 4.75 mm sieve. They both also generally consist of less than 10 percent of their material passing a 75 μm sieve. Bottom ash typically is well-graded and boiler slag more uniformly graded.

As noted in Table C3-1, the specific gravity of bottom ash and boiler slag typically ranges from 2.1 to 2.9, however values as low as 1.9 and as high as 3.4 have been observed. In instances where the specific gravity is particularly low, this is an indication of porous particles in the mix which could contain the agglomerations which should be avoided and removed. In instances where the specific gravity is particularly high, this is a potential indication of the presence of pyrite (iron) which is also a potentially deleterious substance which should not be present.

As there are typically no admixtures used to enhance the combustion of coal, the chemical composition of the resultant ash and slag is controlled by the type of coal which is burned and not the type of furnace used. Boiler ash and bottom slag are composed primarily of silica (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3), with smaller quantities of calcium, potassium, sodium, magnesium, titanium, phosphorous and sulphur oxides.

Coal bottom ash has a low pH combined with the presence of mineral salts which may potentially be corrosive to metal structures when used as an embankment, backfill or road base/subbase. It is recommended that standard corrosivity testing (pH, electrical resistivity, soluble chloride content and soluble sulphate content) be completed to ensure its use will not adversely affect the intended design.

When evaluating the use of coal bottom ash as a construction aggregate, the designer should be aware that the degradation under compaction is two to three times greater than conventional aggregates (boiler slag is roughly equal to conventional aggregates). The degradation under compaction is an index which calculates the percent reduction in the mean size before compaction and after compaction.

Toxicity or environmental concerns/impacts

The US Environmental Protection Agency (USEPA) has conducted past regulatory determinations (1993 and 2000) and did not identify environmental hazards associated with the use of coal combustion products (CCP) such as coal bottom ash and boiler slag. The USEPA also indicated that CCP's can vary, sometimes significantly based on the source and that the unencapsulated uses of CCP's require independent environmental testing as well as a thorough hydrogeologic evaluation to ensure that local water quality guidelines are met and local groundwater is protected (EPA 2005).

Technical Limitations

Although it would result in additional cost, coal ash producers should put in place a process to ensure that pyrites are removed from the coal prior to burning if they want their by-products to be considered for use as recycled aggregates. If the resultant boiler ash contains pyrite, this can have deleterious effects to the boiler ash end product.

Research has shown that coal bottom ash particles have a lower durability than conventional aggregates. As such, they are better suited for use in low duty applications such as in binder course, shoulder and cold mix applications for low volume and secondary roads.

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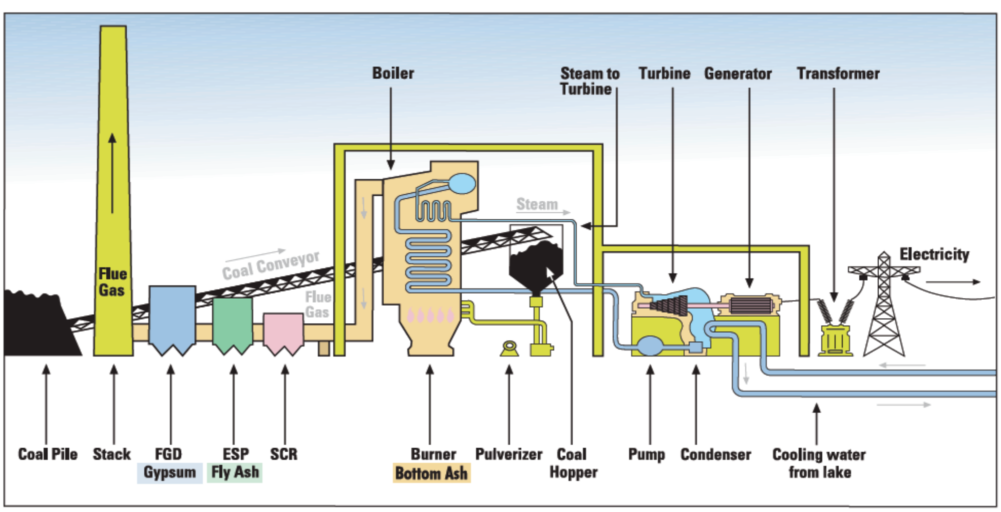
C-4 – COAL FLY ASH

Coal fly ash is a coal combustion product which is recovered from the emission control system of thermal power generation plants. Coal fly ash is a light, airborne particulate entrained in the flue gases created in the combustion of pulverized or finely ground coal and is collected in the flue gas emission control system using electrostatic precipitators, baghouses, or cyclones. Once the coal has been burned, as much as 80 percent of the unburnt material (depending on the type of plant) is removed as ash in the hot combustion gases (flue gas) and recovered as fly ash, with the remaining 20 percent of the unburnt material collected in the bottom of the combustion chamber (bottom ash).

How it is generated/quantities generated

Coal fly ash is most commonly generated during the production of electricity at coal-fired thermal generation plants by the combustion of pulverized coal. There are three general types of coal-fired boiler in use in North America: dry-bottom boilers, wet-bottom boilers and cyclone furnaces. By far the most common coal-fired boiler type in Canada is the dry-bottom boiler. Once the coal has been burned, the remaining unburnt material either settles to the bottom of the furnace or remains airborne and escapes as fine particulate entrained in the flue gases. This fly ash is then captured in the flue gas emission control system of the plant as outlined in Figure C4-1.

Figure C4-1 Typical Thermal Generation Plant Flow Chart (courtesy of www.opg.com)

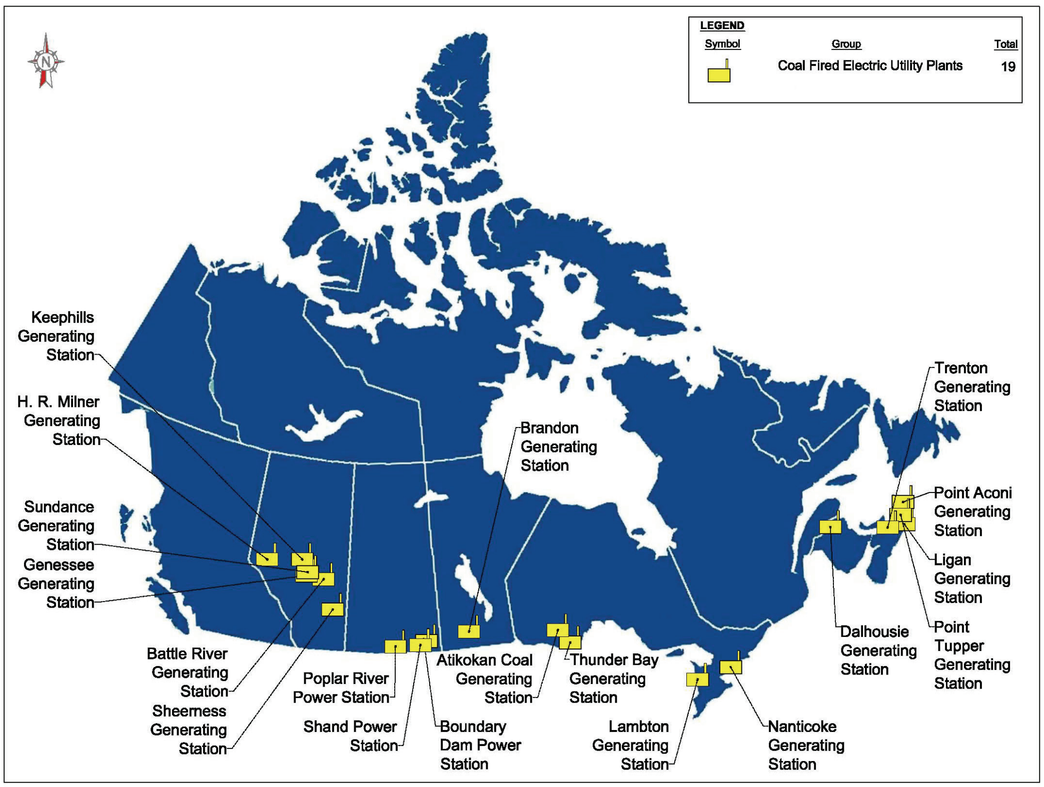


The association of Canadian industries recycling coal ash estimates that annual production of fly ash is nearly 4.7 million tonnes.

Typical sources

As coal fly ash is by-product in the generation of electricity from thermal generation plants, these by-products can be found at coal fired electric generating facilities such as electrical utilities and to a lesser extent, some major industries which employ coal fired electric plants. Currently there are 20 active coal fired electric generating facilities in operation in Canada. Figure C4-2 shows the typical sources in Canada. Coal fly ash would typically be obtained from commercial ash vendors as electrical utilities do not tend to market the materials themselves.

Figure C4-2. Location of Coal Fired Electric Utilities in Canada



In what forms can Coal Fly Ash be used and in what quantities

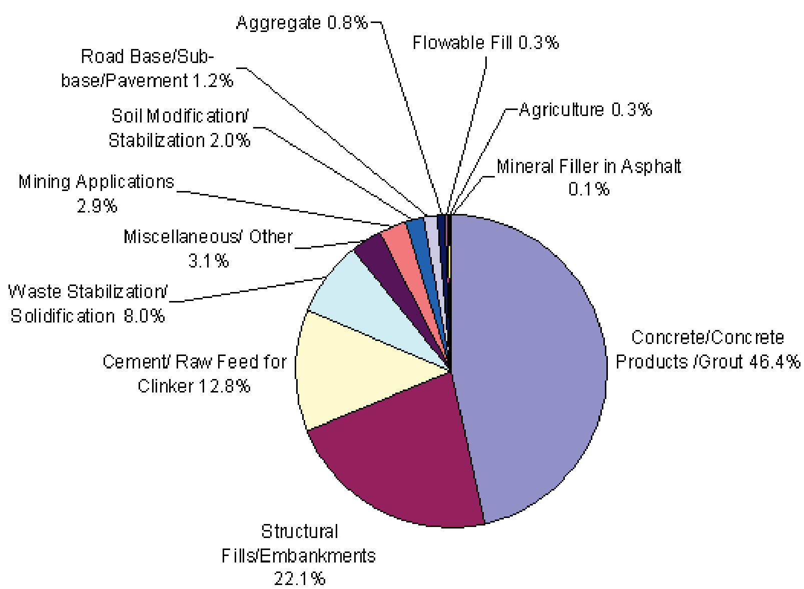
The fly ash which is recovered from the emission control system of the coal furnaces consists of fine powdery particles that are predominantly spherical in shape and mostly glassy in nature. The fly ash particle size is similar to that of a silt or very fine sand as shown in Photograph C4-1.

Photograph C4-1 Coal Fly Ash (ACC, 2010)

There is a limited amount of reuse of coal fly ash in Canada according to Association of Canadian Industries Recycling Coal Ash estimates (31 percent (CIRCA 2006)) and Canadian reuse is less than that of the United States (43 percent (ACAA 2011)) and Europe (88 percent (CIRCA, 2006)). Only 25 percent of survey respondents for this Guide indicated that coal fly ash is currently permitted for use, or is being used on a trial basis in their jurisdictions.

Figure C4-3 (ACAA, 2011) illustrates some common applications of coal bottom ash in the United States which would be similar to those in Canada. The most common use of coal fly ash in transportation infrastructure is as a cement and mineral admixture in the production of concrete and concrete products and is also widely used as an embankment or structural fill material. Other, less prevalent, uses in transportation infrastructure include use as a stabilizing agent in pavement base/subbases, flowable fill and mineral filler in asphalt concrete.

Figure C4-3. Common Applications of Coal Fly Ash in the United States (ACAA, 2011)



Fly Ash Use in Portland Cement Concrete

Coal fly ash has been used as a mineral admixture in portland cement concrete for nearly 60 years. Fly ash can be used as a partial replacement for, or addition to, portland cement and can be added directly into ready-mix concrete at the batch plant without any special equipment or processes. In addition to use as an admixture, fly ash can also be interground with cement clinker or blended with portland cement to form two blended cement products: portland-pozzolan cement (Type IP) which may contain 15 to 40 percent fly ash; and pozzolan modified portland cement (Type I-PM) which may contain up to 15 percent fly ash.

Fly ash for use in concrete must meet the chemical and physical requirements of one of the two classes identified in CSA A3001 (ASTM C618 in the United States): Class F fly ash and Class C fly ash. Class F fly ash is usually derived from the burning of anthracite or bituminous coal. It generally is composed of less than 10 percent lime and is considered as a pozzolan (cement extender), with little to no cementing value. Class C fly ash is usually derived from the burning of lignite or subbituminous coal. It is generally composed of between 15 and 35 percent lime and can be used as an admixture due to its cementing properties as a partial replacement for portland cement as well as its pozzolanic properties. In both cases, high quality fly ash has been shown to improve many of the properties of the resultant finished concrete product.

In order to ensure the quality of resultant portland cement concrete mixes, fly ash providers should have thorough quality control/quality assurances practices in place to ensure that the fly ash that is provided is as consistent and uniform as possible.

The quality of fly ash is highly dependent on the source of the fuel for the furnace and less dependent on the burning process. In this regard, there are some general guidelines on which materials to avoid when evaluating the materials from a particular source (reproduced from FHWA, 2008):

- Ash from a peaking plant instead of a base loaded plant;
- Ash from plants burning different coals or blended coal;
- Ash from plants burning other fuels (wood chips, tires, trash) blended with coal;
- Ash from plants using oil as a supplementary fuel;
- Ash from plants using precipitator additives, such as ammonia;
- Ash from start-up or shut-down phases of operation;
- Ash from plants not operating in 'steady state'; and
- Ash that is handled and stored using a wet system.

Embankment or Structural Fill

The use of fly ash in the construction of structural fills and embankments has been used for over 40 years in the United States with similar experience in Canada. Such use is covered by a standard guide in ASTM E2277-03. When used as an embankment or structural fill, fly ash would replace natural soils in their entirety. In areas where fly ash is readily available in bulk quantities, the cost of fly ash may be less expensive than sourcing equivalent borrow materials. In addition, when designed properly, fly ash has comparable engineering properties to most borrow materials, while also having a lower dry unit weight.

Virtually any fly ash can be used for embankment construction or as structural fill as long as the material meets environmental (leachate) regulations. However, fly ash derived from bituminous coal is almost solely used in embankment construction as fly ash derived from lignite or subbituminous coal is self-cementing and can harden prematurely during construction which can make it difficult to handle and may prevent it from being properly compacted. There are procedures, however, where lignite or subbituminous coal fly ash can be pre-conditioned with water prior to delivery with the resultant slightly cemented particles run through a crusher to remove any agglomerations prior to delivery.

Fly ash is composed of very fine, silt sized particles and as a consequence has a tendency to wick water, making it possible that the lower portions of the fly ash fill may become saturated. In order to mitigate this capillarity, it is recommended that a drainage layer be placed at the base of the embankment. In addition, fly ash may be susceptible to frost. This results in loss of bearing strength as well as frost heaving. It has been observed that the addition of a moderate amount of lime or cement to the top portion of the fly ash embankment is effective at mitigating the frost heave.

Stabilized Base and Subbase

Granular base and subbase stabilization refers to a process where aggregate materials are mixed with a binder such as portland cement, lime, asphalt cement or asphalt emulsion in order to increase it's strength and durability. This process is quite common in transportation infrastructure projects and includes highways, roads, driveways, parking lots, aprons and runways. Fly ash can also be used in this type of application due to its pozzolanic and self-cementing properties.

Both bituminous (Class F) and lignite or subbituminous (Class C) fly ashes can be used to stabilize base and subbase materials. Due to its self cementing properties, Class C fly ash can be used for stabilization without an additional activator. Depending on the source and the amount of stabilization required, it would typically be added at a rate of between 5 to 20 percent by mass. When bituminous fly ash is used, an activator such as portland cement or lime must also be added to stimulate the stabilization process. For most coarse grained granular base materials, an 8 to 20 percent addition rate is typical while a 15 to 30 percent would be expected for fine grained (sandy) subbases.

Flowable Fill

Flowable fill, also known in other jurisdictions as unshrinkable fill, controlled low strength material (CLSM), controlled density fill (CDF) and lean concrete slurry, is the term given to a self compacting blend of sand and other proportions of fine aggregate which is combined with a cementitious binder to form a self levelling backfill material which replaces compacted earth fill in utility cut restorations. Fly ash is ideally suited for this type of application given its fine particle size and spherical particle shape and can be used in this type of application both as a fine aggregate and as a supplement to, or full replacement for the cementitious binder.

There are two general categories of flowable fill mix which contain fly ash: high fly ash content mixes and low fly ash content mixes. The general mix requirements are outlined in ACI 116R. In high fly ash content mixes, up to 95 percent of the mix consists of Class F fly ash with the other 5 percent the cementitious binder which is often portland cement but may also be composed of Class C fly ash. There can be many different mix designs and proportions for low fly ash content mixes, but they would generally consist of a majority of fine aggregate or filler along with a percentage by mass of fly ash. Class C fly ash is almost always used in low fly ash content flowable fill mixes due to its cementitious properties.

Asphalt Concrete

Asphalt concrete is produced by combining asphalt cement with various blends of mineral aggregate. In some mixes mineral filler is added to improve the density and strength of the mixture. Mineral fillers such as lime are used to not only improve the density and strength of the mixture but also to provide additional resistance to moisture sensitivity (stripping resistance). Because Class C fly ash contains over 30 percent calcium, and fly ash is hydrophobic in nature, it to can also be used as a mineral filler to improve stripping resistance of asphalt concrete mixes. Research has also been completed at Dalhousie University which has shown that fly ash can be used as an asphalt cement extender (up to 30 percent replacement of asphalt cement) without any significantly negative effects on the strength and durability of the mix (Simms 1998). There is not much documentation however of the commercial use of fly ash as an asphalt cement extender in Canada.

The use of fly ash in asphalt pavements is governed by the specification requirements of ASTM D242 and AASHTO M-17. Mineral filler may be added up to 6 percent by mass of the hot-mix asphalt concrete mixture, but more typically is added at less than 3 percent by mass. The amount of mineral filler added is subject to proper mix design to ensure that all mix design compliance parameters are met.

Engineering Properties of Coal Fly Ash

The engineering properties of interest for fly ash vary considerably based on the application in which it is used. The engineering properties of fly ash have been subdivided based on its potential use in various transportation infrastructure projects and is outlined below (FHWA, 2008).

Portland Cement Concrete (PCC)

The engineering properties of interest for fly ash when used as an admixture or portland cement extender in PCC mixes include fineness, loss on ignition (LOI), chemical composition, moisture content and pozzolanic activity.

Fineness

Fineness is the primary physical characteristic of fly ash that relates to pozzolanic activity. As the fineness increases, the pozzolanic activity can be expected to increase. Current specifications include a requirement for the maximum allowable percentage retained on a 0.045 mm sieve when wet sieved. ASTM C618 specifies a maximum of 34 percent retained on a 0.045 mm sieve.

Loss on Ignition (LOI)

Many specifying agencies specify a maximum LOI value that does not exceed 3 or 4 percent, although ASTM criteria allow a maximum LOI content of 6 percent as carbon contents (reflected by LOI) higher than 3 to 4 percent have an adverse effect on air entrainment. For fly ashes to be used, they must have a low enough LOI (usually less than 3 percent) to satisfy ready-mix concrete producers that are concerned about product quality and the control of air-entraining admixtures. Furthermore, consistent LOI values are almost as important as low LOI values to ready-mix producers that strive for consistent and predictable quality.

Chemical Composition

The chemical properties of fly ash are influenced to a great extent by the chemical content of the coal burned, the air pollution control strategy at the power plant, and the techniques used for handling and storage.

Table C4-1 summarizes the normal range of chemical constituents of fly ashes from bituminous coal, lignite coal, and subbituminous coal. Lignite and subbituminous coal fly ashes have higher calcium oxide content and lower LOI than fly ashes from bituminous coals. Lignite and subbituminous coal fly ashes may have a higher amount of sulfate compounds than bituminous coal fly ashes.

Table C4-1. Normal range of chemical composition for fly ash produced from different coal types (expressed as percent by weight).

COMPONENT	CLASS F	CLASS C	
	BITUMINOUS (%)	SUBBITUMINOUS (%)	LIGNITE (%)
SiO_2	2.1 – 2.7	40-60	15-45
Al_2O_3	7.1 – 15.7	20-30	10-25
Fe_2O_3	None	4-10	4-15
CaO	0.8 – 2.0	5-30	15-40
MgO	38 – 42	1-6	3-10
SO_3	12 – 24	0-2	0-10
Na_2O	30 – 50	0-2	0-6
K_2O	1.5 – 10	0-4	0-4
LOI	1 x 10-3	0-3	0-5

The chief difference between Class F and Class C fly ash is the amount of calcium, silica, alumina, and iron percent in the ash. In Class F fly ash, total calcium typically ranges from 1 to 12 percent, mostly in the form of calcium hydroxide, calcium sulfate, and glassy components in combination with silica and alumina. In contrast, Class C fly ash may have reported calcium oxide contents as high as 30 to 40 percent. The amount of alkalis (combined sodium and potassium) and sulphates (SO_4) are more abundant in Class C fly ashes than in Class F fly ashes.

Moisture Content

ASTM C618 specifies a maximum allowable moisture content of 3 percent.

Pozzolanic Activity

Pozzolanic activity refers to the ability of the silica and alumina components of fly ash to react with available calcium and/or magnesium from the hydration products of portland cement. ASTM C618 requires that the pozzolanic activity index with portland cement, as determined in accordance with ASTM C311(8), be a minimum of 75 percent of the average 28-day compressive strength of control mixes made with portland cement.

Embankment or Structural Fill

The engineering properties of fly ash of interest when used in an embankment or structural fill application are moisture density relationship, particle size distribution, shear strength, consolidation characteristics, bearing strength and hydraulic conductivity.

Moisture Density Relationship

Fly ash has a relatively low compacted density, thereby reducing the applied loading and settlement of the underlying subgrade. Conditioned fly ash tailgated over the slope of an embankment can have a loose dry density as low as 6.3 to 7.9 kN/m^3. However, when well compacted at optimum moisture content (usually between 20 and 35 percent), the dry unit weight of fly ash may be greater than 13.4 kN/m^3, as high as 15.7 kN/m^3.

Particle Size Distribution

Fly ash is predominantly a silt-sized nonplastic material. Between 60 and 90 percent of fly ash particles are finer than a 75 μm sieve. As such, fly ash can be considered to be frost-susceptible. Laboratory test results show that unconfined compressive strength of compacted fly ash was not affected by freeze-thaw cycles, because the degree of saturation was not 100 percent, which allowed for volumetric expansion of freezing water to occur without affecting the fly ash strength.

Shear Strength

The shear strength of freshly compacted fly ash samples is primarily from internal friction, although some apparent cohesion has been observed in bituminous (pozzolanic) fly ashes. The shear strength of fly ash is affected by the density and moisture content with maximum shear strength occurring at optimum moisture content. Bituminous fly ash has a friction angle that is usually in the range of 26° to 42°. A test program involving shear strength testing for 51 different ash samples resulted in a mean friction angle of 34°, and a standard deviation of 3.3°, therefore, a friction angle of 30° would be a reasonable estimate for design.

Consolidation Characteristics

An embankment or structural backfill should possess low compressibility to minimize roadway settlements or differential settlements between structures and adjacent approaches. Consolidation has been shown to occur more rapidly in compacted fly ash than fine-grained soil because fly ash has a higher void ratio and greater hydraulic conductivity than most fine-grained soils. For fly ashes with age-hardening properties, including most Class C fly ashes, the magnitude of the compressibility is reduced.

Bearing Strength

California bearing ratios (CBR) for Class F fly ash have been found to be similar to fine grained soil, with CBR values ranging from 5 to 15 percent. For naturally occurring soils, CBR values normally range from 3 to 15 percent for fine-grained materials (silts and clays), from 5 to 40 percent for sand and sandy soils, and from 20 to 100 percent for gravels and gravely soils.

Hydraulic Conductivity

The hydraulic conductivity of well-compacted fly ash ranges from 10^{-4} to 10^{-6} cm/s, which is roughly equivalent to the hydraulic conductivity of a silty sand to silty clay soil. The hydraulic conductivity of fly ash is affected by the degree of compaction, grain size distribution, and internal pore structure.

Stabilized Base and Subbase

The engineering properties of interest for fly ash when used in stabilized base applications include water solubility, moisture content, pozzolanic activity, and fineness.

Water solubility

The physical requirements most frequently cited for the use of fly ash (Class F) in PSB mixtures are provided in ASTM C593 which specifies a maximum water soluble fraction of 10 percent.

Moisture content

If conditioned fly ash is used, the moisture content of the conditioned ash should be determined prior to mixing to confirm the moisture content is in the same range as the ash used during mix design.

Pozzolanic activity

Pozzolanic reactivity is an indicator of the ability of a given source of fly ash to combine with calcium to form cementitious compounds. The pozzolanic reactivity of fly ash is influenced by the fineness, silica and alumina content, LOI, and alkali content. Besides the gradation of the aggregate used, the pozzolanic reactivity of the fly ash is the major contributor to the strength of the base mix. Pozzolanic activity of fly ash with either lime or Portland cement can be determined using the test methods described in ASTM C311.

Fineness

Fineness requirements for stabilization of soil with Class F fly ash, which requires mixing with lime, are given in ASTM C593. ASTM C593 specifies that 98 percent of the fly ash should be finer than 0.6 mm sieve and 70 percent finer than 75 μm sieve.

Flowable Fill

The engineering properties of interest for fly ash when used in flowable fill applications include compressive strength, flowability, stability, bearing capacity, modulus of subgrade reaction, lateral earth pressure, time of set, bleeding and shrinkage, density and hydraulic conductivity.

Compressive strength

Strength development in flowable fill mixtures is directly related to cement content and water content, particularly when Class F fly ash is used. Most high fly ash content mixes only require from 3 to 5 percent of the cementitious material be portland cement to develop 28-day compressive strengths in the 345 to 1000 kPa range. For low fly ash content mixes with Class C fly ash, the fly ash contributes to the strength development and can also be a complete replacement for portland cement. Ultimate strengths may gradually increase well beyond the 28-day strength, perhaps even beyond 90 days, especially in high fly ash content mixes.

Flowability

Flowability or fluidity is a measure of how well a mixture will flow when being placed. Mixes with higher water content are more flowable. Flowability can vary from stiff to fluid depending on the job requirements. Flowability can be measured using a standard concrete slump cone, a flow cone, or a modified flow test using an open ended 75 mm diameter by 150 mm high cylinder.

Flowability ranges associated with the standard concrete slump cone (ASTM C143) generally vary from 150 mm to 200 mm. For high fly ash content mixes, the slump ranges can be expected to be at least 25 to 50 mm higher than low fly ash content mixes at comparable moisture contents.

Stability

For low fly ash content flowable fill materials, triaxial testing indicates a drained friction angle of 28° and a cohesion of 33 kPa for 7 day strength. For high fly ash content flowable fill materials, triaxial testing indicates a drained friction angle of 33° and a cohesion of 34 kPa for 7 day strength.

Bearing capacity

The unconfined compressive strength of flowable fill increases with time; therefore, the bearing capacity increases with time. With an unconfined compressive strength of 685 kPa, flowable fill has two to three times the capacity of most well-compacted granular soil fill materials.

Modulus of subgrade reaction

The modulus of subgrade reaction (k), used for the design of rigid pavement systems, is usually in the range of 8.2 to 49.2 MPa/m for most soils and 82 MPa/m for a good granular subbase material. For flowable fill, k is usually 820 MPa/m or higher, meaning flowable fill is superior to any earthen backfill.

Lateral earth pressure

Because of lateral fluid pressure at the time of placement, flowable fill installations at depths in excess of 1.8 m are normally placed in separate lifts, with each lift not exceeding 1.2 to 1.5 m. Once flowable fill has hardened, the lateral pressure is reduced.

Time of set

For most flowable fill mixes, especially those with high fly ash content, an increase in the cement content or a decrease in the water content, or both, should result in a reduction in hardening time. Typical high fly ash content flowable fill mixes (containing 5 percent cement) harden sufficiently to support the weight of an average person in about 3 to 4 hours, depending on the temperature and humidity. Within 24 hours, construction equipment can operate on the surface without damage. Some low fly ash content flowable fill mixes, especially those containing self-cementing fly ashes, have hardened sufficiently to allow street patching within 1 to 2 hours following placement.

A setting time of 15 hours for mixes of fly ash and crushed sand, regardless of cement content, have been observed with test method ASTM D6024, which takes into account field parameters. As the cement is the main component that dominates the setting time for flowable fill mixes, reduced setting time is expected as the cement content increases. However, when fly ash in large quantities (500 kg/m^3) is used, the fly ash contributes to the setting process by shortening the setting time, and the change in the cement content is less dominant.

Bleeding and shrinkage

High fly ash content flowable fill mixes with relatively high water contents (250 mm slump) tend to bleed water prior to initial set. Evaporation of the bleed water often results in shrinkage of approximately 1 percent of flowable fill depth. The shrinkage may occur laterally as well as vertically. No additional shrinkage or long-term settlement of flowable fill occurs once the material has reached an initial set. Low fly ash content mixes, because of their high fine aggregate content and ability to more readily drain water through the flowable fill, tend to exhibit less bleeding and shrinkage than high fly ash content mixes.

Density

The density of standard flowable fill is similar to that of well-compacted soil in the range of 1850 to 2300 kg/m^3, with the material being heaviest when first placed. High fly ash content flowable fill mixes are usually lighter than low fly ash content fills and can have densities as low as 1450 kg/m^3. With the addition of lightweight aggregate, such as crumb rubber, flowable fill can have a relatively low density 1170 to 1570 kg/m^3 and be considered a lightweight fill.

Hydraulic conductivity

Hydraulic conductivity of high fly ash content flowable fill mixtures decrease with increasing cement content and are in the range of 10^{-6} to 10^{-7} cm/sec. The hydraulic conductivity of low fly ash content flowable fill mixtures is greater than that of high fly ash content mixtures, and typically are in the 10^{-4} to 10^{-6} cm/sec range. In general, hydraulic conductivity increases as the slump increases.

Asphalt Concrete

The most important engineering properties of fly ash for use as mineral filler in bituminous paving mixtures are defined in AASHTO M-17 and are shown in Table C4-2. These requirements include gradation, organic impurities, and plasticity characteristics. Other properties of interest include fineness and specific gravity.

Table C4-2. AASHTO M-17 specification requirements for mineral filler use in asphalt paving mixtures.

CLASS F		ORGANIC IMPURITIES	PLASTICITY INDEX
SIEVE SIZE	PERCENT PASSING		
0.006 mm	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
0.003 mm	95-100		
75 µm	70-100		

Toxicity or environmental concerns/impacts

The US Environmental Protection Agency (USEPA) has conducted past regulatory determinations (1993 and 2000) and did not identify environmental hazards associated with the use of coal combustion products (CCP) such as fly ash. The USEPA also indicated that CCP's can vary, sometimes significantly based on the source, and the unencapsulated uses of CCP's therefore require independent environmental testing as well as a thorough hydrogeologic evaluation to ensure that local water quality guidelines are met and local groundwater is protected (EPA 2005).

When fly ash is used in unencapsulated applications, there is a potential for issues with fly ash dust during storage, processing and during placement. Workers involved in handling fly ash should take additional precautions to protect their eyes and lungs from dust by wearing appropriate safety goggles and using a suitable respirator. Dust issues can be minimized by ensuring that it remains moist until overlaid or by keeping it covered. Also, there are specialized trucks with pneumatic delivery systems specially designed to reduce dusting during placement that can be used.

Technical Limitations

The main technical limitations associated with the use of fly ash in concrete are slower early strength development, extended initial setting time, difficulty in controlling air content, calendar restrictions to its use in cold weather, and uniformity of product from fly ash sources. The use of Class F fly ash usually results in slower strength development, but the use of Class C fly ash does not and may enhance early strength development.

Fly ash has a low pH combined with the presence of mineral salts which may potentially be corrosive to metal structures when used as an embankment, backfill or road base/subbase. It is recommended that standard corrosivity testing (pH, electrical resistivity, soluble chloride content and soluble sulphate content) be completed to ensure its use will not adversely affect the intended design.

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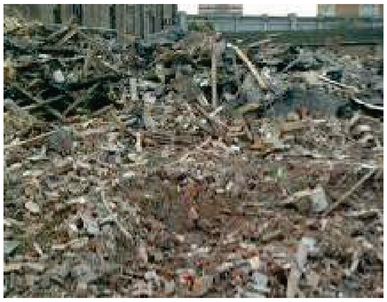

C-5 CONSTRUCTION AND DEMOLITION MATERIALS

Construction and demolition materials (C&D) consist of the wastes generated during the construction, renovation and demolition (CR&D) of residential, commercial, industrial and institutional buildings and structures. While they are sometimes sorted by demolition companies into their constituent materials and delivered to various processors for recycling, they are often composed of a heterogeneous mixture of demolition wastes such as portland cement concrete, asphalt concrete, asphalt shingles, various types of wood, paper, metals and drywall.

Due to the heterogeneous nature of most construction and demolition wastes, extreme care must be taken by agencies that are considering the use of these materials to ensure that constituents which are generally considered to be deleterious for construction such as paper, wood, organics, steel, and drywall are completely removed prior to use. In some cases where mixed C&D materials have been used in transportation infrastructure construction, major performance related issues have been observed that have required costly repairs.

How it is generated/quantities generated

Construction and demolition materials are commonly generated in two ways: wastes generated during construction or rehabilitation activities; and wastes generated during the demolition of residential, commercial, industrial and institutional buildings and structures. If these C&D wastes are in sufficient quality and quantities to justify the additional effort, they can be separated at the construction and demolition sites and then individually transported to processors that are able to recycle these materials into new products. More often, the C&D wastes either become combined or are blended together as part of the demolition process and then disposed of in landfill.

Recently, there have been a number of specialized waste recycling facilities that have been constructed which specialize in the sorting and separating of mixed C&D wastes and offer cost competitive or environmentally preferred alternatives to landfilling. One of these examples is the Construction and Demolition waste recycling facility at the Edmonton Waste Management Centre (Edmonton, 2012). At this facility, mixed construction and demolition wastes can be delivered at a tipping fee of $60/tonne. The facility then separates the mixed wastes into their individual constituents for recycling into new products.

Tracking of the quantities of C&D waste generated and disposed of in Canada is quite poor. The most recent estimates of C&D waste indicate that between 2.8 and 4.75 million tonnes are generated on an annual basis with 1.5 to 2.6 million tonnes generated annually (Concrete, Asphalt, Wood) which are potentially reusable in transportation infrastructure projects (NrCan, 2006).

Uses and Properties of C&D Materials

As construction and demolition materials can include various wastes such as portland cement concrete, asphalt concrete, asphalt shingles, various types of wood, and metals, the potential uses, engineering properties, toxicity or environmental concerns, and technical limitations of the use construction and demolition materials depend on the specific constituent material under consideration. For more detailed information on the potential for reuse of the various constituent materials, please refer to the appropriate appendix worksheets.

- Portland Cement Concrete – C14
- Asphalt Concrete – C13
- Asphalt Shingles – C15
- Wood Wastes – C22

Technical Limitations

As mentioned previously, due to the heterogeneous nature of most construction and demolition wastes, extreme care must be taken by agencies that are considering the use of these materials to ensure that constituents which are generally considered to be deleterious for construction such as paper, wood, organics, steel, and drywall are completely removed prior to use. If not properly cleaned and sorted, there is a potential for volumetric expansion of C&D concrete which contains wood, steel or gypsum which can cause performance related issues depending on the application which it was used.

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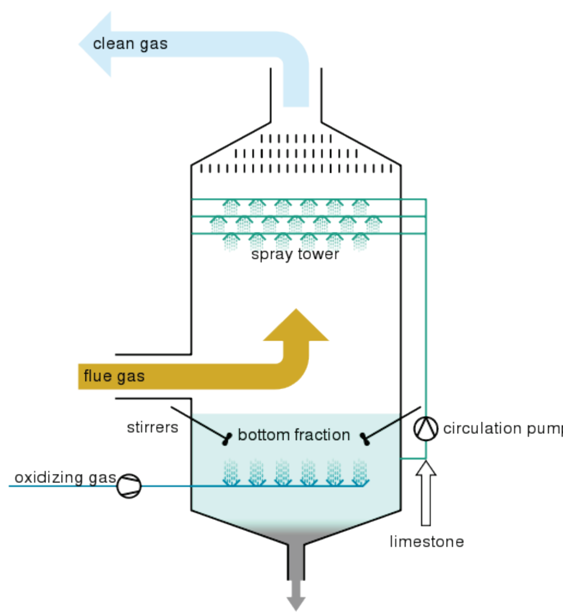
C-6 – FLUE GAS DESULPHURIZATION SCRUBBER MATERIAL

The burning of coal produces sulphur dioxide gas (SO_2), which is one of the elements which form acid rain. Since the early Nineties, most industries have been required to remove sulphur dioxide from the exhaust flue gas stream to meet environmental regulations. This is accomplished by the installation of a flue gas desulphurization emission control system. The process involves reacting the hot sulphur dioxide gases with a lime mixture in order to remove the sulphur which produces calcium sulphite ($CaSO_3$) or calcium sulphate ($CaSO_4$). Most systems are capable of removing 95 percent or more of the sulphur dioxide from the flue gases.

How it is generated/quantities generated

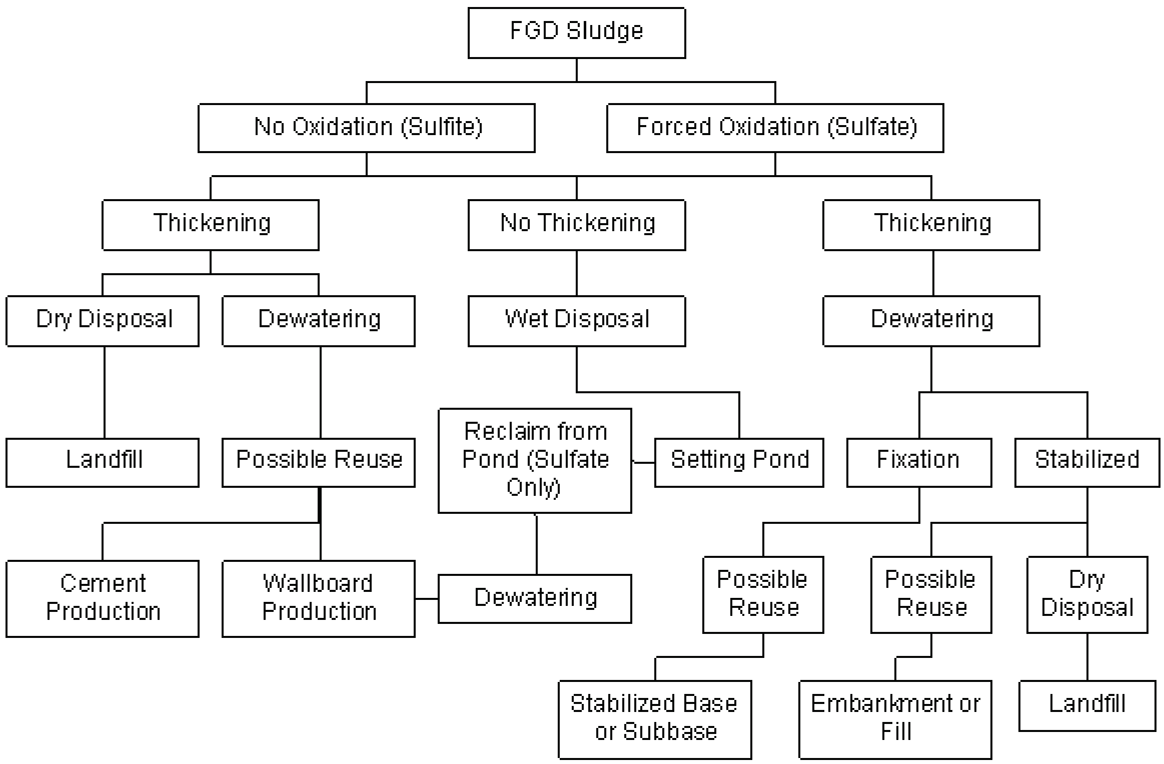
There are two main scrubber technologies in use today which can be used to remove sulphur from the flue gases prior to expulsion to the environment: wet and dry systems. In the wet system (Figure C6-1, Wikipedia, 2010) a spray of emulsified lime or limestone is sprayed into the exhaust gas. The lime reacts with the sulphur dioxide gas to produce either calcium sulphite or calcium sulphate that is collected from the bottom of the emission control unit. If oxidizing gases are introduced prior to collection, most of the resulting material will be produced as calcium sulphate, generally in the form of gypsum. – without this forced oxidation, 20 to 90 percent of the precipitate would be calcium sulphite. By forcing oxidation, synthetic gypsum is created which can readily be used in the manufacture of drywall (wallboard) for use in home construction, resulting in FGD scrubber material being the second most common coal combustion (CCP) product use in North America.

Figure C6-1 Wet Flue Gas Desulphurization Unit Schematic (Wikipedia, 2010)



Fixation and stabilization are processes which are employed in order to treat wet FGD sludges. The stabilization process involves the addition of dry material (such as fly ash) in order to assist with dewatering. FGD sludges are typical stabilized at a 1:1 ratio with fly ash and are then considered suitable for transportation using standard construction equipment. Fixation involves the addition of a stabilization agent (such as portland cement, lime, or Type C fly ash) in order to increase the strength of the sludge to a point where it can be used in structural applications. A decision tree of FGD processing, reuse, and disposal options developed by the Electric Power Research Institute is reproduced as Figure C6-2 (Duvel, 1979).

Figure C6-2. Decision Tree of FGD Processing, Reuse and Disposal Options

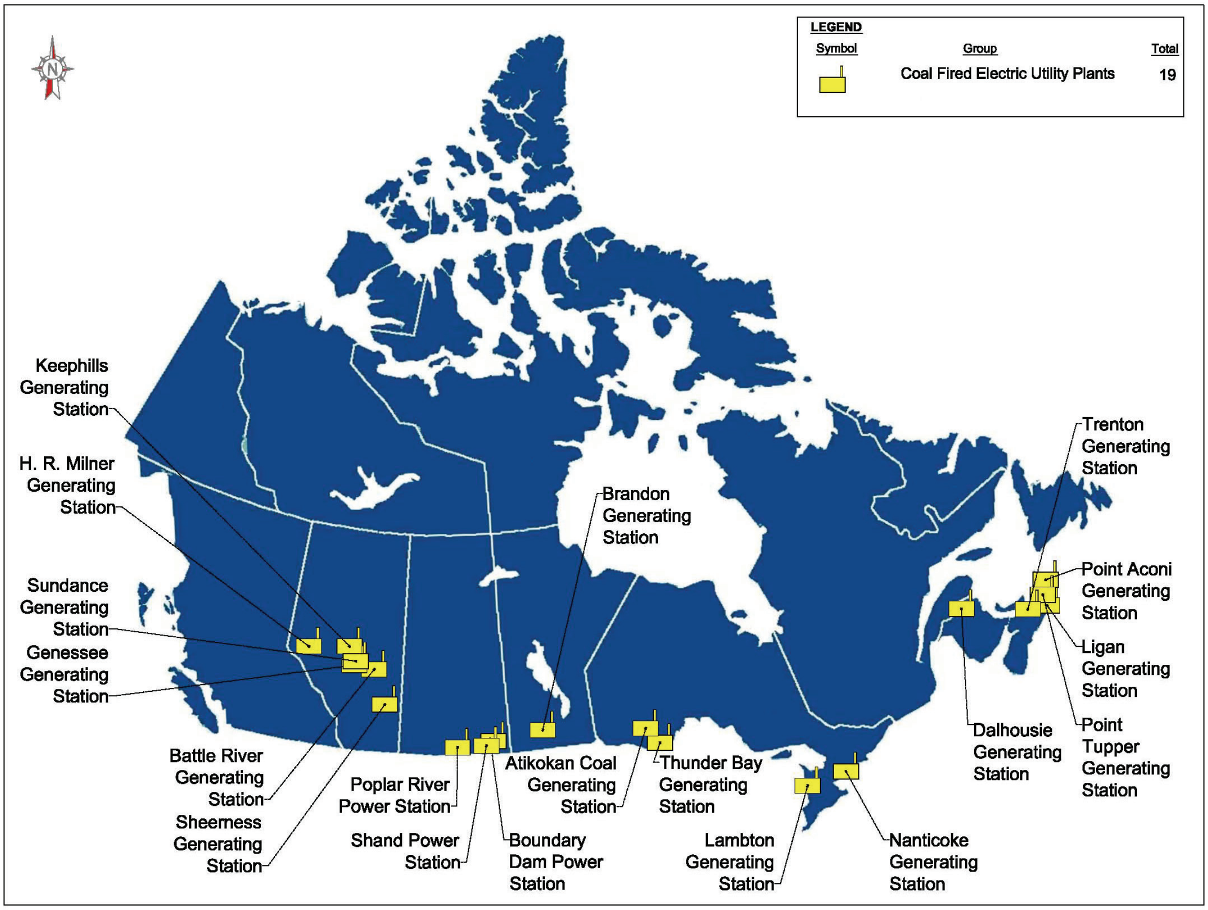


Natural Resources Canada estimates that 385,000 tonnes of flue gas desulphurization gypsum was produced in Canada in 2006, with 95 percent of this material reused, mostly in wallboard applications (NRCan, 2006).

Typical sources

As flue gas desulphurization scrubber material is mainly a by-product generated during the production of electricity in thermal generation plants, the by-product can be found at coal-fired electric generating facilities and to a lesser extent, some major industries which employ coal fired electric plants. Currently there are 20 active coal fired electric generating facilities in operation in Canada. Figure C6-3 shows the typical sources in Canada. Flue gas desulphurization scrubber material would typically be obtained from commercial ash vendors as electrical utilities do not tend to market the materials themselves.

Figure C6-3. Location of Coal Fired Electric Utilities in Canada



In what forms can Flue Gas Desulphurization Scrubber Material be used and in what quantities

As shown in Figure C6-2, dewatered and fixated flue gas desulphurization scrubber material is the by-product that is most typically used in transportation infrastructure projects, while dewatered calcium sulphate FGD scrubber material is typically used in gypsum wallboard production. As previously indicated, the principal use of flue gas desulphurization scrubber material in Canada is in the production of gypsum wallboard with 86 percent of the recycled material going towards this application. The main secondary uses of this material are in transportation infrastructure as flowable fill (total includes use as waste stabilization), and the production of cement products (such as aerated concrete blocks), with 12 and 2 percent used, respectively.

When used as a flowable fill, typically wet fixated FGD scrubber sludge is used. The wet FGD scrubber sludge is commonly fixated with fly ash at a 1.25:1 ratio with an additional 5 percent lime. A typical flowable fill mix design would include the fixated FGD material as well as 6 percent of additional lime or cement.

Engineering Properties of Flue Gas Desulphurization Scrubber Material

The engineering properties of flue gas desulphurization scrubber material that are important to transportation infrastructure projects are for fixated FGD scrubber material, as shown in Table C6-1.

Table C6-1. Typical Physical and Mechanical Properties of FGD Scrubber Material (Adapted from FHWA, 2008)

PROPERTY	DEWATERED	STABILIZED	FIXATED
Solids Content	40 – 65	55 – 80	60 – 80
Wet Unit Weight (kN/m³)	14.9 – 15.7	14.1 – 17.3	14.1 – 18.1
Dry Unit Weight (kN/m³)	9.4 – 10.2	9.4 – 13.3	12.6 – 15.7
Internal Angle of Friction (°)	20	35 – 45	35 – 45
28-Day UCS (kPa)	-	170 - 340	340 - 1380
90-Day UCS (kPa)	-	-	980 – 4600
Hydraulic conductivity (cm/sec)	10^{-4} to 10^{-5}	10^{-6} to 10^{-7}	10^{-6} to 10^{-8}

The type of coal used in the boiler process does not significantly alter the chemical composition of FGD scrubber material as it does with fly ashes and boiler slags and is almost uniquely a function of the process used to precipitate the airborne particulate in the emission control system (NETL, 2006). The major chemical components of FGD scrubber material prior to fixation and for different processing methods are shown in Table C6-2.

Toxicity or environmental concerns/impacts

Flue gas desulphurization material is highly alkaline with a pH that ranges from 9.9 to 12.6 depending on the drying medium that was used. This high end of the pH range exceeds some environmental criteria for hazardous material. The high pH value is attributed to the presence of calcium and magnesium oxides. These oxides convert to carbonates when exposed to water and the atmosphere which effectively decreases the pH over time.

Depending on the leachate test employed, the leachate from FGD material can contain dissolved calcium, sulphite and sulphate solids which may exceed some agency drinking water standards and this should be taken into consideration when choosing the application.

Table C6-2. Typical Composition of FGD (Percent by Mass) (Adapted from FHWA, 2008)

TYPE OF PROCESS	TYPE OF COAL	SULPHUR CONTENT	$CASO_3$	$CASO_4$	$CACO_4$	FLY ASH
Lime (Natural Oxidation)	Bituminous	2.9 – 4.0	50 – 94	2 - 6	0 – 3	4 – 41
Lime (Forced Oxidation)	Bituminous	2.0 – 3.0	0 – 3	52 – 65	2 – 5	30 – 40
Limestone (Natural Oxidation)	Bituminous	2.9	19 – 23	15 – 32	4 – 42	20 – 43
Limestone (Natural Oxidation)	Subbituminous	0.5 – 1.0	0 – 20	10 – 30	20 – 40	20 – 60
Dual Alkali (Ca-Na) (Natural Oxidation)	Bituminous	1.0 – 4.0	65 – 90	5 – 25	2 – 10	0
Fly Ash (Class C) (Natural Oxidation)	Lignite	0.6	0 - 5	5 – 20	0	40 – 70

Technical Limitations

The synthetic gypsum produced from flue gas desulphurization scrubber material is being used quite successfully as a replacement for natural gypsum in wallboard manufacturing with over 86 percent of the by-product directed towards this end use. Considering that there is not likely going to be additional coal fired thermal plant capacity coming on stream in the near future, there is likely not going to be considerable quantities of FGD material available for use in transportation infrastructure projects.

There remains some environmental concerns such as pH and leachate quality in the use of FGD scrubber material for transportation infrastructure use that must be adequately addressed through additional research and field testing before significant additional used can be made of this by-product.

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C-7 – FOUNDRY SAND

Foundry sand is the term given to high quality silica sand which is used in foundries to aid in the ferrous (iron and steel) and nonferrous (copper, aluminum, brass and bronze) metal casting and moulding process. The sand is used in making the outer shape of the mould cavity into which the molten metal is poured. The sand is continually reused in the casting process until heat and mechanical abrasion render the sand unsuitable for further reuse. The spent foundry sand is then stockpiled and either reused in other civil engineering applications as a recycled material or disposed of in landfill.

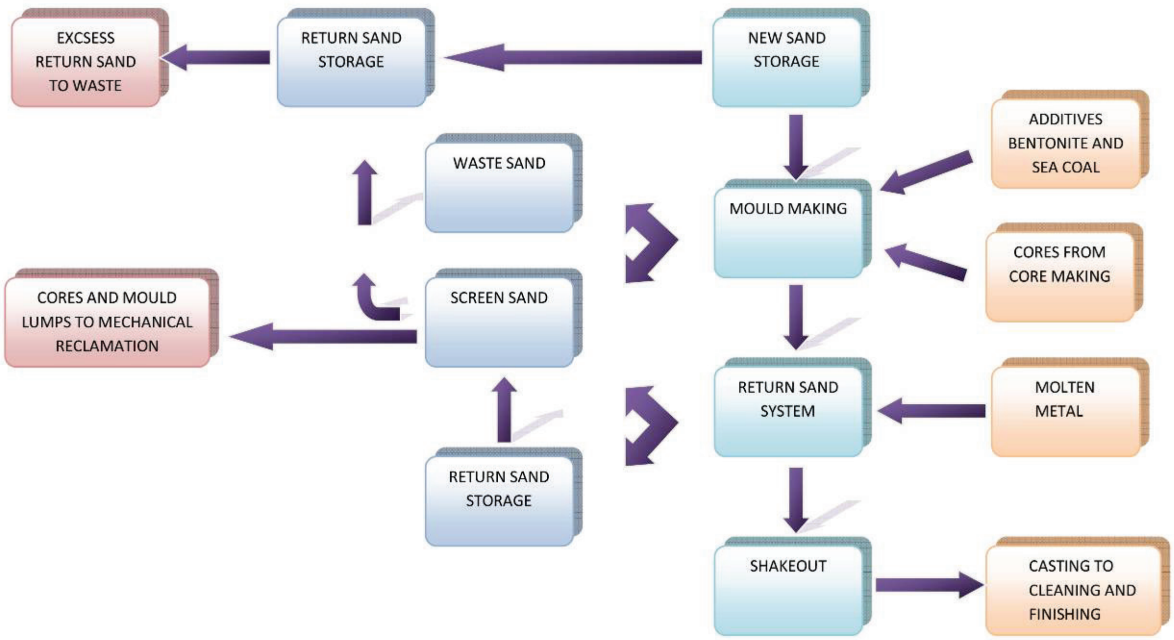
There are two basic types of foundry sand; green sand and chemically bonded sand. Virtually all moulds for ferrous castings are of the green sand variety with chemically bonded sand moulds used to produce cores (moulds that are not practical to create using green sand). Green sand moulds contain a mix of silica sand (85 to 95%), bentonite clay (0 – 12%), as well as a small percentage of carbonaceous additive (2 to 10% - sea coal, for instance) and water. The term green sand is used because molten metal is poured into the mould when the sand is dame or ‘green’. Chemically bonded sand contains silica sand with and organic binder (usually proprietary).

How it is generated/quantities generated

Foundry sand is used in making the outer shape of the mould cavity for the metal casting process. Once the liquid metal is cast into the mould and allowed to solidify, the casting is separated from the moulding and the sand is shaken out for reuse in forming another mould. Excess foundry sand is typically generated when the repeated application of heat and mechanical abrasion render the sand unsuitable for further reuse. This sand is identified in the manufacturing process and separated into what is called a waste pile as shown in Figure C7-1, which can then be used as a recycled material in other civil engineering applications, or disposed of in landfill.

About 800,000 to 1,350,000 tonnes of foundry sand are generated and reused every year in civil engineering (mainly geotechnical) applications in the United States with about 150,000 tonnes in Canada (JEGEL, 1993).

Figure C7-1. Flowchart of Foundry Operations



Typical sources

Currently there are 45 active foundries located in Canada. While foundries can be generally be found throughout Canada, the majority of foundries (75 percent) are located in Ontario. Figure C7-2 shows the typical sources of foundry sand in Canada. Spent foundry sand would typically be obtained directly from the foundry operators.

In what forms can Foundry Sand be used and in what quantities

Foundry sand is used in a number transportation infrastructure applications in the United States. Foundry sand produced by iron, steel and aluminum foundries is considered by the United States Environmental Protection Agency (USEPA) as being non-hazardous and can be used as fill for embankments, fine aggregate for flowable fill, granular road base/subbase, and as an aggregate in asphalt and portland cement concrete.

The use of foundry sand as recycled aggregate in transportation infrastructure in Canada is not very prominent. The Ministry of Transportation in Ontario has historically had the most experience in the use of foundry sand but currently has restricted its use due to concerns with the leachate not meeting Ontario environmental regulations.

In this regard, the majority of foundry sand is either disposed of in landfill or used quite successfully as an alternative material in manufacturing portland cement. Portland cement manufacturing must contain appropriate proportions of calcium oxide, silica, alumina, and iron oxide and these mineral components are significant components of most foundry sands, which can therefore replace virgin minerals.

Figure C7-2. Location of Foundries in Canada

Engineering Properties of Foundry Sand

Foundry sand produced by iron, steel and aluminum foundries has almost all of the same engineering properties as natural or manufactured sand. The quality of foundry sand is influenced by three factors: durability and soundness, chemical composition and variability. These factors change depending on which foundry the sand comes from.

Durability and soundness are determined by how the sand was used at the foundry. Repeated use of sand to form moulds can weaken the sand particles due to the extreme temperature conditions which the sand is exposed to in the metal casting process. When the sand is reused in engineering applications, it is not exposed to the same extreme temperature fluctuations as in the foundry and has shown to be highly durable in the past.

Chemical composition of foundry sand relates to its performance in engineering applications. Chemical composition (amount and type of binder, carbonaceous additives, etc) will depend on the type of metal that was cast at the foundry.

Variability should be kept at a minimum in order to achieve consistent performance when reusing foundry sand in engineering applications. Variability should be controlled by foundry sand suppliers.

Some of the typical physical and mechanical properties of foundry sand material are shown in Table C7-1 (FHWA, 2004b).

Table C7-1. Examples of Physical and Mechanical Properties of Foundry Sands (With and Without Clay)

PROPERTY	TYPICAL RANGE OF VALUES (FOUNDRY SAND WITH 6 - 12% CLAY)	TYPICAL RANGE OF VALUES (FOUNDRY SAND WITHOUT CLAY)
Bulk Density (g/cm^3)	0.96-1.12	1.28-1.44
Moisture Content (%)	3-5	0.5-2
Specific Gravity	2.5-2.7	2.6-2.8
Dry Density (g/cm^3)	1.76-1.84	1.6-1.76
Optimum Moisture Content (%)	8-12	8-10
Permeability Coefficient (cm/s)	103 - 107	102 - 106
Plasticity Index	Nonplastic to 12	–
Internal Angle of Friction (°)	32 - 41	30 - 35
Cohesion loose/dense (kPa)	4.1 – 5.2/9.9 – 12.5	0.4 – 7.2

Green sand constitutes of 85-95% silica, 0-12% bentonite clay, 2-10% carbonaceous additives and 2-5% water. The silica sand resists the high temperatures of the casting process, the clay acts as the binder to form the moulds, the water adds plasticity to the sand mixture and the carbonaceous additives (such as sea coal) aid in preventing the sand from fusing into the casting surface which would otherwise result from the high temperatures. Trace chemicals found in green sands include magnesium oxide, potassium oxide and titanium dioxide. Green sands are black or grey in color.

Chemically bonded sand constitutes 93-99% silica and 1-3% chemical binder. A catalyst is used during the mixing of the sand and the chemical binder, to cure and harden the mixture. The chemical binders used in foundry sand predominantly consist of phenolic-urethanes, epoxy-resins, furfyl alcohol and sodium silicates. Chemically bonded sands are tan or off-white in color.

Silica sand is hydrophilic which causes it to attract water to its surface. Due to this effect, care must be taken when using foundry sand in hot-mix asphalt mixtures to prevent moisture-accelerated damage and stripping of the mix. The hot-mix asphalt mix design should incorporate an appropriate antistripping additive to counteract this material property.

Foundry sands are similar to natural or manufactured sands when comparing physical properties. Foundry sands are subangular to rounded in shape. During the metal casting process, agglomerations form in the sand. When they are broken down, individual sand particles are visible again.

Toxicity or environmental concerns/impacts

Foundry sands from iron, steel and aluminum casting (containing clay) contain trace elements which are similar to those found in natural sands and are considered by the USEPA to be generally safe to reuse in highway applications. Spent foundry sands may contain contaminants such as heavy metals and phenols which may leach into the surrounding environment. Environmental testing should be undertaken to confirm if the leachate exceeds applicable environmental legislation. Should there be exceedances, there are mitigating mechanical methods such as compaction and grading which can reduce leachate development as well as other decontamination techniques which could be employed (stockpiling and watering, for instance).

The use of foundry sand as recycled aggregate in Ontario is currently restricted due to past environmental testing which determined the presence of phenols in the leachate in concentrations which exceeded Ontario environmental regulations.

It is not recommended to use spent foundry sand from brass or bronze foundries as these may contain high concentrations of cadmium, lead, copper, nickel and zinc.

Technical Limitations

There are a number of technical limitations that must be taken into account when considering incorporating foundry sand into transportation infrastructure.

As mentioned previously, silica sand is hydrophilic which causes it to attract water to its surface. Due to this effect, care must be taken when using foundry sand in hot-mix asphalt mixtures to prevent moisture-accelerated damage and stripping of the mix. The hot-mix asphalt mix design should incorporate an appropriate antistripping additive to counteract this material property. In addition, the material should be regularly tested to ensure that its mechanical properties meet project requirements and its environmental (leachate) properties meet provincial/federal regulations.

The pH of foundry sand was observed to range from 4 to 8 depending on the type of metal being cast. Depending on the volume of material being used, this can potentially change the pH of the surrounding soil enough that the soil would be considered corrosive to metal (typically pH of 5.5 or less). In addition, a similarly acidic soil could also react with the lime in concrete to form soluble leachates which can result in a more porous and weaker concrete.

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C-8 – KILN DUST

Kiln dusts are by-products generated as part of the manufacture of either hydrated lime or portland cement during the calcining process in high-temperature rotary kilns. The dust is collected in the manufacturing plant's dust collection system. The portion of the kiln dust which is not reused in the original manufacturing process is typically stockpiled for other potential beneficial uses such as mineral filler in asphalt concrete and as a base and subgrade stabilizing agent.

How it is generated/quantities generated

As the raw materials used to produce both portland cement and hydrated lime are heated and tumbled in rotary kilns, dust particles are generated which become entrained in the exhaust gases. Modern dry-collector emission control systems such as cyclones, electrostatic precipitators and baghouses are then used to trap and remove the dust particles from the exhaust gases.

Lime Kiln Dust (LKD)

Lime kiln dust can be divided into two categories based on the type of raw material that is used for the production of the hydrated lime. When calcitic limestone is used as the feedstock, the lime kiln dust typically contains more free lime which is highly reactive (also known as 'quick' lime kiln dust). When dolomitic limestone is used, the resultant lime kiln dust contains higher quantities of magnesia is less reactive.

Cement Kiln Dust (CKD)

As with lime kiln dust, cement kiln dust contains varying quantities of free lime which is highly reactive. The amount of free lime present will depend on the process employed at the production facility, as well as the source of the dust in the dust collection process.

There are two types of cement kiln processes: wet-process kilns, which accept feed materials in slurry form; and dry-process kilns, which accept feed materials in a dry, ground form. In each process, the dust can be collected in one of two ways: a portion of the dust can be separated and returned to the kiln from a stage in the dust collection system, or the total quantity of dust produced is collected for stockpiling and other potential uses (FHWA, 2008).

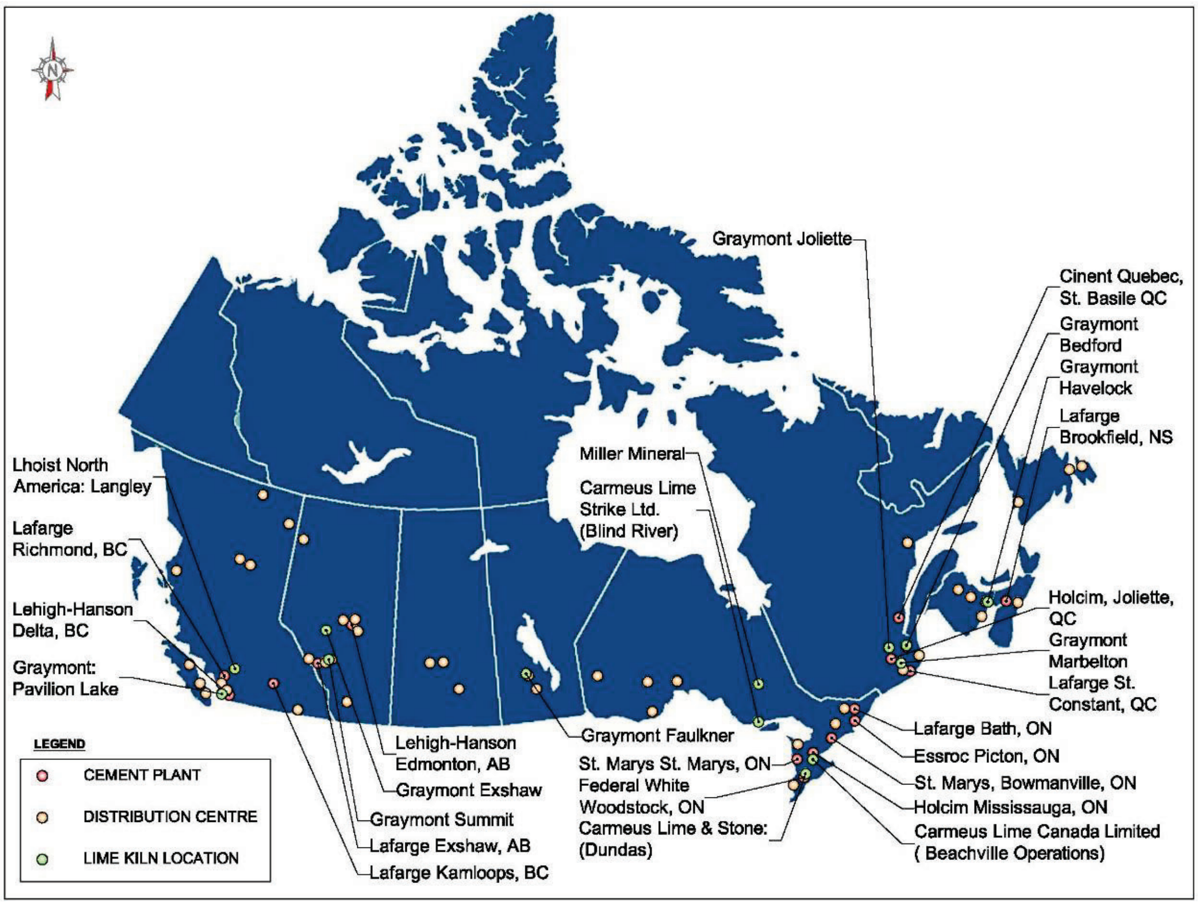
The concentration of free lime in cement kiln dust is typically highest in the coarser particles which are recovered closest to the rotary kiln (FWHA, 2008). In this regard, the concentration of free lime would be highest in cement kiln dust collected at the primary cyclone collector that does not divert this material back into the manufacturing process. The concentration of free lime is typically lower for the fine material which is collected further downstream in the process in the electrostatic precipitators and/or baghouse, and particularly when the coarse portion of the dust has been recycled back into the cement producing process. The material collected in this situation contains higher concentrations of alkalis and sulphates.

About 180,000 to 350,000 tonnes of lime kiln dust and 350,000 to 600,000 tonnes of cement kiln dust are generated each year in Canada (JEGEL, 1993) with an estimated 2 million tonnes contained in existing stockpiles.

Typical sources

Currently there are 70 active lime and portland cement plants as well as material distribution centres located across Canada. Figure C8-2 shows the typical locations across Canada. While lime and cement kiln dust may be obtained directly from the plant in some locales, it would typically be obtained from a distribution centre.

Figure C8-2. Location of Lime and Portland Cement Kilns in Canada



In what forms can Kiln Dusts be used and in what quantities

Lime and portland cement kiln dusts can be used in transportation infrastructure applications as mineral filler in hot-mix asphalt mixtures with research and trial sections having been completed for the use of kiln dusts as a stabilizing agent for granular base, granular subbase and soft or wet pavement subgrades. The current usage of these materials is however quite low with only 6 percent of the estimated available material being used on an annual basis in the United States (FHWA, 2008).

Canadian research has shown that both lime kiln dust and cement kiln dust may be suitable for use as mineral filler for hot-mix asphalt paving (Karszewski, Emery, 1981). Addition rates were reported to be as high as 5 percent by mass of the total aggregates in hot-mix asphalt surface course mixtures. When used at this addition rate in surface course mixes, the resultant material properties were shown to be similar to that of mixes containing natural fillers such as hydrated lime and stone dust. In addition, due to the lime component of these kiln dusts, their use in hot-mix asphalt mixes has reportedly also promoted improved stripping resistance similar to the use of hydrated lime or a liquid antistripping additive (JEGEL, 1996).

The main areas of increased use for kiln dusts appear to be outside of transportation infrastructure. Technical advances in cement manufacturing plants as well as new technologies have resulted in a considerable increase in the amount of portland cement kiln dust being recycled back into the cement kiln as raw feed. In addition, new technology now allows previously landfilled cement kiln dust to be mined as feedstock reducing the need for virgin aggregates (Adaska, Taubert, 2008).

Lime kiln dusts are currently being researched for use as a soil conditioner in lieu of agricultural lime. Research is ongoing and is being completed in consultation with the USEPA.

Engineering Properties of Kiln Dusts

Lime and portland cement kiln dusts are typically fine, powdery materials with over 75 percent passing the 75 μm sieve. When kiln dusts have been stored in such a way to prevent hydration, the free lime which is present in these materials allows them to be used as stabilizing and antistripping agents in transportation infrastructure projects. Some of the typical physical properties of kiln dusts are shown in Table C8-1.

Table C8-1. Typical Physical Properties of Kiln Dusts (FHWA, 2008)

PROPERTY	CEMENT KILN DUST	LIME KILN DUST
Maximum Particle Size	0.300 mm	2.0 mm
Specific Surface (cm^2/g)	4,600 – 14,000	1,300 – 10,000
Specific Gravity	2.6 – 2.8	2.6 – 3.0

Both lime and portland cement kiln dusts have been shown to increase the durability of traditional hot-mix asphalt mixes with lime kiln dusts generally having a greater impact on the increased durability than cement kiln dusts due to the higher free lime content of lime kiln dusts. Portland cement kiln dust was shown to have a negligible effect in reducing hot-mix asphalt stripping while lime kiln dust was shown to be nearly as effective as natural hydrated lime.

The chemical composition of lime and portland cement kiln dusts are similar to those of conventional materials. The principal constituents are composed of lime, iron, silica and alumina. However, when stockpiled and exposed to the environment for long periods, any free lime which was present is consumed. Some of the typical chemical properties of kiln dusts, including the differences between fresh and stockpiled materials, are shown in Table C8-2.

Table C8-2. Typical Chemical Compositions of Kiln Dusts (Collins, Emery, 1983)

PARAMETER	CEMENT KILN DUST (% BY MASS)			LIME KILN DUST (% BY MASS)		
	Fresh	Stockpiled		Fresh		Stockpiled
		Sample 1	Sample 2	High*	Low*	
CaO	40.5	31.4	44.2	54.5	31.2	31.2
Free Lime	4.4	0	0	26.4	5.1	0
SiO_2	14.5	11.7	11.9	9.94	2.46	1.74
Al_2O_3	4.1	3.18	3.24	4.16	0.74	0.71
MgO	1.55	0.97	1.73	0.49	23.5	23.3
Na_2O	0.44	0.13	0.27	0.03	0	0.05
K_20	4.66	1.65	2.92	0.22	0.09	0.03
Fe_2O_3	2.0	2.16	1.45	1.98	0.94	1.3
SO_3	6.5	8.24	2.4	7.97	2.8	3.5

* Two types of lime kiln dust were classified based on their reactivity to water.

Toxicity or environmental concerns/impacts

Due to the presence of various levels of free lime in kiln dusts, runoff collected from kiln dust stockpiles has exhibited pH levels above 12.5 which is considered to be highly corrosive. As a result, the USEPA has required that kiln dusts be handled and stored in such a way as to prevent erosion by wind and uncontrolled water runoff (EPA, 1999).

In recent years, a number of by-products have started to be used as fuel in cement kilns (used tires for instance). There is concern that the use of these by-products as fuel may affect the quality of the resultant kiln dusts, with the potential for the accumulation of heavy metals in the kiln dusts to levels which may exceed local environmental guidelines. It is important that a proposed kiln dust source be tested to ensure that the resultant leachates meet local environmental guidelines before their incorporation in transportation infrastructure projects.

Technical Limitations

The physical and chemical properties of kiln dusts can vary significantly from plant to plant depending on the raw materials and type of collection process used, however the dust collected from the same kiln, and producing the same cement type is usually consistent (Baghdadi, Fatani, 1995).

The CKD and LKD must be stored in silos or cement trucks in order to preserve the chemical properties of the materials as well as prevent excessively high pH of the resultant runoff.

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C-9 – MINERAL PROCESSING WASTE

Mining and mineral processing operations are quite prevalent throughout Canada and are a considerable source of solid waste generation across Canada. Mineral processing wastes can generally be subdivided into two main categories: mine waste rock; and mill tailings.

Most of the mining and mineral processing wastes that are generated have limited potential for reuse as construction aggregate in transportation infrastructure projects due to their fineness, high impurity content (due to commingling of multiple sources of mine waste rock) and/or transportation costs due to their remote location. However, some mineral processing wastes may be of interest because of favourable location and suitable physical and chemical characteristics and may potentially be used as asphalt aggregate, granular base (or ballast), engineered fill or embankment material.

How it is generated/quantities generated

Mineral processing wastes are generated during the process of extracting and refining mineral ores of various types. This includes the waste rock generated during stripping and blasting operations for open cut mining and blasting to open underground drives and stopes, and mill tailings generated after mechanical and chemical extraction of the mineral ores has been completed in the mill.

<u>Waste Rock</u>

Vast amounts of waste rock are generated during the extraction of mineral ores in open pit mining. This includes soil and organic materials which are stripped from the top of the mine site, as well as overburden rock which must be removed in order to extract the mineral ore. The overburden rock will vary from site to site and can consist of any combination of sedimentary, igneous or metamorphic formation through which the mine or pit is being advanced. During typical mining operations, there is little effort spent in classifying the various 'waste' overburden materials and the overburden materials are typically blended together and stockpiled in large waste piles at the mine site as shown in Photograph C9-1.

Photograph C9-1 Large Stockpile of Mine Waste Rock in Marmora, Ontario

Relatively small amounts of waste rock are generated during the development of underground mines. This includes waste rock which is generated during the development of the shafts which carry ore, equipment and personnel into and out of the mine, the drives which serve as hauling routes for the mineral ores, and the stopes which are where the mineral ores are being excavated.

It was estimated that the Canadian mineral industry creates approximately 350 million tonnes of waste rock each year (Collings, 1984).

Mill Tailings

Mill tailings consist predominantly of fine to extremely fine particles that result from the physical and chemical extraction of mineral ores. Mill tailings are typically uniform in size and consistency with the particles typically ranging in size from sand to silt-clay, depending on the degree of processing required to extract the mineral ore. An example of dried mill tailings is shown in Photograph C9-2.

Photograph C9-2 Tailings Pond at Barrick Goldstrike Mine

Mineral processing techniques will vary depending on the type of mineral ore that is being processed and the deposit where the mineral ore is being extracted from. Typical mineral processing involves a combination of crushing and/or milling to a fine particle size followed by either physical extraction (gravity separation, flotation, magnetic separation, for instance) or chemical extraction of the ore.

It is estimated that the Canadian mineral industry creates approximately 300 million tonnes of mill tailings each year (Collings, 1984).

Typical sources

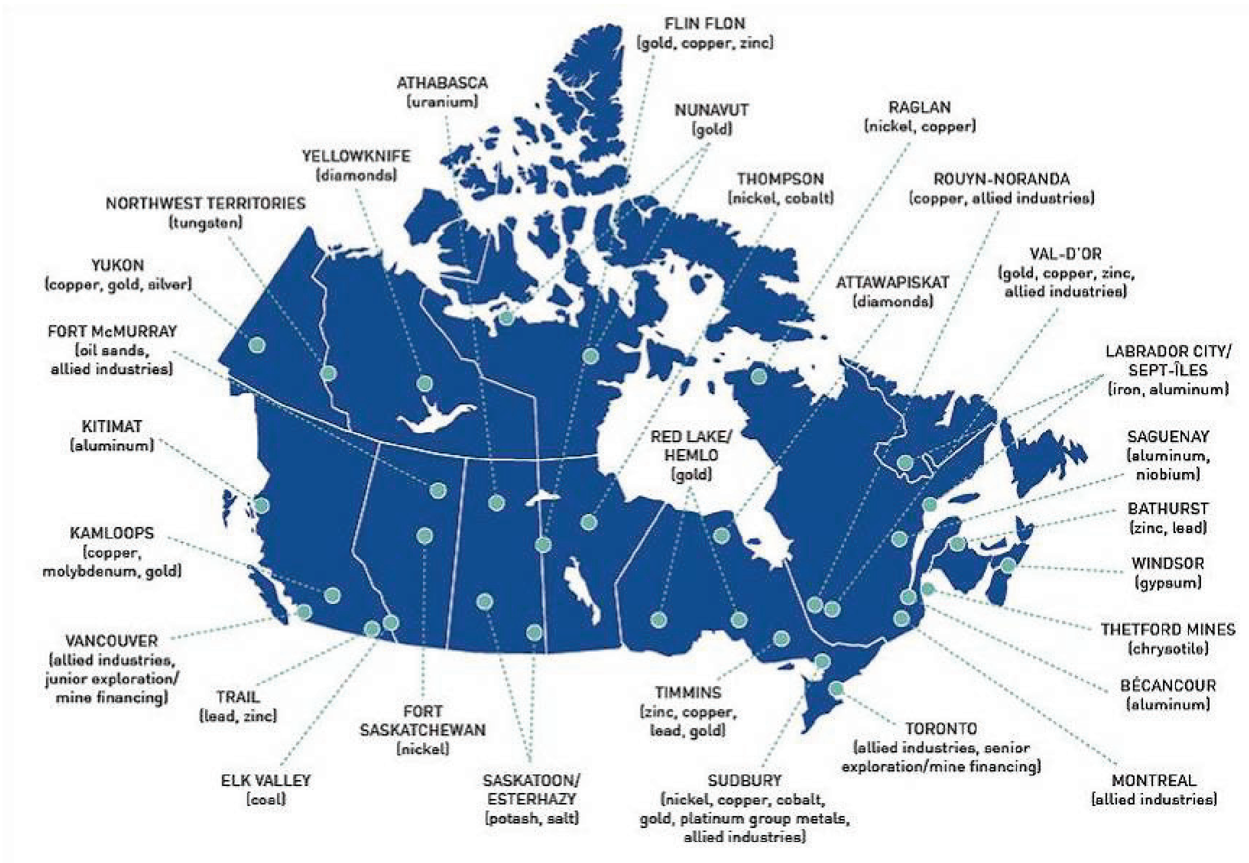
As mineral processing wastes are a by-product in the mining of ores, the can be found wherever a mine is located. There are currently over 200 active principal mines in operation in Canada (NRCan, 2006). Figure C9-1 shows the areas where active principal mines are located in Canada.

In what forms can mineral processing wastes be used and in what quantities

Depending on the geological unit from which mine waste rock has been processed (limestone, traprock or granite, for instance), mine waste rock can have the same engineering properties as natural or manufactured aggregates. Assuming that the mine waste rock can be adequately separated from deleterious materials and can be crushed and screened to meet agency specifications, mine waste rock can be used as a partial or complete replacement for natural aggregates in hot-mix asphalt mixtures, granular base and subbase course and embankment fill operations. Regardless, each potential source should be separately investigated to determine is suitability for specific use(s) in transportation infrastructure projects.

Mill tailings have been used as a partial replacement for natural fine aggregate in granular base courses, asphalt mixes and embankment fill materials. It should be noted however that some mill tailings can be contaminated with various chemical reagents used to extract the mineral from the ore. In these cases, a detailed investigation of each potential tailings source should be carried out to determine if its environmental properties meet all agency requirements.

Figure C9-1. Areas of Principal Mining Activity in Canada (MAC, 2010)



Engineering Properties of Mineral Processing Wastes

The engineering properties of mineral processing wastes are highly dependent on the source and each source should be verified independently to determine their suitability for use in transportation infrastructure projects. Some general guidelines are provided below.

Mine waste rock will consist of a range of sizes from boulders to sand sized particles. Waste rock, however, can be processed to a desired gradation by conventional crushing and screening as with conventional aggregates.

The hardness of mine waste rock is also dependent on the type and formation from which the rock was derived. As an example, iron ores are typically found in hard igneous or metamorphic formations and the resultant waste rock is typically hard and dense. Lead and zinc ores are typically found in carbonaceous rocks (limestone and dolomite, for instance) and the resultant waste rock is similar to processed carbonate aggregates.

The specific gravity of waste rock will be in the same range as those measured for similar conventional construction aggregates except for those derived from the mining of iron ores which will have a considerably higher specific gravity. The specific gravity of typical waste rock can be expected to range from 2.4 to 3.0 while the specific gravity of iron ore derived waste rock can be high as 3.6 (FHWA, 2008).

The physical properties of mill tailings will vary considerable depending on the ore type, physical processing method employed, chemical processing method employed and where it has been sampled in the tailings pond. There is also little published data on the physical properties of various mill tailings. Similarly, there is little published data on the chemical properties of Canadian waste rock and mill tailings. As such, it is recommended that each potential source should be separately investigated to determine is suitability for use in transportation infrastructure projects.

Toxicity or environmental concerns/impacts

As with most of the other properties of mineral processing wastes, the environmental properties of mineral processing wastes are highly dependent on the source, and consequently, each source should be verified independently to determine their suitability for use in transportation infrastructure projects. Some known potential environmental impacts from various mineral processing sources include:

- some waste rock and tailings have been leached with cyanide as a means of further ore extraction;
- certain sources of taconite are know to contain asbestos-like fibres;
- uranium mill tailings can be a source of low-level radiation;
- phosphate rock can be a source of low-level radiation;
- the leachate from sulphide-based inorganic metal ores may be acid generating; and
- there is little research on how variations in mineral processing techniques affect the quality of the resultant mineral processing wastes.

Technical Limitations

The main limitation that prevents enhanced used of mine waste rock in transportation infrastructure projects is that due to the remoteness of many mining sites, the transportation and additional processing costs of using this resource continue to prevent mineral processing wastes from becoming an economically viable alternative.

Existing mineral processing waste stockpiles and tailings ponds have been developed without consideration for using these wastes in other engineering applications. As such, much of the usable material such as limestone and granite are commingled with deleterious particles making their extraction and use more difficult and costly.

As mineral processing wastes are not frequently used, there is very little technical information regarding the physical and chemical properties of various mineral processing waste types. In this regard, comprehensive prior investigations are required to verify each source to determine their suitability for use.

There are known environmental issues with some mineral processing wastes which must be evaluated prior to their use as a construction aggregate alternative.

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C-10 – MUNICIPAL SOLID WASTE COMBUSTOR ASH

Municipal solid waste (MSW) refers to the stream of garbage collected though municipal sanitation services. In most jurisdictions, over 30 percent of MSW, such as medical wastes from hospitals and items that can be composted or recycled, are diverted from the waste stream with the remaining 70 percent of the MSW requiring disposal, typically through landfilling.

In some jurisdictions, as an alternative to direct landfilling, the MSW is directed to a waste-to-energy facility for combustion in order to generate electricity. As a component of the fuel source for this combustion is the waste which is normally being sent to landfill, and the composition of the waste consists mainly of organic materials such as food, paper, and wood products, MSW is considered to be a renewable fuel source not a waste.

After incineration, the volume of MSW is typically reduced by 70 percent. The remaining 30 percent of the material consists of the post-combustion products including bottom ash (grate ash, siftings, and boiler ash), and fly ash (scrubber ash, precipitator ash and baghouse ash). As the bottom ash is considered to be relatively stable, it is typically used as landfill cover, while the fly ash contains potentially leachable contaminants and is typically stabilized and disposed of in a specialized disposal facility. Recently, the bottom ash has been used on a limited basis in transportation infrastructure projects as an aggregate in asphalt concrete and in granular base/subbase applications.

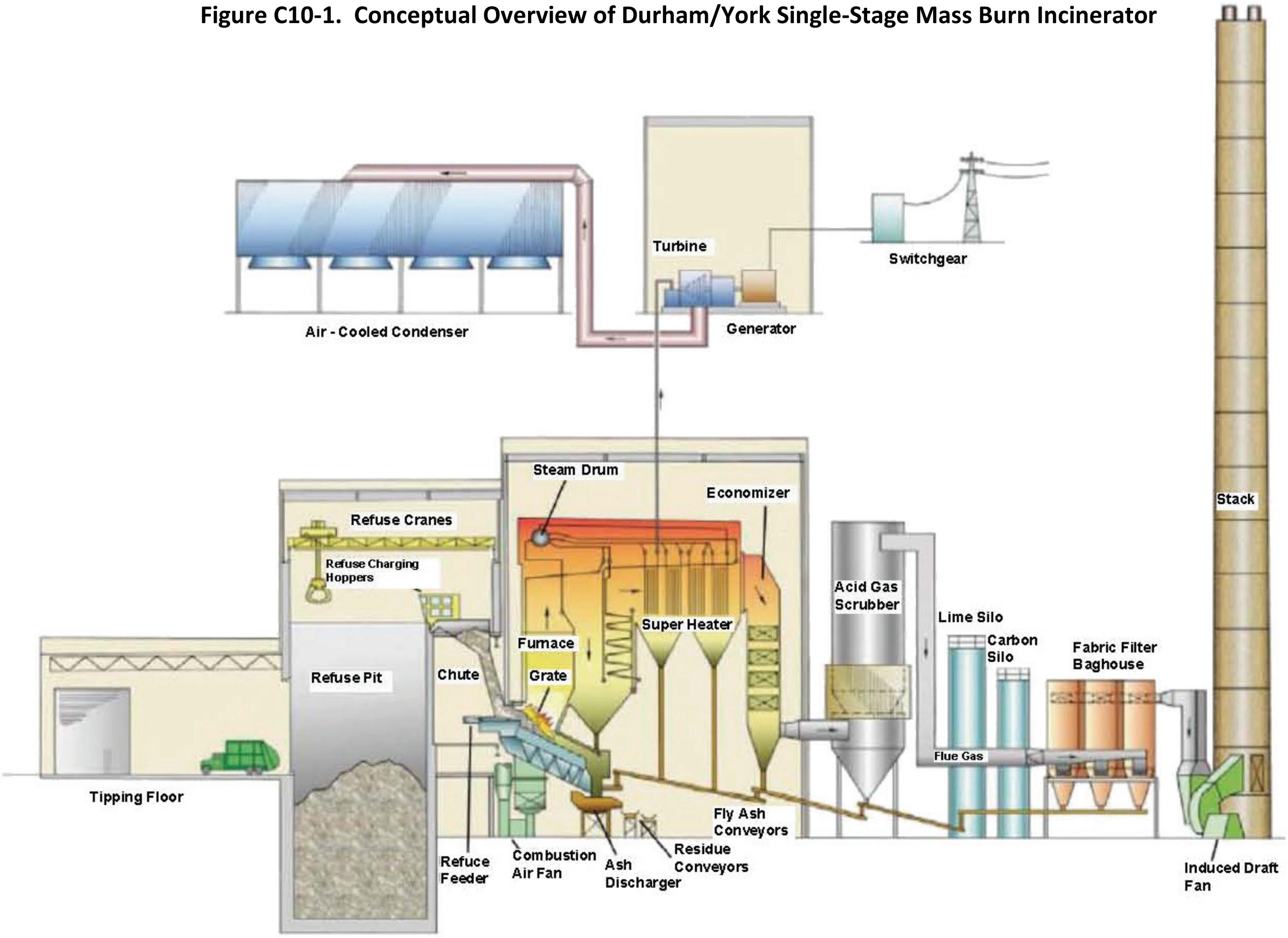
How it is generated/quantities generated

There are two main types of municipal solid waste combustion systems in operation in North America: mass burn facilities and refuse-derived fuel facilities. In Canada, other than the few refuse-derived fuel demonstration facilities, the majority of the current active MSW combustion systems employ mass burn technology.

Mass burn facilities are designed to handle unsorted solid waste and as such, minimal pre-processing is required. In these facilities, the MSW is typically brought directly into the plant and discharged into a holding pit. From there, the MSW is charged into the system by loading cranes – the cranes are also used to sort and remove large and non-combustible materials from the waste stream.

There are several stages of combustion in mass burn incinerators as shown in the example from the Durham/York (Ontario) incineration facility Figure C10-1 (Stantec, 2011). The by-products of these combustion stages are bottom ash (grate ash, siftings, and boiler ash), and fly ash (scrubber ash, precipitator ash and baghouse ash).

Figure C10-1. Conceptual Overview of Durham/York Single-Stage Mass Burn Incinerator



After incineration, the resultant bottom ash is then typically passed through a secondary screening circuit to further remove metallic residues for recycling. The organic constituents are typically consumed in the incineration process, however there are a number or inorganic constituents which remain in the bottom ash. The concentrations of the inorganic constituents vary considerably depending on the composition of the MSW. Research has shown however, that the inorganic constituents in bottom ash are typically not leachable using standard methods and have been shown to be chemically/mechanically bound in the ash matrix (Stantec, 2011). As a result, bottom ash is typically classified as non-hazardous, and in Ontario, does not require leachate testing prior to disposal. Subject to the bottom ash having residual organic contents less that 5 to 10 percent (depending on the Canadian jurisdiction), the recovered bottom ash is potentially suitable for use as a construction aggregate substitute.

MSW fly ashes are not considered to be stable and have been shown to leach inorganic constituents under standard test methods. As such, they are often classified as hazardous wastes unless site specific testing confirms that it meets local environmental regulations. Regardless, MSW fly ash in Canada is typically stabilized and disposed of in special waste disposal facilities.

About 200,000 tonnes of municipal solid waste bottom ash are generated each year in Canada with their regional quantities and uses outlined in Table C10-1 (adapted from Stantec, 2011).

Table C10-1. Generated Quantity and Utilization/Disposal of MSW Bottom Ash in Canada in 2006

FACILITY NAME	PRODUCTION TONNES (2006)	BOTTOM ASH UTILIZATION/DISPOSAL (%)
Metro Vancouver Waste to Energy Facility	46,719	90% landfill cover, 10% road base construction (mostly on landfill site)
Algonquin Power Peel Energy-From Waste Facility	38.215	74% landfill cover, 24% landfill, 2% aggregate use
L'incinerateur de la ville de Québec	86,300	100% Landfill
PEI Energy Systems EFW Facility	12,289	100% Landfill
Ville de Levis, Incinerateur	Not Known	100% Landfill
MRC del iles de la Madeleine	440	Not Known
Wainwright Energy from Waste Facility	Not Known	100% Landfill

Typical sources

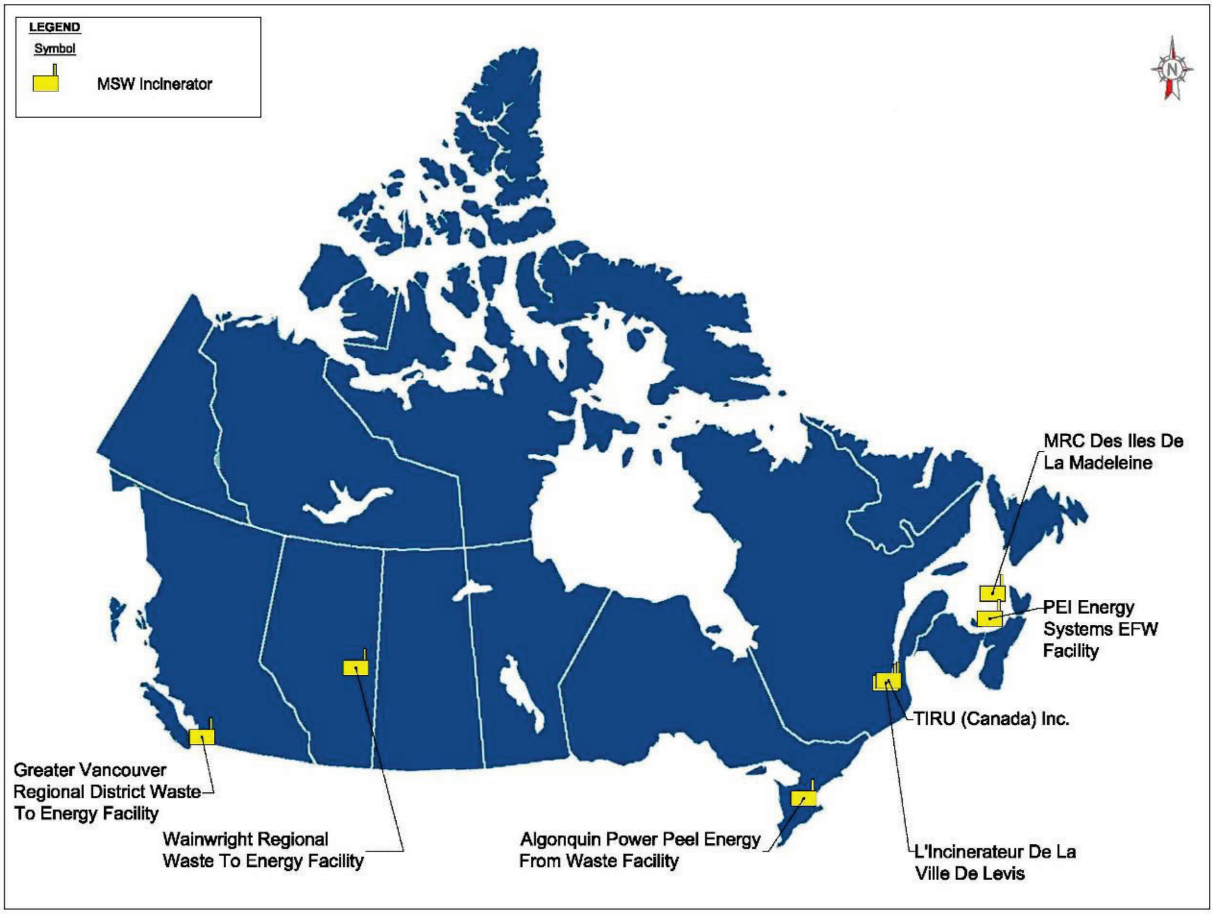
Currently there are seven active municipal solid waste thermal treatment facilities located in Canada, as shown in Figure C10-2. MSW bottom ash would typically be obtained directly from the incinerator operators.

In what forms can MSW bottom ashes be used and in what quantities

MSW bottom ash has the potential for use as aggregates in the construction of granular bases for roadways and as an aggregate in hot-mix asphalt binder and surface course production.

The use of MSW bottom ash as an aggregate replacement in granular base and subbases is considered to be a proven technology that has been used extensively in Europe (Denmark, Germany and The Netherlands, for instance) for the past 30 years. However, North American use has been limited to localized trial sections with the majority of the material still ending up in landfills. International experience indicates that MSW bottom ash can either be used exclusively as a substitute for natural aggregates in granular base applications, or more frequently is blended with natural aggregates in order to obtain the desired gradation.

Figure C10-2. Location of Municipal Solid Waste Thermal Treatment Facilities in Canada



Literature searches have revealed that there is no wide scale commercial use of MSW bottom ash in hot-mix asphalt paving. Trial sections have been completed by the Region of Peel (Ontario) which incorporated about 10 percent MSW bottom ash into hot-mix asphalt binder and surface course mixes. Early performance has been reported to be similar to that of conventional hot-mix asphalt binder and surface course mixes (OGRA, 2004).

Engineering Properties of MSW Bottom Ash

Municipal solid waste bottom ash is similar in gradation to fine graded sands and gravels, with 40 to 55 percent of the material passing 4.75 mm, 30 to 50 percent retained on 4.75 and 2 to 16 percent fines (passing 75 μm sieve). It should be noted however that the gradation properties can vary quite substantially from source to source.

MSW bottom ash is also highly absorptive with typical absorptions ranging from 4 to 17 percent. As a result, the natural moisture content of bottom ash can range from 22 to 66 percent for freshly stockpiled bottom ashes.

MSW bottom ash can also have relatively high loss on ignition values. In such cases, this suggests that the MSW bottom ash has a higher (unburnt) organic content which may make preclude recycling.

Los Angeles abrasion test results indicate that MSW bottom ash has relatively poor durability but is within the limits normally specified for hot-mix asphalt coarse aggregate. Soundness and CBR test results indicate that this material is capable of withstanding freeze-thaw cycles and has excellent bearing capacity.

Some typical physical and mechanical properties of MSW bottom ash, along with the observed ranges in these parameters, are shown in Table C10-2.

Table C10-2. Typical Physical and Mechanical Properties of MSW Bottom Ash (Adapted from FHWA, 2008)

PROPERTY	MSW BOTTOM ASH
Bulk Specific Gravity Fine Coarse	 1.5 – 2.2 1.9 – 2.4
Absorption (%)	4.1 – 17.0
Moisture Content (% Dry Weight)	22 - 66
Unit Weight (kg/m^3)	960 - 1400
Loss in Ignition (%)	1.5 – 6.4
Proctor Compacted Permeability (cm/sec)	10^{-3} – 10^{-4}
Los Angeles Abrasion Loss (%)	41 - 60
Sodium Sulphate Soundness (%)	1.6 – 2.9
California Bearing Ratio (%)	74 – 155
Angle of Internal Friction (°)	40 – 45

The chemical composition of MSW bottom ash can vary significantly depending on the source of the MSW as well as the incineration process employed. The principal constituents are typically composed of aluminum, calcium, iron and silica. Some of the typical chemical properties based on international studies are shown in Table C10-3.

Table C10-3. Typical Chemical Properties of MSW Bottom Ash (Stantec, 2011)

PROPERTY	CONCENTRATION RANGE UNITS (MG/KG)
Total Organic Content (% by mass)	0.1 – 2.2*
Aluminum	22,000 – 73,000
Antimony	10 – 430
Arsenic	0.1 – 190
Barium	400 – 3,000
Cadmium	0.3 – 70
Calcium	370 – 123,000
Chlorine	800 – 4,200
Chromium	23 – 3,200
Copper	190 – 8,200
Iron	4,100 – 150,000
Lead	100 – 13,700
Magnesium	400 – 26,000
Manganese	80 – 2,400
Mercury	0.02 – 8
Molybdenum	2 – 280
Nickel	7 – 4,200
Potassium	750 – 16,000
Silicon	91,000 – 308,000
Sodium	2,800 – 42,000
Sulphur	1,000 – 5,000
Vanadium	20 – 120
zinc	610 – 7,800

*Typical German Values

Toxicity or environmental concerns/impacts

The concentrations of some of the inorganic materials in MSW bottom ash have been shown to exceed the criteria limit of typical Canadian environmental regulations when tested using a bulk analysis procedure. Studies have indicated however that the constituents in the MSW bottom ash are chemically/mechanically bonded and are not leachable using standard test methods (Stantec, 2011). As such, MSW bottom ash is typically classified as a non-hazardous waste and can be considered for use in recycled applications.

Technical Limitations

The use of MSW bottom ash has not been commercially developed in North America for granular base or hot-mix asphalt applications and as a result, there are no current specifications for its use. Project specific requirements will have to be developed in order to ensure that the quality of the material and its properties are maintained to reduce the variability of the resultant materials.

MSW bottom ash is highly absorptive with typical absorption ranging from 4 to 17 percent. As a result, the natural moisture content of bottom ash can range from 22 to 66 percent for freshly stockpiled bottom ashes (MacViro, 2003). Consideration should therefore be given to allowing freshly stockpiled bottom ashes to condition such that its moisture content is reduced prior to transport. In addition, special handing may be required to ensure that the moisture content is suitable for use in hot-mix asphalt applications. The high absorption also results in higher asphalt cement content in HMA mixtures where MSW bottom ash is used as HMA aggregate which increases the cost with little added benefit to the mix.

In some cases, MSW bottom ash can have relatively high loss on ignition values. In these cases, this may suggest that the bottom ash has a higher (unburnt) organic content which may make preclude recycling in aggregate applications.

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C-11 – NONFERROUS SLAGS

Nonferrous slags are a molten by-product which is produced in the process of extracting nonferrous metals from natural ores. This refining process effectively separates the metal and non metal constituents with the resultant slag generally air cooled to develop 'clinker'. The clinker can then be crushed and processed for use in asphalt concrete, granular base and/or embankment or fill.

The following nonferrous slags were evaluated for use in transportation infrastructure projects: copper; nickel; phosphorous; lead; lead-zinc; and zinc. As there has been no documented commercial use of lead, lead-zinc or zinc slags during our agency scan or in the technical literature (other than research articles), they have been excluded from this analysis.

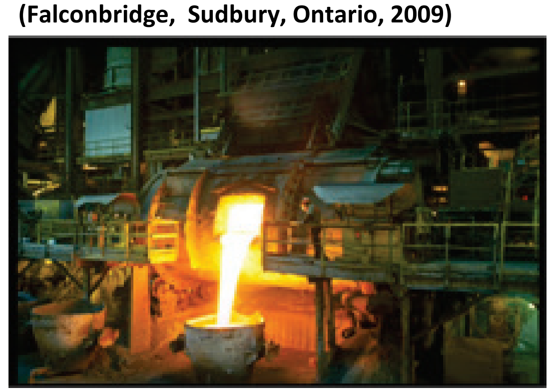
How it is generated/quantities generated

Nonferrous slags are generally produced in two different processes: smelting furnaces for copper and nickel slags; and electric arc furnaces for phosphorous slags.

Smelting Furnaces (copper and nickel slags)

In the production of copper and nickel slags, copper and nickel ore concentrates are delivered to the smelting furnace, combined with coke (to remove oxides) and a siliceous flux (to remove waste 'gangue') and superheated. The resultant product is a mix of elemental metal and slag which are tapped off as shown in Photograph C11-1. The slag is then delivered to a cooling pit where it is dumped and allowed to air cool and form 'clinker'. The clinker can then be processed in the same manner as natural aggregates for use in hot-mix asphalt mixes, granular base courses and embankment and fill operations.

Photograph C11-1 Nickel Smelting Furnace (Falconbridge, Sudbury, Ontario, 2009)



It is estimated that there is at least 1 million tonnes of copper and nickel slag generated in Canada annually (MAC, 2010).

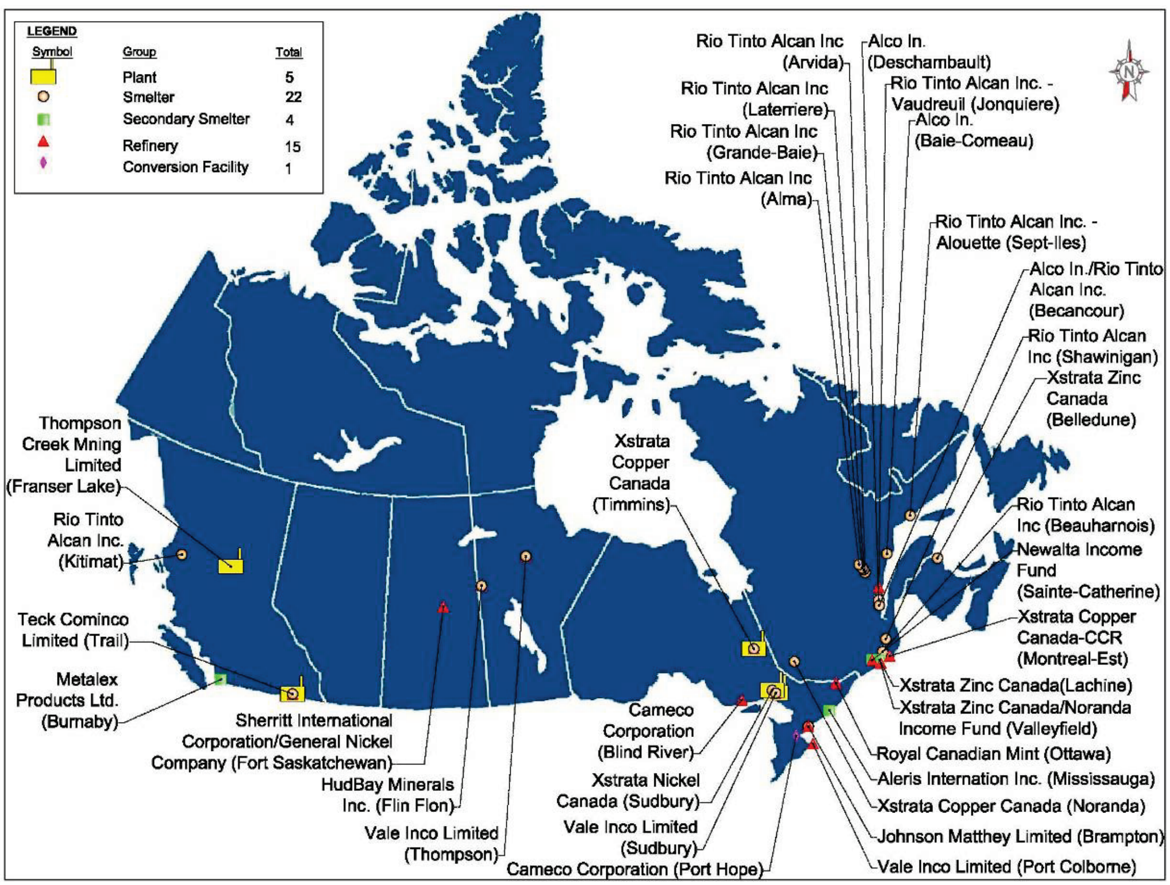
Electric Arc Furnace (Phosphorous Slag)

Phosphorous slag is a by-product in the refining of elemental phosphorous. The elemental phosphorous is typically separated from the phosphorous ore in an electric arc furnace. In this process, the phosphorous ore is combined with a fluxing agent (silica) and coke inside the furnace and heated to a liquid state by means of an electric current. The molten slag is less dense than the elemental phosphorous and floats to the top of the furnace where it is channelled out through the slag door and transported (typically through a slag pot) to a location where it is dumped and air cooled.

Typical sources

The majority of nonferrous slags are produced in locations which are rarely located near potential markets. Currently there are 33 active nonferrous smelters in operation in Canada with 9 of the smelters producing either nickel, copper or phosphorous. Figure C11-1 shows the locations of nonferrous smelters in Canada. Nonferrous slag would typically be obtained directly from the foundry operators.

Figure C11-1. Location of Nonferrous Smelters in Canada (MAC, 2010)



In what forms can Nonferrous Slags be used and in what quantities

Nonferrous slags have the potential for use as aggregates in the construction of granular bases for roadways, as embankment or fill material and as a premium aggregate in hot-mix asphalt surface course production.

Nickel and copper slags have been used quite successfully for many years as a granular base for mining roads which are typically very heavily loaded. In Ontario, nickel slag is considered a conventional aggregate and is approved as a blended aggregate or as a complete replacement for natural aggregates in Granular A, S and Granular B Type I and II (OPSS, 2004), however the use of copper slag aggregate is restricted. Blending may be required as crushing nickel slag tends to produce very little fine material and supplement natural fine material may be required to satisfy gradation requirements. It should be noted that similar to blast furnace slag, the use of nickel slag is subject to meeting the placement guidelines of the Ministry of Environment (MOE) as well as obtaining a MOE site notification.

While copper, nickel and phosphorous slags have been used as aggregate substitutes in hot-mix asphalt production internationally (copper slag in California, USA; nickel slag in Japan, United Kingdom, Dominican Republic; phosphorus slag in Tennessee, USA), the use of these slags in Canadian hot-mix asphalts is currently restricted. Successful nickel slag use in the Duarte Highway construction project in the Dominican Republic (JEGEL, 2004) serves as an example of successful incorporation into hot-mix asphalt pavements.

Where copper, nickel or phosphorous slag are suitable for use as granular base materials, they will have suitable engineering properties for use as embankment or fill materials. There were no standard specifications found outlining the requirements for nonferrous slag use in embankment or fill construction. As such, should these materials be contemplated for use in this type of application, they should be tested to ensure they meet local specified physical properties for natural aggregate as well as meet all environmental (leachate) requirements.

Engineering Properties of Steel Slag

The engineering properties of nonferrous slags are shown in Table C11-1 and Table C11-2 (adapted from FHWA, 2008).

Table C11-1. Typical Physical Properties of Various Nonferrous Slags

PROPERTY	NICKEL SLAG	COPPER SLAG	PHOSPHOROUS SLAG	LEAD LEAD-ZINC, AND ZINC SLAGS
Appearance	Reddish brown to brown-black, massive, angular, amorphous texture	Black, glassy, more vesicular when granulated	Black to dark gray, air-cooled is flat and elongated but granulated is uniform, angular	Black to red, glassy, sharp angular (cubical) particles
Unit Weight (kg/m³)	3500	2800 to 3800	Air cooled: 1360 to 1440 Expanded: 880 to 100	<2500 to 3600
Absorption (%)	0.37	0.13	1.0 to 1.5	5.0

Table C11-2. Typical Mechanical Properties of Various Nonferrous Slags

TEST	NICKEL SLAG	COPPER SLAG	PHOSPHOROUS SLAG	LEAD LEAD-ZINC, AND ZINC SLAGS
Los Angeles Abrasion Loss (%)	22.1	24.1	< 30	No Data
Sodium Sulphate Soundness Loss (%)	0.40	0.90	< 1	No Data
Angle of Internal Friction (°)	40	40 - 53	No Data	No Data
Hardness (Moh's scale)	6 – 7	6 – 7	No Data	No Data

Toxicity or environmental concerns/impacts

The main environmental issue with the use of nonferrous slags in transportation infrastructure projects is the potential of these materials to leach heavy metals in concentrations which exceed most local environmental regulations. This may require modifications to the metallurgical process to reduce the concentrations of the potentially leachable components or special design considerations which ensure that the nonferrous slag materials are not subjected to conditions that promote leaching (such as moist, stagnant or slow moving water). Regardless, the environmental suitability of each potential source should be investigated prior to use and quality control measures put in place to ensure that it does not become an issue if or when the metallurgical process is altered.

Depending on the type of ore and metallurgical process used to create the nonferrous slag there is a possibility that resultant slags produced from sulphide ores may contain leachable elemental sulphur. While the leaching of sulphur is mostly aesthetic, the resulting odour and water discolouration is generally unpleasant to the public.

Phosphate rocks can contain between 30 and 300 ppm of uranium. The majority of the uranium is incorporated in the phosphorus slag during processing (EAF) and has reportedly resulted in the release of some radiation in the form of radon gas. However, testing which was completed in the United States (Tennessee Valley Authority, 1995) has shown that the level of radiation which is released would be considered as non- hazardous.

In Ontario, placing nickel slag is subject to specific placement guidelines and a potential user is also required to obtain a Ministry of Environment (MOE) site notification prior to its use.

Technical Limitations

As nonferrous slags are typically produced in remote locations they are not commonly used in transportation infrastructure projects. In locations such as the City of Sudbury, where nickel slags are quite prevalent, they are commonly used in construction applications.

Due to the aesthetic environmental concerns regarding the discolouration and odour of phosphate slag aggregates submerged in stagnant or slow moving water, these aggregates should only be used above grade as granular base in the pavement structure and must be adequately separated from water courses to prevent immersion.

Due to previous experience, the use of nickel and copper slag aggregates in hot-mix asphalt production is not permitted in Ontario as outlined in OPSS 1003.

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C-12 – QUARRY BY-PRODUCTS

During the production of construction aggregates, the quarry materials must be crushed, washed and screened to the appropriate gradations according to the product that is being produced. These processes produce by-products in the form of crushed stone screenings, settling pond fines as well as baghouse fines.

How it is generated/quantities generated

When quarry materials are crushed, the aggregates are fractured into a number of different size fractions. The portion of the crushed aggregate which passes the 4.75 mm sieve is typically referred to as screenings or stone dust. The specific grain size distribution of screenings will vary from quarry to quarry depending on the crushing method used as well as the type of natural aggregate being crushed.

In quarries that use dry crushing operations or do not wash their aggregate products, a significant amount of dust can be created. In these situations a dust collection system consisting of some combination of cyclones and baghouses are required in order meet local dust emission regulations. The resulting material from the dust emission control systems is commonly referred to as baghouse fines.

In quarries that produced washed crushed aggregate, the washing process causes sand and silt sized particles to become entrained in the wash water. The sand comes out of suspension rather quickly and is typically removed adjacent to the crusher with the silt entrained water sent to a settling pond where they are allowed to settle either using gravity or with the help of flocculants.

There is very little published information on quantities of quarry by-products available in Canada. However, in the United States, it is estimated that at least 159 million metric tonnes of quarry by-products are generated each year and as much as 3.6 billion metric tonnes of quarry by-products have probably accumulated (FHWA, 2008).

Typical sources

Quarry fines are available wherever there is an active quarry. Quarry fines would typically be purchased directly from the quarry operator.

In what forms can quarry by-products be used and in what quantities

Quarry screenings are suitable for use as a fine aggregate substitute in portland cement concrete, flowable fill, and asphalt paving applications. The amount that can be used is predicated on the mix design requirements of the application and can generally be used in any similar application as is considered suitable to use the coarse quarry aggregate from which it is derived.

Baghouse fines and/or settling pond fines have the potential to replace much of the fine aggregate content in flowable fill mixes, depending on strength requirements, which are usually fairly low.

The only quarry by-products that would require any significant processing is the settling pond fines, which would obviously have to be brought to an appropriate moisture content prior to use.

Engineering Properties of Quarry By-products

The most important engineering property when considering quarry by-products for use in transportation infrastructure applications is material gradation. Quarry screenings are typically uniformly graded, sand sized crushed particles with less than 10 percent of the material passing the 75 μm sieve. Baghouse fines are often uniformly graded ranging from 75 μm to finer than 0.001 mm in size. Settling pond fines typically range in size between quarry screenings and baghouse fines, consisting predominantly of particles ranging in size between 0.15 mm and 0.01 mm.

Toxicity or environmental concerns/impacts

Quarry by-products are no different in composition than their constituent geological rock formation and as such should not have an adverse environment impacts if used.

Technical Limitations

Settling pond fines which are recovered from a settling pond will be saturated and additional processing such as stockpiling for natural dewatering or mechanical dewatering will be required in order to ensure this material has a suitable moisture content for transport and use.

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C-13 – RECLAIMED ASPHALT PAVEMENT (RAP)

Reclaimed Asphalt Pavement (RAP) is the term given to removed and/or processed flexible pavement materials which are composed of a mix of asphalt cement and aggregates. RAP is generated when asphalt pavements are removed as part of roadway reconstruction and maintenance (during excavations to access buried utilities, for instance) or during flexible pavement resurfacing (milling).

Reuse and recycling of old asphalt is not a 'new' concept, with both hot and cold recycling of asphalt materials having been completed since at least the early 1900's (ARRA, 2001). However, little advancement in asphalt recycling technology and equipment was made until the 1970's, when, spurred by the Energy Crisis, asphalt recycling efforts increased in response to social and environmental pressure to reduce the demand for products made using non-renewable fossil fuels/petroleum hydrocarbons.

Asphalt recycling has become a key component of the Canadian paving industry, and it is critical that the appropriate technology is adopted to ensure that the desired pavement quality is achieved. While RAP grindings, millings and/or pieces can be blended with conventional aggregate (sand and gravel or crushed rock) or RCM for use as granular subbase or shouldering material (unbound application), such use is discouraged as it does not utilize the asphalt cement binder or recover the energy invested in its production unless the material was otherwise unusable in a bound application (physical or environmental characteristics unsuitable) (MTQ, 2002). Reuse in paving mixtures (bound application) is therefore preferred from both materials management and sustainable development viewpoints.

The use of reclaimed asphalt pavement (RAP) to produce recycled hot-mix in a central asphalt plant (batch drum or combined batch-drum plants) is well-established and continues to grow across Canada, with recycled hot mix (RHM) included in most Canadian agency (provincial and many municipal) specifications for binder course mixes in particular, and some use in surface course mixes (Emery, 1991). However, continuing advancements in recycling technologies, including hot in-place recycling (HIR), cold in-place recycling (CIR, with emulsion or foamed asphalt), cold central plant recycling (CCPR), and full-depth reclamation (FDR), and their successful implementation and growing positive performance record, are providing pavement managers with a wider variety of technically acceptable, cost effective reuse and recycling options for roadway maintenance and rehabilitation work. In recent years, CIR and FDR have become the preferred cold recycling processes for structural improvement/strengthening and maintenance of municipal asphalt pavements, while evolving Canadian third generation forced hot-air preheater technology is resulting in enhanced quality for HIR asphalt rehabilitation. These pavement rehabilitation methods have been proven to provide cost effective, enhanced life-cycle performance.

How it is generated/quantities generated

RAP is generated when asphalt pavements are removed as part of roadway reconstruction and maintenance (during excavations to access buried utilities, for instance) or during flexible pavement resurfacing (milling). During roadway reconstruction and maintenance, removal of the asphalt concrete is typically completed using heavy construction equipment such as bulldozers or front end loaders which break the entire pavement structure into slabs which are then load them into dump trucks and hauled to a dump site (typically the paving contractor's construction yard). At the construction yard, the RAP from various sites is typically stored in common piles prior to the completion of crushing and screening operations. This commingled material is then crushed down to produce a RAP with a suitable top size for use in new asphalt mixes. Crushing allows for the creation of a more consistent product when using RAP from various sources.

RAP millings are typically generated from pavement rehabilitation projects where the upper layer(s) of pavement are removed and then replaced to increase the pavement's service life. When the milling process is properly controlled, the RAP that is produced is generally ready to be recycled without further crushing or screening. RAP millings are frequently segregated in separate stockpiles at processing facilities.

Typical sources

Reclaimed asphalt pavement is typically obtained from central RAP processing facilities usually found near hot-mix asphalt plants. It is at these locations where old asphalt concrete is crushed, screened, or where RAP millings are stockpiled for use in various products flexible pavement products. As flexible pavements comprise the majority of pavement roadway in Canada, RAP can be found in almost every jurisdiction where hot-mix asphalt is produced.

RAP can be processed and stored in a number of fashions. The RAP products available at processing facilities can vary from unprocessed stockpiles containing large chunks or slabs, to stockpiles of processed RAP with consistent properties. Some agencies require that only RAP obtained from specific asphalt concrete types be used in specific recycled hot-mix asphalt mixes. Otherwise, RAP is typically stockpiled from material from multiple sources into coarse and fine stockpiles to assist in incorporating the RAP into various mixes.

In what forms can it be used and in what quantities

Milled or crushed RAP can be used in a number of highway construction applications. These include its use as an aggregate substitute and asphalt cement supplement in recycled asphalt paving (hot mix or cold mix), as a granular base or subbase, stabilized base aggregate, or as an embankment or fill material. Current methods for reuse and recycling of RAP are briefly described in the following sections. The ARRA *Basic Asphalt Recycling Manual* (ARRA, 2001) and the OHMPA *ABCs of Asphalt Pavement Recycling* (OHMPA, 2003) are recommended references for additional information.

When used in asphalt paving applications (hot mix, warm mix, or cold mix), RAP can be processed at either a central processing facility or on the job site (in-place processing). Introduction of RAP into asphalt paving mixtures is accomplished by either hot or cold recycling with the use of warm mix asphalt (WMA) having been completed in many jurisdictions.

<u>Hot Mix Asphalt (Central Processing Facility)</u>

The use of processed RAP in batch, drum, and combined drum-batch asphalt plants to produce recycled hot-mix (RHM) is the most common type of asphalt recycling, and is considered standard asphalt technology in Canada and internationally (TAC, 1994; MTO, 1995; OECD, 1997; FHWA, 2008, OHMPA, 2003, for instance).

Recycled hot mix is normally produced at a central RAP processing facility, which usually contains crushers, screening units, conveyors, and stackers designed to produce and stockpile a finished granular RAP product processed to the desired gradation. This product is subsequently incorporated into hot mix asphalt paving mixtures as an aggregate substitute.

For batch mix plants, the amount of RAP incorporated is typically limited to less than 30 percent to ensure adequate drying and heat transfer in the pugmill from superheated aggregate, and to limit 'blue smoke' emissions. Depending on the amount of RAP to be incorporated in the RHM, it may be necessary for the new asphalt cement to have a higher (softer) penetration grade (lower viscosity) in order to offset the harder 'aged' asphalt cement in the RAP; this is generally not necessary with RAP addition rates less than about 25 percent. The need to soften the aged asphalt cement and to control potential emissions (blue smoke) limits the amount of RAP that can be incorporated in drum asphalt plants to between 40 and 60 percent (Earl and Emery, 1987).

The maximum amount of RAP permitted in HMA varies somewhat from province to province. All provinces except Nova Scotia and Prince Edward Island permit RAP to be used in HMA, provided that testing is completed to ensure the quality (penetration/viscosity, or performance grading for Superpave mixtures or the asphalt cement) and uniformity of the RAP source and that the RHM meets all specification requirements for asphalt concrete. Ontario limits the amount of RAP in surface course HMA to 15 percent maximum, with 30 percent in conventional binder course mixes and up to 50 percent in certain situations subject to confirmatory testing. Newfoundland allows 10 percent RAP in leveling course only, whereas Québec accepts up to 15 percent RAP in RHM (Québec City allows for up to 50 percent RAP use in certain situations subject to confirmatory testing). Alberta and New Brunswick permit higher RAP addition levels (30 percent and 40 percent (± 5 percent), respectively). The amount of RAP allowed in British Columbia mixes varies based on the roadway classification. For instance, on Freeways and Primary Highways they do not allow RAP in the surface course but allow up to 30 percent RAP in the binder course mix, while for low volume (secondary) roads they allow 30 percent in the surface course mix up to 100 percent in the binder course mix. Saskatchewan and Manitoba do not limit the amount of RAP that can be added to HMA.

Hot Mix Asphalt (In-Place Recycling)

In Hot In-Place Recycling (HIR), the old asphalt pavement surface is heated, softened and scarified to depths of 20 to 60 mm, the scarified material is then remixed, placed, and compacted as a part of a continuous in-place process. New aggregates, new asphalt cement, recycling/softening agents, and/or new HMA (commonly referred to as 'admix') can also be added to improve the engineering properties of the existing pavement and for increased structural capacity (for a total treatment thickness up to 75 mm). Pavement distresses which can be treated by HIR include: flushing/bleeding; raveling; rutting; shoving; poor surface friction (macrotexture and microtexture); and longitudinal and transverse cracking, and reflection cracking (Emery et al, 1989; Dunn et al, 1997).

There are three types of HIR treatment (MacKay and Emery, 1990):

- Surface Recycling: To improve the profile of an asphalt surface course deformed by rutting or wearing, but in comparatively unaged condition with only minor cracking (no rejuvenation required). Surface Recycling consists of heating, scarifying, leveling, reprofiling and compaction of the mixture.
- Remixing: To improve the quality of old, cracked, aged surface course through the addition of a recycling agent/rejuvenator, aggregate or new hot-mix asphalt. Remixing involves heating, scarifying (with rejuvenator, mixing aggregates and/or new hot-mix asphalt added), mixing, leveling, reprofiling and compaction.

- Repaving: To improve the profile of an asphalt surface course severely deformed by rutting or wearing, improve frictional characteristics, and/or provide some strengthening. Repaving involves heating, scarification (with rejuvenator, aggregate and or new hot-mix added, if necessary), mixing, leveling and laying of new hot-mix asphalt, reprofiling and compaction, all in one pass.

  HIR technology has been steadily evolving, with continuing improvements in the overall quality and performance of HIR pavements (Photograph C13-1). New Canadian third generation combined forced hot-air/radiant low-level heat preheaters have overcome previous issues with heater-scarification quality and depth, allowing increased treatment depth without degradation (aging) of the existing asphalt cement binder, including polymer-modified asphalt cements. This equipment has also reduced 'blue smoke' (emissions factor) to below that of conventional hot-mix asphalt plants.

Photograph C131 - Current HIR Remixing train rehabilitating a municipal roadway in a single pass

Cold Mix Asphalt (In-Place Recycling)

Cold in-place recycling (CIR) is an on-site process for the rehabilitation of asphalt-surfaces (on both flexible and composite pavements) to depths up to 150 mm. The old asphalt is milled to a specified depth, mixed with emulsified asphalt, and repaved to the required grade and profile. A surface treatment or hot-mix asphalt wearing surface is applied after the CIR mix has properly cured (typically 14 days).

The CIR process involves: milling or grinding of the existing asphalt surface to depth typically 75 to 125 mm; processing/mixing of the pulverized RAP (with addition of beneficiating aggregate, if any, water and emulsion (plus cement (1 to 3 percent) or lime (1 to 2 percent) addition to increase mix stability and reduce stripping potential, if necessary); compaction with water as an aid to densification, and densification as the water content comes into equilibrium with ambient conditions and surroundings. The CIR mixture continues to increase in strength and stiffness with time. Once fully cured (approximately two weeks), the CIR mix must be overlaid with a wearing surface (conventional hot-mix asphalt or other surfacing depending on AADT).

It is recommended that a pavement evaluation be carried out to assess overall suitability for CIR treatment, and the specific CIR process requirements. Materials characterization and mix design by a qualified, experienced laboratory, in conjunction with quality control (QC) and quality assurance (QA) verification testing during the rehabilitation work, are critical components of a successful CIR project.

CIR of the existing pavement overlaid with a surface course hot-mix asphalt layer designed to meet Superpave mix requirements has been used for enhanced durability and to minimize reflective and/or thermal cracking. CIR of the existing pavement, in conjunction with the placement of open graded cold mix wearing surface, is being developed for a 'total cold' system.

Cold Mix Asphalt (Central Processing Facility)

Cold central plant recycling (CCPR) produces the same end product as cold in-place recycling. The RAP obtained from the roadway, or from centrally-located homogeneous stockpiles, is processed (crushed and/or screened), then fed into a central mixing plant where the emulsified asphalt and any additives are added and blended. The CCPR mixture is then transported to the paving site and placed in the same manner, using conventional hot mix asphalt or RHM paving equipment. The cold central plant recycling option should be considered where large stockpiles of high quality RAP are readily available and where it may not be practical to recycle the existing pavement in place due to variability in the existing pavement or in-place recycling equipment may not be available.

Full-Depth Reclamation

There are a number of different types of full depth reclamation (FDR) techniques available to Canadian municipalities, including pulverization-mixing ('pulvi-mixing')/in-place reprocessing (without stabilization); FDR with bituminous stabilization (using asphalt emulsion (normal, high-float, polymer modified) or foamed asphalt); FDR with chemical stabilization (using cementitious systems such as portland cement, fly ash, lime (hydrated or quicklime), cement kiln dust or lime kiln dust, or additives such as calcium chloride or magnesium chloride); and/or FDR with mechanical stabilization (by addition of corrective aggregate).

Full depth reclamation involves pulverization and in-place mixing of the full thickness of the asphalt pavement and a predetermined portion of the underlying materials (base, subbase and/or subgrade) to provide a homogeneous base material (ARRA, 2001). Full depth pulverization ensures mitigation of reflective cracking by eliminating pre-existing cracks. The pulvi-mixed base material may be structurally enhanced by stabilization. Typical processing depths range from 100 mm to as much as 300 mm and generally depend on the ability to provide suitable compaction for the entire processed thickness.

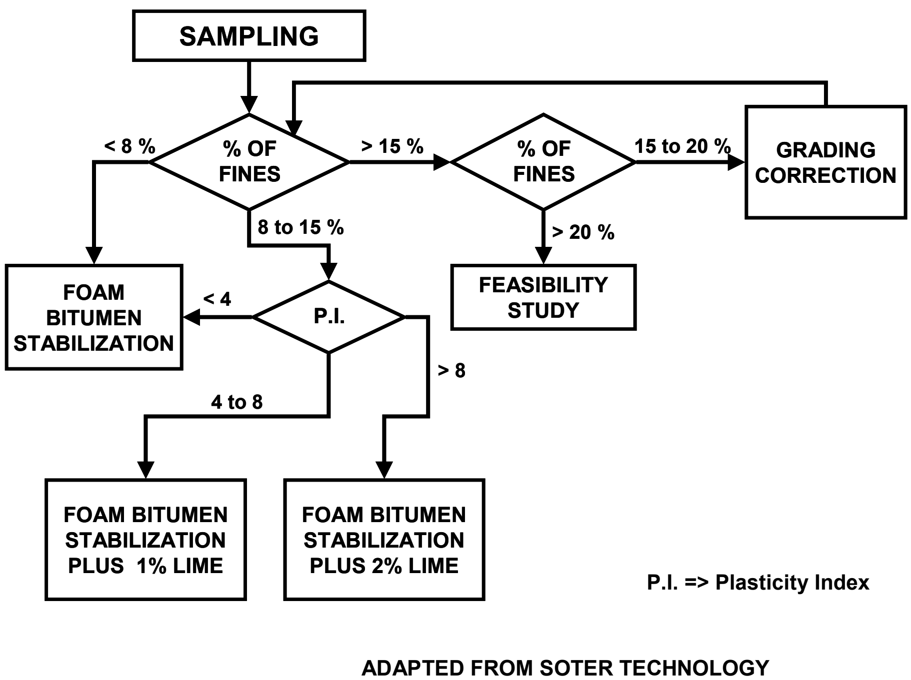
The most common form of FDR includes bituminous stabilization with foamed asphalt. Up until the early 2000's this technology was not widely used in Canada, but is rapidly growing. Two foamed asphalt stabilization processes in current use are shown in Photographs C13-2 and C13-3.

PhotographC13- 2 - Conventional full-depth foamed asphalt stabilization unit

Photograph C13-3 - Paver-Laid surface recycling foamed asphalt train

FDR with foamed asphalt stabilization consists of full depth pulverization of the existing roadway followed by addition and mixing of foamed asphalt with the pulverized material (typically at addition rates between 2 and 3.5 percent) to create a stabilized base. Depending on the properties of the material being stabilized, the FDR with foamed asphalt stabilization process may be enhanced by addition of lime or portland cement (JEGEL, 2002). One to 2 percent lime may be added, if necessary, subject to the plasticity of the granular base/subbase or subgrade material to be stabilized, to increase mix stability or provide enhanced resistance to moisture damage/stripping (Figure 1). If the base material does not contain adequate fines for lime stabilization and/or increased stability is required, typically 1 to 3 percent portland cement may be added to the FDR with foamed asphalt process. Treatment depths vary depending on the thickness of the existing pavement structure, but generally range between 100 and 300 mm (4 to 12 inches). Additional corrective granular or RAP material (mechanical stabilization) may be added if necessary to increase the pavement structural capacity.

Figure C13-1 – Decision tree for the determination of lime addition to foamed asphalt stabilization (JEGEL, 2002)



The main advantages of foamed asphalt stabilization include: ease of application in a variety of municipal and highway settings; provision of a flexible layer with good rut resistance and fatigue properties; the ability to correct the pavement profile; and reflective cracking mitigation.

The design of a foamed asphalt mixture should be carried out by an experienced and qualified asphalt laboratory. The foamed asphalt cement expansion properties (expansion ratio and half-life with percent injection water) are determined in the laboratory, and a foamed asphalt mix design is developed for the optimum tensile strength ratio (TSR, resistance to moisture). There are several similar mix design methods available which are essentially based on the Wirtgen procedure (Wirtgen, 2010).

Proper quality control (QC) and quality assurance (acceptance) (QA) testing of both the foamed asphalt cement and the foamed asphalt mix during a foamed asphalt project are critical to its successful performance. During construction, the asphalt cement temperature, injection water percentage, expansion ratio and half-life are monitored for process control.

The technology and equipment for full depth reclamation with stabilization using chemical/cementitious systems is also widely available in Canada. Two full depth reclamation projects demonstrating the use of hydrated lime and portland cement to stabilize the full-depth pulverized granular base/subbase and subgrade are shown in Photographs C13-4 and C13-5.

Photograph C13-4 - Full depth reclamation with lime stabilization

Photograph C13-5 - Full depth reclamation with cement stabilization

In a 2001 Canadian research project carried out by Laval University, a pavement section in the City of Québec was rehabilitated by pulverizing and mixing the existing asphalt pavement and underlying granular base/subbase to a depth of 500 mm. A Portland cement slurry was then added to the pulverized mixture in-place (at relatively high cement contents of 9%, 12% and 15% by dry mass), then compacted using conventional pavement compaction procedures. This trial FDR with cement slurry project effectively resulted in a roller compacted concrete base. Similarly, cement stabilization was successfully used to rehabilitate a major arterial road in Verdun, Québec and this type of process has been adopted for other Québec municipal roadways.

As with bituminous stabilization, chemical stabilization may also be combined with one or more bituminous or mechanical stabilization processes to achieve the optimal final product meeting project requirements. Chemical stabilization also begins with full depth pulverization of the existing roadway followed by chemical stabilization (typically 3 to 5 percent lime or Portland cement depending on the required strength; the addition of fly ash as a supplementary cementitious material or pozzolan can also be considered). Treatment depths are dependent on the ability to compact the stabilized material and may be up to 500 mm (20 inches).

Pavements exhibiting block cracking, edge cracking, longitudinal and transverse cracking, and slippage cracking; bleeding; inadequate structural capacity; stripping; and permanent deformations (corrugation, rutting, shoving) can be considered as candidates for full depth reclamation.

Granular Base Aggregate

To produce a granular base or subbase aggregate, RAP must be crushed, screened, and blended with conventional granular aggregate, or sometimes reclaimed concrete material. The can be completed at a central facility or on site by in-situ full-depth pulverization and blending of the existing asphalt concrete and a portion of the underlying granular base/subbase material. Blending granular RAP with suitable materials is necessary to attain the bearing strengths needed for most load-bearing unbound granular applications. RAP by itself may exhibit a somewhat lower bearing capacity than conventional granular aggregate bases.

Shouldering Material, Embankment or Fill

Stockpiled RAP material may also be used as a granular shouldering material, fill or base for embankment or backfill construction, although such an application is not widely used and does not represent the highest or most suitable use for the RAP. The use of RAP as an embankment base may be a practical alternative for material that has been stockpiled for a considerable time period, or may be commingled from several different project sources. Use as an embankment base or fill material within the same right of way may also be a suitable alternative to the disposal of excess asphalt concrete that is generated on a particular highway project.

Engineering Properties of the Recycled Products

The properties of RAP are largely dependent on the properties of the constituent materials and asphalt cement type used in the old pavement. Since RAP may be obtained from any number of old pavement sources, quality can vary unless the RAP is carefully segregated into a stockpile from a single or similar source (traceable source RAP). Excess granular material or soils, or even debris, can sometimes be introduced into old pavement stockpiles. The number of times the pavement has been resurfaced, the amount of patching and/or crack sealing, and the possible presence of prior seal coat applications will all have an influence on RAP composition. In addition, the aggregates in surface course asphalt concrete layers are typically selected due to their increased frictional properties compared to some binder course layers where frictional resistance is not of concern. Quality control is needed to ensure that the processed RAP will be suitable for the prospective application.

Both the milling and crushing processes can cause aggregate degradation in the RAP. This causes the gradation of milled RAP to be generally finer and denser than virgin aggregates for similar mixes. Crushing has been found to not cause as much degradation as milling; consequently, the gradation of crushed and screened RAP is generally not as fine as a milled RAP, but again finer than virgin aggregates for similar mixes.

At most processing facilities, RAP stockpiles contain milled or crushed particles which are 37.5 mm or less, with a typical maximum allowable top size of 50 mm (processing plants that have oversized piles). Table 1 lists the typical range of particle size distribution of RAP stockpiles.

The asphalt cement content of RAP will vary depending on the source but can be expected to range between 3 and 7 percent by weight. The existing asphalt cement in the RAP will have aged and is typically somewhat harder (stiffer) than similar new asphalt cement. This is due primarily to exposure of the pavement to atmospheric oxygen (oxidation) during use and weathering. The degree of stiffness depends on several factors including: the mixing temperature/time (increased mixing temperatures can harden asphalt binders); the degree of compaction (stiffness increases if asphalt concrete mix not well compacted); ratio of asphalt cement to air voids content (stiffness increases with lower asphalt/higher air voids content); and age in service (stiffness increases with age).

Table C13-1. Typical range of particle size distribution for reclaimed asphalt pavement (RAP) (percent by weight passing)

SCREEN SIZE (MM)	PERCENT PASSING AFTER PROCESSING OR MILLING
37.5	100
25	95 – 100
19	84 – 100
12.5	70 – 100
9.5	58 – 95
4.75	38 – 75
2.36	25 – 60
1.18	17 – 40
0.600	10 – 35 a
0.300	5 – 25 b
0.150	3 – 20 c
75µm	2 – 15 d
a. Usually less than 30 percent b. Usually less than 20 percent c Usually less than 15 percent d. Usually less than 10 percent	

Aggregates constitute the majority (93 to 97 percent by weight) of RAP materials with the remaining (3 to 7 percent) consisting of hardened asphalt cement. Consequently, the overall chemical composition of RAP is essentially similar to that of the naturally occurring aggregate.

The mechanical properties of RAP depend on the original asphalt pavement type, the method(s) utilized to recover the material, and the degree of processing necessary to prepare the RAP for a particular application. Since most RAP is recycled back into pavements, there is a general lack of data pertaining to the mechanical properties for RAP in other possible applications.

In 2009, the National Centre for Asphalt Technology (NCAT, 2009) completed a study comparing the performance of hot-mix asphalt mixes produced with virgin aggregates and with blends of RAP using data from the LTPP program. The Long Term Pavement Performance (LTPP) Project was established in 1987 as part of the Strategic Highway Research Program (SHRP) in order to study how pavement performance is affected by a number of factors including: design features; traffic loading and composition; environment; pavement structure materials; and various maintenance and rehabilitation treatments. The LTPP data that is available in the database is considered reliable because it has been collected in consistent manner in accordance with LTPP protocols and it has gone through a number of validation checks prior to being admitted into the database.

The data from 18 projects across North America, ranging from 6 to 17 years in age, were analyzed to compare representative sections of virgin asphalt mix and with recycled asphalt mix containing 30 percent RAP. The distress parameters that were considered were rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling.

The NCAT analysis indicated that the performance of recycled and virgin sections were not statistically different except for fatigue, longitudinal cracking, and transverse cracking, where the virgin sections performed slightly better overall than the RAP sections. Table 2 summarizes the NCAT analysis and shows that RAP sections generally performed equal or better than virgin mixes (NCAT, 2009). The NCAT study concluded that, in most cases, using 30 percent RAP in an asphalt pavement can provide the same overall performance as virgin asphalt pavement.

Table C13-2. Summary of Performance of RAP Mixes versus Conventional Mixes at the NCAT Test Track

DISTRESS PARAMETER	VIRGIN PERFORMED SIGNIFICANTLY BETTER THAN RAP (PERCENT)	RAP PERFORMED SIGNIFICANTLY BETTER THAN VIRGIN (PERCENT)	INSIGNIFICANT DIFFERENCE BETWEEN RAP AND VIRGIN (PERCENT)	RAP PERFORMED EQUAL OR BETTER THAN VIRGIN (PERCENT)
IRI	42	39	19	58
Rutting	33	29	38	67
Fatigue Cracking	29	10	61	71
Longitudinal Cracking	15	10	75	85
Transverse Cracking	32	15	53	68
Block Cracking	3	1	96	97
Ravelling	7	15	78	93

Toxicity or environmental concerns/impacts

Asphalt concrete consists of a mix of aggregate and asphalt binder containing volatile and semi-volatile constituents (e.g., polycyclic aromatic hydrocarbons (PAHs)). Other flexible roadway surfacings include surface treatments, asphalt concrete containing rubberized materials or contaminants from vehicle or other emissions. Research into the difference in emissions of bound applications such as hot-in-place and cold-in-place recycling compared standard hot-mix asphalt production has not been conducted. However, for unbound applications such as the use of RAP in granular base or as embankment fill, detailed leachate testing has been completed in Florida (Brantley, 1999) which indicated that the concentrations of VOCs, PAHs, and heavy metals (Ba, Ca, Cr, Cu, Pb, Ni and Zn) were below the detection limit and hence below the applicable Florida State regulatory groundwater guidance concentrations.

There have been a limited number of trials across Canada that has incorporated asbestos fibres into hot-mix asphalt. While research appears to suggest that these fibres remain encapsulated in the asphalt cement, concern still exists that these fibres may become airborne during recycling, potentially causing associated respiratory health effects. If there is concern that an asphalt concrete may contain asbestos fibres, cores should be taken and tested prior recycling completed in order to determine the quantity of material that requires disposal prior to recycling.

Are there any concerns that using this material/process will impact future recyclability

There are certain asphalt concrete recycling processes that, once used, may limit the ability of the recycled asphalt concrete from being recycled in the future. Experience in British Columbia has been that the use of crumb rubber or sulphur in hot-mix asphalt mixes precludes future hot-in place recycling. The major concerns have been that the fumes generated when hot in-place recycling mixes containing sulphur have been unacceptable, while asphalt rubber mixes have caused reprocessing issues with the HIR equipment (gumming up milling teeth).

In certain jurisdictions there may roads that have been constructed with coal tar as the binder. In these jurisdictions, care should be taken to prevent the mixing of the coal tar binder with the proposed recycling option (in the RAP or during FDR, for instance), as exposing the coal tar can be hazardous to health.

Similar to coal tar, asbestos fibres have been incorporated into hot-mix asphalt mixes in some jurisdictions. While research appears to suggest that these fibres remain encapsulated in the asphalt cement, concern still exists that these fibres may become airborne during recycling, potentially causing associated respiratory health effects.

Technical Limitations

According to AASHTO M 323, the current binder selection guidelines for RAP mixtures were formulated based on the assumption that complete blending occurs between the virgin and RAP binders. However, current understanding is that blending of the RAP and virgin binder can range anywhere from complete blending and no blending at all and there is no direct method available to accurately determine the amount of blending that occurs. For high RAP mixtures, blending charts can be used to properly determine the blended binder grade, however, this is an expensive and time-consuming process that in itself, uses hazardous solvents. As a consequence, many agencies simply do not permit the use of RAP contents that would then require this additional and costly testing. Additionally, this is considered to be specialized testing for which many contractors are not equipped to perform.

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C-14 – RECLAIMED CONCRETE MATERIAL (RCM)

As Canadian infrastructure ages, our roads, bridges, utilities, sidewalks, runways etc. go beyond their useful service lives and are required to be replaced. This material is typically primarily composed of asphalt and portland cement concrete materials and until recently was disposed of in landfills. Recent estimates of aggregate production indicated that over a 4 year period an average of 175 million tonnes of natural aggregate were extracted every year in Ontario with the majority of them used to fuel transportation infrastructure renewal and expansion.

Concrete is the term used to describe a construction material that consists of a combination of cement (most commonly portland cement), aggregate (made uniquely or in combinations of naturally occurring and engineered (crushed) rock such as limestone, granite and sand), water and chemical reagents. There is a considerable amount of energy invested in the production of cement and extraction of aggregates that gets wasted when this material is sent to a landfill which is why it is critical to find suitable recycling options that use this invested energy to its fullest. One such application is as recycled concrete aggregate.

How it is generated/quantities generated

When transportation infrastructure structures such as concrete roads, bridges, culverts, sewers, curb and gutter, sidewalks, driveways, runways and aprons reach the end of their service lives these structures must be demolished in order to make room for new structures. Rather than hauling the demolished concrete material to a landfill, the reuse and recycling of this material is well-established and it can be processed for use in new transportation infrastructure projects as roadway base and subbase courses, in portland cement concrete mixes, or as an embankment or fill material. Typical reprocessing methods include: in-place reprocessing (rubblization); hauling to a central processing facility for stockpiling and processing; or processing on site using a mobile plant.

In-place Reprocessing (Rubblization)

Rubblization is an in-place rehabilitation technique that involves breaking in-place portland cement concrete pavements into pieces having a nominal maximum size of about 75 mm or less above and 200 mm or less below any reinforcement (AI, 2000). Prior to rubblization, if the portland cement concrete pavement has previously been overlain with an asphalt concrete wearing surface, it should be removed by milling to expose the underlying concrete slabs.

The two most common types of rubblization equipment are resonant breakers and multiple head breakers. Resonant breakers, shown in Photograph C14-1, produce low amplitude, high frequency blows by vibrating a large steel beam connected to a foot than can vary in width from 150 to 300 mm. The foot is moved along the concrete pavement surface in multiple passes to rubblize the full width of the pavement. Typical production rates using a single resonant breaker are approximately 2 lane kilometres per day per unit. If higher production rates are required, multiple resonant breakers can be used in echelon to reduce the number of passes required to rubblize the full lane width.

Photograph C14-1 Resonant Concrete Breaker

Multiple head breakers employ a number of large drop hammers (550 to 675 kg) in two rows with half of the hammers in a forward row and the remainder diagonally offset in the rear row. Each pair of hammers is attached to a hydraulic lift typically capable of cycling between 30 to 35 impacts per minute. Multiple head breakers can rubblize up to 3.95 m wide at 1.6 lane km per shift. The use of multiple head breakers has fallen out of favour in some jurisdictions as it creates a high volume of construction noise which adversely affects surrounding residents and businesses during recycling, however this method is still successfully being used for recycling roadways in Winnipeg.

As portland cement concrete pavements only form a fraction of Canadian surfaced roads, this technique is not in use on a frequent basis. While the amount of rubblization is not currently tracked, it is estimated from project experience that only about 5 to 15 lane kilometres of rubblization is completed each year.

<u>Reclaimed Concrete Material (RCM)</u>

When concrete roads, bridges, culverts, sewers, curb and gutter, sidewalks, driveways, runways and aprons are no longer in a serviceable condition, they are usually demolished, excavated and can be processed on site (if the quantities of recycled material are sufficient to justify this process) but are more transported to a material yard where they are stockpiled for future processing as shown in Photograph C14-2.

Photograph C14-2 Processing of Reclaimed Concrete Material

Processing of RCM typically consists of breaking down any large concrete pieces/slabs using crane and ball-drop, hydraulic or pneumatic breakers and removal of any exposed reinforcing steel. This is followed by primary crushing and sizing (using jaw crushers most typically) and secondary crushing (cone, roll or impact crushers) and final screening to meet typical agency gradation specifications. The crushing and screening circuit may also include a magnetic separator for additional metals removal/recovery (as scrap, potentially providing an additional source of revenue that may partially offset processing costs), and spray bars for dust control.

After processing, the RCM may also include some old asphalt from composite (asphalt over concrete) pavements. It is recommended that the amount of old asphalt be limited to about 30 to 50 percent by mass in order to not have an adverse effect on the strength conditions of the RCM granular material.

Reclaimed concrete material is permitted for use by most cities and agencies across Canada subject to the material meeting local agency specification criteria. In general, the quantities of concrete reuse as recycled aggregate is not being tracked by agencies but conservative estimates by NRCan indicated that at least 75% of the 10 million tonnes of concrete waste generated annually is currently being recycled (NRCan, 2006).

Typical sources

Reclaimed concrete material is typically obtained from central RCM processing facilities usually found near hot-mix asphalt plants. It is at these locations where old concrete is crushed and screened into the various approved products. As concrete is used in transportation infrastructure in almost every jurisdiction in Canada, there is typically a local or regional processor which is capable of providing RCM products.

In what forms can reclaimed concrete material be used and in what quantities

Reclaimed concrete material can be used as aggregates in the construction of granular bases for roadways (either processed in-place or at a mobile or central recycling facility), as recycled concrete aggregate in the production of portland cement and asphalt concretes and in embankment and structural fill applications.

Granular Base

The use of reclaimed concrete material (RCM) as a granular base aggregate is a common practice in Canada with most agencies and municipalities allowing its use in their specifications. Crushing and screening of RCM results in a well-graded, 100 percent crushed, angular material that has high strength when used in pavement base course applications (equivalent to 100 percent crushed natural aggregates) with good drainage properties. Some additional positive features of RCM processed material is its ability to stabilize wet, soft, underlying soils as well as its excellent durability.

A granular roadbase can also be created using the rubblization process. During rubblization, the concrete pavement is fractured into small pieces (generally 50 to 150 mm). The effectiveness of the rubblizing equipment in producing the desired particle sizes is also a function of the condition of the underlying base/subgrade, with smaller sizes more readily achieved over a firm stable base/subgrade (Wolters, 2009). Proper drainage is critical to the success of a rubblization project. In areas of weak subgrade or high water table, the drainage system should be functioning as far in advance of the rubblizing as possible to allow the subgrade to be as stable as possible.

In granular base and subbase applications, RCM can either be blended with natural aggregate or used as a complete replacement of natural aggregates in many agency specifications.

Recycled Concrete Aggregate

Reclaimed concrete material (RCM) can be used as a coarse and/or fine aggregate in portland cement concrete pavements. Crushed RCM which meets specification requirements for concrete aggregate is considered by many jurisdictions to be conventional coarse aggregate and can be used interchangeably. However, the use of RCM fines in portland cement concrete mixtures has sometimes led to significant reductions in concrete workability, strength and finish quality. In this regard, blending of RCM fines is recommended with substitution rates of RCM fines for natural fines of a maximum of 10 to 20 percent.

With careful attention at the mix design stage, quality concrete can be produced using recycled concrete aggregates. The higher absorption of recycled concrete aggregates may require adjustment to water and portland cement content to achieve the appropriate water:cement ratio for concrete strength and durability (CAC, 2002; Kasai, 2004). Due to their high absorption, prewetting of recycled concrete aggregates is recommended or it will absorb water from the concrete mix (FHWA, 2008).

Reuse of recycled concrete aggregate in portland cement concrete may be particularly appropriate in locations where there is a lack of natural aggregates satisfactory for use in quality concrete. However, in Canada, the use of processed RCM has been mainly in granular subbase in urban areas where supply and transportation costs favour such use.

Embankment or Structural Fill

As most reclaimed concrete materials are generally considered to be equivalent to conventional aggregates, they are more than suitable for use in embankment or structural fill applications. This application is discouraged however as it is not considered to make the best use of this high quality material unless either no other suitable aggregates are available or there are no other local uses for the RCM.

It should be noted that RCM has an elevated alkalinity due to the nature of portland cement concrete and this can be potentially corrosive to aluminum or galvanized steel pipes and this application should be avoided. In addition, in some lower quality concretes which have free CAO, tufa-like precipitates ($CaCO_3$) can form which have been know to clog drainage systems.

Engineering Properties of Reclaimed Concrete Material

When properly processed, reclaimed concrete material will have many of the same engineering properties of natural aggregates. Some of the typical physical and mechanical properties that may differ from natural aggregates are shown in Table C14-1 (Adapted from FHWA 2008).

Table C14-1. Typical Physical and Mechanical Properties of Reclaimed Concrete Material

PROPERTY	VALUE
Specific Gravity	
Coarse Particles	2.2 to 2.5
Fine Particles	2.0 to 2.3
Absorption (%)	
Coarse Particles	2 to 6
Fine Particles	4 to 8*
Magnesium Sulphate Soundness (%)	3.8
Los Angeles Abrasion (%)	36.5
Dry Density (kg/m^3)	2070
CBR (%)	148

*Absorption values as high as 11.8 have been reported

Toxicity or environmental concerns/impacts

Recycled concrete material may be contaminated with chloride ions from the application of deicing salts to roadway surfaces or with sulphates from contact with sulphate-rich soils which may exceed provincial environmental regulations when tested. It is also important to ensure that the RCM used does not contain aggregate susceptible to alkali-silica reactions as this can have a detrimental effect on the performance (FHWA, 2008).

In Québec, old concrete which is obtained from existing road infrastructure for use as RCM is considered to be 'clean' and can be used in either bound or unbound applications without chemical (environmental) testing (NQ-2560-600, 2002).

RCM has an elevated alkalinity due to the nature of portland cement concrete and this can be corrosive to aluminum or galvanized steel pipes and this application should be avoided. In addition, some lower quality concretes will have free CaO which will create a white tufa-like precipitate ($CaCO_3$).

Technical Limitations

Proper drainage is critical to the success of a rubblization project. In areas of weak subgrade or high water table, the drainage system should be functioning as far in advance of the rubblizing as possible to allow the subgrade to be as stable as possible or the effectiveness of the pneumatic breaker could be impacted.

There is concern that resonant style breakers may impart energy below the pavement structure and potentially damage underlying utilities (TAC, 2006) and this should be considered when selecting a rubblizing process for a particular roadway.

The quality of the original portland cement concrete will greatly affect its potential recyclability. Some recycled concrete material can contain potentially deleterious substances, such as sulphates/sulphides (from old drywall and plaster for instance if blended with construction and demolition wastes), chlorides and alkali reactive aggregates. The gypsum in modern drywall reacts very strongly with the portland cement materials in RCM to form expansion products including thaumasite and ettringite. Recycled concrete aggregate with as little as 3 percent of contamination with gypsum has been shown to have a volumetric expansion of 10 percent or even greater. As a result, it is imperative that the quality of the RCM must be strictly controlled to be successfully used as a recycled aggregate.

Recycled concrete aggregate has a higher absorption than conventional natural aggregates and generally yields concrete of lower strength at equivalent water/cement ratios and lower slump than conventional aggregates (MNR, 1992). If fine recycled concrete aggregate is used, the workability of the fresh concrete also decreases.

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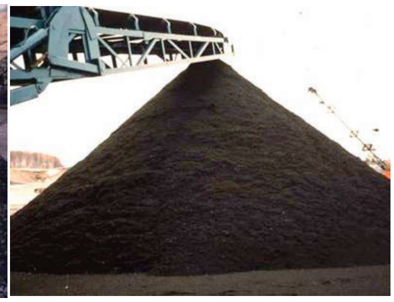



C-15 – ROOFING SHINGLE WASTE

There are a number of different roofing materials that are commercially available, but asphalt-based roofing products are by far the most common comprising 90 percent of the residential market and nearly 80 percent of the low slope industrial, commercial and institutional (ICI) roofing market in Canada (Athena, 2007).

Asphalt-based roofing shingles are manufactured by impregnating felt (typically either cellulose fibres or fibreglass) with hot asphalt which is then coated on both sides with roofing granules. At the end of their service lives, asphalt roofing shingles were historically disposed of in landfills. Considering that asphalt roofing shingles are composed primarily of hard, fine aggregate particles (66 percent) and asphalt (25 percent), they would be considered as a logical substitute for these very same constituents in the production of hot-mix asphalt mixes.

How it is generated/quantities generated

Roofing shingle waste is generated during the manufacturing of asphalt shingles, installation of new roofs and demolition or replacement of existing asphalt shingled roofs. Roofing shingle waste is classified into two general categories based on their source: roofing shingle tabs; and roofing shingle tear-offs.

"Roofing shingle tabs" is the term given to roofing shingle waste that is generated during the manufacture of new asphalt roofing shingles. This includes portions of asphalt shingles that are trimmed during production as well as "out-of-specification" shingles. This waste is highly favourable for recycling it is are generally homogeneous, relatively free of debris and other wastes and are composed of new, unaged asphalt cement binder.

"Roofing shingle tear-offs" is the term given to asphalt shingle waste generated during the construction of a new roof or demolition or replacement of existing asphalt shingled roofs. The quality of tear-off singles is much more variable and can be affected by the degree of hardening of the asphalt, the amount of weathering (loss) of the roofing granules, as well as debris such as nails, wood and paper.

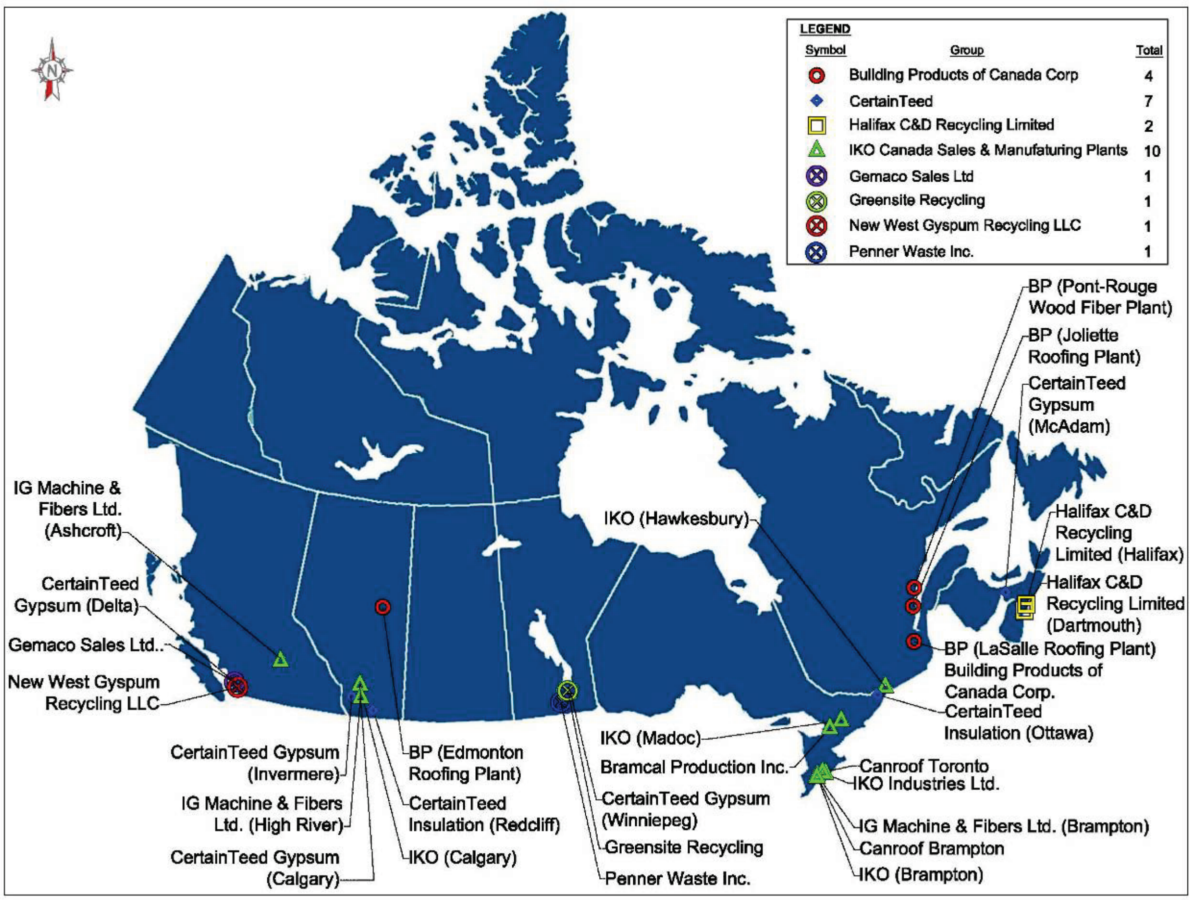
The roofing shingle tabs and tear-offs are typically collected and transported to shingle recyclers who use state-of-the-art processing equipment which removes contaminants and processes the shingles into a useable product commonly referred to as recycled asphalt shingles (RAS) or manufactured shingle modifier (MSM, if composed solely of roofing shingle tabs).

It is estimated that there is at least 1.5 million tonnes of asphalt based roofing shingle waste generated in Canada annually (Athena, 2007).

Typical sources

Roofing shingle waste is typically processed and marketed by integrated shingle recycling firms. Figure C15-1 shows the locations of major shingle recycling facilities across Canada.

Figure C15-1. Location of Major Shingle Recyclers in Canada



In what forms can roofing shingle waste be used and in what quantities

Shingle recycling technology has been developing for the past 30 years. The technology for use of RAS material in hot-mix asphalt mixtures is fairly well developed where the investment in the asphalt cement and premium mineral aggregates can be recovered to their highest best potential.

RAS material which is free of nails, asbestos and processed to a relatively uniform state can be used in hot-mix asphalt mixes, but more recent research has also shown positive use of RAS material in granular base and subbases, in cold patch mixtures as well as for dust control on gravel roads.

Hot-Mix Asphalt Pavement

As the main constituents of shingles are components of hot-mix asphalt mixtures, recycling shingles into flexible pavements is a natural, value-added recycling option.

In order to use RAS material in hot-mix asphalt mixtures, it must first be processed to remove any construction debris (nails, wood, roofing paper, insulation, for instance) followed by shredding of the processed scrap to a nominal aggregate size of 4.75 mm. Shingles which are processed in this manner can be used as a partial replacement for the fine aggregate portion in hot-mix asphalt mixes. The amount of RAS material used in hot-mix asphalt mixtures is typically limited to 5 percent by mass of the mixture and this may depend on the mechanical properties of the aged asphalt cement binder and the amount of granules remaining. Higher amounts of RAS material may be used, however this requires a more detailed laboratory examination of the shingle source and modification of the grade of the new asphalt cement in order to ensure that the blended asphalt cement binder does not make the recycled hot-mix asphalt prone to high temperature cracking.

RAS material has been successfully used in hot-mix asphalt binder and surface course mixes as well as in mixes such as stone mastic asphalt (SMA) to take advantage of the cellulose fibres in the RAS material and providing a high resilient modulus and improved rutting resistance (CTAA, 1999). SMA mixes are well suited for RAS material use as it not only provides asphalt cement and high quality fine aggregate, but is also an economic source of fibre which is required in such mixes.

Hot-mix asphalt pavements containing RAS material can be mixed, placed and compacted using standard hot-mix asphalt equipment. The stockpiled RAS material is typically pre-blended with conventional hot-mix aggregate to keep it from consolidating and enabling it to be more easily introduced into the mix.

Cold Patch

Another use for RAS material, which is well developed in the United States, is in the production of RAS cold patch. The advantages of RAS cold patch are that it is lighter in weight, easier to handle and apply, and that it has a longer life (likely due to the entrained fibres) (Krivit, 2007). It does however have a higher cost, and is typically considered to be better suited to high performance hot-mix asphalt mixtures (CMRA, 2011).

RAS Material in Granular Base and Subbase

While considerably less prominent, RAS material has been successfully incorporated in typical unbound granular bases and subbases in road construction. While some US States have specifications for this type of application, there currently are no standard specifications for RAS material use in granular base or subbase construction in Canada.

Research completed by the Construction Materials Recycling Association (CMRA) indicates that up to 10 percent by volume of RAS material can be blended into aggregates in this type of application (Krivit, 2007). However, Canadian research indicates that the optimum RAS material addition appears to be 5 percent by mass (TAC, 2008).

Dust Control on Gravel Roads

A scan of Canadian literature does not reveal any specific work which has been completed in relation to the use of RAS material as cover on rural, unpaved roads, however there have been a number of trials in the United States. In this application, relatively finely processed RAS material (typically < 9.5 mm) is windrowed, graded and then compacted and has reportedly lasted for over two years without maintenance (Marks, Petermeier, 1997).

Engineering Properties of Recycled Shingles

Some of the typical physical and mechanical properties of RAS material that may be of interest differ from natural aggregates are shown in Table C15-1.

Table C15-1. Typical Physical and Mechanical Properties of RAS (Adapted from FWHA, 2008, CTAA, 1999)

PROPERTY	RAS	COMMENT
Asphalt Cement Content (%)	15 – 35	Depends on weathering of shingle and shingle type (organic shingles have higher AC content than fibre glass shingles)
Mineral Granules (%)	30 - 50	Typically composed of hard, durable granules
Asphalt Cement Grade	N/A	The precise determination of AC grace must be completed on samples from the RAS source
Moisture Content (%)	3 – 10	Lower for fibreglass than organic shingles
Specific Gravity	1.29 – 1.37	
Thermal Cracking	-	Improved
Rutting Resistance	-	Improved
Resilient Modulus	-	Increased

Toxicity or environmental concerns/impacts

The biggest concern with the use of RAS cited by the USEPA is the potential health hazards associated with processing waste shingles which contain asbestos fibres (EPA, 2007). Asbestos fibres were used in some asphalt shingles until the early 1980's when the detrimental health effects of asbestos were determined. As such, there is the possibility that waste shingles may contain asbestos fibres which may become airborne during processing. However, data complied in the United States indicates that asbestos fibres were observed in approximately 1 percent of samples out of the 27,000 samples which were tested and in many cases, the asbestos occurrence was attributed to have occurred from other materials in the samples (EPA, 2007).

Given that the traditional lifetime of an asphalt shingle is close to 20 years, many of the asbestos containing shingles have likely already been disposed of in landfills. Regardless, it is still highly recommended that RAS processors employ best practices to mitigate dust during production to ensure that asbestos fibres do not become airborne.

Concerns have also been raised regarding the potential for PAHs to leach from ground-up shingles. While asphalt cement does contain small amounts of PAHs, research by the USEPA has indicated that a few PAH concentrations may be greater if shingles themselves are compared to risk-based thresholds for clean soil (EPA, 2007). In these cases, RAS material has been blended with other materials in order to mitigate this potential (EPA, 2007).

Technical Limitations

Increased use of RAS in hot-mix asphalt mixtures can result in a reduced resistance to high temperature cracking depending on the amount of age hardening that has occurred in the asphalt cement in the RAS. In this regard, it is recommended that a more detailed laboratory examination of effective grade of the blended RAS and virgin asphalt cement be completed during the mix design stage in order to ensure that the effective grade is as required for the contract and adjustments made as necessary.

RAS may be potentially susceptible to moisture damage. The moisture sensitivity of the resultant hot-mix asphalt should be investigated during the mix design stage and an appropriate antistripping additive used if required.

Increased care must be taken when processing roofing shingle tear-offs to ensure that there is no contamination from other components of the roof including paper, wood or nails. A statistics based quality control program is recommended to be employed when using this material to confirm no contamination.

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C-16 – SCRAP TIRES

Every year, approximately 30 million tires on Canadian vehicles come to the end of their serviceable lives. In the past, typical management options for these discarded tires included landfills, tire stockpiles and illegal dumps. However, scrap tire stewardship has evolved across Canada which has turned this waste into a resource which is used in a wide array of products such as mulch, mats, playground surfaces, athletic tracks, synthetic sport fields, auto parts, shingles, and tire derived fuel to name a few.

As the most of the Canadian tire stewardship programs are processing the majority of their scrap tires for various end-uses, the focus of many of the stewardship programs is to evaluate uses of scrap tires that are higher value and unlock more of the energy invested in their original production. The use of scrap tires in transportation infrastructure projects is one of the competing stewardship options which has the potential to maximize the use of this invested energy while improving the characteristic performance fundamentals of the transportation infrastructure in which it is used.

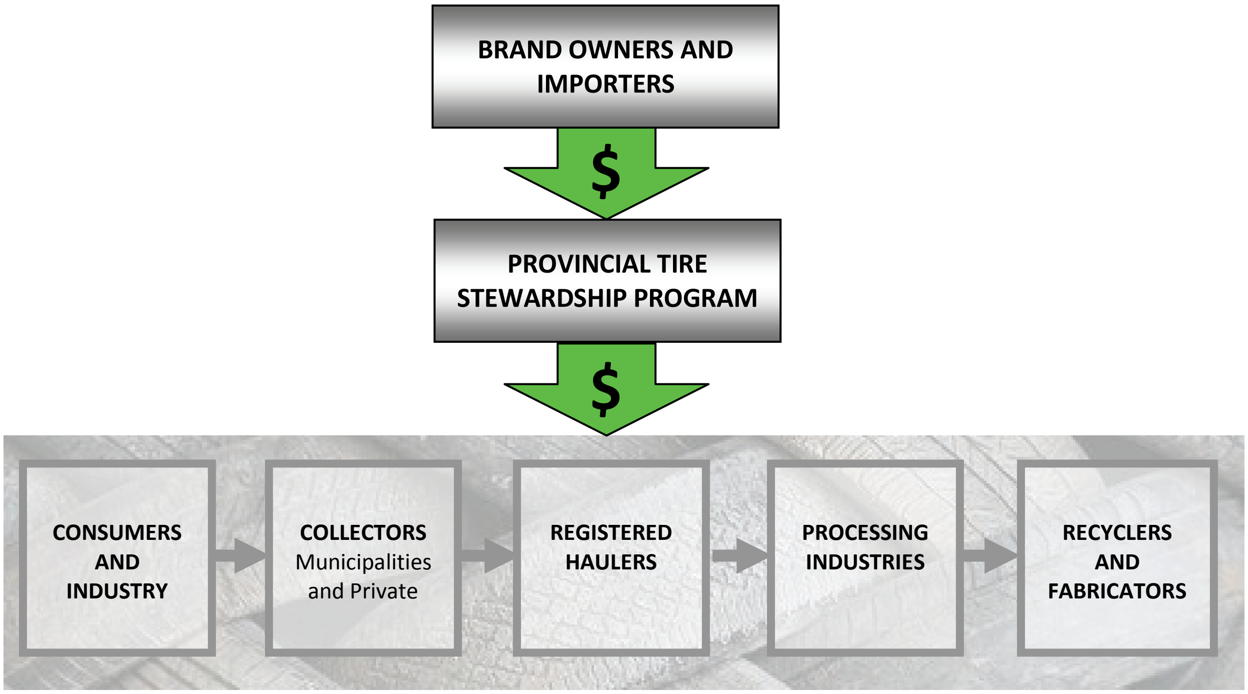
How it is generated/quantities generated

When tires are either replaced or have reached the end of their service lives they eventually enter a province's tire stewardship stream. While the tire stewardship streams can vary from province to province, a general description of the typical stewardship streams are shown in Figure C16-1.

Tires typically enter the tire stewardship stream via tire collectors. Tire collectors can include tire retailers (who collect tires which are being replaced), dedicated tire collection locations and vehicle scrap yards. The collected tires are then typically transported to tire processors using registered haulers. The processors take the discarded tires and process them into one of four main tire derived product categories: fabricated products; tire-derived aggregate; crumb rubber; and tire-derived fuel. Tire-derived aggregate can be further processed by recycled product manufacturers to create many proprietary moulded and stabilized products (playground surfaces, auto parts, synthetic sport fields, etc.) which are not part of transportation infrastructure.

While varying somewhat from province to province depending on the respective stewardship program, discarded tires can include passenger vehicle tires, off-road tires (large open pit mining trucks, for instance), large truck tires (which can no longer be retreaded), and to a lesser extent, recreational vehicle tires (ATV's and golf carts, for instance). In order to be able to compare the quantities of tires generated in each category, each tire class is converted into a unit tire called the Passenger Tire Equivalent (PTE's – approximately 9 kilograms per PTE) which is the typical weight of a passenger tire. Based on recent estimates, there are approximately 30 million PTE's generated in Canada on an annual basis. When divided into the main constituents, this represents approximately 225,000 tonnes of synthetic and natural rubber, 43,000 tonnes of steel and 16,000 tonnes of fabric which are generated on an annual basis.

Figure C16-1. Example Provincial Tire Stewardship Stream



Typical sources

Tire-derived products for potential use in transportation infrastructure projects would typically be obtained from tire processors. Figure C16-2 shows the locations of major tire processing facilities across Canada.

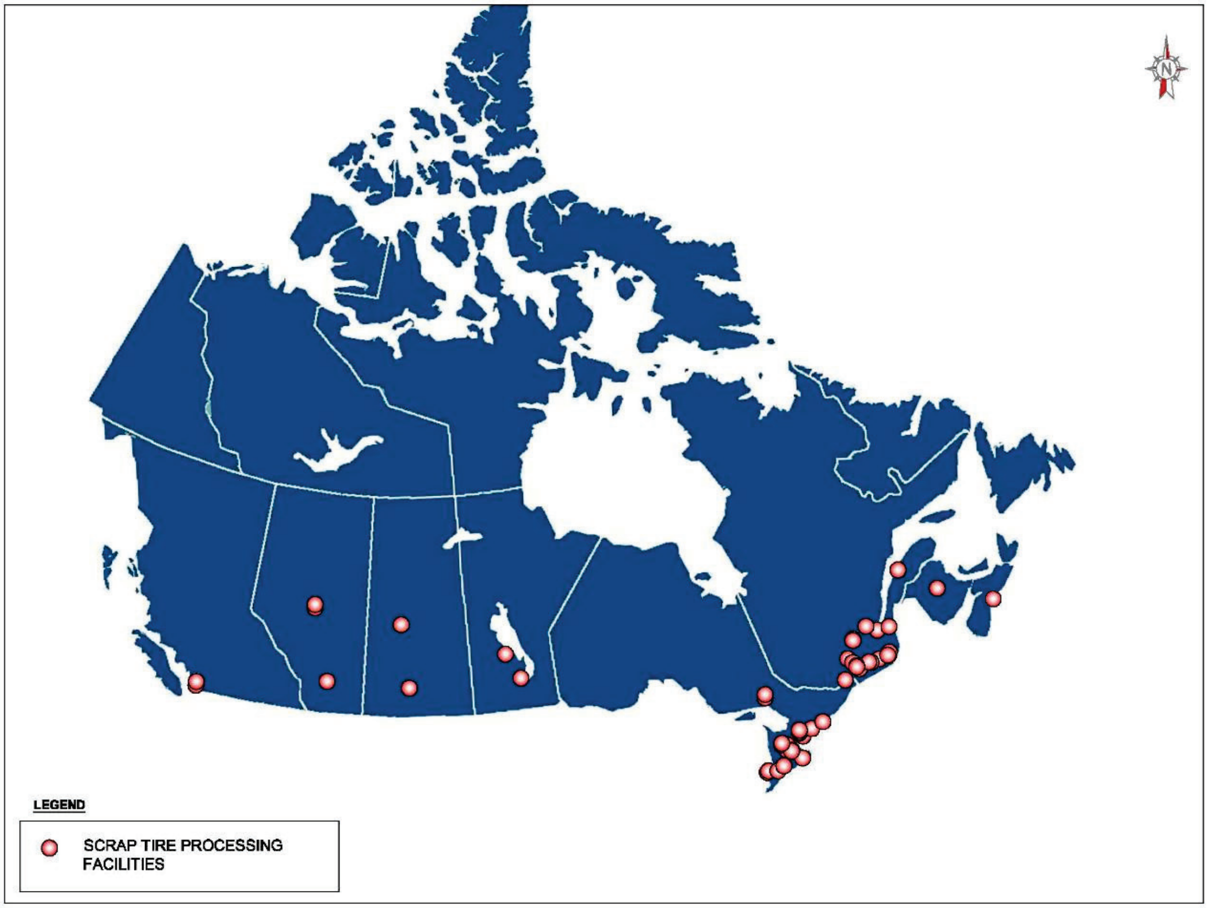
In what forms can scrap tires be used and in what quantities

Properly processed scrap tires are used in transportation infrastructure projects primarily in the form of tire-derived aggregate (embankment and fill construction) (ASTM 2008) and crumb rubber (asphalt paving mixtures) but are also used, in a more limited fashion as fabricated products (rings for traffic barrels, and for slope stabilization) (ASTM 2008) and tire derived fuel (used in some jurisdictions in the manufacture of portland cement). The main uses as tire derived aggregate and crumb rubber are described in greater detail below.

<u>Tire Derived Aggregate</u>

Tire derived aggregate (TDA) is the term given to scrap tires that have been processed (shredded or cut) into pieces typically ranging in size between 25 to 300 mm (OTS, 2012). TDA is typically used as a lightweight fill material in the construction of embankments or backfills for walls and bridge abutments. In New Brunswick, TDA can be used as a compressible fill material for induced trenches over deep culverts which have a substantial amount of overlying fill. When used in these applications, the processed tires are used as a complete substitute for natural borrow material.

Figure C16-2. Location of Major Tire Processors in Canada



Crumb Rubber

Crumb rubber is the term given to the rubber portion recovered from scrap tires. During scrap tire processing, usually either a mechanical or cryogenic process is employed to break the tires down into smaller pieces with a consistency of coarse sand or fine gravel. Once the steel belts and fibres are removed, the tire rubber is processed further to produce crumb rubber with a consistency of fine gravel or coarse sand.

Crumb rubber can be incorporated into asphalt concrete mixes using two different processes commonly referred to as the dry process and the wet process.

In the dry process, crumb rubber is used to replace a portion of the fine aggregate in the asphalt concrete mix. It has been used in dense-graded, open-graded and gap graded mixtures but is considered not suitable for use in cold mixes, chip seals and surface treatments. In this process, the crumb rubber is combined with the natural hot-mix asphalt aggregate prior to mixing with asphalt cement. The crumb rubber is added at 1 to 3 percent by mass of the aggregate in the mix (FHWA, 2008). Unlike the wet process, the crumb rubber typically does not react significantly with the asphalt cement producing a modified asphalt binder except for some proprietary processes which include reaction catalysts which can result in a partially modified asphalt cement. It should be noted that trials completed in Ontario in the 80s and 90s as well as in the City of Québec (in the 1990's) using the dry process indicated inferior performance to conventional pavements with 75 percent of the trial sections having a service life of 10 years or less (MERO, 2009).

In the wet process, very fine crumb rubber is blended with asphalt cement prior to the asphalt cement being added to the aggregate effectively modifying the properties of the resultant asphalt cement. The crumb rubber can either be blended at the terminal (Terminal Blend) or at the asphalt cement plant (Field Blend). Typical crumb rubber addition rates range from 10 to 25 percent by mass of the blended AC (depending on the nominal size of the crumb rubber and the mixing time required) (MTO, 2011). Canadian experience with the wet process (both terminal and field blend) have had similar or better performance than conventional pavements with improved rutting and crack resistance.

Engineering Properties of Scrap Tires

Some of the typical physical and mechanical properties of processed scrap tires that may be of interest differ from natural aggregates are shown in Table C16-1 (Adapted from FHWA 2008).

Table C16-1. Typical Physical and Mechanical Properties of TDA and RMA (TAC, 1996, FWHA, 2008)

PROPERTY	TIRE DERIVED AGGREGATE	RUBBER MODIFIED ASPHALT
Viscosity		Increases depending on the amount of crumb rubber added. May require addition of diluent to ensure material is workable
Softening Point		Increases the softening point by 11 – 14°C resulting in improved resistance to rutting and shoving
Resilient Modulus		Lowers the resilient modulus of the resultant mix
Permanent Deformation		Somewhat less resistant to permanent deformation
Thermal Cracking		Less brittle and hence more resistant to low temperature thermal cracking
Compacted Density (kg/m^3)	320 – 860 (depending on amount of residual steel)	
Angle of Internal Friction	19° to 25°	
Permeability (cm/sec)	1.5 to 15	

Toxicity or environmental concerns/impacts

Crumb rubber used in the production of asphalt concrete mixes using both the wet and dry processes have reported higher emissions which in some cases exceeded local air quality criteria (MTO, 2011). Crumb rubber has been successfully incorporated into rubber modified asphalt (RMA) mixes in many jurisdictions, however emissions should be monitored when producing a rubber modified asphalt mix to ensure they do not exceed local criteria.

Tire-derived aggregate is nonreactive under normal environmental conditions (Schnormeier, 1992). However, there have been reported incidents where tire derived aggregate fills have caught fire due to exothermic reactions within the fill. This was likely due to a combination of the use of tire derived aggregate which was contaminated with liquid petroleum products in addition to the presence of organic materials in the cover material which allowed for the creation of combustible gases (Humphrey, 1996).

Technical Limitations

Tire derived aggregate fills are difficult to compact and prone to settlement. It is recommended that a minimum 1.0 m soil cover be used to promote consolidation of these fills. If heavier wheel loads are contemplated above TDA fills, additional soil cover should be used to promote maximum consolidation. The additional soil cover can be removed once the desired consolidation has been met.

In order to limit exothermic reactions in TDA fills, experience in New Brunswick recommends the following (TAC, 2008):

- TDA shall be free of contaminants such as gasoline, diesel, oil, grease, etc.
- TDA shall not contain remnants of tires that have been subjected to a fire.
- TDA shall be free of fragments of wood, wood chips, and other fibrous organic matter.
- The TDA shall have less than 1 percent (by weight) of metal fragments, which are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge on 75 percent of the pieces and no more than 50 mm on 90 percent of the pieces.
- Minimize infiltration of air and water into the TDA. This is typically accomplished using a layer of low permeable soil (with a minimum 30 percent fines) surrounding the TDA.
- TDA shall not be in direct contact with soil containing organic matter, such as topsoil.
- The TDA should be separated from the surrounding soil using a geotextile.
- Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided. ASTM D6270-08 provides comments that if drains are to be used by the designers that a well graded material be used to minimize access to air.
- 3 metres maximum TDA layer thickness (after compression).

There has been limited study in Canada on the recyclability of RMA mixes. While there have been reported successes (Grey County in Ontario, for instance) just as many jurisdictions have reported issues with RMA recycling (MTO, 2011). Additional research is required to ensure that RMA mixes can be practically recycled into conventional recycled cold and hot mix asphalts without exceeding emission regulations or being a detriment to pavement performance.

Experience in British Columbia has indicated issues with hot in-place recycling mixes containing rubber. The concern has been specifically that RMA mixes tend to ‘gum up’ the scarifiers, preventing effective recycling.

RMA technology is not well established and certain jurisdictions have observed anywhere between 15 to 65 percent cost increase in using this technology. Once the technology is well established, it is expected to be equivalently priced (or provide a cost savings) with comparable tradition hot-mix asphalt mixes.

With some exceptions, Canadian experience has indicated that the dry process provides inferior performance to conventional pavements and this process has generally been abandoned in favour of the wet process (both terminal and field blend) which has demonstrated similar or better performance to conventional pavements with improved rutting and crack resistance.

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C-17 – SEWAGE SLUDGE ASH

Sewage sludge ash is the term given to the by-product produced in an incinerator during the combustion of dewatered sewage sludge. It is predominantly a silty material with some sand-size particles. The type of incineration system and the chemical additives introduced in the wastewater treatment process will have an effect on the particle size range and properties of the sludge ash (FHWA, 2008).

Sewage sludge ash can be used as mineral filler or as a portion of the fine aggregate in hot mix asphalt. Addition of about 2 to 5 percent of sewage sludge ash by weight of aggregate has shown to produce mix design properties that are similar to properties of mixes containing typical fillers such as hydrated lime. It has also been previously used as a raw material in Portland cement concrete, as aggregate in flowable fill, and as a soil conditioner mixed with lime and sewage sludge (FHWA, 2008).

Most of the sewage sludge ash generated in the United States is disposed of at landfills (FHWA, 2008).

How it is generated/quantities generated

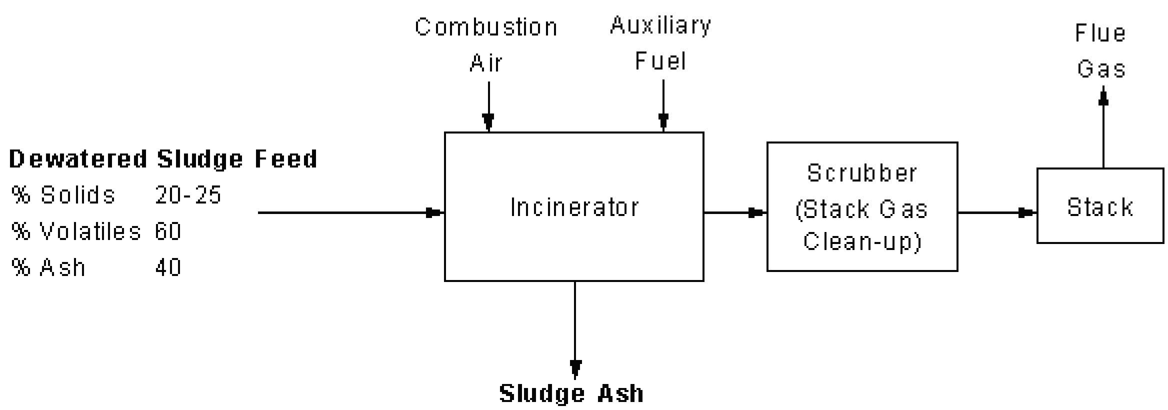
Figure C17-1 shows a simplified flow diagram of a sludge incinerator. The complete system includes sludge pretreatment operations (sludge thickening and sludge dewatering) followed by incineration, air pollution control, and ash handling. Auxiliary fuel is typically required to maintain the combustion process. The amount of auxiliary fuel required depends on the heating value of the sludge solids and on the moisture content of the incoming sludge (FHWA, 2008).

The annual Canadian production of sewage sludge ash is currently not available.

Typical sources

Sewage sludge ash can be obtained from municipal wastewater treatment plants with sludge incinerators, or from private companies responsible for disposing of the ash (FHWA, 2008).

Figure C17-1 Simplified Flow Diagram of a Sludge Incinerator (FHWA, 2008).



In what forms can sewage sludge ash be used and in what quantities

In the United States, over the past 15 years various laboratory and field studies have been performed on sewage sludge ash in pavement applications (as mineral filler or as fine aggregate substitute). Results from these studies have indicated that asphalt mixes containing sewage sludge ash can readily be prepared and pavements perform up to standard. The pavement sections in which sewage sludge ash was used showed no visible difference from pavement sections in which contained conventional materials. The sludge ash content added in the base, binder and wearing courses in the investigations contained about 2 percent (FHWA, 2008).

In 1993, a test pad containing sewage sludge ash in the surface mix (as a sand substitute) was completed in Suffolk County, New York. The mixes contained 5.5 percent sludge ash by weight. Testing of the test pad was focused on surficial texture (namely, skid resistance and surface runoff properties). Control mix test pads were also constructed in order to compare the results from the two types of pavements. The results showed that the mixes with ash did not have a considerable effect on the skid resistance of the pavement, and were comparable to the results of the control test pads (FHWA, 2008).

Despite the laboratory and field studies completed, there is no widespread commercial use of sewage sludge ash (FHWA, 2008). To our knowledge, there has been no use of sewage sludge ash in construction applications in Canada.

AASHTO M17-83 contains specification requirements for mineral fillers, and requires that 100 percent of the mineral filler material must pass the 0.600 mm (No.30) sieve. Some sludge ash sources may require crushing and/or screening to remove particles greater than this size requirement. If used as mineral filler and fine aggregate in hot mix asphalt mixes, this crushing and/or screening process would likely not be required (FHWA, 2008).

Engineering properties

The properties of importance when using sewage sludge ash in hot mix asphalt mixtures are particle size, plasticity and organic content (FHWA, 2008).

Particle Size

Sewage sludge ash may contain particles larger than 0.6 mm (No. 30 sieve), however this depends on the source. If the ash contains particles of this size, then it will not meet the requirements of AASHTO M17-83, which are outlined in Table C17-1, and would require supplemental processing by either crushing and/or screening, or would be required to be introduced into the mix as a mineral filler as well as fine aggregate. If ash is used as a fine aggregate, it must meet the gradation and soundness requirements outlined in AASHTO M29.

Table C17-1 AASHTO M17-83 Specification Requirements for Mineral Filler for use in Bituminous Paving Mixtures (AASHTO, 1983)

PARTICLE SIZING		ORGANIC IMPURITIES	PLASTICITY INDEX
Sieve Size	Percent Passing		
0.600 mm (No.30)	100	Mineral filler must be free from any organic impurities.	Mineral filler must have plasticity index not greater than 4.
0.300 mm (No.50)	95-100		
75 µm (No.200)	70-100		

Plasticity

Sludge ash is nonplastic in nature, and meets the plasticity requirements set out in AASHTO M17-83 for mineral filler and AASHTO M29 for fine aggregate.

Organic Impurities

Depending on combustion efficiency, sludge ash can contain up to about 2 percent of organic matter. This small organic content does not appear to affect the pavement performance if sludge ash is used as mineral filler.

The properties of importance of the asphalt mixture containing sludge ash are stability, mix density, air voids, asphalt demand, durability and asphalt cement viscosity.

Stability

Stability of an asphalt mixture is reported to increase with the addition of sludge ash of up to about 5-6 percent by weight of aggregate.

Mix Density

Density of an asphalt mixture is reported to decrease with the addition of sludge ash.

Air Voids and Asphalt Demand

Content of air voids increases with the addition of sludge ash, which results in an increase in demand for asphalt cement in the mix.

Durability

Mix durability may be slightly increased with the addition of sludge ash (as measured in the laboratory).

Viscosity

The ductility of the binder in an asphalt mixture is reduced with the addition of sludge ash. The penetration values decrease, viscosity is increased, resulting in a high consistency binder.

Addition of sludge ash into an asphalt mixture can form a high-consistency asphalt grade binder, exhibiting relatively high viscosity and hardness, and low ductility which could increase the susceptibility of the pavement to thermal cracking (FHWA, 2008).

Physical properties

Table C17-2 shows the physical properties of sewage sludge ash (values taken from various references). As shown, a large portion (up to 90 percent) of the particles are smaller than 75 μm (No. 200 sieve). Sewage sludge ash is most often a silty-sandy material, has a relatively low organic and moisture content, is nonplastic in nature and its permeability and bulk specific gravity properties are similar to those of a natural inorganic silt.

Table C17-2 Typical Physical Properties of Sewage Sludge Ash (FHWA, 2008)

PROPERTY	VALUES
Gradation (% passing)	Based on Various Studies
0.85 mm (No. 20 sieve)	100
0.42 mm (No. 40 sieve)	98
0.21 mm (No. 80 sieve)	83
0.150 mm (No. 100 sieve)	-
75 μm (No. 200 sieve)	56
20 μm	20
5 μm	12
> 1 μm	2
Loss on Ignition (%)	1.4
Moisture Content (% by Total Weight)	0.28
Absorption (%)	1.6
Specific Gravity	2.61
Bulk Specific Gravity	1.82
Plasticity Index	Nonplastic
Permeability (ASTM D2434 – cm/sec)	1×10^{-4} to 4×10^{-4}

Chemical properties

Chemical properties of sewage sludge ash depend on the nature of the wastewater and the chemicals introduced in the wastewater treatment and sludge handling process. Sludge combustion almost always requires dewatering with pretreating the sludge with chemicals such as ferrous salts, lime, organics and polymers. Depending on the type and amount of chemicals added, the chemical composition of the sewage sludge can vary. The pH of the ash ranges between 6 and 12, but is generally alkaline (FHWA, 2008).

The primary constituents of sludge ash are silica, iron and calcium. The composition can vary substantially depending on the amount and types of chemicals added during the conditioning and dewatering process. Sludge is not known to exhibit any significant pozzolanic or cementitious activity (FHWA, 2008).

Sludge ash contains higher trace metal concentrations (such as cadmium, copper, lead and zinc) than concentrations found in natural fillers or aggregates. Although trace concentrations create a reluctance to use this material, leachate investigations reveal that the trace metal concentrations are not excessive and do not pose any detectable leaching problem (FHWA, 2008).

Table C17-2 Typical Range of Elemental Concentrations in Sewage Sludge Ash (FHWA, 2008)

		CONCENTRATION (%)	
Element	**Oxide**	**Reported as Elemental Concentration**	**Reported as Oxides**
Silicon (Si)	(SiO_2)	20	27.0
Calcium (Ca)	(CaO)	8	21.0
Iron (Fe)	(Fe_2O_3)	4	8.2
Aluminum (Al)	(Al_2O_3)	7	14.4
Magnesium (Mg)	(MgO)	2	3.2
Sodium (Na)	(Na_2O)	0.3	0.5
Potassium (K)	(K_2O)	0.5	0.6
Phosphorus	(P_2O_5)	6	20.2
Sulphur(S)	(SO_3)	-	0.9
Carbon (C)	-	-	-

Environmental Concerns

Historically, there has been some concern with regards to the trace metals found in sewage sludge ash. As mentioned earlier, the results of studies completed show that leaching does not appear to be a problem while using sludge ash in asphalt mixtures, especially since no more than 5 percent is added into a mixture. However, environmental criteria are required to define specifications for trace metal content, acceptable loss on ignition or organic impurity data (FHWA, 2008).

Technical limitations

It is recommended that sludge ash be added to asphalt mixtures with an upper limit of 5 percent by weight of aggregate in the binder course, and 3 percent in the surface course. A higher percentage of sludge ash incorporation has shown to result in excessively high stabilities (FHWA, 2008).

References

FHWA, 2008. User Guidelines for Waste and Byproduct Materials in Pavement Construction, Federal Highway Administration, Available from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/ss1.cfm and

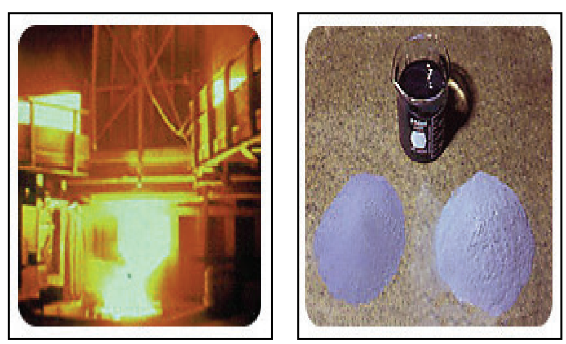
http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/ss2.cfm

C-18 – SILICA FUME

The American Concrete Institute (ACI) defines Silica Fume as "very fine non-crystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon" (FHWA, 2005). It is typically light to dark grey in colour, and looks similar to portland cement and some fly ashes. During the mid-1970s, environmental concerns about exhaust particulates being released into the atmosphere led to the requirement of many industrial producers to reduce the particulate emissions in their processes using dust collection emission control systems. In the early years, the only disposal option that was considered for the captured material was landfilling. However, discovery of its cementitious properties lead to its eventual use as a supplementary cementitious material in the manufacture of portland cement concrete.

One of the most beneficial uses for silica fume is as a supplementary cementitious material (SCM) in portland cement concrete to improve its mechanical properties. Due to the nature of silica fume's chemical and physical properties, it is a very reactive pozzolan. Portland cement concrete containing silica fume is known to have very high compressive strength, bond strength and abrasion resistance (resulting in increased durability). It is also known to greatly reduce permeability, and therefore increase the protection of reinforcing steel from corrosion (FHWA, 2008).

Figure C18-1 Silica Fume (SFA, 2012)

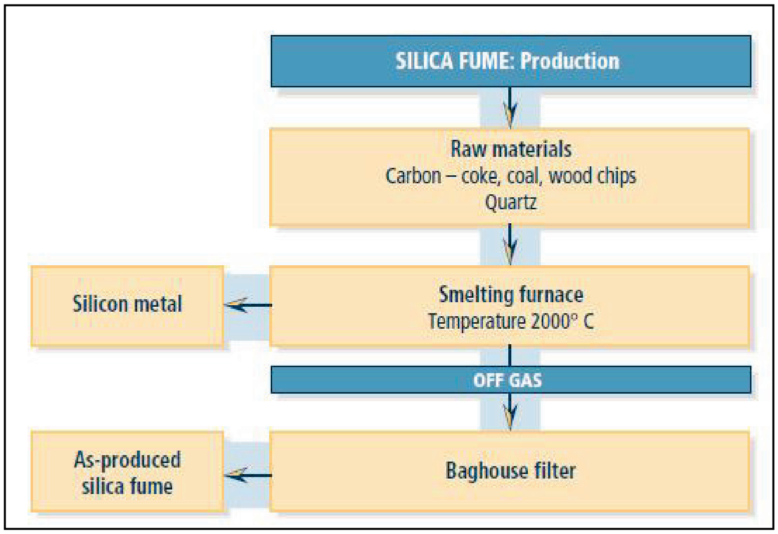


Silica fume used in portland cement concrete is available in both wet and dry form. It is usually added during concrete production at a concrete plant as shown in the Figure C18-1. Silica fume-concrete has been successfully produced in both central-mix and dry-batch plants.

How it is generated/quantities generated

Silica fume is a by-product in the production of silicon metal and ferrosilicon alloys in smelters using electric arc furnaces. During smelting operations, free silica becomes entrained in the hot exhaust gases which is then collected in the plant's emission control system (typically a baghouse). Historically, silica fume was available in either undensified, slurried and densified form, however the only substantial current use of silica fume is in the densified form. A flow chart showing the production of silica fume is presented in Figure C18-2.

Figure C18-2 Flow Chart of Production of Silica Fume (FHWA, 2005)



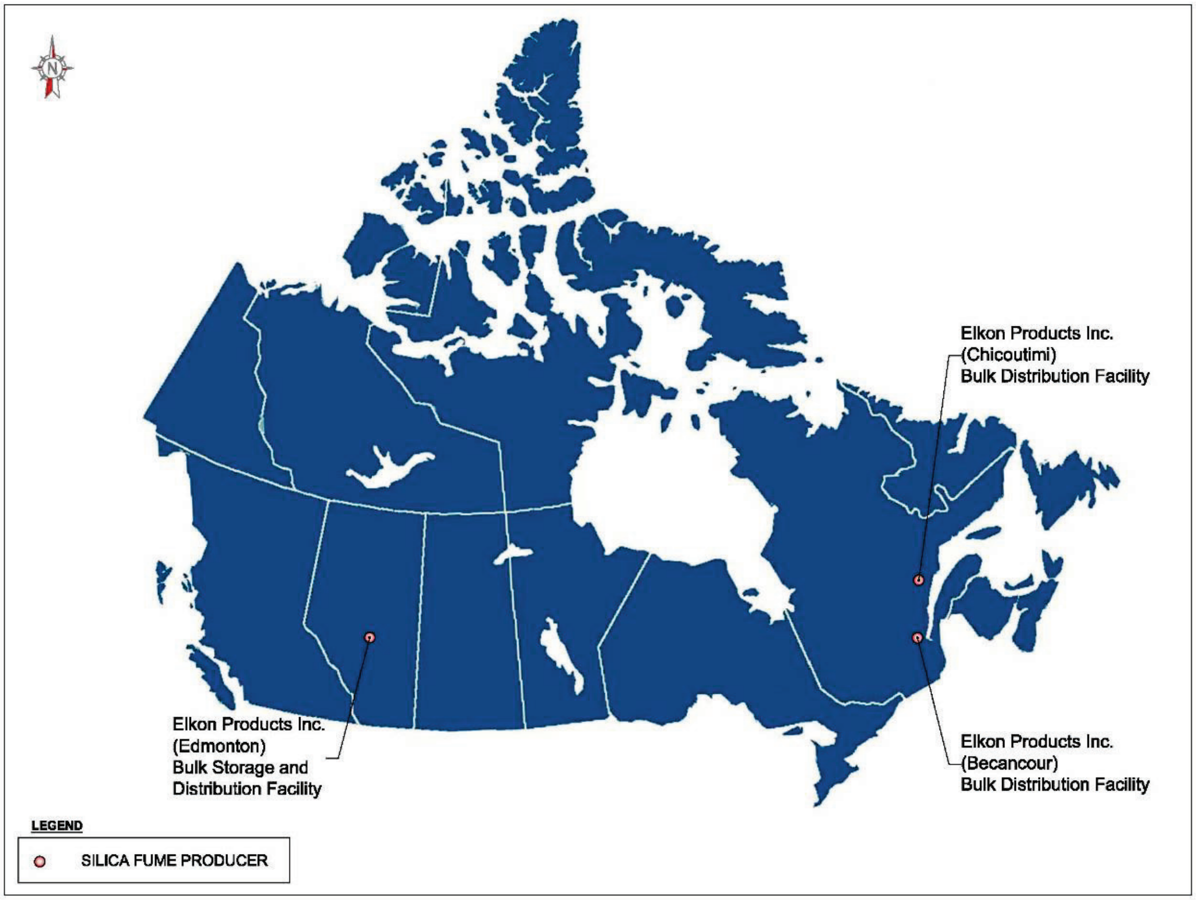
Densified silica fume is produced by treating undensified silica fume to increase the bulk density up to a maximum of about 480 to 720 kg/m^3 (FHWA, 2005). The treatment typically consists of tumbling the silica-fume particles in a silo causing surface charges to build up. The surface charges then draw the particles together forming weak agglomerations. The main purpose for densifying silica fume is to make the material more economical for truck transportation. The only issue with densifying silica fume is that portland cement concrete producers must ensure that the mixing process employed is adequate to break up these loose particle agglomerations.

An estimate for Canadian annual production of Silica Fume is not available; however annual U.S. production is in the order of 100,000 to 120,000 tonnes (Wolsiefer, 2012).

Typical sources

The only reported source of densified silica fume in Canada is Elkon Products Inc. Elkon has bulk distribution facilities at manufacturing sites in Becancour and Chicoutimi, Quebec, as well as bulk storage and distribution facilities in Edmonton, Alberta and Tacoma, Washington. Elkon also produces some undensified silica fume, while the rest of the undensified silica fume in Canada is supplied to cement manufacturers. The Elkon distribution facilities in Canada are shown on Figure C18-3.

Figure C18-3 Locations of Densified Silica Fume Production in Canada



In what forms can silica fume be used and in what quantities

The main use of silica fume in transportation infrastructure projects is in high-performance portland cement concrete typically for the construction of long-life bridge structures (long-term durability could exceed 100 years). Silica fume has also been used to improve the compressive strength in roller compacted concrete used as a pavement in high load areas such as ports, intermodal terminals, and marshalling yards.

Typical specifications in Canada allow for the replacement of between 5.0 and 10 percent of portland cement by mass (CEMENT, 2011) with the silica fume required to meet the requirements of CAN/CSA A3001 (ASTM C 1240).

In the United States, there are two major specifications of interest ASTM C1240, Standard Specification for Silica Fume Used in Cementitious Mixtures, and AASHTO M 307, Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar and Grout (FHWA, 2005).

Engineering, physical and chemical properties of silica fume

Some of the typical chemical, physical and mechanical properties of silica fume that may be of interest are shown in Tables C18-1 and C18-2 (Adapted from FHWA, 2005).

Table C18-1 Chemical Properties of Silica Fume (FHWA, 2005)

CHEMICAL PROPERTIES
Amorphous
Silicon dioxide content > 85%
Contains trace elements depending on type of fume

Table C18-2 Typical Physical and Mechanical Properties of Silica Fume (FHWA, 2005)

PROPERTY	SILICA FUME
Particle Size (typical)	<1 μm
Bulk Density (as produced)	130-430 kg/m^3
Bulk Density (as densified)	480-720 kg/m^3
Specific Gravity	2.2
Specific Surface	15,000-30,000 m^2/kg
Silicon Dioxide content	>85%

The addition of silica fume to a concrete mixture contributes millions of very small particles to the mixture and as a result, particle packing, also known as micro-filling, occurs. In other words, silica fume particles fill in the spaces between the cement grains as the size of a silica fume particle is 90 times smaller than a cement grain. Even if silica fume did not chemically react in the concrete mixture, the micro-filling would significantly improve the properties of the concrete. Table C18-3 shows a comparison between silica fume particles and other concrete ingredients (FHWA, 2005).

Table C18-3 Comparison of Size of Silica Fume Particles and Other Concrete Ingredients (FHWA, 2005)

MATERIAL	NOMINAL SIZE	SI UNITS
Silica Fume Particle	N/A	0.5 μm
Cement Grain	No.325 sieve	45 μm
Sand Grain	No.8 sieve	2.36 mm
Coarse Aggregate Particle	¾" sieve	19 mm

The other benefits that occur as a result of adding silica fume to a concrete mixture are of a chemical nature. Silica fume is a very reactive pozzolanic material in concrete due to its very high amorphous silicon dioxide content. As the portland cement reacts with the concrete mixture, it releases calcium hydroxide. Silica fume reacts with calcium hydroxide, forming extra binder material (called calcium silicate hydrate) which is similar to the calcium silicate hydrate formed from the portland cement. It is mainly this additional binder content (produced as a result of adding silica fume to concrete) that results in improved hardened concrete properties. Table C18-4 compares silica fume chemical properties with other commonly used supplementary cementitious materials (FHWA, 2005).

Table C18-4 Comparison of Chemical and Physical Characteristics of Portland Cement, Fly Ash, Slag Cement and Silica Fume (FHWA, 2005)

PROPERTY	PORTLAND CEMENT	CLASS F FLY ASH	CLASS C FLY ASH	SLAG CEMENT	SILICA FUME
SiO_2 content, %	21	52	35	35	85 to 97
$Al2O_3$ content, %	5	23	18	12	
Fe_2O_3 content, %	3	11	6	1	
CaO content, %	62	5	21	40	<1
Fineness as surface area, m^2/kg	370	420	420	400	15,000 to 30,000
Specific gravity	3.15	2.38	2.65	2.94	2.22
General use in concrete	Primary binder	Cement replacement	Cement replacement	Cement replacement	Property enhancer

Environmental Concerns and Potential Health Impacts

Silica fume is often incorrectly associated with silicosis, a general health concern which has been widely publicized within the construction industry. However, since silica fume is amorphous and non-crystalline, silicosis is not a health issue.

Although silica fume is a non-hazardous material, it falls into the category of nuisance dust (similar to other fine powders). The main health concern while using silica fume is to avoid creating dust by taking care in all operations involving silica fume. In addition, an appropriate dusk mask or respirator (and other personal protective equipment) must be worn while handling dry silica fume.

The Silica Fume Association has not reported any cases in which a worker that was exposed to silica fume has been diagnosed with any disease attributed to its handling and use.

Technical limitations

Limitations for the use of silica fume are related to the amount of silica fume added to the concrete mixture. If more than 15 percent by weight of portland cement is added, the workability of the concrete is affected, costs may increase due of the need to add more chemical admixtures, and the resulting concrete may be very strong and brittle. If too little silica fume is added (less than 3 percent), it has no beneficial effect on the concrete. The acceptable range of silica fume replacement in the concrete mixture is between 4 and 15 percent by weight of portland cement (Lemoyne, 2012).

References

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C-19 – STEEL SLAG

Steel slag is a non-metallic by-product produced in the process of steel manufacturing. Steel slag is formed when hot iron and/or iron scrap are mixed with lime/dolomite (fluxing agent) and are melted together in either a basic oxygen furnace or electric arc furnace. When the process has been completed, the lime in the flux has been chemically combined with the non-metallic components (silicates, aluminum oxides, magnesium oxides, manganese oxides and ferrites) to form steel slag.

Steel slag is typically cooled using an air-cooling process. After the steel slag has cooled, it is processed to remove any residual free metals (which are subsequently re-introduced into the steel making process) and then crushed and screened into various aggregate products. There are many grades of steel that can be produced, and the properties of the by-product steel slag can change significantly depending on the grade.

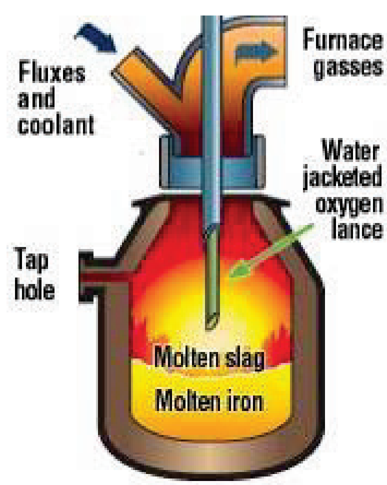
How it is generated/quantities generated

Virtually all steel made in North America is made in either Integrated Steel Mills which employ a version of the basic oxygen furnace (BOF) process or in steel plants which employ the electric arc furnace (EOF) process. These two processes are described in more detail below.

Basic Oxygen Furnace (BOF)

In an Integrated Steel Mill, the molten iron (“hot metal”) which is produced from the blast furnace process is diverted to the steel making shop’s basic oxygen furnace. The hot metal is then combined with steel scrap and fluxes (lime and/or dolomite) inside the furnace and a water jacketed oxygen lance is lowered into the mix to inject high-pressure oxygen as shown in Figure C19-1. The high-pressure oxygen combines the impurities, which consist of the silicates, aluminum oxides, magnesium oxides, manganese oxides and some ferrites (iron) to form the slag. At the end of the process, the molten steel is first removed from the furnace through the tap hole followed by the removal of the steel slag which is then transported (typically through a slag pot) to a location where it is dumped and air cooled.

Figure C19-1 Oxygen Furnace (NSA, 2011)



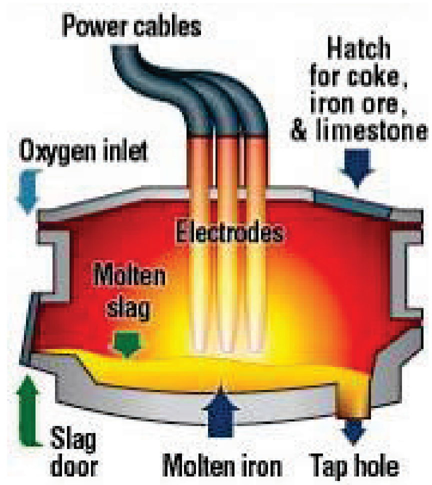
It should be noted that there are other slags produced during additional refining stages of the steel making process such as raker slag, ladle slag and clean out or pit slag. These slags typically involve high flux additions which dramatically change the properties of the slags which generally make them unsuitable for use as construction aggregates.

Electric Arc Furnace (EAF)

In an electric arc furnace operation, steel scrap is combined with fluxing agents (lime and/or dolomite) inside the furnace and heated to a liquid state by means of an electric current shown in Figure C19-2. The molten slag is less dense than the steel and floats to the top of the furnace where it is channelled out through the slag door and transported (typically through a slag pot) to a location where it is dumped and air cooled.

The Canadian Slag Association estimates that 1.2 million tonnes steel furnace slag were produced in Canada in 2009 (www.csa.org).

Figure C19-2 Electric Arc Furnace (NSA, 2011)



Typical sources

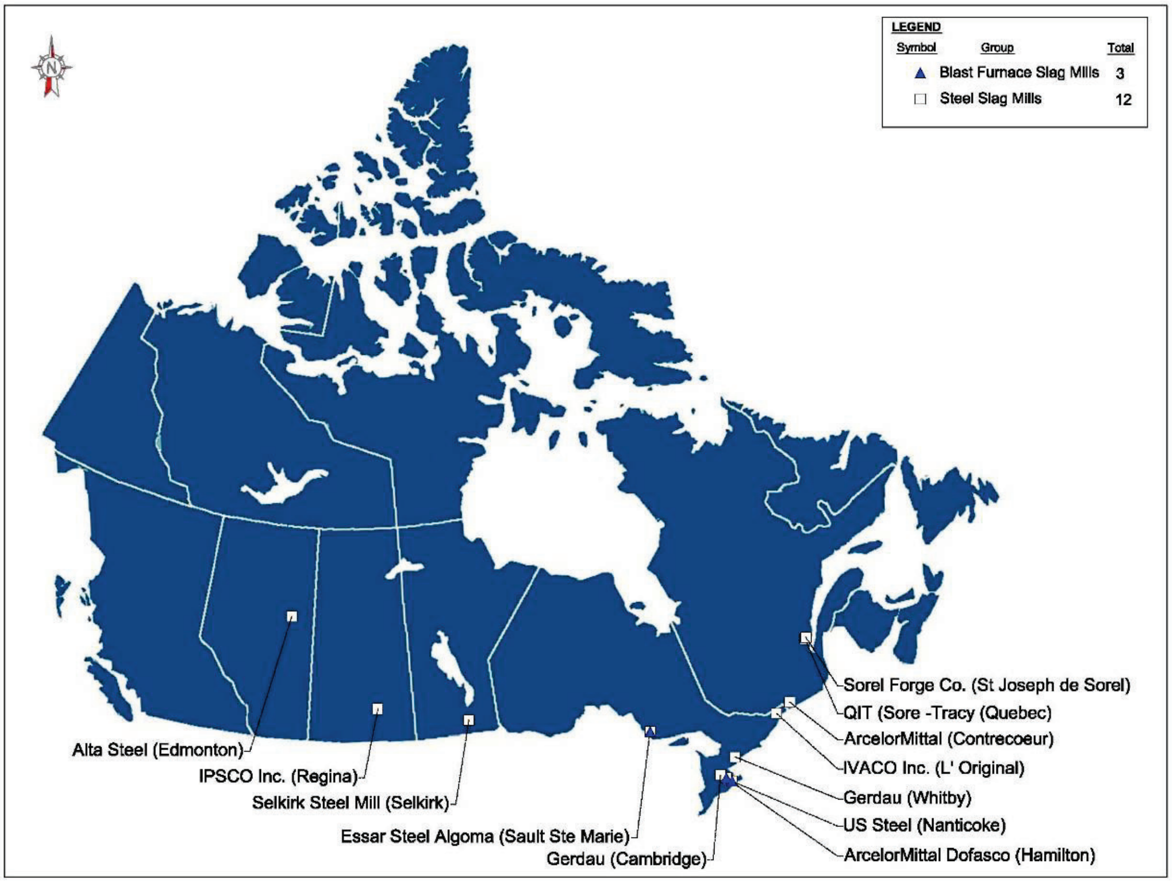
As steel slag is a by-product in the production of steel, steel slags can generally be found wherever basic oxygen furnaces (Integrated Steel Mill locations) or electric arc furnaces are located. Currently, there are 12 active steel mills in operation in Canada. Figure C19-3 shows the typical sources of steel slag in Canada. Steel slag would typically be obtained directly from the steel mill operators.

In what forms can Steel Slag be used and in what quantities

Steel slags can be used as aggregates in the construction of granular bases for roadways and as a premium aggregate in hot-mix asphalt surface course production.

When properly processed and controlled, steel slag is considered by many agencies as an equal replacement for conventional aggregate in granular base construction which can normally exceed the aggregate physical requirements of naturally sourced granular base aggregates. Proper processing should consist of a set of quality control processes which ensure that steelwork rubbish such as furnace brick, wood, lime and unfused steel fragments are not included in the steel slag aggregate. In addition, the steel slag must be washed and stored for a minimum of one month before use in HMA and, most importantly, the steel slag must not contain any discernible soft lime particles or lime-oxide agglomerations (MNR, 1992).

Figure C19-3. Location of Steel Slag Producers in Canada



The volumetric instability is caused by the remaining free lime (CaO) and magnesium oxides (MgO) reacting chemically with silicates in the slag in the presence of water. Volume changes of up to 10 percent (JEGEL, 1992) have been observed which make steel slag unsuitable for use in confined conditions such as backfill behind structures, and granular bases and subbases which are confined by curb and gutter. In addition, the formation of tufa precipitates (primarily $CaCO_3$) have been known to clog subdrains leading to water retention and associated frost damage of pavements and structures.

When properly processed and controlled, steel slag can be processed into either a coarse or fine aggregate material as an either partial or full replacement for natural aggregates in hot-mix asphalt concrete pavements and surface treatment applications. The processed steel slag aggregates normally exceed the physical property requirements of natural hot-mix asphalt aggregates. As with their use as granular base aggregates, proper processing is vital to limit the potential for expansion due to the chemical reaction of free lime and free magnesia which results in damage (random map cracking (Photograph C19-1) to the pavement surface. In addition, this map cracking allows water to infiltrate the surface of the pavement which can cause potholes during freeze thaw cycles.

Due to previous experience with volumetric instability and the associated pavement distress that is caused, the use of steel slag aggregates in hot-mix asphalt production is not permitted in Ontario as outlined in OPSS 1003. Limited use of steel slag aggregate in hot-mix asphalt has continued in the Hamilton area, mainly in commercial applications. The experience in Saskatchewan with EOF steel slag aggregates is quite different with very successful production and quality control of the resultant steel slag resulting in a source of premium aggregate for hot-mix asphalt production.

Photograph C19-1 showing map cracking distress caused by steel slag aggregate

Engineering Properties of Steel Slag

The engineering properties of steel slag are considered by many agencies to be the same as natural aggregates. Some of the typical physical and mechanical properties of steel slag are shown in Table C19-1 (Noureldin, McDaniels, 1990).

Table C19-1. Typical Physical and Mechanical Properties of Reclaimed Concrete Material

PROPERTY	AIR-COOLED
Specific Gravity	3.2 – 3.6
Compacted Unit Weight (kg/m³)	1600 - 1900
Sodium Sulphate Soundness Loss (%)	< 12
Micro-Deval Abrasion (%)	20 - 25
Absorption (%)	Up to 3 percent
Internal Angle of Friction (°)	40 – 50
Hardness (Moh's Scale)	6 – 7
CBR (%)	Up to 300

The chemical composition of steel slag from a basic oxygen furnace is outlined in Table C19-2 (JEGEL, 1992). As mentioned previously, because free calcium and free magnesia are not completely consumed in the steel making process, this free calcium and free magnesia has been shown to hydrate when in contact with moisture and is responsible for the observed expansive behaviour in steel slag aggregate. Steel slag is generally mildly alkaline with a pH of 8 to 10 however there have been some instances where its leachate can exceed a pH of 11 which is considered potentially corrosive to either embedded aluminum or galvanized steel pilings which are in contact with the steel slag.

Table C19-2. Typical Composition of Steel Slag (JEGEL, 1992)

CONSTITUENT	COMPOSITION (PERCENT)
Calcium Oxide (CaO)	41.0
Silicon Dioxide (SiO_2)	16.0
Aluminum Oxide (Al_2O_3)	2.2
Magnesium Oxide (MgO)	6.9
Iron (FeO or Fe_2O_3)	20.0
Manganese Oxide (MnO)	8.9
Titanium Dioxide (TiO_2)	0.5
Free Calcium Oxide (CaO)	3.3

As mentioned previously, tufa precipitates have been reported when steel slag aggregates have been exposed to both water and the atmosphere. Tufa is a white, powdery precipitate that consists primarily of calcium carbonate ($CaCO_3$). It occurs in nature and is usually found in water bodies. The tufa precipitates associated with steel slags are attributed to the leachate combining with atmospheric carbon dioxide. The free lime in steel slags can combine with water to produce a calcium hydroxide ($Ca(OH_2)$) solution. Upon exposure to atmospheric carbon dioxide, calcite ($CaCO_3$) is precipitated in the form of surficial tufa and powdery sediment in surface water.

Toxicity or environmental concerns/impacts

Steel slag is generally mildly alkaline with a pH of 8 to 10 however there have been some instances where its leachate can exceed a pH of 11 which is considered potentially corrosive to either embedded aluminum or galvanized steel pilings which are in contact with the steel slag.

Technical Limitations

When exposed to stagnant water, steel slag aggregates have been known to leach tufa precipitates. These tufa precipitates (primarily $CaCO_3$) have been known to clog subdrains leading to water retention and associated frost damage of pavements and structures.

The volumetric expansion of steel slag aggregates has led to random map cracking and associated potholing during freeze thaw cycles of hot-mix asphalt surface courses incorporating steel slag aggregates. While practical experience has shown that this cracking has generally been mostly aesthetic and does not affect the structural integrity of the pavement (there are currently steel slag aggregate surface course in the City of Toronto which are nearing 20 years of age), these surfaces are unsightly and unappealing to the general public.

As volume changes of up to 10 percent have been observed, steel slag is unsuitable for use in confined conditions such as backfill behind structures, and granular bases and subbases which are confined by curb and gutter.

Due to previous experience with volumetric instability and the associated pavement distress that is caused, the use of steel slag aggregates in hot-mix asphalt production is not permitted in Ontario as outlined in OPSS 1003 nor is it permitted for use as a construction aggregate as outlined in OPSS 1010.

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C-20 – SULPHATE WASTE

The term sulphate waste is used to describe the materials fluorogypsum and phosphogypsum, which are sulphate-rich by-products generated during the production of hydrofluoric and phosphoric acid.

How it is generated/quantities generated

Fluorogypsum is generated in slurry form during the production of hydrofluoric acid. After processing the fluorogypsum slurry is discharged into holding ponds where it is naturally dewatered through evaporation. Once dried, it is crushed and processed into a well graded, sulphate rich, sandy silt material using standard crushing and screening equipment.

Phosphogypsum is also generated in slurry form during the production of phosphoric acid. After processing the phosphogypsum slurry is discharged into settling ponds where the silt sized particles eventually settle out of solution (FHWA, 2008).

Production estimates are not published in Canada. In the United States, it is estimated that about 90,000 tonnes of fluorogypsum and 32 million tonnes of phosphogypsum are produced annually (fluorogypsum is mainly from Delaware, New Jersey, Louisiana and Texas, and phosphogypsum is mostly produced in central Florida, Louisiana and Southern Texas) (FHWA, 2008).

Typical sources

Both fluorogypsum and phosphogypsum are only available from the chemical companies that produce them (fluorogypsum from Delaware, New Jersey, Louisiana and Texas and phosphogypsum from Florida, Louisiana and Texas) (FHWA, 2008).

In what forms can sulphate wastes be used and in what quantities

Fluorogypsum has been evaluated for use as a road base material and has been previously used in West Virginia as a fill material, subbase and as aggregate in a lime-fly ash stabilized base. There is no documented use of sulphate wastes in construction applications in Canada (FHWA, 2008).

Phosphogypsum has been used in the United States with some success, in stabilized road bases, unbound road bases and roller-compacted concrete. The only processing required of phosphogypsum is the use of a vibrating power screen to break up lumps before mixing with a binder (FHWA, 2008).

Physical properties

Table C20-1 outlines some typical fluorogypsum particle sizes, moisture content and specific gravity values.

Table C20-1 Typical Physical Properties of Fluorogypsum (FHWA, 2008)

PROPERTY	VALUE
Size Range	Coarse Fraction – minus 38 mm Fine Fraction – minus 2 mm
Moisture Content	Coarse Fraction – 6 to 9 percent Fine Fraction – 6 to 20 percent
Specific Gravity	2.5 (Coarse and fine fractions)

The results of Los Angeles Abrasion tests performed on coarse fluorogypsum show a relatively high abrasion loss of 84 percent.

Table C20-2 outlines some typical physical properties of phosphogypsum produced in Florida.

Table C20-2 Typical Physical Properties of Phosphogypsum (FHWA, 2008)

PROPERTY	VALUE
Maximum Dry Density	1474 – 1666 kg/m^3
Optimum Moisture Content	15 – 20 percent
Specific Gravity	2.3 – 2.6

The particle size range of phosphogypsum varies between about 0.5 mm (No. 40 sieve) and 1.0 mm (No. 20 sieve) and between 50 and 75 percent passing a 75 µm (No. 200 sieve). Most of the particles are finer than 75 µm (No. 200 sieve), with the moisture content ranges from about 8-20 percent (FHWA, 2008).

Chemical properties

The main constituent in fluorogypsum is calcium sulphate which causes this material to be slightly acidic in nature. Other typical chemical constituents of fluorogypsum are shown in Table C20-3.

Table C20-3 Typical Chemical Composition of Fluorogypsum (FHWA, 2008)

CONSTITUENT	COARSE SULPHATE (PERCENT)	FINE SULPHATE (PERCENT)
Sulphate ($CaSO_4$)	71	65.6
Fluoride (F)	1.6	2.5
Free Water	8.6	10.4
Combined Water	14.9	15.2
Acidity (H_2SO_4)	0.06	0.06
pH	4.5	4.6

Mechanical properties

Table C20-4 presents some mechanical properties of interest of phosphogypsum.

Table C20-4 Typical Mechanical Properties of Phosphogypsum (FHWA, 2008)

PROPERTY	VALUE
Friction Angle	32°
Cohesion Values	125 kPa
Coefficient of Permeability	1.3×10^{-4} to 2.1×10^{-5} cm/sec

Environmental Concerns

Phosphogypsum often contains trace concentrations of uranium and radium. The radium concentration is a major concern as when it decays it forms radon which is a gas known to cause cancer (EPA, 2012).

Technical limitations

There is little documented successful use in transportation infrastructure projects in Canada and any such use would be considered to be experimental.

References

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C-21 – WASTE GLASS AND CERAMICS

Waste glass used in the construction of transportation infrastructure consists of the glass collected in municipal recycling programs which cannot be recycled by the glass industry to produce new glass, due to colour, coatings and contaminants.

Waste ceramics generally consist of waste toilets, tubs and other bathroom fixtures which cannot be processed to produce new ceramic materials.

How it is generated/typical sources

With the advent of municipal curbside recycling programs (Ontario's 'blue box' program, for instance) in the late 1980s and early 1990s, the collection and sorting of waste glass and ceramic materials from the municipal waste stream became much more feasible. Modern recycling facilities are equipped to sort and classify the various recyclable materials into different recyclable streams.

Municipal collection of toilets as part of water-reduction incentive programs (rebates for switching to low-flow toilets) along with the recycling of old bathroom fixtures (after removal of hardware and gaskets) provide a source of fairly homogeneous waste ceramic materials.

While much of the recycled glass and ceramic materials are able to be recycled into new products, some of the waste glass and ceramic materials cannot be recycled and have traditionally been sent to landfills for disposal (JEGEL, 2007).

While municipal curbside recycling programs are responsible for the collection and classification of the various recyclable products, once classified, they are typically sold to processors, who in turn process and market the various recycled products.

In what forms can waste glass and ceramics be used and in what quantities

Waste glass and ceramics have been successfully used as a partial replacement for the fine aggregate portion of granular base and subbase materials in Canada. Waste glass that has been properly sized and processed exhibits characteristics similar to gravel or sand. Currently most specifications allow for a maximum 15 percent substitution rate in granular materials.

In order to be used in construction applications, waste glass and ceramics must be crushed and screened to produce an acceptable gradation. Crushing equipment used for these materials is similar to rock crushing equipment (including hammermills, rotating breaker bars, rotating drum and breaker plate and impact crushers) however it is generally smaller and uses less energy than conventional rock crushing equipment. Magnetic separation and air classification may be required to remove any residual ferrous materials or papers mixed in with the crushed waste glass (FHWA, 2008).

Since small communities generate relatively low waste glass amounts, adequately sized stockpiles need to be accumulated in order to provide a consistent supply of waste glass that can be practically used for pavement construction applications (FHWA, 2008).

In 2003, the City of Toronto completed a pilot study project using waste glass blended with 50 mm minus crushed concrete for use as granular subbase for road construction. The performance monitoring of this roadway section completed during the trial period indicated no performance related issues for this recycled roadway base. In 2004, another trial section was constructed incorporating waste ceramic material in crushed concrete granular base. To date there have been no reported construction or performance issues associated with its use (JEGEL, 2007).

Waste glass has been used in highway construction as an aggregate substitute in hot mix asphalt in the United States. However, Canadian studies have shown that due to technical limitations, it is not economically feasible to use waste glass or ceramics in hot mix asphalt or portland cement concrete mixtures. See the Technical Limitations section for more details.

Physical and Engineering Properties of Waste Glass

Properties of interest of waste glass when used in granular base applications include gradation, density, friction angle, bearing capacity, durability, and drainage characteristics.

Gradation: Unprocessed crushed glass collected from municipalities can be expected to exhibit a large range of sizes. In general, the coarse crushed glass particles are angular and can contain some flat or elongated particles. In some cases, very sharp particles can be found, however, the smaller glass particle sizes are generally well-rounded. The type of equipment used to crush the waste glass will have an effect on the gradation and shape produced. In general, crushed glass can be expected to be a well-graded material and can yield engineering properties that compare favourably with natural aggregates used in granular base applications. Waste glass should be crushed and screened to produce a material that can be blended with other natural or recycled aggregate materials to meet the grading requirements of the specific granular base/subbase specifications (OPSS 1010, for instance).

Unit Weight and Compacted Density: Crushed glass has a unit weight of about 1120 kg/m^3 which is somewhat lower than the unit weight of conventional aggregate. The compacted density of crushed glass will vary with the size and grading of the glass as well as the degree of contamination (extraneous debris, such as paper and plastic caps). A maximum dry density of approximately 1800 to 1900 kg/m^3 has been reported for the blended granular material, which is also somewhat lower than that of conventional granular material . Crushed glass exhibits a relatively flat moisture-density curve, which indicates that the compacted density is insensitive to moisture content.

Stability: Relatively high angles of internal friction (compared with conventional aggregates) of greater than 50 degrees have been reported for crushed glass with maximum sizes of 19 mm and 6.4 mm. California Bearing Ratio (CBR) test results of crushed glass blended with conventional aggregate were found to exhibit values ranging from 42 to 125 percent for blends of 50 percent glass with crushed rock. Lower glass additions of 15 percent were found to exhibit values almost identical to that of the crushed rock used in the tests (approximately 132 percent).

Durability: Larger size glass particles have marginal durability, as measured by the Los Angeles Abrasion test, with values of approximately 40 to 45 percent. This suggests that additional processing (crushing) of the waste glass would be desirable to eliminate the larger, less durable glass fraction.

Drainage: Crushed glass is a free-draining material that exhibits permeabilities ranging from 10^{-1} to 10^{-2} cm/sec (similar to coarse sand). The permeability depends on the distribution of the glass particle sizes (FHWA, 2008).

The crushed waste glass exhibits lower specific gravity values than natural aggregates, from about 1.95 to 2.4 and about 2.5 for fine waste glass. Breakdown of the crushed glass can occur during handling especially in the larger size particles (JEGEL, 2007).

Physical and Chemical Properties of Waste Ceramics

The physical and chemical (mineralogical) properties of crushed ceramic materials preclude their use as aggregates in Portland cement concrete and hot mix asphalt mixtures. However, based on evaluation of waste ceramic materials by MTO (Senior, Szoke and Rogers, 1994), OPSS 1010 was amended to permit incorporation of up to 15 percent waste ceramic materials by mass in Granular B subbase material. As a component of the 2003 City of Toronto waste glass/ceramic material pilot study, a trial section of a low volume residential roadway was constructed in October 2004 using 15 percent waste concrete material blended with Granular A (crushed concrete) base. While this trial was relatively small, involving less than 50 tonnes of crushed ceramic/porcelain, the blended material met all City of Toronto specification requirements (gradation and physical properties) and there were no problems observed during placement and compaction. Also, environmental analysis of a representative sample of the materials did not indicate any bulk or leachate analysis concerns (JEGEL, 2007).

Toxicity or Environmental Concerns/Impacts

Processed crushed glass can contain some organic debris including paper, plastic labels, wood debris, food residue, plants, cork and inorganic materials such as plastic (caps and fibres), metal (caps and lids), ceramics, glass, bricks, concrete, stones and dust. (JEGEL, 2007)

Technical Limitations

Technical limitations which were reported when using waste glass in hot mix asphalt mixtures in Canada were moisture susceptibility/stripping resistance, ravelling, high tire wear and poor skid resistance. Addition of hydrated lime or other anti-stripping additive is required to mitigate potential stripping problems. It has also been shown that waste glass is generally not recommended for use as concrete aggregate, due to its potential reactivity with Portland cement concrete (alkali-silica reaction), and due to the possible presence of sugars in waste glass that can interfere with Portland cement hydration affecting the final strength of the Portland cement concrete (JEGEL, 2007), however research has been completed on the use of coloured glass to enhance the aesthetics of architectural concrete (ACI, 2004).

References

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C-22 – WOOD WASTES

During the manufacture of products such as lumber, furniture, pallets and paper, it is estimated that less than 50 percent of the tree ends up in the final product (FEMP, 2004). The resultant wood waste which is not used in engineered wood, landscaping mulch, animal bedding or biomass fuel is typically disposed of in landfill. Rather than landfill, consideration can be given to using these wood wastes as lightweight fill for the construction of road embankment foundations.

How it is generated/quantities generated

Wood wastes are classified under a number of different trade names across the country such as sawdust, sawmill waste, hog fuel and bark chips to name a few.

Sawdust is the term given to wood wastes which are generated when cutting wood with a saw. In industrial applications, sawdust is often captured in dust suppression systems in order to prevent ignition.

Hog fuel is a term given to wood waste composed of a blend of tree bark and wood chips. Hog fuel is considered to be lightweight and durable if placed and maintained below the water table and is therefore suitable as a cost-effective alternative material to use in lightweight road embankment construction (T-17/06, 2006).

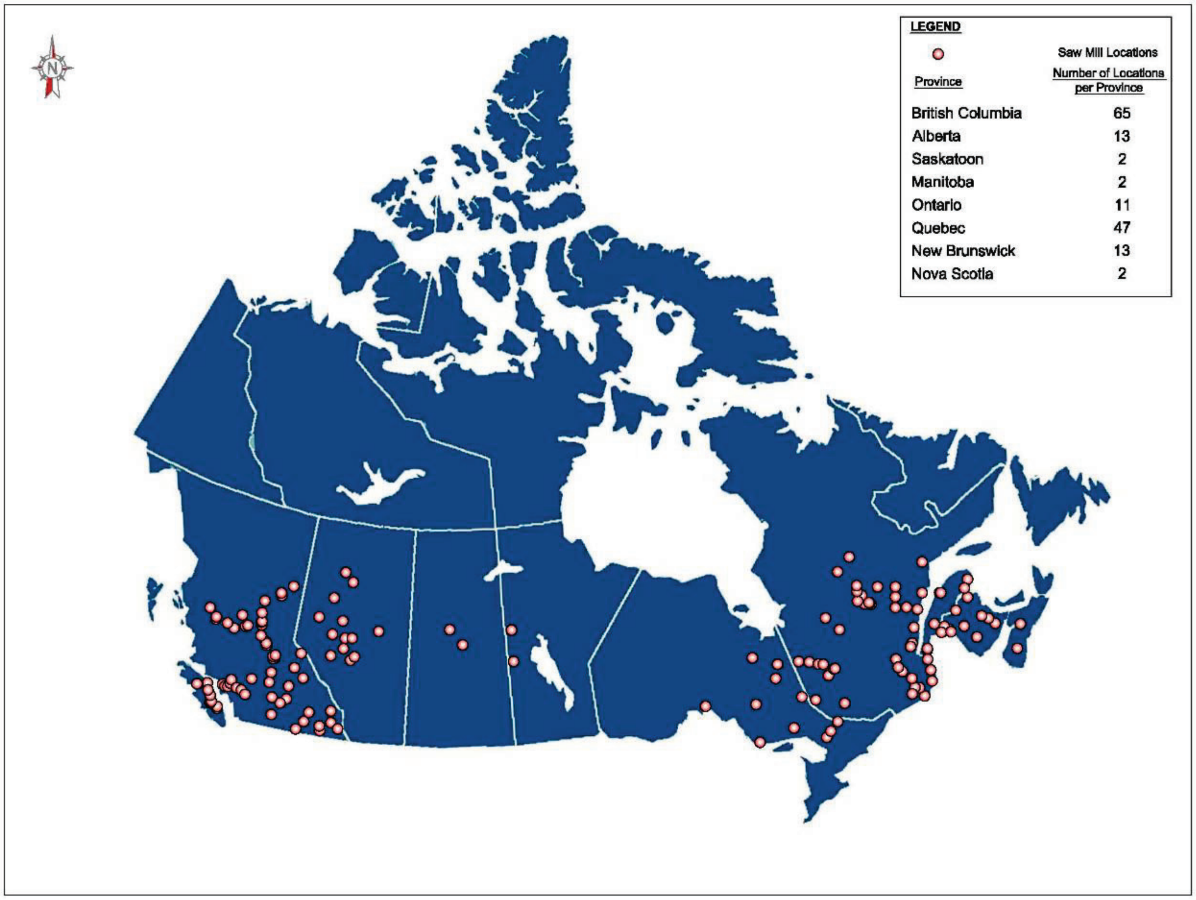
Bark is the term given to the outermost layer of the tree which is exposed to the atmosphere. Bark is an abundant waste product of sawmills and has been used to replace Styrofoam as frost insulation in frost sensitive road construction (Rayner).

Environment Canada estimates that approximately 2 million tonnes of waste wood are disposed of in landfills every year in Canada (Environment Canada, 2012).

Typical sources

If suitable material was not available on or near site as part of cleaning or grubbing activities, waste wood would typically be sourced directly from local sawmills as transporting for distances greater than 75 kilometres may be considered to be uneconomical. The general locations of sawmills across Canada are shown in Figure C22-1.

Figure C22-1. Location of Saw Mills in Canada

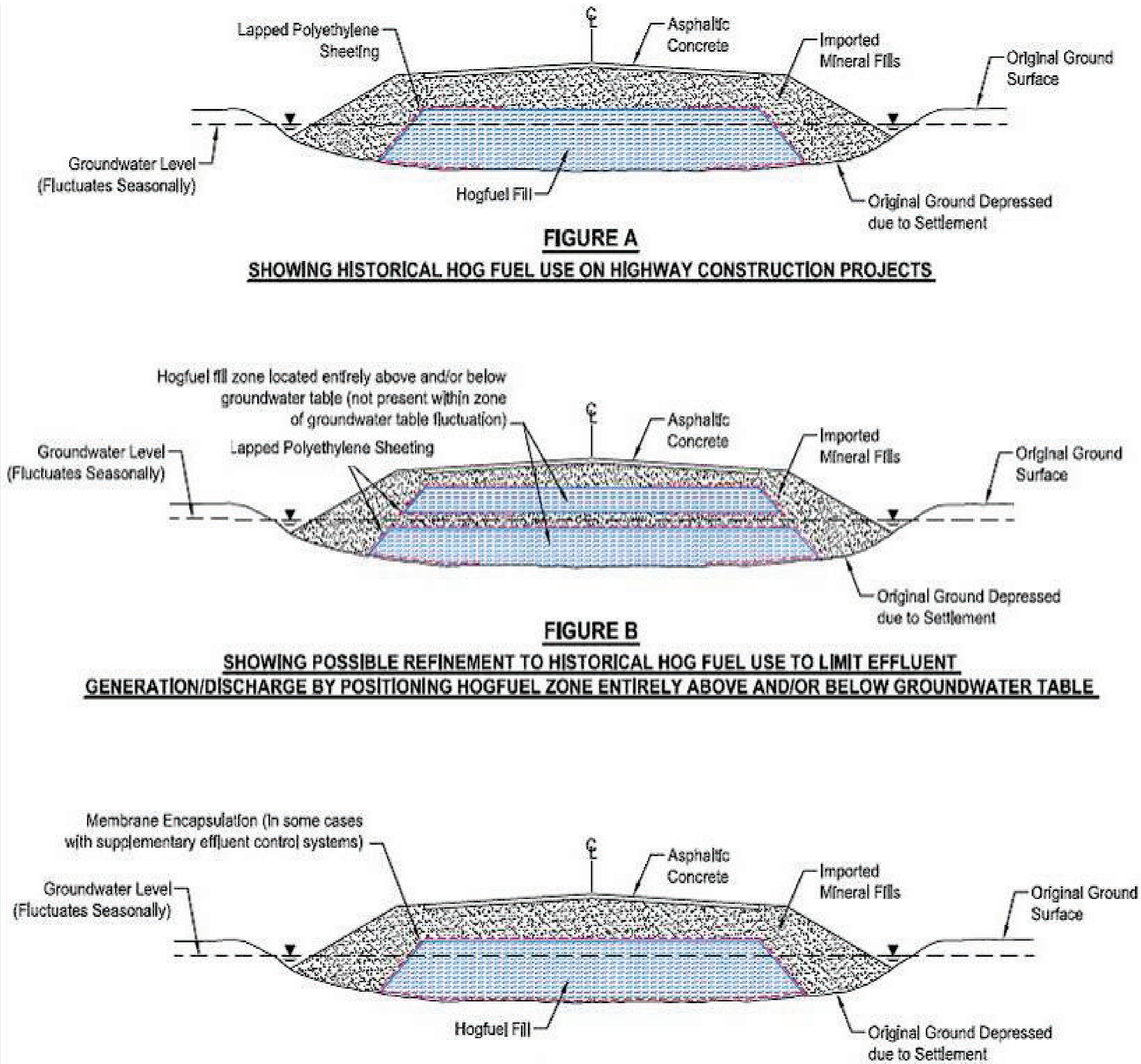


In what forms can wood waste be used and in what quantities

While the use of wood in the construction of 'corduroy' roads is well known historically, the controlled use of wood waste in transportation infrastructure is not common in North America. There have been trials completed in Ontario of tree bark use to replace Styrofoam as insulation in frost sensitive road construction as well as documented use of hog fuel as lightweight fill in highly compressive or environmentally sensitive wetland areas in Washington State (TR News, 1993). In addition, a 1974 Technical Report by the U.S. National Technical Information Service studied the use of sawdust as lightweight fill which had a service life of at least 15 years (FHWA, 1974). In New Brunswick, sawdust is used as a compressible fill material for induced trenches over deep culverts which have a substantial amount of overlying fill.

The only Canadian province which provides guidelines on the use of waste wood as lightweight fill is British Columbia (T-17/06, 2006). The technical circular outlines the approved uses of hog fuel in the construction of lightweight road embankment foundations. The technical circular provides conceptual designs for embankment construction which are reproduced in Figure C22-2.

Figure C22-2. Conceptual Hog Fuel Embankment Designs (T-17/06, 2006)



Engineering Properties of Wood Wastes

The engineering properties of wood wastes can vary greatly depending on the wood type and the processing method. However, some typical engineering properties of hog fuel are shown in Table C22-1 (FHWA, 1974).

Table C22-1. Typical Properties of Hog Fuel

PROPERTY	VALUE
Angle of Internal Friction (°)	31
Cohesion (kPa)	0
Permeability (cm/sec)	1.0×10^{-3}
Moisture Content (%)	Up to 250
Average Unit Weight (kg/m^3)	580

Toxicity or environmental concerns/impacts

Hog fuel can potentially produce leachate which may require consideration of environmental impacts. As a result, design engineers should address the potential for adverse impacts to the environmental in accordance with the following guidelines. Appropriate design features for mitigating leachate problems include locating the hog fuel outside the zone of the fluctuating water table, engineered ditches and containing ponds. In addition, the leachate that may be generated should be controlled and prevented from entering watercourses. Appropriate berms, ditches and containment structures and/or encapsulation materials should be considered in the design. Using aged hot fuel is more acceptable in terms of production of leachate (T-17/06, 2006).

Technical Limitations

The use of cedar as a source of hog fuel should be avoided due to the aforementioned leachate concerns (T-17/06, 2006).

Sawdust should remain above or below the groundwater level so it is not subject to alternate wetting and drying that could result in decay (TR News, 1993).

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APPENDIX D

Best Practices Survey

BEST PRACTICES GUIDE FOR THE USE OF RECYCLED MATERIALS IN TRANSPORTATION INFRASTRUCTURE PROJECTS

SURVEY

Name: ______________________ Title: ______________________

Agency: ____

E-Mail: ______________________ Phone: ______________________

TYPES OF MATERIALS

1) Does your agency use any of the following in-situ recycling procedures? Please circle if used, and where possible, indicate the approximate quantity completed in 2010 including the units (m^2, for instance), and the associated specification(s) used to control quality.

2) Does your agency use or has used in the past any of the following residuals or by-product materials as substitutes for natural aggregate or in bulk aggregate-related uses? For each material, please indicate on what basis (Trial, Occasionally, Regularly, Banned) along with the number of years of use. If possible, please complete Form 1 (appended) for each material indicating the application, specification and source of the material.

3) Does your agency permit the use any of the following residuals or by-products as replacements in manufacturing processes or substitutes for materials in cementitious applications? Please circle if used, and where possible, indicate the approximate quantity completed in 2010 including the units (m^2, for instance) and the associated specification(s) used to control quality.

EXPERIENCES AND ECONOMICS

1) Are recycling options considered during design?

2) If cost savings are a major impetus to the use of recycled materials, what is the typical cost savings that you would expect by using certain recycled materials? *Please identify the material and application along with typical cost savings observed*

3) How do you determine what recycling technologies and materials are appropriate for your agency/project?

4) Have any of the methods that were identified in Form 1 been particularly successful for your agency?

5) Are there any specific items that discourage your agency from using more recycled materials in your transportation infrastructure projects?

6) If you have experienced any above mentioned problems, please briefly elaborate below?

7) If you have experienced any environmental related problems, please briefly elaborate below?

POLICIES THAT PROMOTE RECYCLING

1) Does your agency have a policy on the reuse and recycling of construction materials? If so, can we have a copy?

2) What incentives would be useful to encourage your agency and contractors completing your work to increase the use of recycled materials?

3) Would your agency consider the implementation of a zero waste policy for transportation infrastructure projects, or has your agency developed other recycling goals/targets? If so, for what materials?

4) Would you consider giving bidders who offer recycling preference in the bidding process? What would be the best way to manage this type of incentive?

RESEARCH AND DEVELOPMENT

1) Do you currently have any research underway on the use of recycled materials in transportation infrastructure projects?

    b) What specific construction materials have been addressed by research within your agency?

2) Are there any other issues you would like to see addressed in a best practices guide on the use of recycled materials in transportation infrastructure projects?

BEST PRACTICES GUIDE FOR THE USE OF RECYCLED MATERIALS INTRANSPORTATION INFRASTRUCTURE PROJECTS

QUESTIONNAIRE PRIMER

TYPES OF MATERIALS

1) In-Situ Recycling Procedures

In this section we would like to know if your agency uses any of the following in-place recycling techniques. If these technologies are in fact used in your jurisdiction we are also interested in the specification(s) that are used to control quality. If available, we would also like to know the approximate quantity completed in 2010 (2009 is acceptable if the process was not used in 2010, but please advise) including the units of measure used by your agency to calculate the quantities along with the typical processing depth(s) (more than one can be circled).

i. Cold In-Place Recycling (CIR)

   CIR is an on-site process for the rehabilitation of asphalt-surfaces (on both flexible and composite pavements) to depths up to 150 mm. The old asphalt is milled to a specified depth, mixed with emulsified asphalt, and repaved to the required grade and profile. A surface treatment or hot-mix asphalt wearing surface is applied after the CIR mix has properly cured.

ii. Hot In-Place Recycling (HIR)

   The asphalt pavement surface is heated, softened and scarified to depths of 20 to 60 mm, the scarified material is then remixed, placed, and compacted as a part of a continuous in-place process. New aggregates, new asphalt cement, recycling/softening agents, and/or new HMA (commonly referred to as ‘admix’) can also be added to improve the engineering properties of the existing pavement and for increased structural capacity (for a total treatment thickness up to 75 mm).

iii. Full Depth Reclamation (FDR) with Foamed Asphalt Stabilization

   FDR with foamed asphalt stabilization is a cold recycling process whereby the full thickness of the asphalt concrete and a predetermined portion of the underlying granular base and subbase are uniformly pulverized and blended with corrective aggregate (when necessary to obtain a suitable mix design gradation) followed by addition and mixing of foamed asphalt with the pulverized material (typically at addition rates between 2 and 3.5 percent) to create a stabilized base.

iv. Partial Depth Reclamation with Foamed Asphalt

   Partial depth reclamation with foamed asphalt, also known as CIREAM in Ontario, is similar to the FDR process however typically only a portion of the asphalt concrete thickness is reclaimed without blending any of the underlying granular base or subbase. In this process, the reclaimed asphalt concrete is screened, weighed and a predetermined amount of foamed asphalt is blended and placed using standard paving techniques using a pugmill type mixer/paver.

v. In-Place Reprocessing

In place reprocessing is a process whereby the full thickness of the asphalt concrete and a predetermined portion of the underlying granular base and subbase are uniformly pulverized producing a new granular layer.

vi. Rubblization of Portland Cement Concrete Pavement

Rubblization is an in-place rehabilitation technique that involves breaking the concrete pavement into pieces having a nominal maximum size of about 75 mm or less above and 200 mm or less below any reinforcement (AI, 2000). This process results in a structurally sound, rut resistant base layer which prevents reflective cracking (by obliterating the existing concrete pavement distresses and joints) that can then be overlaid with asphalt or portland cement concrete.

2) Use of Recycled Aggregate in Bulk Uses

In this section we would like to know if your agency uses any of the listed residuals or by-product materials as substitutes for natural aggregate or in bulk aggregate-related uses. The bulk uses in transportation infrastructure considered for this project are: asphalt concrete; portland cement concrete; granular base; embankment or fill; stabilized base; and flowable fill. For each material that your agency uses, we would like you to indicate your relative experience with the material by indicating on what basis (Trial, Occasionally, Regularly, Banned) the material is used along with the number of years you have been using it. In addition, if the information is readily available, we would like you to complete the attached Form 1 (appended) for each material that you have identified so that we can get an understanding of the application of the bulk material, the specification(s) used to control quality and where you are sourcing the material.

Some brief examples of typical applications of by-product materials use as bulk aggregate are provided below.

a. Hot mix asphalt baghouse fines are dust particles that are captured from the exhaust gases of asphalt mixing plants. Secondary collection equipment called baghouses is commonly used to capture these very fine sized materials. Most asphalt producers whose plants are equipped with baghouses try to recycle as much of the dust back into their own paving mixes as possible. Although precise figures are not available, it is estimated that as much as 80 to 90 percent of baghouse fines are currently being recycled into hot mix asphalt.

b. Blast furnace slag is a nonmetallic co product produced in the production of iron. It consists primarily of silicates, aluminosilicates, and calcium-alumina-silicates. The molten slag, which absorbs much of the sulphur from the charge, comprises about 20 percent by mass of iron production. Various bulk aggregate products include air-cooled blast furnace slag, expanded or foamed blast furnace slag, pelletized blast furnace slag and granulated blast furnace slag.

The majority of blast furnace slag being produced is air cooled blast furnace slag (ACBFS). ACBFS has been used as an aggregate in portland cement concrete, asphalt concrete, concrete, asphalt and road bases. Pelletized blast furnace slag has been used as lightweight aggregate and for cement manufacture. Foamed slag has been used as a lightweight aggregate for portland cement concrete. Granulated blast furnace slag has been used as a raw material for cement production and as an aggregate and insulating material.

c. Coal bottom ash and boiler slag are coarse, granular, incombustible materials that are collected from the bottom of furnaces that burn coal. The majority of coal bottom ash and boiler slag are produced at coal-fired electric utility generation stations, although bottom ash and boiler slag are produced by industrial and institutional coal-fired boilers and also from independent coal-burning electric generation facilities. Bottom ash is used mainly in transportation applications such as structural fill, road base material, and as snow and ice control products but has also been used as aggregate in lightweight concrete masonry units. The leading boiler slag application is blasting grit and roofing shingle granules however it is also used in transportation applications including structural fills, mineral filler, and snow and ice control and as aggregate in asphalt paving and as a road base and subbase.

d. Coal fly ash is produced from burning pulverized coal in a coal-fired boiler. It is used the majority of the time in the production of concrete, concrete products, and grout.

e. Coal fired power plants installed flue gas desulphurization (FGD) technology for reducing SO_2 emissions. The main product of dry FGD systems is calcium sulphite with minor amounts of calcium sulphate. Fixated or stabilized calcium sulphite FGD scrubber material has been used as an embankment and road base material.

f. Foundry sand is a high-quality silica sand that is used to form moulds for ferrous (iron and steel) and nonferrous (copper, aluminum, brass, etc.) metal castings. While the majority of foundry sand is recycled into the original processes, some other uses include: Aggregate replacement in asphalt mixtures, portland cement concrete; Source material for portland cement; Sand used in masonry mortar mixes; and embankments, retaining walls, subbase, flowable fills, barrier layers, and HMA mixtures.

g. Kiln dusts are fine by-products of portland cement and lime high-temperature rotary kiln production operations that are captured in the air pollution control dust collection system. Most of the cement kiln dusts produced is reused within the cement plant. Both cement and lime kiln dusts have been used as pelletized lightweight aggregate material, as mineral filler in asphalt pavements, and as a fill material in earth embankments.

h. Mineral processing wastes are referred to as wastes that are generated during the extraction and beneficiation of ores and minerals. The mining and processing of mineral ores results in the production of large quantities of residual wastes that are for the most part earth or rock-like in nature. Many mineral processing waste materials have limited potential for use as aggregates because of their fineness, high impurity content, trace metal leachability, propensity for acid generation, and/or remote location (i.e., away from aggregate markets).

However, when the location and material property characteristics are favourable, some sources of waste rock or coarse mill tailings may be suitable for use as granular base/subbase, railroad ballast, portland cement concrete aggregate, asphalt aggregate, flowable fill aggregate or fill, and engineered fill or embankment.

i. Municipal solid waste (MSW) combustor ash is the by-product that is produced during the combustion of municipal solid waste in solid waste combustor facilities. Most of the ash that is recovered is generally used as a landfill cover material however there is some commercial use of ash as a granular subbase in road construction.

j. Nonferrous slags are produced during the recovery and processing of nonferrous metal from natural ores. Examples of nonferrous slags include: copper and nickel slags; phosphorous slags; and lead, lead-zinc and zinc slags. Copper and nickel slags have been used as granular base and embankment materials, aggregate substitutes in hot mix asphalt, mine backfill materials, railway ballast materials, grit blast abrasives, roofing granule material, and in the manufacture of blended cements (granulated copper and nickel slags). Phosphorus slag has been used as an aggregate substitute in hot mix asphalt, as a lightweight masonry aggregate, and as cement kiln feed. Some zinc slags have reportedly been used in the manufacture of ceramic tiles and as an aggregate substitute in hot mix asphalt.

k. Quarry by-products are produced during crushing and washing operations. There are three types of quarry by-products resulting from these operations: screenings, pond fines, and baghouse fines. Quarry by-products have been used as an embankment material with some limited use in base or subbase and hot-mix asphalt applications.

l. Reclaimed asphalt pavement (RAP) is the term given to removed and/or reprocessed pavement materials containing asphalt and aggregates. These materials are generated when asphalt pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement. Recycled RAP is almost always returned back into the roadway structure in some form, usually incorporated into asphalt paving by means of hot or cold recycling, but it is also sometimes used as an aggregate in base or subbase construction.

m. Recycled concrete aggregate (RCA) consists of high-quality, well-graded aggregates (usually mineral aggregates), bonded by a hardened cementitious paste. RCA can be used as an aggregate for cement-treated or lean concrete bases, a concrete aggregate, an aggregate for flowable fill, or an asphalt concrete aggregate. It can also be used as a bulk fill material on land or water, as a shore line protection material (rip rap), a gabion basket fill, or a granular aggregate for base and trench backfill.

n. There are two types of roofing shingle scraps. They are referred to as tear-off roofing shingles, and roofing shingle tabs, also called prompt roofing shingle scrap. Tear-off roofing shingles are generated during the demolition or replacement of existing roofs. Roofing shingle tabs are generated when new asphalt shingles are trimmed during production to the required physical dimensions or from "out-of-spec" shingles. The typical use for recycled shingles is in the production of hot mix asphalt (HMA) however they have also been used in road construction applications in addition to HMA applications.

o. Scrap tires are typically managed as a whole tire, a slit tire, a shredded or chipped tire, as ground rubber, or as a crumb rubber product. Currently, the largest single use for scrap tires is as a fuel in power plants, cement plants, pulp and paper mill boilers, utility boilers, and other industrial boilers however ground tire rubber has been used as lightweight fill as well as a fine aggregate addition (dry process) in asphalt friction courses. Crumb rubber has been used as an asphalt binder modifier (wet process) in hot mix asphalt pavements.

p. Sewage sludge ash is the by-product produced during the combustion of dewatered sewage sludge in an incinerator. Sludge ash has been previously used as a raw material in portland cement concrete production, as aggregate in flowable fill, as mineral filler in asphalt paving mixes.

q. Steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling. The primary applications for steel slag in the United States are its use as a granular base or as an aggregate material in construction applications.

r. Fluorogypsum and phosphogypsum are sulphate-rich by-products generated during the production of hydrofluoric and phosphoric acid, respectively. Fluorogypsum is not being used in any commercial applications; however, fluorogypsum has been evaluated for use as a road base material. Phosphogypsum has been recovered and reused with some success in stabilized road bases, unbound road bases, and roller-compacted concrete.

s. Traditionally, glass recycling has involved the collection and sorting of glass by color for use in the manufacture of new glass containers. Waste glass has been used in highway construction as an aggregate substitute in asphalt paving. Crushed glass or cullet, if properly sized and processed, can exhibit characteristics similar to that of a gravel or sand. As a result, it has been used in some demonstration projects (City of Toronto) as a road base or fill material.

t. Waste ceramics are the by-product of the recycling of porcelain toilets, tubs, etc. When properly crushed and sized, it can be used (in limited quantities) as a additive to traditional road base materials.

3) Use of Recycled Aggregate in Cementitious Applications

In this section we would like to know if your agency uses any of the listed residuals or by-product materials as replacements in manufacturing processes or substitutes for materials in cementitious applications. Typical cementitious applications would include: asphalt cement binder; portland cement binder; and soil and or base stabilization. For each material that your agency uses, we would like you to indicate (circle) the material and provide information (if readily available) on the approximate quantity used (including the unit of measure) along with the specification(s) used to control quality. Typical sources of supplemental cementitious materials have been described in the previous section (Section 2).

EXPERIENCES AND ECONOMICS

1) In this section we are trying to determine what considerations are currently being made in your agency when deciding on the use of various recycled materials. You can circle as many of the options as are applicable.

2) If the information is readily available to you, we would like to know what kind of cost savings you have enjoyed by using recycled materials. For each of the materials that you have cost data for, you can either give it as a percentage, as a dollar figure or any other unit of measure that you see fit.

3) We would like to know how your agency determines what recycling technologies and materials are appropriate for your agency/project? This could include literature reviews from other jurisdictions, construction trials (by your agency or by contractor associations), construction projects or other methods.

4) In this section we are interested in any methods or materials that have a proven track record with your agency which you would definitely recommend to other agencies.

5) We would also like to know about any of the methods or materials that you have had difficulties with in your agency which you would discourage the use of without technical improvements to the product along with identify generally what the issues were. If there are a number, then we would like to get as many as possible and will fill out additional forms.

6) If you have experienced any problems in section 5 then any associated commentary that you could provide in this regard would also be helpful.

7) In this section we would like to know specifically about environmental related problems that you may have encountered in the past.

APPENDIX E

Material Evaluation Checklist

MATERIAL EVALUATION CHECKLIST

STEP 1: Select Recycled Material and Application

(describe proposed material and in what applications it will be used)

STEP 2: DEFINE/EVALUATE THE ISSUES

History and Previous Experience

History

□ Has the recycled material previously been used anywhere? If so, identify uses.

□ Is there any information available about the source of the recycled material? If so, obtain it.

□ Has the material been previously used for transportation applications? If so, identify applications.

□ Has the material been used in geographically diverse locations? If so, identify locations.

□ Has the material been previously used in a similar application? If so, identify location.

□ Has the material been used in other agencies? If so, identify agencies.

□ Have other agencies approved the material for this use? If so, identify agencies.

Previous Experience

□ Is there any information available about important prior experiences (such as previous use, prior objections and similarity with other materials?) if so, obtain this information.

□ Are there experts available to discuss prior experiences? (This can include regulators, scientists, practitioners, waste generators and associations). If so, contact the experts.

□ Is there any published literature about prior experiences? If so, obtain the information.

Engineering and Materials Properties

Engineering

□ Is information available about the engineering properties of the material? (such as gradation, bulk density, durability and compaction data). If so, obtain this information.

□ Is the material characterized with respect to time-dependent engineering properties? (such as time-dependent variation in gradation, bulk density, durability and compaction). If so, collect this information.

□ For the proposed application, are there appropriate engineering criteria for the product? (such as durability, grain size and compaction requirements). If so, collect this information.

□ Is engineering information available about important prior experiences? (such as previous use, prior performance criteria and similarity with other materials). If so, gather this information.

Material Properties

□ Is information available about the material properties of the material? (such as loss on ignition, mineralogy and pozzolanic activity of the waste material). If so, collect this information.

□ Is the recycled material characterized with respect to the time-dependent material properties? If so, collect this information.

□ For the proposed application, are there material properties criteria for the product? If so, identify the criteria.

Environmental, Health and Safety (EHS) Properties

□ Is information available about the environmental properties of the material? (such as information about the total elemental composition, total available element composition and volatile and semi-volatile organics composition data). If so, obtain this information.

□ Is the material characterized with respect to time-dependent environmental properties? (such as time-dependent variation in total elemental composition, total available element composition and volatile and semi-volatile organics composition. If so, collect this information.

□ For the proposed application, are there appropriate environmental criteria for the product? (such as leaching data, total content data, particle size, etc). If so, obtain this information.

□ Is environmental information available about prior experiences? (such as previous use, prior performance criteria and similarity with other materials). If so, gather the information.

□ Have there been any environmental assessments undertaken relative to the use of the proposed material? If so, summarize this information.

Public Health

□ Are there Material Safety Data Sheets (MSDS) for the recycled materials? If so, collect them.

□ Have there been health risk assessments (HRA) undertaken relative to the proposed use of the material? If so, summarize the information.

Safety

□ Have there been prior OSHA issues for generation, processing, storage and use in previous projects? If so, summarize the information.

Implementation Issues

□ Are there any political constraints? If so, describe them.

□ Are there any regulatory constraints? If so, describe them.

□ Are there any public acceptability constraints? If so, describe them.

Recycling Issues

□ Are there any recycling or life-cycle issues? If so, identify them.

□ Has the material or its application been reused within other areas of the transportation infrastructure environment? If so, identify them.

Economic Issues

□ Are there any economic constraints against using the material? If so, identity them.

STEP 2 Summary of any Issues Identified

Historical Experience ____

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Engineering Issues ____

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Environmental Issues ____

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Implementation Issues ____

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____

Recycling Issues ____

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____

Economic Issues ____

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Is the Information Sufficient to Proceed to a Stage 1 Screening?

STEP 3: STAGE 1 SCREENING

Engineering, Environmental and Health and Safety Screening Checklist

Parameter: *Material Source*

To determine whether the proposed material is generated from similar source materials and the same process or operation as the reference material.

- □ Will the quality of feedstock materials to be used in the production or generation of the proposed material be sufficiently similar to that used to produce or generate the reference material so that the engineering and environmental properties of the proposed material will be not significantly impacted and will still be comparable to the referenced material?
- □ Will the operating conditions associated with the production or generation of the proposed material be sufficiently similar to that of the reference material so that the engineering and environmental properties of the proposed material will not be significantly impacted and will still be comparable to the reference material?
- □ Will the post-production operations (e.g. material processing, handling and storage) associated with the production or generation of the proposed material be sufficiently similar to the reference material so that the engineering and environmental properties of the proposed material will not be significantly impacted and will still be comparable to the reference material?

Parameter: *Engineering and Environmental Properties*

Assess whether there is sufficient data to compare the engineering properties of the proposed material and reference material, and whether the respective properties are sufficiently similar to approve the proposed material for use.

- □ Is appropriate engineering and environmental property data available for both the proposed and reference materials, and is the data reliable?
- □ Can it be determined that the proposed and reference materials have statistically similar environmental and engineering properties that are in conformance with the specifications of the proposed application, and are they comparable?

Parameter: *Field Performance*

Determine whether the reported historical data for the reference material provided gives reasonable assurance that the proposed material will provide satisfactory performance in the intended application.

- □ Is there a sufficient and reliable historical performance record available?

- □ Are there experienced personnel available with whom to review the results of the historical performance data, and have the above-referenced contacts provided positive feedback regarding the application?
- □ Is the historical performance data of the material sufficient to warrant a Stage 1 approval?

Stage 1 Recycling Screening Checklist

Parameter: *Engineering Acceptability*

If the proposed material is incorporated into the engineered product, could it significantly impact the engineering quality of the product if used in a secondary application at the completion of its useful service life?

- □ Could the proposed material adversely impact the production process during a post-service life application?
- □ Could the proposed material properties be altered during either its service life or post-service life processing to such an extent that it could significantly impact the properties of the secondary material?

Parameter: *Environmental Acceptability*

If the proposed material is incorporated into the engineered product, could it significantly impact the environmental quality of the product if used in a secondary application at the completion of its useful service life?

- □ Could the proposed material adversely impact the environment (air, water, or soil quality) during post-service life processing if introduced into a secondary application?
- □ Could the proposed material adversely impact the environment (air, water, or soil quality) during its post-service life if introduced into a secondary application?
- □ Could the proposed material adversely impact the environment (air, water, or soil quality) if disposed of as construction and demolition debris after its initial service life?

Parameter: *Worker Health and Safety Acceptability*

If the proposed material is incorporated into the engineered product, could it significantly impact the worker health and safety properties of the product if used in a secondary application at the completion of its useful service life?

- □ Could harmful fugitive dust or volatile gaseous emissions resulting from the use of the proposed material impact worker health or safety during post-service life processing or construction activities?

□ Could the use of the proposed material create a hazard to the physical safety of workers during post-service life processing or construction activities?

Stage 1 Implementation Screening Checklist

Parameter: *Institutional Acceptability*

Consider the probability that the regulatory community will approve and the technical community will accept and utilize the material in the proposed application.

□ Rate the degree of difficulty that can be anticipated in obtaining approval to incorporate the material-application match into existing construction specifications (High (H), Medium (M) or Low (L)).

□ Rate the degree of difficulty that can be anticipated prior to the receipt of environmental approvals from regulatory agencies (H, M or L)

□ Rate the degrees of reluctance that engineers might have in specifying the material in the proposed application (H, M or L)

□ Rate the degrees of reluctance that contractors might have in utilizing the material in the proposed applications (H, M or L)

Parameter: *Political Acceptability*

Consider the degree to which public officials will support or impede the proposed application.

□ Rate the degree to which political opposition could impede the application (H, M or L).

Parameter: *Public Acceptability*

Assess the degree to which the public will accept the proposed material-application strategy.

□ Rate the degree to which the public opposition due to perceived environmental, health, safety, or economic impacts would impede the application (H, M or L).

Stage 1 Economic Screening Checklist

Material Cost

$D_P = P_{RM} + C_{PR} + C_{ST} + C_{LD} + C_{TR} + P$

□ Is D_P < or = D_C? (where D_C = Delivered price of conventional material)

Installation Cost

$C_{IP} = C_{DR} + D_P + C_C + C_{TI}$

□ Is C_{IP} < or = C_{IC}? (where C_{IC} = Cost of installation using conventional materials)

Parameter: *Life-Cycle Cost*

$A_{CP} = C_{IP}\, CRF(i,n) + C_{AM}$

□ Is A_{CP} < or = A_{CC}? (where A_{CC} = Annual cost using conventional materials)

STEP 3 STAGE 1 SCREENING SUMMARY

Engineering ____

____

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Environmental, Health, Safety ____

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____

Recycling ____

____

____

Implementation ____

____

____

Economic ____

____

____

Is existing information sufficient to accept or reject proposed material? If not, proceed to STEP 4 - Stage 2 Laboratory Testing

STEP 4: STAGE 2 LABORATORY TESTING

The Stage 2 evaluation screen is intended to characterize the engineering and materials properties and the environmental, health and safety properties of the proposed recycled material and its application product. These data can then be compared with established criteria or with the performance of reference materials using available laboratory and analytical engineering and environmental protocols.

In a Stage 2 engineering and materials properties evaluation, a laboratory testing program must be developed that will provide sufficient data to demonstrate that the proposed material is suitable for use in the proposed application. Inherent in the evaluation is that laboratory testing requires assessment of the engineering and materials performance of the proposed material as well as the engineering and materials performance of the product or the application it will be used in.

In a Stage 2 environmental, health and safety laboratory evaluation, a laboratory testing program must be developed that will provide sufficient data to demonstrate that the proposed material is suitable for use in its intended application. Inherent in the evaluation is that laboratory testing requires assessment of the environmental performance of the proposed material as well as the environmental performance of the product.

It is important to consider engineering and materials performance and environmental performance in potential post-service life utilization scenarios. While these reuse scenarios cannot be precisely described, it is important to identify to the extent possible future engineering and environmental issues that may arise if the recycled material is reused.

Is the information obtained through the Stage 2 laboratory test sufficient to accept or reject material? If not, proceed to STEP 5 – Stage 3 Field Evaluation

STEP 5: STAGE 3 FIELD EVALUATION

The Stage 3 field testing stage is most applicable in situations where the proposed recycled materials has not been used historically so there is little or no field data, there is little or incomplete historical data for the recycled material and more field data are needed, or the proposed recycled material is being considered for new use in applications and there is no pertinent field data. Both short-term and long-term monitoring activities may be required.

Short-term monitoring activities are designed to evaluate how the new material might affect the application during the end-product production process, such as asphalt or Portland cement concrete production, and during and/or immediately after construction.

Long-term monitoring activities are designed to evaluate how the proposed application performs during the post-construction period, and can involve a time period ranging from several years up to the design life of the application.

To undertake a Stage 3 evaluation, it is recommended that a demonstration test plan be prepared that delineates the field monitoring requirements, acceptable specifications or performance criteria be identified to evaluate results of the field demonstration and the data be statistically evaluated to determine if specifications are met or if performance is similar to that of appropriate reference materials.

- ☐ Criteria Met (proceed to internal approvals process)
- ☐ Criteria Not Met (additional screening or laboratory testing required or material rejected)
  - ☐ additional screening or laboratory testing required
  - ☐ material rejected